OPTIMAT BLADES: Results and Perspectives

A.M. van Wingerde
Knowledge Centre WMC
A.M.vanWingerde@wmc.tudelft.nl

D.R.V. van Delft
Knowledge Centre WMC
D.R.V.vanDelft@wmc.tudelft.nl

L.G.J. Janssen
Energy research Centre of the Netherlands
l.janssen@ecn.nl

Th. P. Philippidis
University of Patras
philippidis@mech.upatras.gr

P. Brøndsted
RISØ National Laboratory
povl.brondsted@risoe.dk

A.G. Dutton
Rutherford Appleton Laboratory
A.G.Dutton@rl.ac.uk

T.K. Jacobsen
LM Glasfiber A/S
tkj@lm.dk

R.P.L. Nijssen
Knowledge Centre WMC
R.P.L.Nijssen@wmc.tudelft.nl

C.W. Kensche
Deutches Windenergy-Institut GmbH
Christoph.Kensche@dlr.de

D. J. Lekou
CRES
dlekou@cres.gr

D. van Hemelrijck
Vrije Universiteit Brussel
dvhemelr@vub.ac.be

Abstract:

In a major European research project, OPTIMAT BLADES, a large number of material tests have been conducted. For the first time, a material for wind turbines has been characterised in full detail in a single consistent project in terms of static, fatigue and residual strength as well as stiffness. The extensive investigation of the material, a glass expoy with either 0° (UD) or a combination of 0° and ±45° layers (MD), has revealed new and sometimes unexpected material and testing aspects. New coupon geometries and tests procedures have been established for fatigue and residual strength testing as well as for biaxial loading.
Keywords: material properties tests standards.

1 Introduction

This paper outlines the first results and findings of the project OPTIMAT BLADES, a M€ 4.4 research project, which was started in January 2002. More details will be shown in a workshop for the European wind energy industry, which is to be held adjacent to the EWEC conference, on the afternoon of Thursday March 2 2006.

1.1 Background of the project

In the past, various programmes have been carried out to investigate the behaviour of materials for rotor blades. This has led to design recommendations that have proven to be essential for designing the blades. However, not all the different aspects of the complex loading and stress state have been addressed properly and on some aspects contradictory effects are reported. It is concluded that research carried out to date has limitations, which restrict the effectiveness of current design recommendations.

In order to be able to build larger wind turbines in an economical way, it is necessary to fully utilise the material properties. Very large blades may even become practically impossible without further knowledge of the material behaviour since a major component of the loads on the material is the blade mass itself. Therefore, a consistent approach to material testing and use in design recommendations is required, covering all major aspects, as well as interactions.

1.2 Aim of the project

The project aims to provide a consistent and integral approach to the design of rotor blades. It offers a basis for updated design recommendations, necessary for a full utilisation of the material as required for large rotor sizes.
The static and fatigue behaviour are investigated for:

- Constant amplitude fatigue
- Variable amplitude fatigue
- Bi-axial stress state
- Extreme conditions
- Thick and repaired laminates

Furthermore, a number of interactions between these aspects are investigated as well.

2 Organisation of the project

In order to achieve the stated goal of the project and maintain a clearer overview of the project the consortium partners were organised in a number of committees and task groups, as outlined in Figure 1.

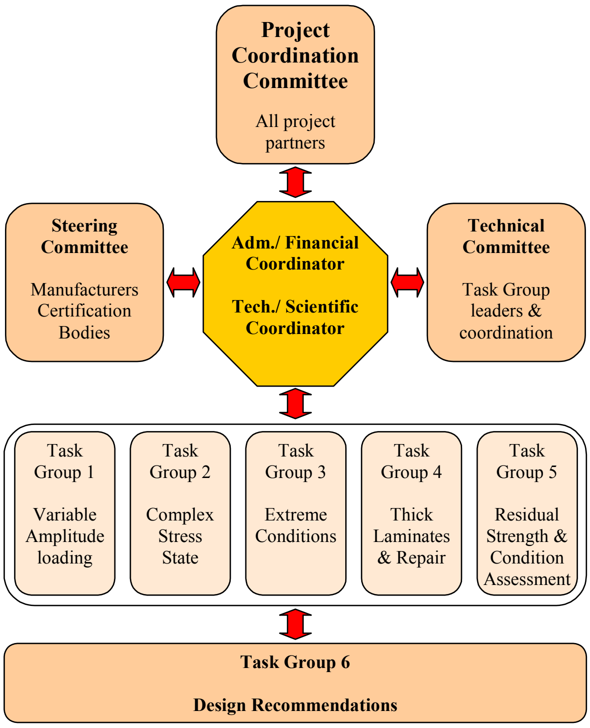


Figure 1 Organisation of OPTIMAT consortium

The main work within the project has been divided into six task groups. Task groups (TG) 1 to 5 carry out the main testing work, consisting of currently over 2500 tests that have been reported in the database OPTIDAT. The participants are research institutes and industry from 7 countries. Task group 6 converts the results of task groups 1 to 5 into design recommendations.

A technical committee monitors the technical progress, whereas the steering committee checks the relevance for the industry. The project coordination committee handles the formal and legal matters in the consortium, whereas the administrative/financial coordinator handles the paperwork for Brussels, and the technical/scientific coordinator, also the chair of the technical committee (and of TG6, until DNV took over this task) oversees the technical coordination.

3 Results per task group

3.1 Task Group 1

Variable Amplitude Loading

In this group, basic material data, such as the effects of uniaxial static load, constant amplitude fatigue load at various R-ratios ($R=\sigma_{min}/\sigma_{max}$) have been determined as a basis for the whole project. S-N lines have been established for a number of R-ratios. The information was used to derive a constant life (CL) diagram for the material. A comparison with the GL guidelines shows major differences, see Figure 2.

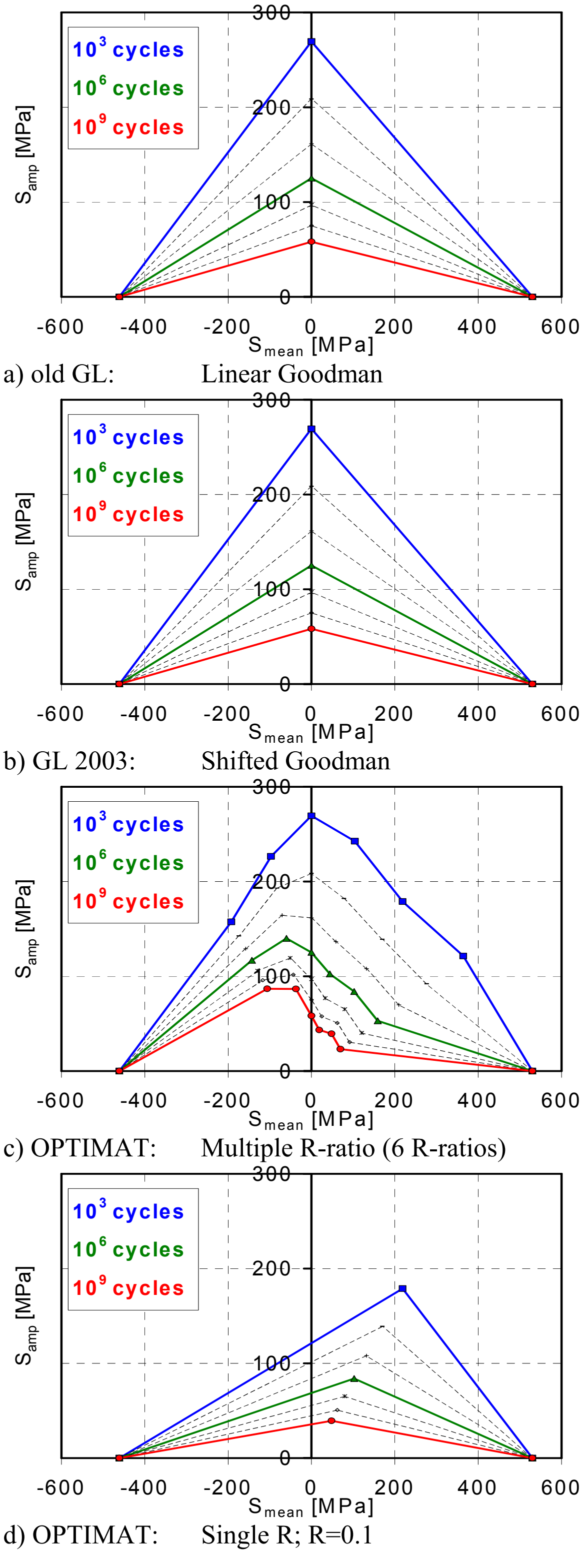


Figure 2 various CL diagrams

Furthermore, fatigue test have been carried out with block tests and variable amplitude loads.

Another work carried out within this task group is the generation of a new version of the WISPER spectrum [1], which can be used to rank materials for wind turbines. The NEW WISPER spectrum differs from the old one in that it is more representative for the modern variable speed turbines. Compared to the current WISPER spectrum, it has fewer cycles per block and fewer load levels, see Figure 3 and Table 1. WISPER X is a condensed version of the WISPER spectrum, aimed at reducing the testing time by omitting the many small cycles.

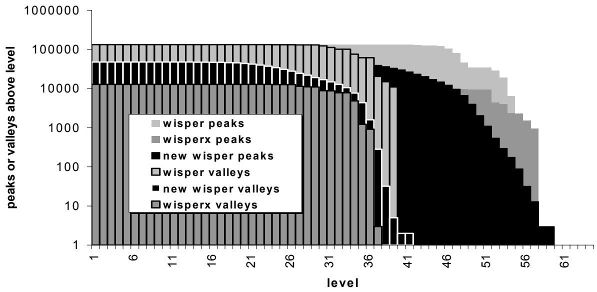


Figure 3 Old and new WISPER spectrum

Spectrum	WISPER	WISPERX	NEW WISPER
Min. level	1	1	5
Max. level	64	64	59
σ=0 level	25	25	22
# Of cycles	132711	12831	47735
Av. R-ratio	0.394	0.248	0.213
Cum. Levels	3612010	487864	1397142
Av. Level	41	41	34
Av. Δlevel	14	19	15
Max. at segment	34482	5298	95459
Min. at segment	123303	13482	1

Table 1 Comparison between old and new WISPER spectrum

3.2 Task Group 2

Complex Stress State

Materials are typically characterised by uni-axial tests, as these are more easily carried out. However, the effect of multi-axial stress states is typically quite important, even for isotropic materials like steel. For typical wind turbine materials, such as Uni-Directional (UD) fibre reinforced materials, which are highly anisotropic, this effect is even more important: the fibres are typically oriented in the direction of the main load. In that case, even relatively small forces in the other direction can have highly detrimental effects on the strength of the material.

In order to test the behaviour of the material under bi-axial stress conditions, unidirectional tests where the material was loaded at various angles to the main fibre orientation (see Figure 4), were augmented by tests on cruciform test specimens using four tightly controlled actuators [2] (see Figure 5,), as well as tension-torsion tests on cylindrical test specimens.

A related aspect that is important for assessment of the complex stress state is the type of structural analysis of the wind turbine blade. In order to assess this effect for a typical wind turbine blade, the stresses from beam-type analysis were compared to the stresses generated from shell type (2-dimensional) Finite Element Analyses and the results were checked by comparing with strain gauges measurements on an actual blade.

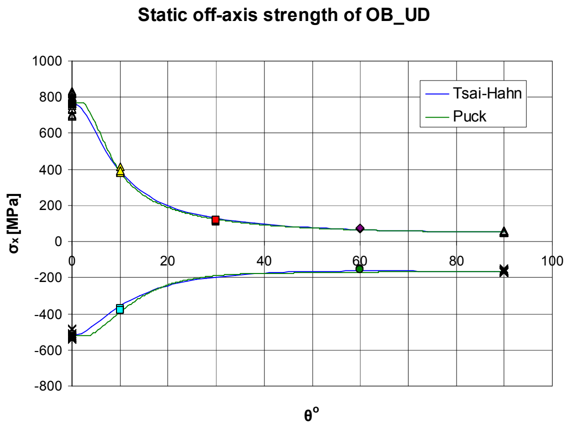


Figure 4 Static strength as a function of the angle between load and fibre direction

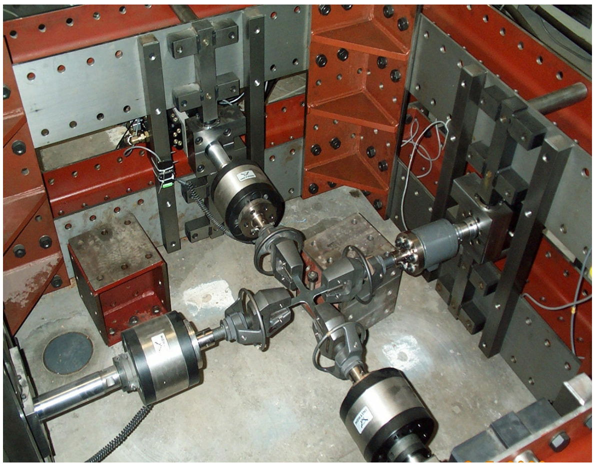


Figure 5 Bi-axial test set-up

3.3 Task Group 3

Extreme Conditions

Typical material tests are carried out at ambient conditions (room temperature, RT and normal humidity). However, wind turbines are employed in areas in all parts of the world and as such can be subjected to extreme temperatures, high humidity and exposure to seawater.

Tests were carried out at ambient conditions, as well as at –40°C, +60°C, to study the effect of temperature, or, after submersion in seawater for 6 and 12 months and at 100% RH.

The resin material was found to be particularly sensitive to the temperature, with the results at –40°C being about 65% higher than at room temperature, but those at +60°C about 40% lower than room temperature, see also Figure 6. The strength of the epoxy resin system used in this project can be expected to decrease quite substantially even at a modest increase in temperature.

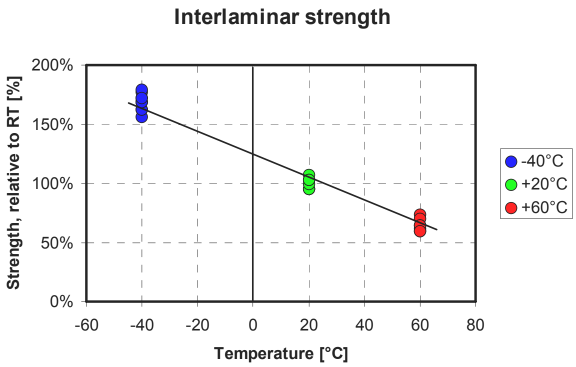


Figure 6 Interlaminar strength vs. Temperature

A related more far-reaching effort within TG3 is the analysis of damage mechanisms and damage evolution that one day may result in knowledge of what damage mechanisms are the most sensitive [1]. This analysis also helps in providing a basic understanding of what would happen if the lay-up of the laminate would be changed. Failure modes will be studied by visual inspection and microscopy. For this purpose, loading-unloading-reloading static tests are performed and the stiffness determined at each load step.

3.4 Task Group 4

Thick Laminates & Repair

Material tests are typically carried out on small and thin coupons, whereas the results are directly translated into behaviour of thick laminates as used in current rotor blades. By testing some thicker laminates in the 2500 kN test set-up at WMC, a comparison can be made regarding the static and fatigue strength of thick and thin laminates, see Figure 7.

Another aspect to be studied is the performance of repair techniques. A number of repair techniques were selected. The scarf bond was tested extensively, studying the effect of the slope and repair depth on static strength on specimens produced by LM Glasfiber and GAMESA. For the material used in the project, the LM specimens showed a rather high strength (about 80% of the strength of the reference specimen) for slopes of 1:50 and higher. Below this slope, the strength of the repair dropped rather drastically as can be seen in Figure 8.

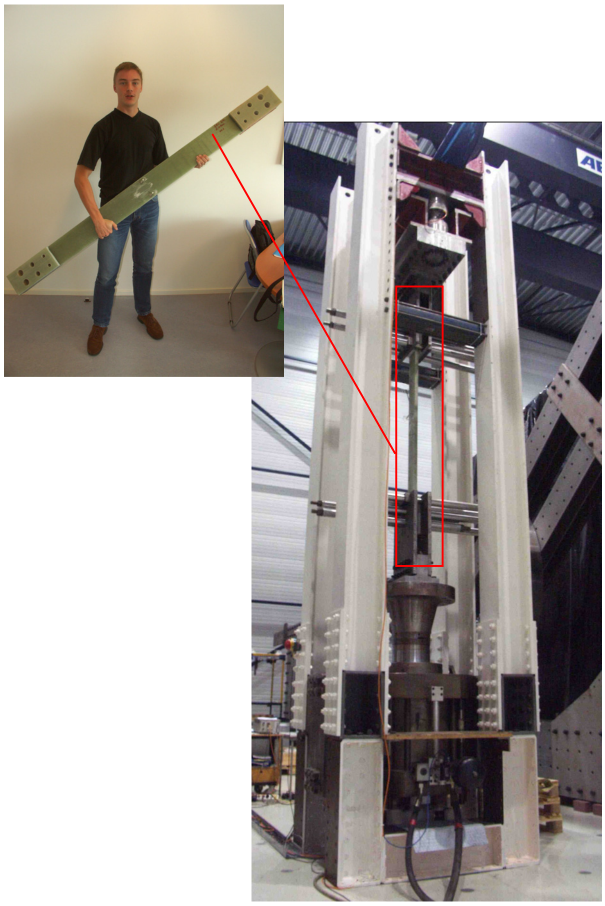


Figure 7 2500 kN test machine and test specimen

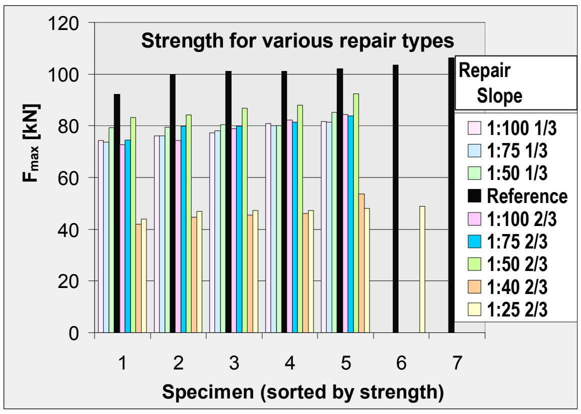


Figure 8 Influence of repair slope on static strength

3.5 Task Group 5

Residual Strength and Condition Assessment

Typically, the blades of a wind turbine are analysed for static strength and stiffness (extreme load cases) as well as for fatigue. The detrimental effects of fatigue loads on the static strength and the stiffness are often ignored. In the work of this task group, specimens of various lay-ups, typical of rotor blade structure, are loaded in constant amplitude fatigue to a percentage of the average fatigue life of the specimen, after which they are subjected a residual static test. In Figure 9, the static tensile and compression strength degradation is shown for the three R-ratios tested at three load levels.

Per figure it shows the fatigue load belonging to that R-ratio and load level (black line), as well the decrease in static tensile (red line) and compressive (blue line) strength during the fatigue life of the test specimen.

It was shown that compression fatigue (R=10) did not result in any noticeable strength degradation until close to the end of the fatigue life, a so-called "sudden death" behaviour. On the other hand, the static tensile strength (red line) after a tensile (R=0.1) or alternating (R=-1) fatigue load decreases almost linearly. The static compressive strength (blue lines) seems largely unaffected for all R-ratios and load levels.

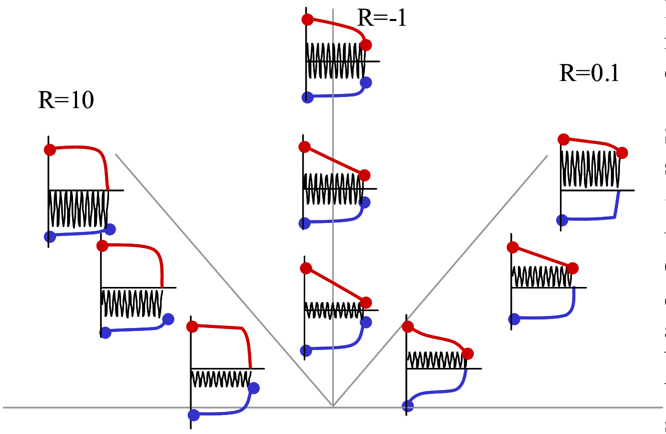


Figure 9 Strength degradation after fatigue

3.6 Task Group 6

Design Recommendations

Based on the results of the programme, DNV and GL are drafting design recommendations that can be used as a basis for their future design guidelines. Since this work can only be started after the results of the other task groups are largely or completely available and analysed, work of this task group is currently in progress.

A few examples of items under discussion at the time of writing are:

Should the current practice of S-N line for R = -1 + Constant Life (CL) (Goodman) diagram be used or are there better alternatives?

Although the current approach will likely not be replaced with a radically different approach, results from the extensive testing campaign are being evaluated comparing available methodologies.

Although R=-1 (alternating stress) is the most common fatigue test as it covers both tension and compression and seems to fit most logically in the Constant Life diagram, which in its simplest form is directly based on static tensile strength, static compressive strength and R=-1 fatigue (see Figure 2a), this type of fatigue is actually not so common for most areas in the rotor blade, which tend to be loaded more either in tension or in compression. For instance the WISPER spectra (see also Chapter 3.1) has an average R-ratio between R=0.2 and R=0.4, making R=0.1 a more suitable choice for the base S-N line. As will be shown in Chapter 5.1, and Figure 11, the influence of the type Constant Life (CL) diagram can have a major impact in fatigue life predictions.

Lately, in potentially interesting alternative has been advocated, which essentially links the S-N lines of various R-ratios together so that test results for one R-ratio also support the results for other R-ratios. In its simplest form, this could be accomplished by a linear CL diagram, as shown in Figure 2a. Adding more parameters allows for a more accurate modelling of the influence of the R-ratio.

Should the S-N lines be based on stresses or on strains?

Stresses are more easily determined during testing and under CA loading remain constant during the test. On the other hand, strains are typically used in blade design since, except for bending, strains are constant across the thickness of the laminate. Also comparison between various materials and fibre directions tends to be easier on a strain basis. Therefore, although the specimens are tested on a force basis (constant force range for constant amplitude test) the results will be presented as ε-N lines, rather than σ-N lines.

4 Test specimen geometry

Within OPTIMAT BLADES a large number of different tests has been conducted. Especially for the work within task group 5, where a fatigue test was to be followed with a tensile or compressive static test, demand for a "universal" test specimen was felt. ISO, ASTM and EU design recommendations provide only a limited basis for fatigue tests, let alone for residual strength tests.

Because of the use for both UD and MD lay-ups, a dogbone shape was thought to be generally less suitable: for UD material, the load tends to be carried by the continuous fibres only, shearing from the tapered part. Combined with the added effort required for cutting dogbone shaped specimens, a straight geometry was thought to be preferable.

Although it would be possible to cut a compressive specimen, such as used for ASTM D6641, out of the fatigue test specimen and test this for the residual compressive strength, again this step requires significant extra effort. Also, determining which part of the fatigue specimen should be used for the static test raises new issues.

Thus, the specimen was determined to be stocky enough so as to withstand the compressive static test without significant buckling. On the other hand, the test specimen needed to be long enough to allow for the use of various test equipment, such as strain gauges, clip gauges, temperature sensors and occasionally infrared cameras and other larger equipment. Increasing the thickness would allow a longer free specimen length, but would lead to problems with the load introduction.

A number of geometries, which were used in the project, are shown in Figure 10. After some preliminary tests, a rectangular shape was determined, using tabs for a more secure load introduction.

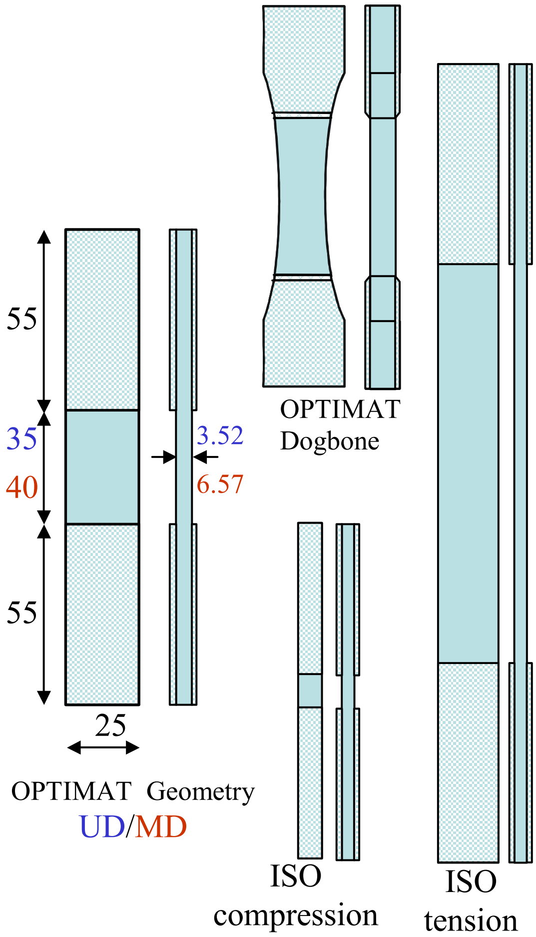
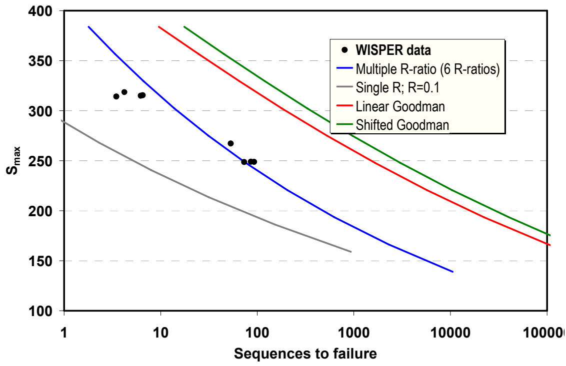


Figure 10 Some geometries used in the OPTIMAT BLADES project

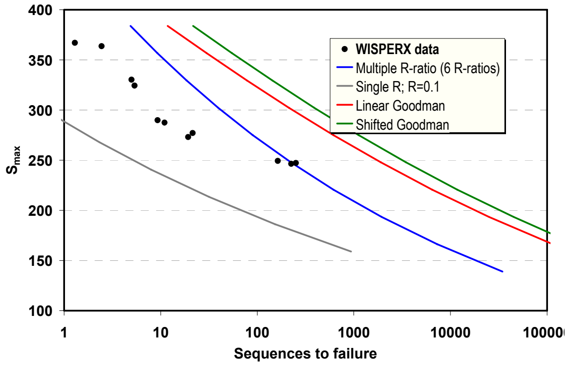
5 Lessons Learned

Within a project of this magnitude, probably the largest EU project on materials for wind turbines ever, quite a few aspects are discovered, of which a few will be discussed here.

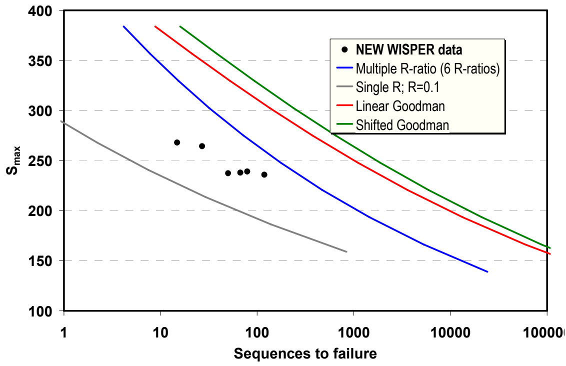
5.1 Influence Constant Life diagram



a) WISPER



b) WISPERX



c) NEW WISPER

Figure 11 Predictions various load spectra based on different CL diagrams

Compared to the CL diagrams in the GL guidelines (the green lines in Figure 11), the OPTIMAT predictions for WISPER and WISPER X are both considerably more accurate and conservative to the GL guidelines, which are clearly shown to be highly unconservative for spectrum loads and overestimate the fatigue stress by about 20% or the fatigue life by about an order of magnitude. The new GL guidelines (2003) are shown to be even more unconservative than the old guidelines. The NEW WISPER spectrum shows worse results still, the OPTIMAT CL diagram is also unconservative in this case.

5.2 Influence testing frequency

The testing frequency had a larger than expected influence on the results. Matrix material properties, such as inter-laminar shear were shown by VTT, RISØ and WMC to deteriorate linearly from –40° C to RT to +60° C (see Figure 6), which suggests that even modest increases in temperature may effect the fatigue results. Hence a fatigue rate for each lay-up, R-ratio and load level was established to be used by the partners. The frequencies chosen here turned out to be well below the test frequencies used by the partners in past research programmes. Furthermore, the partners had to monitor the temperature of the test specimen for at least a few tests within a series.

5.3 Specimen production

Within OPTIMAT BLADES, over 2500 tests were carried out and reported in the database OPTIDAT to date, putting a lot of stress on the specimen manufacturer, LM Glasfiber. Many of the effects investigated within the project are secondary effects on the static and fatigue strength. Therefore, the test specimens should be of a highly uniform quality so as not to blot out the secondary effects.

Ideally, all plates, from which the specimens are cut, should be produced in a narrow time frame under tightly controlled circumstances, to minimize any effects of changes in resin, fibres, manufacturing process etc. Alternatively, the plates should be mixed as much as possible, in order to allow a multiple-regression analysis of the results afterwards and filter out variability of the plate quality.

Due to time constraints, manufacturing of specimens started rather late and hence all specimens were quickly distributed and tested as soon as they became available.

It seems that, although the resin system and fibres are stated to be the same throughout the project, the static strength of the newer specimens is slightly higher than the old specimens, making a proper analysis of the results more difficult. Also, a direct relation between various plates based on for instance static strength cannot be made, because some aspects like fibre volume fraction can enhance static strength, while the fatigue strength might decrease. Variations within one plate are hard to quantify too.

6 Future research

Within the 6th framework project UPWIND [4], the current consortium will continue its research into material standards for wind turbines within Work Package 3. The work in this project consists of three parts:

- The existing OPTIDAT database is extended with new materials.
- The micromechanics based material model will be extended
- A damage tolerant design concept will be studied. The effect of fatigue on static strength and stiffness, as well as the effect of post first-ply failure strength are studied and included into the material models.

7 Conclusions

For the first time, a material for wind turbines has been characterised in full detail in a single consistent project. The results are not just relevant for the material selected, but are expected to have a strong impact on material testing procedures and application in design recommendations for wind turbines.

Other aspects uncovered by the investigation are plate-to-plate variations and lab-to-lab variations, which can only be assessed in large research projects.

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9 References

[1].Bulder B., Peeringa, J.M., Lekou, D., Vionis, P. Mouzakis, F., Nijssen, R.P.L., Christoph Kensche, C., Krause, O., Kramkowski, T., Kauffeld, N., Söker, H., *"NEW WISPER - Creating a New Standard Load Sequence From Modern Wind Turbine Data"*. Optimat Final report, OB_TG1_R020, doc. No. 10278_000.

[2].Smits A., Van Hemelrijck D., Philippidis T. van Wingerde A.M. and Cardon A. "Optimisation of a cruciform test specimen for bi-axial loading of fibre reinforced material systems", *11th European Conference on Composite Materials*, 2004, Rhodes (Paper)

[3].Megnis, M, Brøndsted, P. and Mikkelsen, L.P., "Damage evolution in laminated composite materials", *Proceedings of Dansk Metalurgisk Selskab*, (DMS) p. 33-42, 2004)

[4].UpWind: Integrated Wind turbine Design, Contract no.: 019945. EU 6th framework contract proposal call FP6-2004-Energy-3.