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L.G.J. Janssen
A.M. van Wingerde
Ch. W. Kensche
T.P. Philippidis
P. Brøndsted
A.G. Dutton
R.P.L. Nijssen
O. Krause

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PARTNERS
ENERGY RESEARCH CENTRE OF THE NETHERLANDS ECN NL
KNOWLEDGE CENTRE WIND TURBINE MATERIALS AND CONSTRUCTIONS WMC NL
DEUTSCHES ZENTRUM FÜR LUFT- UND RAUMFAHRT E.V. DLR DE
DEUTSCHES WINDENERGIE-INSTITUT GMBH DEWI DE
COUNCIL FOR THE CENTRAL LABORATORY OF RESEARCH COUNCILS CCLRC UK
RISO NATIONAL LABORATORY RISØ DK
CENTRE FOR RENEWABLE ENERGY SOURCES CRES GR
VRIJE UNIVERSITEIT BRUSSEL VUB BE
UNIVERSITY OF PATRAS UP GR
TECHNICAL RESEARCH CENTRE OF FINLAND VTT FI
GERMANISCHER LLOYD WINDENERGIE GMBH GL WIND DE
DET NORSKE VERITAS DANMARK A/S, DNV DK
LM GLASFIBER A/S LM DK
NORDEX ENERGY GMBH NORDEX DE
GAMESA EÓLICA SA GAMESA ES
GE WIND ENERGY GMBH GE DE
VESTAS WIND SYSTEMS A/S VESTAS DK

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2. EXECUTIVE SUMMARY

2.1. Industrial objectives and strategic aspects

As the required financial investments to achieve the expansion of the installed capacity of wind turbine grow, the economical pressure on reliable and structurally optimised blades, that are fit for their designed life, will increase. Very large blades may even become practically impossible without further knowledge of the material behaviour since the dominating loads on the material are caused by the blade mass. Therefore, a sound and accurate understanding of the structural behaviour of the material under all for wind turbine applications possible loading conditions is necessary.

The project aims to provide accurate design recommendations for the optimised use of materials within wind turbine rotor blades and to achieve improved reliability. The major deliverable of the project will be improved design recommendations for the next generation of rotor blades. With the accurate and reliable design recommendations resulting from this project, reliable blades with optimised use of materials can be designed.

The increased reliability and weight reduction of the blades will stimulate further the offshore exploitation with large capacity wind turbines. This supports the increase in wind energy and by that helps to reach the White Paper target of 40GW of installed power by 2010. The possible reduction of the material use will lower the impact on earth’s resources and environment. The reduction can result from direct weight saving and from the increased reliability which prevents the need for replacements and waste of material.

To execute the research activities a consortium was formed consisting of 10 research institutes from 7 EU countries; 5 wind turbine and/or blade manufactures from 3 EU countries; and the two leading certification bodies that carry out wind turbine certification throughout the world today.

2.2. Results

Over 3000 individual tests have been carried out on epoxy GFRP coupons, with numerous technical reports being issued to analyse and understand this data.

The work is performed by individual Task Groups (TG) who each performs a cluster of comprehensive Work Packages (WP) in a specific area of interest.

Technical reports from each TG are available through the OPTIMAT website for public review. Additionally, all more than 3000 TG test data has been captured within the comprehensive OptiDAT.

For the design recommendations to be usable and accepted, it was essential that the OPTIMAT research findings were presented in a logical way, so that they can be reviewed by interested parties including manufacturers.

The major results of the project are:

- Recommendations on testing and characterisation of materials
- Validated composite mechanics and FEM guidelines and recommendations
- Suitable repair techniques for FPR rotor blades
- Validated micro mechanics models
- New Wisper standard load spectrum
- Validated engineering model for residual strength prediction
- OptiDAT data base including analysis software
- Design recommendations for next generation of rotor blades

In total 39 design recommendations were formulated. These design recommendations will be considered for inclusion in the next version of the DNV/GL guidelines.

The OptiDAT date base can be made available to parties outside of the consortium via a user licence.
3. OBJECTIVES AND STRATEGIC ASPECTS

3.1. Issues involved

As the required financial investments to achieve the expansion of the installed capacity of wind turbine grows, the economical pressure on reliable and structurally optimised blades, that are fit for their designed life, will increase. Especially for larger wind turbines, optimisation of the use of material becomes more effective and necessary since the blade mass increases more than proportional to the blade energy output capacity. Very large blades may even become practically impossible without further knowledge of the material behaviour since the dominating loads on the material are caused by the blade mass. At the same time, economical utilisation of large wind farms, offshore and onshore, consisting of MW wind turbines demands reliable and non-stop operation. This is especially true for offshore turbines, due to poor accessibility.

Rotor blades are unique because of a combination of factors:

- Blades are subjected to complex and severe fatigue loadings (variable amplitude loadings), comprising often more than one billion of fatigue cycles.
- Blades are subjected to a variety of external environmental conditions.
- The inner structural parts of the blades where most of the material is located consist of thick laminates that have a complex stress state.

Therefore, a sound and accurate understanding of the structural behaviour of the material under complex loading, complex stress states and a variety of environmental conditions and their possible interactions is necessary, in order to optimise the use of material in the blade and to obtain reliable blades. This also includes the knowledge of thick laminates and the effects of residual stresses.

The actual remaining life of existing blades might be different from what is expected from the design due to the uncertainties in the current design recommendations and/or loading conditions. This requires a development of a methodology for condition assessment and accurate prediction of the residual strength and life of the blade.

In case of damage, or deficiencies during production, in the structural part of the blade, which means particularly in the thick laminate areas, repair can avoid rejection of the products and therefore unnecessary waste of material. This requires knowledge about reliable repair methods and consequently of the structural behaviour.

3.2. State of the art

In the past, various programmes have been carried out to investigate the behaviour of materials for rotor blades under static and fatigue loading. The results of these research projects were useful and have led to design recommendations that were necessary for designing the blades.

In the majority of these research programs, the behaviour of the blade material was investigated for the uni-axial stress state and mainly constant amplitude loading. A relatively small number of specimens have been tested under variable amplitude loading using the established Wisper load sequence. The material coupons tested were relatively thin (1-8 mm). The research on the effect of external condition up till now is limited to a few conditions (humidity and temperature) for a limited number of test series, which yields no firm conclusion on the effect. Although the effect of the mean stress level has been investigated, this might not be applicable for the thicker laminates since the residual stress resulting from the production might differ substantially from the residual stress level in the relatively thin coupons. Furthermore, most of the different topics were investigated in different research programs using different material, geometries etc. so the results are not always consistent with each other and therefore of limited use for establishing consistent design recommendations.
The fact that the blade material behaviour under complex stress state conditions, as present in the structural part of the blade, is not extensively investigated explains why most of the existing design recommendations do not account for the complex stress state for fatigue. However, the few experimental data indicate a strong dependency of the fatigue behaviour on the complex stress state.

The experimental data available for variable amplitude loading indicate that the current design recommendations do not lead to a correct prediction of the results. Differences of two orders of magnitude in the fatigue life on the non-conservative side have been reported. Due to the fact that the effect of external conditions is not clear, the current design recommendations have different conversion factors, if any, for the external conditions. As a consequence of the fact that the effect of the mean stress level is investigated on thin specimens only, the design recommendation on this point might not be applicable to the thicker laminates.

It might be concluded that research up till now was necessary to arrive at the current design recommendations for resistance of the blade structure. However, this research had its limitations, which hamper as a consequence the derived design recommendations. It is shown that the uncertainty of failure of a blade is for the largest part caused by the uncertainties in the fatigue behaviour of the blade.

Therefore the design recommendations for the resistance of the blade structure have to be improved to be able to predict the static and fatigue behaviour more accurately under the actual conditions. The fact that the number of blade failures is relatively limited can be caused by implied conservatism or by the compensating effect of the different influencing factors. Conservatism means unnecessary use of material. If the cause is the compensation of different effects, the consequence could very well be that under other circumstances (e.g. larger blades or different external conditions) unexpected failures will occur.

Currently there are no recommendations available for repairing structural parts of the blades or for assessment of the residual strength and life of the blade. Blades that are damaged or have production deficiencies in the thick structural parts are being destroyed even if the damage or deficiencies are local. As the blades become larger more material is wasted due to such a localized deficiency.

3.3. Measurable objectives

The project aims to provide accurate design recommendations for the optimised use of materials within wind turbine rotor blades and to achieve improved reliability. This considers the design of new blades, but also the prediction of the actual residual strength and life of blades in operation, which can extent the life of the blade or avoid unexpected failures and will result in a better use of material. Furthermore, the possibility of repair will prevent unnecessary waste of material. The improved understanding of the material and rotor blade behaviour will be implemented in accurate and reliable design recommendations.

Based on the above the following scientific and technical (verifiable and measurable) objectives can be summarized:

- To obtain improved and profound knowledge of blade material behaviour under variable amplitude loading.
- To obtain improved and profound knowledge of blade material behaviour under complex stress states
- To obtain improved and profound knowledge of blade material behaviour under external (extreme) conditions

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2 M.L. Thegersen, Sensitivity Analysis of Rotor Blades Using a Probabilistic Fatigue Model, IEA expert meeting on Fatigue, Delft, 1999
To obtain improved and profound knowledge of the mechanical behaviour of thick laminates.
To obtain improved knowledge of the interaction effects of the conditions mentioned above.
To develop methodologies for repair
To develop methodologies for condition assessment, residual strength and life prediction
To implement the obtained knowledge into a consistent set of accurate and reliable design recommendations.

3.4. Innovation

Although some of these topics mentioned above have been investigated before in a more tentative way and in separate projects, it is now done extensively in one research project aiming at consistent results. The knowledge on the behaviour of the blade material and structure will be enhanced. Addressing these topics simultaneously in a consistent way will increase the quality of the results. Moreover, due to the possible compensation effects of the various influencing factors, it can be considered a necessary requirement at this stage. Addressing just one influencing factor accurately could actually lead to a loss of compensation, resulting in an unreliable design.

The partnership is aimed at including the necessary knowledge to cover all the aspects of the blade material. The level of enhancement is expected to be substantial. Implementing these results in the design recommendation is one of the main objectives of this project. This will direct the research to this objective. It guarantees that the results are available in a form suitable for implementation in design recommendations.

The input of a substantial part of the European wind industry and research institutes as well as that of the two main Certification Bodies, increases commitment and acceptance of the resulting European design recommendations. It is therefore expected that the design recommendations will be improved and harmonized. These design recommendations will be better qualified to design blades that are reliable and have optimised use of material.

3.5. Contribution to the Programme

In the structural part of the blade the stress state is complex and the laminates can be extremely thick for larger blades. Moreover, the loading on the blades is complex and at the same time external conditions become more extreme due to the trend towards offshore and the possibility of arctic or desert like locations. Accurate design recommendations are required to optimise material use. For blades already in operation, the actual remaining strength and life might be different from what is expected from the design. Condition assessment of existing or future blades can extend their operational life or avoid unexpected failures. Other material and costs savings can be made by adequate repair of locally damaged blades or blades with localised production deficiencies.

With the accurate and reliable design recommendations resulting from this project, reliable blades with optimised use of materials can be designed. Together with the application of condition assessment and repair, this will result in:

- Reliable blades (fewer unexpected or premature failures)
- Reduced use of material and environmental impact
- Life extension of blades
- Less waste of material (less rejected blades and components)
- Larger availability of the wind turbine
- Extension of the possible size of turbine.

All these aspects can contribute to the reduction of costs for wind energy. This concerns investment costs by lighter components and less waste of material as well as running cost due to the larger availability.

The increased reliability and weight reduction of the blades will stimulate further the offshore exploitation with large capacity wind turbines. This supports the increase in wind energy and by that helps to reach the White Paper target of 40GW of installed power by 2010.
The possible reduction of the material use will lower the impact on the earth resources and environment. The reduction can result from direct weight saving or from the increased reliability which prevents the need for replacements and waste of material.

The amount of material and cost reduction will depend on the results of the project. However, assuming a 10% reduction of blade material, either by direct weight savings or by preventing replacement, would save 300,000 kg of blade material for a (offshore) wind farm comprising of 100 wind turbines of 3 MW. At the current production costs this amounts to about 4 million Euros. Further saving in the same order can be expected on the turbine and substructure as a consequence of the lower gravitational loads. This adds up to about 2-3% on the total investment. However, the results could also lead to figures that are in the order of 5%.

In case of preventing the replacement of unexpected failed blades also the availability will be increased. Especially for offshore wind turbines the availability is strongly reduced by unexpected failures. A required replacement of 10% of the blades (during the wind turbine lifetime) due to unexpected failures might result in a loss of availability of about 2-3% and similar increase of the price per kWh. However, in case the blades turn out to be completely inadequate due to the inaccuracy of the current design recommendations and have to be redesigned and replaced, the losses could be dramatic. The results of the project will prevent this situation.
4. SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

4.1. General introduction

To meet the ambitious objectives of this project, much work by partners having specialist knowledge and experience has to be carried out. Since the results must be used for the design of the next generation of blades, the commitment and cooperation of the manufacturers and Certification Bodies is essential. Therefore, the project required the establishment of a new consortium of 18 (17 since mid 2004) partners from 8 EU countries. These include 10 research institutes from 7 EU countries and 6 (5 since mid 2004) wind turbine and/or blade manufactures from 4 EU countries. Also the two main Certification Bodies, which carry out the certification in most of the EU countries, are included. The participation of these partners will also ease the dissemination of the results within the European Community.

The work is performed by Task Groups, each of which performs a cluster of comprehensive Work Packages (WP). The management of the project is done by a scientific/technical co-ordinator and a financial/administrative co-ordinator. Furthermore a Steering Committee (SC) and a Technical Committee (TC) are installed. The Task Group leaders are members of the Technical Committee which is chaired by the scientific/technical co-ordinator. The industrial partners and the Certification Bodies formed the Steering Committee. During the MTA meeting in February 2005 it was decided that the activities of the Steering Committee will be stopped and that the industrial partners will be directly involved in the work of Task Group 6.

In order to deal with contractual matters it was decided during the kick-off meeting that a Project Coordinating Committee (PCC) was needed, since the structure mentioned above did not foresee in committee in which all partners are represented and have one vote.

The Task Groups and their Work Packages are listed below. The partners acting as task group leaders are given between brackets.

Task Group 1. (DLR)
Investigation of blade material behaviour under variable amplitude loading.
   WP 3: Variable Amplitude Fatigue loading
   WP 4: Establishment of new Wisper spectrum
   WP 5: Basic interaction tests with alternative material

Task Group 2. (UP)
Investigation of blade material behaviour under complex stress states.
   WP 6: Complex loading
   WP 7: Complex loading of alternative material

Task Group 3. (RISØ)
Investigation of blade material behaviour under external (extreme) conditions.
   WP 8: Mechanical properties at extreme conditions
   WP 9: Extreme conditions for alternative material

Task Group 4. (WMC)
Investigation of the stress state and behaviour of thick laminates and development of methodologies for repair.
   WP 10: Comparison of thin and thick laminates
   WP 11: Repair of high-loaded flat blade parts
   WP 12: Properties of repaired thick laminates
Task Group 5. (CCLRC)
Development of methodologies for residual strength and life prediction and condition assessment.
   WP 13: Residual strength of uni-directional material
   WP 14: Residual strength of multi-directional material

Task Group 6. (WMC)
Implementation the obtained knowledge of the above tasks into a consistent set of design recommendations.
   WP 15: Design recommendations

An overview of the Task Groups and the project structure is given in Figure 1. The Work of the Technical Committee and Steering Committee are described in the Work packages WP 1 and WP 2 respectively. The TC is also responsible for the fabrication of the specimens for the reference material\(^3\) (WP 16).

In Task Groups 1 to 5 the fundamental research is carried out (WP 3 - WP 14). This implies the required literature study, experimental work, numerical simulations, analysis and reporting. The work is mainly carried out by the research institutes with some specific tasks for the industrial partners.

The Task Group leaders together with the certifications bodies and industries will perform the work of Task Group 6 that has the objective to implement the results of the Task Groups 1 to 5 into design recommendations. The fact that the Task Group leaders are also responsible for and carrying out the implementation should guarantee that the results of each Task Group are suitable for the implementation into design recommendations.

\[^3\] The fabrication of the specimens for Phase I (WP 16) was mainly carried out by one manufacturer (LM) to exclude possible interactions due to different materials or preparation.
4.2. Description of work and results of Task Group 1 (WP 3, WP 4 and WP 5)

Objectives
The main objective of TG1 was the "Investigation of blade material behaviour under variable amplitude loading". The reach this objective the work was divided over three corresponding work packages:

WP 3: Variable amplitude loading
WP 4: Establishment of New Wisper spectrum and
WP 5: Interactions with variable amplitude loading.

The work within these work packages included an extensive fatigue testing program and detailed analysis of effects related to the variable amplitude loading of rotor blade material. In this report, the work and the major results will be briefly explained.

Description of work

Variable amplitude loading (WP3)
The objective of this work package was to address the effect of variable amplitude fatigue loading by comparing test results of dedicated tests with constant amplitude and variable amplitude loading. Before the testing phase, a benchmarking in lifetime analyses with different engineering models of life assessment and existing material data was carried out to achieve a common basis for an apt damage accumulation theory and/or material fatigue model. A detailed plan of action was generated (OB_TG1_O002) for the constant amplitude tests aimed at establishing a constant amplitude life diagram and variable amplitude tests with different maximum stress levels to have more information on the difference between theory and experimental results. Additionally to the S-N lines of the chosen OPTIMAT reference material at the three widely used stress ratios R=0.1, -1 and 10, also other stress ratios were investigated to get a constant life diagram as complete as possible. The results served also as an input for work packages in other task groups such as the WP’s 6, 8, 10 and 13. Variable amplitude tests included the WISPER standard as well as – for investigating the influence of omission – also its short version WISPERX and additionally an extensive experimental part on block testing to check the applicability of various lifetime predictions models. The results of the investigations were intended as an input for a revision and updating of the existing design guidelines.

Establishment of NEW WISPER spectrum (WP4)
The objective of this work package was to define a new standard load spectrum, based on the size and use of contemporary large wind turbines, and to compare the results of this to the present spectrum.

The content of this work package can be described as followed:

1. Set-up of criteria for acceptance and normalisation of available load measurement data and specification of a common data format for further processing and preparation of 10 databases. The load spectrum assembly method will be defined and applied for assembly of a flaps wise load spectrum for each database for a selected turbulence level and a selected wind distribution.
2. The assembled measured load spectra are compared to the WISPER standard through fatigue life estimation on the basis of the constant amplitude properties and the linear Palmgren-Miner damage accumulation theory. From this the NEW WISPER spectrum will be established.
3. Variable amplitude tests will be accomplished with NEW WISPER on the reference material. Similar to the tests described in WP 3 with WISPER, the influence of omission will be investigated for the NEW WISPER spectrum.
4. The results of the tasks described will be compared to the results of the constant amplitude tests and the tests with the WISPER spectrum (both WP3). This must be performed also analytically by lifetime prediction on the basis of both the WISPER standard and the NEW WISPER. Then, the difference between the test results and the predictions has to be compared.
Interactions with variable amplitude loading (WP5)

In this work package basic interaction tests were carried out on an alternative material to enable the evaluation of combinations of aspects like load variation and bi-axial loading and extreme conditions providing basic material data on fatigue life to other work packages. Only MD-lay up was investigated. The alternative material (MD4) has the same lay up as the reference material (MD2), however another epoxy resin system. CA tests at R=0.1 by DLR should give a link to the corresponding tests in WP3, CA tests at R=-1 by WMC a link to the tests at extreme conditions in WP9 (TG3) and to WP3 as well. Additionally, some tests on the alternative material with WISPER should allow a comparison to the WP4-investigations. Tests with cruciform specimens were foreseen for interaction purposes with WP7 in TG2.

Activities carried out

Variable amplitude loading (WP3)

Benchmarking of lifetime prediction

The participating partners DLR, UP and WMC used different lifetime prediction methodologies. Being aware that each methodology consists of different steps (e.g. statistical analysis, rain flow counting) and that each of these steps is done in a different way by each partner, the analytical results probably differ very much although the corresponding engineering models can be very similar.

To synchronize the basic steps of lifetime prediction, a benchmarking procedure was performed at the beginning of the project (OB_TG1_P002, OB_TG1_R012). The benchmarking contained following steps of lifetime prediction

- Statistical analysis of constant amplitude test data
- Rain flow counting
- Form of constant life diagram
- Damage accumulation rule

The results were only slightly affected by the chosen statistical models. The derived parameters during statistical evaluation were practically identical although different routines were used. Analysis showed that the different rain flow counting algorithms can have a significant influence on the predicted lifetime and therefore partners had to agree on the algorithm and the matrix. A cyclic counting algorithm was chosen for further calculations. The results of lifetime prediction are strongly dependent on the constant life diagram and the considered damage accumulation rule, but no direct influence of the different codes could be recognized.

Constant amplitude tests: Establishment of S-N lines

A series of preliminary programs was accomplished to define an appropriate geometry of the specimens. Already these tests showed that the testing frequency may be lower than originally expected. The first constant amplitude tests showed a significant heating of the specimen, which only could be avoided by using very low testing frequencies. For the UD material only 2 S-N curves could be derived, because of buckling problems in compression-compression loading. The buckling problems could not be solved although additional tests using other specimen geometries were done. For the MD material more than 7 S-N curves could be derived showing also the tendency for buckling in compression loading. A very detailed constant life diagram is available for this material acting as a basis for the lifetime prediction. The lower testing frequencies, which had to be used (OB_TG1_R021), caused significant delay in the experimental program. Therefore not all foreseen tests could be accomplished.

Variable amplitude tests: Establishment of S-N lines

The original experimental program for variable amplitude testing contained a large number of various variable amplitude tests. Two basic types of tests were investigated: simple block tests representing a very simple load spectrum with focus on the analysis of load sequence effects and "real" load spectra tests. The investigation of simple block tests should show if the time-consuming load spectra tests can be replaced by the more easy to accomplish block tests. By accomplishment of the load spectra tests the influence of omission should be investigated. The number of variable amplitude tests had to be reduced due to delay of the CA tests. Nevertheless a significant number of tests could be carried out. Most tests were accomplished as block tests to investigate sequence effects. Due to the scatter of test results no clear effects could be detected. It was not possible to
put the load spectra tests and block tests into relation. The influence of omission could not be investigated in detail. Results are reported in OB_TG1_R022, OB_TG1_R025 and OB_TG1_R026.

**Input for design guidelines**
There are numerous results from the experimental program useful for the revised guidelines. Two of them are mentioned especially here. One of them is the recommendation that the testing frequency must be adopted such that the temperature at a certain area of the specimen will not exceed 35°C. The other one is that not the Goodman diagram being described solely by the static and the R=-1 S-N curve should be used for the lifetime prediction but a more complete constant life diagram with at least the additional R-ratios of 10 and 0.1. Otherwise the lifetime prediction might be too optimistic. Figure 2 shows the complete CLD designed on the basis of the 7 S-N curved established with the MD-specimens.

![Constant Life Diagram for MD material](image)

**Figure 2** Constant amplitude diagram for MD-specimens

**Establishment of NEW WISPER spectrum (WP4)**
Definition and collection of blade spectra
The NEW WISPER load spectra should represent the state of art in wind turbine technology. Therefore the spectra should be synthesized using extensive load measurements of modern wind turbines. The selected 3-bladed turbines were of MW or MMW-scale, had rotor diameters up to 100 m, were operated in pitch- or stall-control and with fixed or variable speeds. The database contained information of more than 2600 hours of operation, which is one magnitude more than for WISPER.

**Synthesis of NEW WISPER**
The synthesis of NEW WISPER was accomplished using standard techniques according to IEC 61400-13 and was as close as possible to the synthesis process of the original WISPER. The NEW WISPER sequence was also derived using 64 load levels, but has a different number of cycles and zero load level. Comparing the two sequences, the NEW WISPER looks a little bit artificial because the mean load is permanently increasing, whereas the WISPER looks more randomized, see Figure 3. This is an important point to notice for the analysis of the load spectra tests. See also OB_TG1_R020 and OB_TG1_0005.
Experimental validation of NEW WISPER

Only a limited number of load spectra tests with NEW WISPER are available. These tests show that the failure of the specimen occurs at the maximum peak, which coincides with the end of the sequence. Comparing the WISPER and NEW WISPER test results, no big difference can be seen. This is somewhat surprising, because the total sum of applied load is three times higher for WISPER than for NEW WISPER. Therefore it is clear that the NEW WISPER is significantly more damaging to the material, see also OB_TG1_R024.

Evaluation of variable amplitude influence

The test results were predicted using Miner’s sum prediction and residual strength life descriptions. For both cases it has to be noted that there is a large influence of the S-N parameters. The analysis done showed no advantage for the strength degradation based models. The used constant life diagram is of great influence. The Linear Goodman and Shifted Goodman diagram were non-conservative, whereas the predictions using a detailed CLD were in acceptable agreement with the results. So it’s absolutely necessary to have a very accurate description of the constant amplitude fatigue properties of the material. Sequence effects could not be detected.

Figure 4 Comparison of WISPER and NEW WISPER in Experiment and lifetime prediction
The lifetime prediction for WISPER and NEW WISPER presented in Figure 4 shows a much more optimistic prediction for NEW WISPER than for WISPER. This can eventually be referred to the influence of the more artificial composition of the NEW WISPER sequence on the experimental results. It should therefore be investigated in a possible future project whether a more arbitrary arrangement of the new sequence would lead to an improvement of the test results.

**Interactions with variable amplitude loading (WP5)**

The interaction tests of WP5 in TG1 with the alternative material MD4 were carried out in Phase II of the project. According to the DPA, CA tests with R=0.1 were performed at DLR with a possible link to the CA tests in WP3 where these tests had been accomplished with the reference material MD2. While the static MD4-tensile properties were slightly better than those of MD2, the static compression values did not show significant changes. Also the investigated fatigue properties at R=0.1 were very close to those of MD2. The static tests carried out with the alternative material at WMC showed similar behaviour as tested at DLR. And also the S-N curve at R=-1 which served as a cross link to the tests in WP9 at extreme conditions did not show significant changes compared with the reference material.

**Summary and conclusions**

The work carried in TG1 was dedicated to the aim to increase the knowledge in variable amplitude loading and improved lifetime prediction. Several different disciplines were necessary to solve this task. In the beginning of the project, a benchmarking in lifetime prediction methods was performed. It was found that the results were less affected by the chosen statistical models that, however, the different rain flow counting algorithms can have a significant influence. CA fatigue tests were accomplished at 7 stress ratios with the reference MD-material for achieving a well described constant life diagram (CLD) which, by means of comparing calculations, proved to give better lifetime predictions than the simple Goodman-diagram. It was also found that the frequency has a significant influence on the fatigue properties, which led to the decision to keep the frequency at a level (depending on the applied load) that the temperature did not exceed a certain amount. The CA fatigue tests served additionally as a basis for the chosen load levels for the variable amplitude (VA) testing and the residual strength tests in TG5. CA fatigue tests with UD reference material could be used for comparing the results with the MD-material showing that the fatigue results plotted in strain versus load cycles were close one to another. They served also for cross links to WP6 in TG2. Additionally to this experimental work, the NEW WISPER load spectrum was established to represent the state of art in wind turbine technology on the basis of measurements on selected 3-bladed turbines of MW or MMW-scale with rotor diameters up to 100 m, which were operated in pitch- or stall-control and with fixed or variable speeds. The database contained information of more than 2600 hours of operation, which is one magnitude more than for WISPER. VA tests were then carried out with various different spectra also to compare the results of the old WISPER with those of NEW WISPER. As a result, it was shown that the NEW WISPER sequence seems to have more damaging influence than the old WISPER. A reason might be that the saw-tooth arrangement of the sequence has an influence on the fatigue properties due to sequence effects which should, therefore, be studied in a follow-up project. Interaction tests with an alternative material (same lay up, but other resin system than the reference material) did not show significant changes in the fatigue life at R=0.1 and R=-1 and in the static compression properties neither. However, the static tensile properties were slightly higher.
4.3. Description of work and results of Task Group 2 (WP 6 and WP 7)

Objectives
The objectives of TG2 (WP6) in investigating blade material behaviour under complex stress states were to generate test results of basic plies and multidirectional laminates for the reference material to implement advanced FEM formulations, to define and validate experimentally multi-axial failure theories in static and fatigue loading and to quantify complex stress state effect on blade design by contributing with design recommendations. In the second phase (WP7) of the project, interaction effects, e.g. variable amplitude loading and complex stress states, on the reference UD material were investigated along with limited testing efforts to derive mechanical properties necessary for plane stress analyses for the alternative material.

Description of work
Detailed Plans of Action (DPA) were issued for both WP6 and WP7 defining type and number of specimen to be tested for derivation of necessary material properties. All relevant ‘static’ material properties of the reference material at ambient conditions were characterised using a statistically significant sample size. A large number of uni-axial (basic plies, on- and off-axis) and multi-axial coupon tests (cruciform shape and tubes) were performed to validate failure criteria and assess reliability methods to accurately predict failure probability. In addition, S-N lines were characterised at 3 specific stress ratios, R, and frequency resulting in constant life diagrams of individual material properties, per basic ply. Again, a number of uni-axial and multi-axial different coupon tests were performed: (a) Uni-axial tests on laminates made of the basic plies (on- and off-axis), (b) Multi-axial testing on tension/compression-torsion tubes. Fatigue strength criteria, suitable for complex stress states, were assessed by comparing theoretical predictions with test results.

A large rotor blade was modelled using thick shell FEM formulation and the stress/strain results were compared with results from "conventional" analysis techniques.

Activities carried out
In-plane behaviour of UD material
In the frame of TG2, a comprehensive experimental program was performed to fully characterize the in-plane behaviour of UD material. To this end a number of at least 25 tests per property were performed, to have a statistical description as well, for measuring 19 engineering constants. All experiments were performed at the same lab (UP), same test rig, same procedures so as to minimize variations in material property by other factors such as lab-to-lab or machine-to-machine variation. Test coupons were delivered directly by LM. Test methods and detailed results were presented in a number of OPTIMAT reports, e.g. OB_TG2_R013, OB_TG2_R018 and OB_TG2_R020

Fatigue characterization of the UD material
In addition, a thorough experimental investigation for fatigue characterization of the UD material was performed in TG2 including definition of S-N curves at three R-ratios, 0.1, -1 and 10, both in the fibre and the transverse direction as well as in-plane shear fatigue strength under R=0.1. Standard S-N definitions from these tests are included in OB_TC_R014, while detailed test methods and results are presented in OB_TG1_R013, OB_TG2_R020 and OB_TG2_R021. In all static and fatigue tests, except for in-plane shear characterization tests which were based on ISO 14129 specimen geometry and test method, the standard OB coupon geometry was used, introducing the concept for just one geometry coupon valid for all types of tests, e.g. static or fatigue in tension and compression, residual strength etc. Only thickness was varying from coupons tested in the fibre direction to those loaded transversely to the fibre. Comparison of test results with respective ones derived from ISO coupons and test methods revealed that values for strength and moduli are in very good agreement except the compressive strength in the fibre direction where the OPTIMAT specimen performs not so well due to bending deformation.
at failure present greater differences but it can be argued that in general the OB standard coupon geometry for UD is a viable approach to complete in-plane material characterization.

**FEM study of rotor blade**

Besides the experimental effort in characterizing material behaviour under complex stress states, a thorough FEM study, using various theoretical formulations, was performed to investigate stress states in a rotor blade structure. The bottom line of this investigation report is that a rotor blade even if loaded in a complex mode, it is after all a thin-wall beam structure. As such, the tangential stress resultant in the shell thickness is negligible compared to the axial one. However, the shear stress resultant is of comparable magnitude to the axial one in areas as the shear webs or trailing and leading edges respectively. If the different strength values in the axial direction and in shear are also taken into account, it makes it easier to understand the importance of the combined effect of these actions. The situation described above implies a pure complex stress-state at the ply level; see Fig.1 where stress analysis results from a 35m blade are presented. It is clearly seen that in the plies with fibres oriented in the blade axis, normal stress transverse to the fibres and shear stress are negligible compared to the normal axial stress. However, in plies with fibres oriented at + or -45 the prevailing stress field is complex. In conclusion, 1D stress analysis, i.e. beam theory formulations, could be acceptable but failure prediction should be done in a layer-by-layer basis, i.e. complex stress states at the ply level should be taken into account. Whatever is the type of stress analysis, i.e. beam or shell implementations, provided that failure occurrence is accounted properly, the level of safety (reliability) is increased when taking into account complex stress states.

![Ply stress analysis in the largest chord section of a 35m blade](image)

**Biaxial test programme**

Typical plane stress states as those developed in the layers of the shells shown in Figure 5 were simulated, besides sophisticated biaxial tests, by uni-axial testing in off-axis UD coupons. Failure prediction under static loading was performed satisfactorily using criteria such as Tsai-Wu, Puck and Tsai-Hill as shown in Figure 6. Under cyclic loading, life prediction was also satisfactorily performed when using similar quadratic in stress functions compared to simplistic approaches, such as to consider separately damage from each stress component and add at the end. In Figure 7, test results from off-axis loaded UD coupons, at 10°, are compared to theoretical predictions from the two different approaches. Static tests results from bi-axial tension of cruciform specimens made of MD lay-up suggest that failure prediction according to limit functions as those cited in the
above is fair, in general, although many other parameters such as stiffness degradation scenarios or material non-linearity for example are of paramount importance. An example of such a comparison is presented in Figure 8, where test results from cruciform specimens, reported in OB_TG2_R016, are plotted along with theoretical predictions from various failure criteria as Puck, Tsai-Hahn or EPFS (Elliptic Paraboloid Failure Surface thought as a generalization of Hoffmann anisotropic failure criterion).

Figure 6  Experimental verification from off-axis loaded OB_UD coupons

Figure 7  Experimental verification from off-axis loaded OB_UD coupons

Figure 8  Comparison of test results from bi-axial testing of cruciform specimens and theoretical predictions from various failure criteria

Sampled results from the investigation performed on multi-axial failure theories and validation studies by comparing with experimental data are presented in Figure 9, where the damage pattern of an MD coupon tested to failure under compressive, 60° off-axis loading is compared to the respective experimental one.
Planning vs. accomplished

No major deviations were observed between the Description of Work (OB_TC_R013) and the work actually accomplished within TG2. To be more correct, the work performed by the partners has exceeded that initially described as contractual obligations. All milestones have been reached and the deliverables prepared as scheduled. Concerning the experimental effort by all partners of TG2, it can be said that it has exceeded that initially planned by ca. 35%; 465 tests of all types were foreseen, 629 were finally accomplished.

CA cyclic tests of cruciform specimens have not been performed due to a series of technical difficulties and malfunctions occurred at the biaxial test rig of VUB. They have been substituted by slow Loading-Unloading-Reloading cyclic tests.

Discussion of results

Uniaxial tests

A detailed experimental program was performed in the frame of TG2 for measuring in-plane mechanical properties necessary for complex stress analysis of rotor blades. This included the characterization of stiffness, strength and thermal properties, i.e. thermal expansion coefficients, both in the fibre and transverse directions. Static as well as fatigue strengths, at various R ratios were measured. This unique, for wind turbine rotor blade materials, collection of in-plane material properties can form the basis for comparison with future test data of materials but also for rotor blade design as well taking into account the actual requirements of GL and DNV with respect to complex stress states in blade structures.

In the test series performed, the OB geometry, i.e. same geometry for any test type, either in the fibre or the transverse direction has been established and proved a valid choice. The statistical analysis of data for strength, stiffness and thermal properties (19 engineering constants in total), by fitting appropriate probability distribution functions, forms also a valuable basis for future probabilistic stress analysis of rotor blades.

Biaxial tests

Besides the very extensive test series for material property characterization, a large experimental program including material testing under multiaxial stress states was performed to serve in the verification of failure theories for anisotropic composites. To this end, specimens of special...
geometry and lay-up, e.g. cruciform, tubular, off-axis, have been tested. A new geometry for the cruciform specimen has been introduced and proposed in the related technical literature, based on extensive testing along with innovative whole-field strain measuring methods, such as the Digital Image Correlation Technique (DICT) and FEM analyses. Fatigue tests have not been possible in the biaxial test rig used for testing cruciform specimens due to technical reasons. On the other hand, testing of tubular specimens, either static or fatigue conditions, has revealed many problems in manufacturing the tubes (geometry of overlapping layers)/curing procedures and has resulted in great scatter of the experimental results. Thus, data from the multi-axial stress coupons were not conclusive and only results from axial tests of coupons with off-axis lay-ups could be used for the validation of failure theories.

*Complex stress states in rotor blades*
Finally, concerning the quantification of complex stress state effects on rotor blades by performing optimized numerical stress analyses, the results obtained highlighted the need of taking into account such complex stress states in failure prediction at the ply level of a composite laminate. This is corroborated by the recommendations issued by certifying organisations in their latest editions of design guidelines.
4.4. **Description of work and results of Task Group 3. (WP 8 and WP 9)**

**Objectives**
The summarized objective of Task Group 3 is: To obtain improved and profound knowledge of blade material behaviour under external (extreme) conditions. The reach this objective, the work was divided over two corresponding work packages:
WP 8: Mechanical properties at extreme conditions
WP 9: Extreme conditions for alternative material.

**Description of work**
To reach the objectives in this task group an investigation of blade material behaviour under external (extreme) conditions was carried out. Theoretical models describing the material behaviour with the use of the methods of the mechanics of materials and continuum damage mechanics have been developed and used to analyse the material degradation. Experimental measurements of the mechanical properties were conducted in order to measure the effect of high and low temperatures, and to investigate the effect of salt-water extreme conditions. The mechanical tests also contributed to the overall attempt to optimize test specimen geometries, test set-up, and test conditions and results in an important input to the Task Group 6 work of implementing the obtained knowledge of the OPTIMAT tasks into a consistent set of design recommendations.

DPAs were defined in accordance with the choices made regarding the specimen geometries for the whole project and are described in reports OB_TG3_R001 and OB_TG3_O004.

**Extreme conditions**
Extreme conditions that are relevant to service conditions of wind turbines are determined. The determined conditions are: temperatures at –40°C, +60°C and RT, and salt-water environmental conditions. The salt-water extreme conditions mean that the specimens are submerged in the salt water. Tests and consideration about the effect of temperature variations at ambient relative humidity were given up due to lack of resources.

**Modelling of degradation**
At the first stage of the work, the damage evolution due to the fibre failure as well as stiffness degradation in the unidirectional laminates have been investigated with the use of the thermodynamically consistent damage theory.

To analyse the laminate degradation, the continuum damage mechanics was employed, which enable to develop thermodynamically consistent formulation of constitutive law for media with damage. With the use of this theory, the effects of temperature changes (non-isothermal conditions) and environmental (moisture) conditions can be taken into account by including the additional internal state variables (ISV). In this study, the internal state variable that accounts for damage of UD composite in fibre direction is determined in the framework of the thermodynamically consistent damage theory. The function that describes the corresponding internal state variable is determined and analysed theoretically and experimentally. The stiffness degradation is associated with corresponding damage evolution, providing the tool for experimental determination of ISV accounts for considered damage. The determined functions of ISV are used to predict the lifetime of laminates with arbitrary lay-ups.

Results from the modelling are shown in Figure 10.
Micro Mechanical Modelling

At the next stage of the work, the effects of the properties of the fibres and matrix on the damage evolution and failure strain of the composite were investigated using micromechanical finite element simulations. A new subroutine for the micromechanical simulation of damage evolution in composites, which takes into account the different damage mechanisms in different phases and the statistical variability of properties of fibres, was developed and verified. Using the unit cell approach and real visco-elastic properties of different matrix materials, we demonstrated that the visco-elasticity of the matrix of FRC leads to the quicker failure of composites as compared with an elastic matrix with similar properties.

In order to analyse the effect of loading frequency on the damage growth and lifetime of composites, a new theoretical approach to the analysis of fatigue damage, based on the kinetic theory of strength, was developed. Formulas for the stiffness reduction and damage evolution during the cyclic loading, S-N-curves, lifetime and failure probabilities of homogeneous materials and composites were derived in the framework of this approach. The effect of frequency of the cyclic loading on the lifetime was investigated. It was demonstrated that in the low range of frequencies (when heating effects are negligible), the lifetime of composites increases with increasing the loading frequency. The results were compared with the experimental investigations. Further works will include the analysis of fatigue damage growth in the high frequency range, as well as development of 2D and 3D numerical models of damage evolution in fibre reinforced composites at different scale levels.

Experimental investigations

Based on the experimental observations on the reference material tested in WP 8 the following conclusions were adopted:

- Effect of low temperature (-40°C) did not degrade the mechanical properties.
- Effect of high temperature (60°C) did especially degrade the shear properties more than 20%.
- Effect of submerging the material in saltwater for 6 to 12 months degrades the shear properties considerably. The saltwater uptake (based on weight) seems to saturate after 6-8 months and hence the degradation can be estimated after this period.
- Effect of test specimen geometries and test set-up were a general topic for all task groups and are discussed elsewhere (TG6).

Examples of the degradation on shear properties are shown in Figure 11.

Based on the observation from WP 8 it was decided only to focus on the effect of elevated temperature in WP9, and the micromechanical modelling were focused on the observed temperature effect in conjunction with the observed frequency effect especially in the R=10 fatigue tests. Tests on the alternative material in WP9 also show that the properties degrade at 60°C. The results from the fatigue tests are shown in Figure 12.
Figure 11  Static Shear tests. Results from room Temperature (RT), Seawater 6 months (SW1), Seawater 12 months (SW2), and 60°C.

Figure 12  Fatigue test results on alternative MD material.

The Effect of 60° is found to be high at higher stress levels, but seems to even out at lower load levels. Also remarkable is that the R=10 SN line is found to be nearly horizontal.
4.5. Description of work and results of Task Group 4 (WP 10, WP 11 and WP 12)

Objectives
In WP10, the objective is the establishment of the accuracy of thin-walled theory by comparison to finite element calculations and test results for thin and thick flat plates. In current blade design, the material properties from small specimens are used without any modification for blade design with sometimes much thicker laminates. This WP will check whether this is permissible, with tests carried out in the 2500 kN test machine of WMC, see Figure 13.

In WP11, the objective is the checking of repair methods for their ability to restore functionality and strength to the blades by benchmarking and verification on small components. This could then be used to repair, rather than discard blades with local deficiencies.

WP12 aims to build on the results of WP 10 and WP 11, by carrying out tests on repaired thick laminates to whether the effect of repairs are the same for thick and thin laminates.

Description of work
At the MTA, the DoW has been drastically changed for WP 10, 11 and 12. The updated Detailed Plan of Action of TG4 (OB_TG4_R009) is based upon the adjusted DoW (OB-PC-R013).

In WP 10, FE analyses were carried out to see the stress distribution of the OPTIMAT specimens. Furthermore, a comparison between the properties of thin and thick specimens should directly result in a qualified conclusion on the influence of laminate thickness on important aspects like the stiffness and the static and fatigue strength of the material. This requires tests on thick laminates only, since the thin reference laminates were tested elsewhere.

In WP 11, a number of repair methods were to be tested statically; the preferred repair methods also in fatigue. Due to the slender shape of the test specimens, the tests can only be carried out in tension or tension-tension fatigue (R=0.1). The stiffness and strength are to be compared with the unflawed specimens and this will serve as a basis for the conclusions regarding the effectiveness of the various repair methods available.

In WP 12, a number of repaired thick specimens are to be tested statically and in fatigue to see whether the conclusions on the effectiveness of repair methods can also be extended for thicker laminates. For instance the effect of ending a layer of material might be expected to have a smaller impact when there are many layers available.
Activities carried out

In WP 10, a number of FE analyses were carried out for the influence of the stress patterns by ECN. Also the thick specimens were modelled by WMC, to check the clamping system used in the test machine for thick specimens, see Figure 14.

Furthermore, thick specimens were tested both statically and in fatigue and the results were compared to the results of the standard OPTIMAT specimens with their much thinner lay-up.

![Figure 14 FE analyse of thick laminate test specimens, load introduction into the thick specimens](image)

In WP11, a number of 4 point bending tests were carried out, to tests the unflawed material in bending. Furthermore, a large number of static tensile tests were carried out on a multitude of repair techniques, such as various scarf repairs with slopes running from 1:25 to 1:100, but also of plug and patch repaired specimens, see Table 1. Other variations like using liquid resin or prepregs were tested as well. The tests were carried out for a repair depth that is either 1/3 of the total nominal thickness of the unflawed material or 2/3 of the thickness. The results have been described in a number of reports.

For WP12, the intended work was not carried out, as explained in Chapter 8.

Discussion of results

The results of WP10 do not suggest a major effect of thick laminates as was indeed not expected, as can be seen in Figure 15. However, the disappointing results achieved in the first two static tests tensile tests (yellow data points) should be investigated further and the clamping method and load introduction improved. Indeed, the last result (red data point) resulted in a maximum stress that was within range (if still at the lower bound) of the results of the thin specimens, suggesting that is was indeed the load introduction, rather than some inherent thickness effect that caused the lower results. The fatigue results seem in line with the thin specimens inspiring confidence in the current design practice.

The results of WP 11 give a good first insight into the effect of repair methods. A few problems remain however, which could be further investigated in future research projects:

- The specimen is 1-dimensional and thus the results are conservative compared to repairs in shell structures, where there would also be a sidewise support.
- The industrial partners will be fairly reluctant to show the competition their need for repairs and the methods applied, making it harder for research institutes to carry out investigations that are both of direct practical use and can be broadly used by the whole industry.
The results should be augmented in future projects by 2-dimensional tests and tests on thicker test specimens.

### Table 1 Overview of repair types tested in WP 11

<table>
<thead>
<tr>
<th>PLATE</th>
<th>REP. PROCEDURE</th>
<th>BASE MATERIAL</th>
<th>REPAIR MATERIAL</th>
<th>SLOPE</th>
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| Constant Amplitude Fatigue Tests on specimens produced by GAMESA |
| REFERENCE SPECIMENT | PREPEG | N/A | N/A | N/A |
| SCARF | PREPEG | PREPEG | best slope | 1/3 |
| SCARF | PREPEG | PREPEG | best slope | 2/3 |

| STATIC TEST: Tensile strength on specimens produced by LM |
| REFERENCE SPECIMENT | RIM | N/A | N/A | N/A |
| REFERENCE SPECIMENT | RIM | N/A | N/A | N/A |
| SCARF | RIM | LIQUID RESIN | 1:25 | 1/3 |
| SCARF | RIM | LIQUID RESIN | 1:25 | 2/3 |
| SCARF | RIM | LIQUID RESIN | 1:40 | 1/3 |
| SCARF | RIM | LIQUID RESIN | 1:40 | 2/3 |
| SCARF | RIM | LIQUID RESIN | 1:50 | 1/3 |
| SCARF | RIM | LIQUID RESIN | 1:50 | 2/3 |
| SCARF | RIM | LIQUID RESIN | 1:75 | 1/3 |
| SCARF | RIM | LIQUID RESIN | 1:75 | 2/3 |
| SCARF | RIM | LIQUID RESIN | 1:100 | 1/3 |
| SCARF | RIM | LIQUID RESIN | 1:100 | 2/3 |

| Constant Amplitude Fatigue Tests on specimens produced by LM |
| REFERENCE SPECIMENT | RIM | N/A | N/A | N/A |
| SCARF | RIM | LIQUID RESIN | 1:50 | 1/3 |
| SCARF | RIM | LIQUID RESIN | 1:50 | 2/3 |

![Figure 15 Static and Fatigue results of thin and thick specimens](image-url)
4.6. Description of work and results of Task Group 5 (WP13 and WP14)

Objectives:
The general objectives of TG 5 are:

- To establish engineering models to account for residual static strength reduction induced by cyclic loading in the basic material directions.
- To investigate the feasibility of using non-destructive testing (NDT) techniques for residual strength/life assessment.
- To develop and validate a predictive engineering model for residual strength and life (initially developed for the basic UD reference material in axial and transverse directions, then applied to predicting the residual strength of MD laminates compared with experimental data).

To reach these objectives the work was divided over two corresponding work packages:
WP 13: Residual strength of uni-directional material
WP 14: Residual strength of multi-directional material.

Description of work:
A residual strength test programme has been implemented for the basic OB UD (WP13) and MD (WP14) materials after fatigue loading at three constant amplitude load levels (intended to result in nominal lifetimes of $10^3$ – or $5\times10^5$, $10^6$ cycles) for three R-ratio values (0.1, 10, -1.0), periodically extracting a set of test coupons at given fractions (20%, 50%, 80%) of the nominal lifetime for proof-testing and subsequent testing to failure (i.e. residual strength test). A small number of UD0 specimens were also tested with nominal lifetime of $10^7$ cycles to extend the envelope closer to actual operating conditions.

The UD material tests have been carried out in the axial (UD0) and transverse (UD90) directions, resulting in a basic material characterisation. An engineering model has been developed to characterise the residual strength degradation in the basic material directions. The MD material has only been tested in the nominal axial direction; its residual strength properties have been compared with those predicted using the engineering model.

Activities carried out:
Philippidis and Passipoularidis reviewed the pertinent literature and observed that the in-plane static strength of an orthotropic lamina under a biaxial state of loading can be characterised by 5 strength values related to the principal material directions (see also OB_TG2_003):

- $X$: tensile strength in material direction 1 (fibre-direction),
- $X'$: compressive strength in material direction 1 (fibre-direction),
- $Y$: tensile strength in material direction 2 (transverse-direction),
- $Y'$: compressive strength in material direction 2 (transverse-direction),
- $S$: shear strength in plane 1-2.

The resultant residual strengths $X_R$, $X'R$, $Y_R$, $Y'R$, and $S_R$ after a certain number of cycles, $N$, at a stress ratio $R = \sigma_{\text{min}}/\sigma_{\text{max}}$ can be expressed as functions of the initial strength, maximum fatigue stress components, $\sigma_{\text{max}}$, $\sigma_{\text{min}}$, stress ratios, $R_x$, $R_y$, $R_s$, and $N$.

Experimental evaluation of this model is impossible, due to the overlarge parameter set and complexity of the experiments required. A more simplified approach is possible if each strength component is reduced as function of load components in the same direction, thus:

\[
\begin{align*}
X_R &= f_{XR} (X, \sigma_{\text{max}}, R_x, N) \\
Y_R &= f_{YR} (Y, \sigma_{\text{max}}, R_y, N) \\
X'R &= f_{XR'} (X', \sigma_{\text{max}}, R_x, N) \\
Y'R &= f_{YR'} (Y', \sigma_{\text{max}}, R_y, N) \\
S_R &= f_{SR} (S, \sigma_{\text{max}}, R_s, N)
\end{align*}
\] (1)

Many phenomenological models for residual strength degradation are based on a general power law relationship of the kind:
\[ X_R = X - \left( X - \sigma_{\text{max}} \right) \left( \frac{n}{N} \right)^m \]  \hspace{1cm} (2)

where \( N \) is the characteristic life of the specimen at stress level \( \sigma_{\text{max}} \).

If \( m=1 \) then there is a linear degradation of strength, followed by a much slower degradation, for \( m<1 \) there is an initial rapid drop in strength, followed by a much slower degradation, for \( m>1 \) there is a slow degradation followed by "sudden death". Typically, static strength and fatigue life distribution are fitted by two-parameter Weibull distributions as follows:

\[
P_x(x) = \exp \left[ -\left( \frac{x}{\beta} \right) \right]^\alpha \quad \text{(3a)}
\]
\[
P_N(n) = \exp \left[ -\left( \frac{n}{N} \right)^{\alpha'} \right] \quad \text{(3b)}
\]

More sophisticated models were also considered (see OB_TG5_R003 and text below).

Planning versus accomplished:

According to the original detailed plan of work developed for WP13 and WP14 in the first year of the project, there were nominally 8 specimen tests at each material/R-ratio/nominal lifetime/life fraction "test point", 4 with a residual strength tested in compression, 4 in tension. Due to a decision of the partners, these specimens were always equally split between 2 laboratories, meaning that each laboratory would fatigue 4 specimens to each test point and then test 2 to failure in compression and 2 in tension. The initial programme plan took insufficient account of the probability of "premature" fatigue failures, which were higher than expected from the s-N curve characterisation, presumably due to normal variation in material properties of the manufactured specimens. When it became apparent that there was little or no degradation of compressive strength following fatigue in tension (or reversed loading) these tests were abandoned in favour of additional tensile tests to compensate for the "premature" fatigue failures.

Ultimately, the total number of tests exceeded that originally specified in the DPA and sufficient data was gathered to essay the prediction of MD residual strength degradation from the UD residual strength data (see below).

Discussion of results:

Residual strength

A summary of all strength degradation plots and discussion of trends and comparison with previous results in the literature can be found in OB_TG5_R007.

For UD longitudinal and MD material, reversed loading cycles (\( R=-1 \)) proved to be more harmful to residual tensile strength than purely tensile cycles (\( R=0.1 \)), as can be seen in Figure 16. In fact, linear degradation (\( k=1 \)) is a good descriptor of tensile residual strength at \( R=-1 \) and forms a lower boundary for \( R=0.1 \). Due to various technical problems however, the stiffness degradation was not always measured. From the subset of available tests at \( R=-1 \), stiffness degradation was observed for MD material, but not UD. Insufficient data was available to examine correlations between final residual strength and modulus degradation for given combinations of R-ratio, life fraction, and load level.

Note: cycling loading applied as \( R=0.1 \) (blue), and \( R=-1 \) (red). All stress levels and life fractions are shown together

Figure 16 - Residual strength test results showing greater degradation for reversed cycle loading (\( R=-1 \), red) than for purely tensile cycling (\( R=0.1 \), blue)
From the variety of models fitted to the residual strength data, three were selected as producing consistently acceptable predictions of strength degradation: the Interaction model, the second model of Yang, and the OM model. Details on models, implementation and assessment are reported in OB_TG5_R003, OB_TG5_R007 and OB_TG5_R013. In addition, the linear degradation model (BR, $k=1$ in equation 1) was shown to yield a safe prediction in all cases. The exponential model (REI), used by many researchers, is presented for comparison purposes, though its performance in the current study was poor. From the probabilistic predictions point of view, the second model of Yang presented the best results. Data from tests on ISO ±45 coupons were used for validation of statistical predictions. The cumulative distribution functions (CDF) of the aforementioned models can be seen in Figure 17 and the 90% probability strength degradation curves compared to the experimental results in Figure 18.

![Figure 17 CDF predictions of models for the 50% nominal life at the stress level corresponding to 220000 cycles](image1)

![Figure 18 90% probability of survival strength degradation curves for the ±45 laminate at stress level 2](image2)

The residual strength degradation of the MD laminate can be accurately predicted using the predictions of the UD laminate at the relevant stress ratio, see also OB_TG5_R007. The proposed procedure is to scale the UD prediction by a factor equal to the static strength ratio of the MD versus the static strength of the UD:

$$X^*_r^{MD} = \frac{UTS_{MD}}{UTS_{UD}} \cdot X^*_r^{UD}$$

(4)

![Figure 19 Residual strength degradation predictions of MD specimens at R=0.1, based on UD predictions](image3)
The results shown in Figure 19 indicate good agreement between the predicted degradation curves and MD data. Through interaction with TG1 with regards to implementation of the strength degradation model into life prediction it has been shown that, while the strength degradation model is adequate, the results are no better than can be obtained using the appropriate Miner results, as outlined in OB_TG1_R024.

**Condition monitoring**

Various NDT techniques were assessed for their ability to characterise residual strength. The main techniques examined were acoustic emission and thermoelastic stress analysis. Time and equipment constraints meant that these complex and analysis-intensive techniques could only be applied to a limited number of tests. For acoustic emission monitoring, the initial approach was to utilise a proof-loading cycle, either to the 2500 μstrain limit for stiffness measurement, or to the constant amplitude fatigue stress level. The proof-load was applied before and after the fatigue part of the test, but AE activity proved to be very low (or non-existent) at these stress levels. A high event count was obtained from one MD specimen which was subsequently found to have a particularly low residual strength, but in general the AE response was too small to successfully characterise the strength. More success was achieved from monitoring the residual strength test to failure. In UD specimens AE activity initiated only very close to failure and then increased rapidly, but for the +/-45 shear material the AE Counts parameter was found to initiate at lower stress levels for specimens at higher fatigue life fractions; similar behaviour was noted in some MD specimens, although comparatively few specimens were monitored in this way. The thermoelastic stress responses of the UD and MD materials were found to be very different due to the sensitivity of the technique to surface ply condition. Internal specimen heating, particularly for MD specimens, tended to dominate the signal response, making damage identification very difficult.
4.7. Description of work and results of Task Group 6 (WP 15)

Objectives
The objective was to implement the scientific results from Task Groups 1 to 5 into Design Recommendations.

Description of Work
The TG6 work has reviewed all of the work conducted throughout OPTIMAT and summarized this in the context of practical applications in design for industry. As part of this review, the following key areas were reviewed: test coupon selection, stiffness assessment, S-N curve development, Constant Life Diagrams, rain flow counting, strain rate effects, variable amplitude loading, complex stress states, extreme conditions, thick laminates and repairs, residual strength, and the use of OptiDAT data in design. The current industrial approach, the key OPTIMAT observations, and new perspectives have been identified for each of these areas.

In all, 39 design recommendations have been developed in the following key areas: life time prediction, complex loading, residual strength, extreme conditions, and repair. These design recommendations will be considered for inclusion of the next version of DNV/GL design guidelines. The Work for TG6 was reported in one single report: OB_TG6_R002, "Implementation of OPTIMAT in Technical Standards". The report was presented and distributed at the OPTIMAT workshop in Athens, March 2006.

Activities carried out
The work of this TG started after most of the scientific work was in its final stage. The activities carried out in this TG/WP was meeting activities and reporting. The Task Group Managers from TG 1 to 5 collected the most important scientific results from their groups. The results were discussed with the Certifying bodies DNV and GL. Comparisons were made with existing rules and recommendations published by the certifying bodies. The new scientific results were interpreted and proposals for new recommendations and rules were formulated. Proposals for further research were also identified.

Planning versus accomplished
The reporting was accomplished as planned.

Discussion of the results
The work has made the scientific results from OPTIMAT ready for being included in Rules and Technical Guidelines.
4.8. Production of test specimen (WP16)

Table 2 provides a summary of coupons manufactured and tested. The planned number of tests (~2500) is exceeded by both the achieved number of tests as well as by coupon production. It should be noted that each row represents various laminate orientations, and, sometimes, repair strategies or sub-geometries.

The grey cells are geometries that were deleted from the test plan after production. The hatched grey cells represent specimens that were used to select the geometry. After selection, the unselected coupons were not tested.

The amount of missing coupons/invalid tests/used as dummy/not scheduled is ~800. This means, that an estimated 800 coupons are still in store in the laboratories (i.e. average of 100 per lab). These are either unreported tests, or coupons which are retained for future reference, and it should be noted that often, these 100 coupons are various geometries. Of the left-over coupons, 180 are from phase 2, 620 are from phase 1.

These data are based on OptiDAT. OptiDAT includes information provided by LM, viz. OB_TC_R011 on the delivery of test specimens to the and OB_TC_R016 on the lab tests carried out at LM on the plate material aspects such as the fibre volume fraction, glass temperature, void content etc. A material specification is provided in OB_SC_R001.

<table>
<thead>
<tr>
<th>Description</th>
<th>GAMESA</th>
<th>LM</th>
<th>GAMESA</th>
<th>LM</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM combined loading compression</td>
<td>15</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cruciform</td>
<td>208</td>
<td>89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dog-bone (D02 without tabs)</td>
<td>54</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dog-bone (RISOE standard)</td>
<td>82</td>
<td>36</td>
<td></td>
<td></td>
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<tr>
<td>Four-point bending</td>
<td>20</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iosipescu (in plane shear)</td>
<td>54</td>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISO compression</td>
<td>62</td>
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<td></td>
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<tr>
<td>ISO compression without tabs</td>
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<td>59</td>
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<tr>
<td>ISO tension</td>
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<tr>
<td>ISO tension (250 mm)</td>
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<td>188</td>
<td></td>
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</tr>
<tr>
<td>ISO tension without tabs (300 mm)</td>
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<td>67</td>
<td></td>
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<tr>
<td>Long, rectangular (reference)</td>
<td>6</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long, rectangular (repaired)</td>
<td>84</td>
<td>86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rectangular</td>
<td>3030</td>
<td>2166</td>
<td></td>
<td></td>
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<tr>
<td>Thermal expansion</td>
<td>60</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tubular specimen</td>
<td>96</td>
<td>65</td>
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<td></td>
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<tr>
<td>Very large, rectangular</td>
<td>12</td>
<td>10</td>
<td></td>
<td></td>
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<tr>
<td>Delivered according to LM, but not tested (for instance due to changes in DoW at MTA)</td>
<td>19</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending specimen</td>
<td>26</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending specimen (repaired)</td>
<td>84</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iosipescu (in plane shear, 1-3 direction)</td>
<td>8</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iosipescu (in plane shear, 2-3 direction)</td>
<td>8</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>through-thickness UD</td>
<td>30</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>through-thickness MD</td>
<td>30</td>
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<td></td>
</tr>
<tr>
<td>Grand Total</td>
<td>90</td>
<td>4563</td>
<td>78</td>
<td>3005</td>
</tr>
</tbody>
</table>

Source: OptiDAT, April 20th 2006
4.9. Description of the OptiDAT database

General

OptiDAT is the database from the OPTIMAT BLADES project, and is part of the work completed in WP 2 (deliverable no. 54), see also OB_TC_R018. The OptiDAT database contains results of various tests on some 3000 coupons. In terms of testing time, this is ~40,000 hours; the total number of fatigue cycles approximates 900 million. Tests were performed on two material systems; both are glass-fibre reinforced epoxy, but the resin systems are slightly different. The majority of the tests have been performed on the standard OPTIMAT geometries for Unidirectional and Multidirectional material. The focus is on fatigue results, and test results for various loading conditions can be found in the database, describing material behaviour in fatigue, static, bi-axial (tubular and cruciform), repairs, residual strength, variable amplitude, extreme conditions, thick laminates, shear loading, 4-point bending, loading in transverse direction, etc. Detailed information is also available on the thermal expansion coefficients, and for most plates, the fibre volume fraction and glass transition temperatures were measured and reported.

Database lay-out

The database is constructed in a spreadsheet format (MS Excel). All the test results are reported in a single worksheet. Every row in the worksheet represents a test; every column contains data on various aspects of the test; coupon identification, laminate, dimensions, test type, test results. Although some 100 columns are reserved for detailed information on the various test types, further information may be required by the user. One column contains a reference to the various (ca. 150) technical reports with further information on the particular test. In these reports, information can be found which is, at the time, not feasible to include in the database (without making it difficult to handle), such as stress-strain diagrams, a thorough description of the test set-up, and images of the coupons' failure modes.

The database contains other sheets, with information on how to use the database, plate, geometry, and test type details, and contact information of the project participants. Also, the FACT database is included in a separate sheet. This set-up, where all the test data are located in one sheet, and meta-information is located in other sheets, allows for quick comparison of test results.

Data submission

During the OPTIMAT project, the OptiDAT database was used for storage of the test results. The participating laboratories submitted the data as soon as possible after completion and reporting of the tests. Ensuring consistency, a data submission sheet was available for the contributing partners. Thus, all test results were available for review and further analysis during the test programme, rather than at the end of the programme. The database was updated and loaded to the OPTIMAT Web site after each addition of test data.

Tracking Progress

The availability of the results facilitated tracking the test progress. The database included several progress tracking features, see Figure 20.

Figure 20  Progress tracking by means of OptiDAT
The ‘Manufacturing and Delivery’ sheet, from the project’s main supplier, LM Glasfiber A.G., was included in the database. This showed for each batch of coupons the shipment date, recipient, coupon type, plate number, etc. The information was related to the data in to the database. Thus, for each delivered batch, the user could see directly how many coupons had already been tested – hence, how many should be left. Also, the information from each Task Group’s Detailed Plan of Action was included, describing the test plan. This information was also linked to the test results already in the database, giving a detailed overview of the progress. Finally, the number of records, test hours, or number of cycles, could be visualised automatically using an interactive chart, giving a quick overview of the cumulative test results. These tracking features will not be included in the public version of the database, but can be applied to future projects.

Tools

The database contains some pre-programmed tools, to increase user-friendliness when retrieving data. The vast amount of columns and rows can be viewed in various modes using a specialised toolbar, see Figure 21. This allows the user to limit the visible records to a particular test type, selection of columns, or both. A user-defined column view can also be set.

To display fatigue data quickly, the database is equipped with a plot tool, which allows the construction of an S-N diagram using a selection of data, see Figure 22. The result is a chart with the selected data, and a separate sheet with a copy of the selected records, for further processing.

Prospects

The database is not directly meant for certification purposes, but the information and methodology is used for guidelines for testing of wind turbine blade materials. OptiDAT is available from www.kc-wmc.nl from May 2006 for a small maintenance fee. It is freely available for OPTIMAT members and students. A subscriber set-up warrants regular updates, as well as inventorying the user-population, which helps tailoring the data to user requests. It will be expanded with the results from WP 3 of UPWIND.
5. ASSESSMENT OF RESULTS AND CONCLUSIONS

5.1. Results

Among all the detailed results reached, the following 8 major results have been identified:
- Recommendations on testing and characterisation of materials
- Validated composite mechanics and FEM guidelines and recommendations
- Suitable repair techniques for FPR rotor blades
- Validated micro mechanics models
- New Wisper standard load spectrum
- Validated engineering model for residual strength prediction
- OptiDAT data base including analysis software
- Design recommendations for next generation rotor blades

Below these 8 results are briefly described.

Recommendations on testing and characterisation of materials

Recommendations have been set for the testing and characterisation of materials. These recommendations include the specifications for the test specimens to be used for the different types of testing needed to characterize materials for rotor blades. The testing recommendations include:
- Static tension
- Static compression
- Static shear
- Fatigue

For all test conditions the choice of test specimen is discussed. On top of that for fatigue testing it is recommended that the frequency of fatigue testing should be chosen to limit the temperature rise of the test specimen to a maximum of 10 degrees centigrade above the ambient temperature.

Validated composite mechanics and FEM guidelines and recommendations

Based on a comprehensive experimental program the static and fatigue properties of the reference material were characterized. This information was implemented in advanced FEM formulations, in order to define and validate experimentally multi-axial failure theories in static and fatigue loading and to quantify complex stress state effects on blade design.

From the experimental results and from the analytical evaluations it could be concluded that:
- 1D stress analysis, i.e. beam theory formulations, could be acceptable but failure prediction should be done in a layer-by-layer basis, i.e. complex stress states at the ply level should be taken into account. As for failure prediction under complex stress states, typical plane stress states as those developed in the layers of the shells of a rotor blade can be simulated, besides sophisticated biaxial tests, by uni-axial testing in off-axis UD coupons. Failure prediction under static loading is performed satisfactorily using criteria such as Tsai-Wu, Puck and Tsai-Hill. Under cyclic loading, life prediction is also satisfactorily performed when using similar quadratic in stress functions compared to simplistic approaches, such as to consider separately damage from each stress component and add at the end. Experimental results from cyclic biaxial tests, using specimens either of cruciform or tubular geometry, were not conclusive. Static tests results from bi-axial tension of cruciform specimens made of MD lay-up suggest that failure prediction according to limit functions as those cited in the above is fair, in general, although many other parameters such as stiffness degradation scenarios or material non-linearity for example are of paramount importance.

Suitable repair techniques for FPR rotor blades

Within the scope of the project was the development of repair methodologies suitable for application on the load carrying laminates of fibre reinforced wind turbine rotor blades, so as to avoid possible rejection of products both during production and service life. There were no recommendations available for repairing structural parts of blades. Blades that are damaged or have production deficiencies in the thick structural parts are being destroyed, even if the damage or deficiencies are local. Defects encountered during production, like dry spots and web to skin
delaminations will need different repair techniques than those caused by lightning strikes or impact. Nevertheless, it was selected to concentrate on flaws that are found on parts of the primary structure of the wind turbine blades, e.g. the girder part of the blade and not parts that include structural foam. From the available repair methods for application to composite material structures in general, two were found suitable for the repair of the load carrying laminates of rotor blades, namely the scarf repair and the plug/patch. Within an extensive testing campaign these repaired specimens were tested in uni-axial tension and results with respect to both strength and exhibited stiffness were compared with that of flawless specimens, which were tested to form the necessary baseline. Static test data show that the most promising from the selected repair techniques is the scarf repair with a slope of at least 1:50, which leads to a strength restoration of over 90% and scatter comparable to the reference coupons with adequate material use. Regarding the exhibited stiffness, results are within 10% of the reference elasticity. Verification of behaviour under tension–tension fatigue loading was carried out for the selected repair method with similar results. Other details of repair techniques applicable to composite material blades will be investigated in the near future, in order to arrive at a set of recommendations for the manufacturers leading to reliable repairs, thus prolonging the operating life of the blades and acceptance by accreditation bodies.

**Validated micro mechanics models**

Extended damage mechanics modelling was used to describe the fatigue damage in polymer composite materials. The measurements of the stiffness degradation are used to determine the corresponding internal state variable function experimentally. The relationships between particular internal state variables and corresponding stiffness degradation are formulated for considered damage mechanism. It was observed experimentally that the normalized stiffness degradation of conditioned and reference materials are rather close, and are approximated with the same polynomial. The progressive fibre fracture is considered as main contributing mechanism. The outlined micromechanics methods give possibilities to study the interface strength and debond crack growth effects on formulated damage tensor. The continuum damage mechanics approach was used to characterize the damage evolution in long fibre laminated composites. The internal state variable evolution law associated with damage in fibre direction is formulated in terms of used theory, and determined experimentally and theoretically. The theoretically and experimentally determined evolution law of internal state variable is used in damage dependent constitutive relationships for laminate in order to predict the static strain - stress behaviour of arbitrary laminates. A methodology is proposed to measure the values of the internal state experimentally. The FEM analysis and Monte Carlo simulations are used in order to predict the internal state variable according to the outlined theoretical formulation. The predicted values of internal state variables are compared with experimental results.

**New Wisper standard load spectrum**

Sixteen years back a load sequence for variable amplitude testing of materials in wind energy applications has been defined. The sequence has been synthesized from the measured flap wise blade root bending loads of 9 wind turbines varying from 18 kW to 3 MW in power and from 12 m to 100 m in diameter. This load sequence called Wisper has found international acceptance and is widely used in variable amplitude testing of wind turbine rotor blade materials. In the context of this project, it has been proposed to set up a New Wisper standard load sequence that reflects today’s state-of-the-art in wind energy conversion technology. The resulting New Wisper sequence is evaluated by experimental data and compared to the old Wisper standard sequence. The comparison is carried out on the basis of the rainfall range pair load spectra, 1-Hz equivalent load calculations and even more complex damage calculations using GFRP-material Goodman-diagrams and advanced damage accumulation models. The New Wisper sequence is recommended for future use in material characterization programs.
Validated engineering model for residual strength prediction

In order to be able to predict the residual life of a rotor blade after a number of years of operation, validated engineering models for residual strength prediction are a necessity. In the project the activities of one of the Task Groups were concentrated on this item.

The general approach followed: The laminate strength after (partial-lifetime) fatigue was measured at pre-determined life fractions. Apart from providing useful insights in the material strength behaviour, this formed the basis of strength degradation modelling, which can be used in lifetime prediction methods. Using strength degradation models, lifetime prediction can be improved relative to the "classical" Miner damage rule, by taking into account the effect of loading sequence. The OptiDAT database contains results from more than 700 tests on two different laminate lay-ups, a unidirectional (UD) material and a multi-directional (MD) glass-epoxy laminate. Three R-ratios (R=10, R=0.1, and R=-1) were tested for each material, except where buckling instability proved a problem. The database includes specimens that failed prematurely during the fatigue phase of the test as well as the residual strength of surviving specimens at three life fractions (20%, 50%, and 80%). This data formed the basis for the model developments. From the research it could be concluded that

- No measurable degradation was observed in the residual UCS of the material.
- Due to current strain limits of GFRP and CFRP, residual strength degradation is not to be expected to be a design issue for wind turbine blades when the strains are as expected.
- It is still important however that the residual strength following full scale dynamic testing is evaluated.

OptiDAT database including analysis software

OptiDAT is the database from the OPTIMAT BLADES project. The database is not directly meant for certification purposes, but the information and methodology is used for guidelines for testing of wind turbine blade materials. The database contains results of various tests on some 3000 coupons. In terms of testing time, this is ~40,000 hours; the total number of fatigue cycles approximates 900 million. Tests were performed on two material systems; both are glass-fibre reinforced epoxy, but the resin systems are slightly different. Detailed information is available on all aspects of the experiments, the thermal expansion coefficients, and for most plates, the fibre volume fraction and glass transition temperatures were measured and reported.

**Lay-out**

The database is constructed in a spreadsheet format (MS Excel). One of the columns contains a reference to the various (ca. 150) technical reports with further information on the particular test. The ‘Manufacturing and Delivery’ sheet, from the project’s main supplier, LM Glasfiber A.G., is included in the database. This showed for each batch of coupons the shipment date, recipient, coupon type, plate number, etc.

**Tools**

The database contains some pre-programmed tools, to increase user-friendliness. The vast amount of columns and rows can be viewed in various modes using a specialised toolbar. This allows the user to limit the visible records to a particular test type, selection of columns, or both. A user-defined column view can also be set. To display fatigue data quickly, the database is equipped with a plot tool, which allows the construction of an S-N diagram using a selection of data.

**Prospects**

OptiDAT is available from www.kc-wmc.nl, from May 2006 for a small maintenance fee. It is freely available for OPTIMAT members and students. A subscriber set-up warrants regular updates, as well as inventorizing the user-population, which helps tailoring the data to user requests. It will be expanded with the results from WP 3 of UPWIND.

**Design recommendations for next generation rotor blades**

Based on the results of the project, DNV and GL drafted a set design recommendations that can be used as a basis for future design guidelines. A large number (39) of design guidelines has been drafted. The recommendations will be incorporated in the new versions of the guidelines from both GL and DNV.
5.2. Conclusions

With 17 participants from 8 EU countries and a duration of 52 months, the Optimat Blades project was one of the larger EU-FP5 supported R&D wind energy projects. At the start of the project all participants acted as individual partners in a large project. However at the end of the project all the R&D-participants formed a team that was dedicated to establish the targets set for the project. Almost all of the deliverables (54) have been accomplished. The collaboration in the R&D-team was such that the team preferred to continue as a team in a next R&D project on materials research. (UpWind WP 3)

The activities of the Optimat Blades team resulted in:
- 39 design recommendations that are ready to be incorporated into the guidelines of DNV and GL. This was the main target for the project.
- About 150 technical and scientific reports. All of these reports are non-confidential and available via the Optimat website.
- A database containing all the experimental results of the project. This database will be kept operational and accessible for free for all partners in the projects and for students, and for a small maintenance fee for others.
6. ACKNOWLEDGEMENTS

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The Research performed by ECN and WMC is funded in part by SenterNovem, Utrecht. Project number: 2020-01-12-10-002

The Research performed by CRES is funded in part by the General Secretariat of Research and Technology (GSRT) of the Greek Ministry of Development.
7. LIST OF DELIVERABLES

In Table 3 the complete list of deliverables is presented.

<table>
<thead>
<tr>
<th>No.</th>
<th>WP</th>
<th>Deliverable title</th>
<th>Form</th>
<th>Old Due Date</th>
<th>New (due) Date</th>
<th>Diss. level</th>
<th>Report(s)</th>
<th>% Done</th>
</tr>
</thead>
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<tr>
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<td>3</td>
<td>Test report describing the material, laminates and fatigue tests</td>
<td>Report</td>
<td>5</td>
<td>13</td>
<td>PU</td>
<td>OB_TG1_R005, OB_TG2_R001, OB_TG2_R002, OB_TG2_R003, OB_TG2_R004, OB_TG2_R006, OB_TG2_R007, OB_TG3_R005, OB_TG4_R001, OB_TG5_R014</td>
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<tr>
<td>2</td>
<td>8</td>
<td>Microstructural model and identification of degradation parameters.</td>
<td>Report</td>
<td>5</td>
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<td>Report</td>
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<td>Report</td>
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<td>Report</td>
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<td>3</td>
<td>Report on Benchmarking of Lifetime Prediction Methods</td>
<td>Report</td>
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8. COMPARISON OF INITIALLY PLANNED ACTIVITIES AND WORK ACTUALLY ACCOMPLISHED

Steering Committee (WP 1)
The activities of the Steering Committee, have been taken over by the Project Coordinating Committee, at an early stage in the project. For that reason the Steering Committee has been active only in the phase 1 of the project. All WP 1 activities have been taken over by the PCC.

Technical Committee, (WP 2)
All activities of the Steering Committee have been executed according to the planning.

Task Group 1 (WP 3, WP 4 and WP 5)
Some minor deviations have to be stated between the work accomplished within TG1 and the DoW, the original one and the modified one of the MTA. But all deliverables have been prepared and all milestones were reached. The constant amplitude behaviour was investigated in more detail than foreseen in the original DoW, because the originally foreseen 3 stress-ratios seemed not to be a sufficient basis for the analysis on lifetime prediction models. Concerning variable amplitude fatigue behaviour the influence of omission was not investigated as originally planned.

This is a consequence of the results achieved in WP4, because no omission could be applied on the newly developed NEW WISPER spectrum. Therefore focus of the work was the investigation of simplified load spectra and load sequence effects. The interaction tests of WP5 deviated mainly from the plan in the MTA-DoW in that way that two instead of one S-N curve were established with inputs for WP3 and WP9, and that the foreseen block-tests were replaced by VA-tests with the WISPER standard. The tests at the cruciform specimens as a cross link to WP7 had to be modified as justified in the statement of TG2 below.

Task Group 2 (WP 6 and WP 7)
No major deviations were observed between the Description of Work (OB_TC_R013 rev.016) and the work actually accomplished within TG2. To be more correct, the work performed by the partners has exceeded that initially described as contractual obligations. All milestones have been reached and the deliverables prepared as scheduled. Concerning the experimental effort by all partners of TG2, it can be said that it has exceeded that initially planned by ca. 35%; 465 tests of all types were foreseen, 629 were finally accomplished.

CA cyclic tests of cruciform specimens have not been performed due to a series of technical difficulties and malfunctions occurred at the biaxial test rig of VUB. They have been substituted by slow Loading-Unloading-Reloading cyclic tests.

Task Group 3 (WP 8 and WP 9)
In Work Package 8 most of the experimental work was accomplished. Due to experimental difficulties it was not possible to establish R=-1 and R=10 fatigue tests on material exposed to salt water. Also some of the fatigue tests planned at -40° were cancelled due to experimental difficulties.

In Work Package 9 testing is not fully accomplished. R = 10 Fatigue tests at 60°C and compression tests in 90°-direction have not yet been conducted due to late delivery of test samples, lack in resources and test capacity. These tests will be finalised in relation to the UpWind project. However all deliverables as formulated in the DoW are fulfilled with the exception of D52, which has not been fully accomplished. Laminate calculations are reported in OB_TG3_R027 report. However, the damage and micromechanical modelling is the main topic of UpWind task 3.2, and will be continued during that project.

Task Group 4 (WP 10, WP 11 and WP 12)
In WP 10, the work as outlined in the DoW was carried out. The optional use of optical fibers was not carried out, due to practical problems with the optical measurement system, which were foreseen at the MTA and could not be solved satisfactory afterwards. All milestones were reached and the deliverables are ready.
In WP11, no major deviations were observed between the modified Description of Work (OB_TC_R013 rev.016), issued after the Midterm assessment and the work actually accomplished. In fact, the work exceeded the originally foreseen amount, investigating more types of repair than originally foreseen, also due to the enthusiasm of the manufacturers. All milestones have been reached and the deliverables prepared as scheduled.

In WP12, the planned work could not be carried out, due to a number of reasons:
- The work in the TG4 started very late, and preference was given to the work within WP10 and WP11.
- LM could not get access to the epoxy used for the original specimens. They proposed to make specimens with the new raisin, used for Phase II tests. Unfortunately this would mean that all the basis work on reference thick specimens (WP 10) and thin repaired specimen (WP 11) would need to be duplicated so as to enable a clear distinction between the effect of repairs (compared with specimens from WP 10) or thick versus thin repaired specimens (compared with WP 11) and the effect of the different raisin.
- Fatigue tests in the 2500 kN test machine were carried out at 0.5 Hz, resulting in weeks of testing for larger number of cycles.
- No extension of the project was practical, since the partners would be participating in a subsequent project, UPWIND.

As a result, the work of WP12 could not be carried out and deliverable 38 could not be realized; however the work on thick and thick repaired specimens can be continued in UpWind and other projects.

Overlooking the work planned for TG 4 it can be stated that the activities that could not be carried out in WP 12 on repaired thick specimens are compensated by extra activities carried out for WP 11 on thin repaired specimens testing.

**Task Group 5 (WP 13 and WP 14)**

According to the original detailed plan of work developed for WP13 and WP14 in the first year of the project, there were nominally 8 specimen tests at each material/R-ratio/nominal lifetime/life fraction “test point”, 4 with a residual strength tested in compression, 4 in tension. Due to a decision of the partners, these specimens were always equally split between 2 laboratories, meaning that each laboratory would fatigue 4 specimens to each test point and then test 2 to failure in compression and 2 in tension. The initial programme plan took insufficient account of the probability of “premature” fatigue failures, which were higher than expected from the s-N curve characterisation, presumably due to normal variation in material properties of the manufactured specimens.

When it became apparent that there was little or no degradation of compressive strength following fatigue in tension (or reversed loading) these tests were abandoned in favour of additional tensile tests to compensate for the “premature” fatigue failures.

Ultimately, the total number of tests exceeded that originally specified in the DPA and sufficient data was gathered to essay the prediction of MD residual strength degradation from the UD residual strength data.

All targets and deliverables formulated in the DoW have been reached.

**Task Group 6 (WP15)**

All the work foreseen in the DoW has been accomplished and reported. The activities of TG6 started after most of the work in the other 5 TG’s was in a final stage. TG 6 had to evaluate all the reported results in order to able to formulate the design recommendations and the recommendations for future research.

**WP 16**

Originally it was foreseen the several industrial partners were going to produce small specimens. However quite early in the project it was concluded for reasons of consistency to shift this production to one partner, LM. In total over 4000 small specimens are produced, a lot more than
foreseen during the definition phase of the project. On top of that biaxial specimens, tubular and cruciform specimens, have been produced. For the research on repairs, special repaired and reference specimens are produced by two of the industrial partners (Gamesa and LM). The production of thick specimens has been limited to the amount that could be tested in the test laboratory with the large testing machine needed for this testing. Due to the fact that LM could not get access to the epoxy used for the original specimens no thick repaired specimens were produced.
9. MANAGEMENT AND CO-ORDINATION ASPECTS

The project required the establishment of a consortium of 18 partners from 8 EU countries. These include 10 research institutes from 7 EU countries, 6 wind turbine and/or blade manufactures from 4 EU countries and 2 Certification Bodies from 2 EU countries. (Since mid 2004 one industrial partner left the consortium due to bankruptcy)

**Overall structure of the consortium**

The number of partners, the number of researchers involved and the amount of work to be done, made that a good project management was essential. One of the measures taken was to split the scientific/technical and financial/administrative co-ordination. Netherlands Energy Research Foundation (ECN) and Delft University of Technology (WMC) act as the financial/administrative co-ordinator and the scientific/technical co-ordinator respectively. Furthermore a Project Coordinating Committee (PCC), Steering Committee (SC, the SC stopped its activities after the MTA) and a Technical Committee (TC) were installed.

For each main objective a Task Group was formed, that carried out the comprehensive Work Packages. The Task Group leaders were members of the Technical Committee, which was chaired by the scientific/technical co-ordinator of the project. The industrial partners and the Certification Bodies formed the Steering Committee.

In the Project Coordinating Committee all partners in the project are represented. An overview of the project organization and the members is given in Figure 1.

**Task groups**

In Task Groups 1 to 5 the fundamental research was carried out (WP 3-WP 15). At the start of the project the Task Groups prepared a detailed plan of action for their work. The work was mainly carried out by the research institutes, with some specific tasks for the industrial partners. The results of the work of Task Groups 1 to 5 were implemented in design recommendations by Task Group 6. The Task Group leaders were responsible for the scientific/technical co-ordination within their Task Group and had the responsibility for drafting the detailed plan of action, progress reports and final reports for their Task Group. The Task Group leaders reported to the TC. They were also participants in TG 6 where one of their tasks was to report the results from their TG. This ensured that all the knowledge gained in TG 1-5 was easy accessible for TG 6 and was well interpreted for writing the design recommendations.

**Technical Committee**

The members of the TC were the TG leaders and the co-ordinators of the project. The TC was chaired by the scientific/technical co-ordinator (WMC). The TC had the responsibility to co-ordinate the project, to check the consistency of the proposed work in the detailed plan of actions. If necessary it will took action for improvement. The TC was also responsible for editing the progress reports from the Task Groups. Until the MTA meeting the TC reported to the SC, after this meeting the TC reported report to the PCC. The fact that the Task Group leaders were the members of the Technical Committee made that the Technical Committee had direct access to, and knowledge of, the work in the Task Groups. This enabled the Technical Committee to check the consistency of the work and to guarantee the required flow of information between the Task Groups. The Technical Committee was responsible for organizing the general project meetings, workshops and the assessment meetings

**Steering Committee**

The Steering Committee consisting of industrial partners and the Certification Bodies was established to monitor the project. During the MTA meeting it was decided to stop the activities of the SC. The industrial partners preferred to take part in the activities of WP 16, where the design recommendations were established. The major part of the activities of the SC, were already taken over by the Project Coordinating Committee

**Project Coordination Committee**

In the Project Coordination Committee (PCC) all partners were represented and had one vote. The PCC was established to deal with contractual matters as the consortium agreement. The PCC is
chaired by the financial/administrative coordinator. Besides the contractual matters the PCC had taken over tasks from the Steering Committee and evaluated progress reports, and guided the overall objective.

At the start of the project, a number of combined meetings were scheduled on a semi-annual basis. All meetings of the various task groups, the PCC and the TC are held within three days at the same location. In general such a meeting session started with a PCC meeting, followed by the Task Group meetings and concluded with a TC meeting.

**Collaboration with the consortium**

The consortium as a whole performed very well. The collaboration between the partners appeared to be very smoothly and if necessary activities were easily shifted between partners, if the overall progress of the work asked for such a shift.

Furthermore the partners were willing to discuss problems encountered by a certain partner and the help to resolve or overcome the problems.

The contribution of all research partners, the Certifying Partners and two out of the original six industrial partners was excellent. In fact many of these partners spend more person months than originally planned.

**Industrial partners**

One industrial partner had to leave the project due to two bankruptcies within a short span of time. From three other industrial partners the contribution was very limited. In fact they only contributed at the very beginning of the project in the kick off meeting and the first progress meeting and in the last progress meeting and a TG 6 meeting. Two of the partners did not send in any cost statement during the duration of the project because of their very limited contribution. Fortunately the planned contribution of those industrial partners was very limited, and their activities for the production of test specimen including the reserved budgets was taken over completely by one of the other industrial partners.

**Conclusions**

As a conclusion it can be stated, that the collaboration between the research partners, the certifying partners and the two really involved industries was that good that most of them wanted to continue as a team the R&D collaboration started in this project. And in fact the "Rotor Structures and Materials" R&D team of the UPWIND project is almost identical to this Optimat Blades team.

**Contact persons**

For the follow-up of the project the persons in Table 4 can be contacted:

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
<th>Telephone</th>
<th>E-mail</th>
</tr>
</thead>
<tbody>
<tr>
<td>L.G.J. Janssen</td>
<td>ECN</td>
<td>+31 224 56 46 64</td>
<td><a href="mailto:l.janssen@ecn.nl">l.janssen@ecn.nl</a></td>
</tr>
<tr>
<td>A.M. van Wingerde</td>
<td>KC-WMC</td>
<td>+31 227 50 49 22</td>
<td><a href="mailto:a.m.vanwingerde@kc-wmc.nl">a.m.vanwingerde@kc-wmc.nl</a></td>
</tr>
<tr>
<td>T.P. Philippidis</td>
<td>UPAT</td>
<td>+30 26 10 99 72 35</td>
<td><a href="mailto:philippidis@mech.upatras.gr">philippidis@mech.upatras.gr</a></td>
</tr>
<tr>
<td>P. Brøndsted</td>
<td>RISØ</td>
<td>+45 46 77 57 04</td>
<td><a href="mailto:povl.broendsted@risoe.dk">povl.broendsted@risoe.dk</a></td>
</tr>
<tr>
<td>A.G. Dutton</td>
<td>CCLRC</td>
<td>+44 12 35 44 58 23</td>
<td><a href="mailto:A.G.Dutton@rl.ac.uk">A.G.Dutton@rl.ac.uk</a></td>
</tr>
<tr>
<td>Ch.W. Kensche</td>
<td>DLR *</td>
<td>+49 471 90 26 29 20</td>
<td><a href="mailto:ken@ifam.fhg.de">ken@ifam.fhg.de</a></td>
</tr>
<tr>
<td>R.P.L. Nijsen</td>
<td>KC-WMC</td>
<td>+31 227 50 49 27</td>
<td><a href="mailto:R.P.L.Nijssen@kc-wmc.nl">R.P.L.Nijssen@kc-wmc.nl</a></td>
</tr>
</tbody>
</table>

* Mr. Kensche changed jobs after the project.