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Introduction to the OPTIMAT BLADES project

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Summary

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, increases. A sound 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. Current design guidelines are based on a larger number of smaller research projects and hence contain a number of inconsistencies and over- or unconservative safety factors that might hamper deployment for future rotor blades designs. The OPTIMAT project, which started in January 2002, aims to provide a consistent and integral approach to the design of rotor blades and as such offers a basis for updated design recommendations. This paper introduces and outlines the OPTIMAT project. It describes the rationale behind the project, the organization of the most important tasks and it details the foreseen approach to arrive at the project's ambitious goals.

Keywords: fatigue, composites, rotor blades, material research, design recommendation

Introduction

In order to fulfil the potential of wind energy, the development of larger wind turbines and more extensive use of offshore locations will be necessary. 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, increases. For large wind turbine blades, optimisation of the use of material becomes necessary to tackle the problems of the square-cube law. 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, the 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.

Wind turbine rotor blades are a unique application of composite materials in the sense that they are subject to an unusual loading environment, which is characterized by:

- Severe and complicated fatigue loadings, comprising often more than 10^8 fatigue cycles
- A variety of external environmental conditions
- Complex stress states, e.g. in the inner structural parts of the blades where most of the material consists of thick laminates

Important constraints are price and mass. Wind turbine blades must be both lightweight and very cost-effective.

In the past, various programmes have been carried out to investigate the behaviour of materials for rotor blades. This has led to design recommendations that have proven themselves to be essential for designing the blades. However, not all the different aspects of the complex loading and stress state have been addressed properly and on some aspects contradictory effects are reported. It is concluded that research carried out to date has limitations, which restrict the effectiveness of current design recommendations. Since January 2002, all these aspects are extensively investigated in one coordinated effort in the 'OPTIMAT BLADES' project.

Approach

A sound 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

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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.

Organisation of the Consortium

In order to meet the ambitious objectives of this project, a large amount of research know-how, input from major certification bodies and input from and support by the industry is vital. Hence a consortium of 18 partners from 8 EU countries was established, including research institutes, manufactures and certification bodies. The technical activities are carried out within 5 Task Groups, each dealing with a particular set of aspects of the structural design of rotor blades of wind turbines, as outlined in this paper. Many partners are involved in several task groups, but in order to enhance communication between the task groups, a Technical Committee with the leaders of the task groups and project co-ordinators was established to facilitate communication. The same people, with members of the certification bodies will form task group 6, which is primarily responsible with the drafting of the design guidelines. The members of OPTIMAT are listed in Table 1, whereas the organisation is shown in Figure 1. The European commission has supported OPTIMAT by means of a 5th framework research grant.

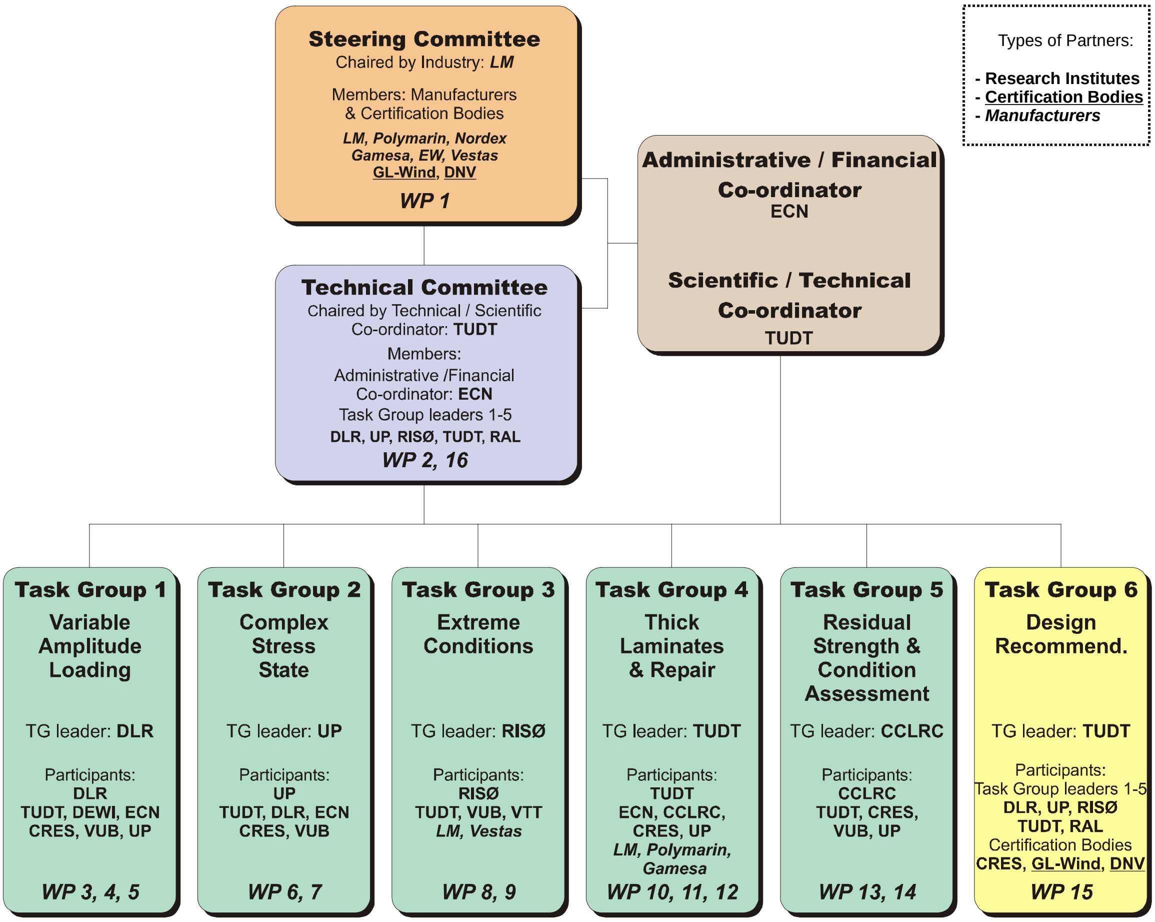

Figure 1 Consortium organisation

Table 1 Participants in the OPTIMAT project

R&D institutes	Certification bodies
♦ Delft University of Technology (Knowledge Centre Wind turbine Materials and Constructions) (NL) ♦ Netherlands Energy Research Foundation (ECN, NL) ♦ Centre for Renewable Energy Sources (CRES, GR) ♦ German Wind Energy Institute (DEWI, DE) ♦ German Aerospace Institute (DLR, DE) ♦ Rutherford Appleton Laboratory (RAL, UK) ♦ Risø National Laboratory (RISØ, DK) ♦ University of Patras (UP, GR) ♦ Technical Research Centre of Finland (VTT, FI) ♦ Free University Brussels (VUB, BE)	♦ Det Norske Veritas (DNV, DK) ♦ Germanischer Lloyd (GL, DE) **Manufacturers** ♦ Gamesa (SP) ♦ GE Wind Energy (DE) ♦ LM Glasfiber (DK) ♦ Nordex (DE) ♦ Polymarin Beheer (NL) ♦ Vestas (DK)

Expected Results and Scientific Innovation & Relevance

- An improved and profound knowledge on rotor blade material behaviour under different conditions and interaction effects.
- Further development of methodologies for repair, condition assessment, residual strength and lifetime prediction.
- Implementation of the obtained knowledge in a consistent set of accurate and reliable design recommendations.

Task Group 1: Variable amplitude loading

Variable amplitude loading or spectrum loading provides a considerable challenge to the designer in terms of estimating the expected fatigue life of the component or construction. The problem of obtaining accurate lifetime predictions in spectrum fatigue for composite materials is similar to that of metallic materials. Due to the relatively small slope of the composites S-N curve, life-predictions are very sensitive to the fatigue model. Methods that may work for metals, such as the linear Goodman interpolation of the constant life diagram, can lead to life estimates that may be as much as two orders of magnitude too optimistic [1]. For tension-tension fatigue, a linear or cubic interpolation of S-N data can lead to a much better life estimate for load spectra [2, 3].
Also, it is commonly agreed that the Pålmgren-Miner linear damage accumulation rule is unsatisfactory in spectrum load situations, since deviations from the targeted damage number of 1 can be large. Many alternative lifetime prediction models have been developed, but recent research suggests that as a simple first approach, a Miner's sum of 0.1 is most adequate [4, 5].

The approach in the OPTIMAT project includes ample constant amplitude data (basic S-N curve characterizations) to provide a statistically viable basis for subsequent lifetime prediction calculations. Usually, S-N curves are characterized at R=0.1, -1 and 10, but in the current project additional R-ratios are foreseen.
Also, to enable residual strength degradation to be incorporated into a possible fatigue model, residual strength tests are necessary. There is considerable interaction with TG 5.
Variable amplitude loading spectra are incorporated for validation. The simplest spectrum is a two-block test, where the total load signal consists of two blocks with each a different stress state. Note that there are two types of block tests foreseen in the project, i.e. repeated block tests (where a sequence of two blocks constituting a small fraction of the envisaged lifetime is repeated until failure), and block tests where the first block is until 50% of the expected lifetime, and the second block is continued until failure. These latter tests are carried out in sets of two, where the block order is reversed. Multiple block tests, as e.g. done in [5, 6], are not planned.
Finally, material performance can be compared using a standard spectrum test load, representative for blade loading. This spectrum can also be used as a more realistic spectrum for validation of the variable amplitude model. Classically, the WInd turbine reference SPEctRum (WISPER) and the shortened variant WISPERX have been used to this effect. However, it was decided that an updated spectrum should be devised in order to follow recent developments in wind turbine technology so that the test-loading spectrum is more representative for the current rotor blades. This new spectrum, named NEW WISPER, is currently under development, following largely the procedures used in the definition of the original WISPER spectrum (see Figure 3 for an impression, more details in [7]).

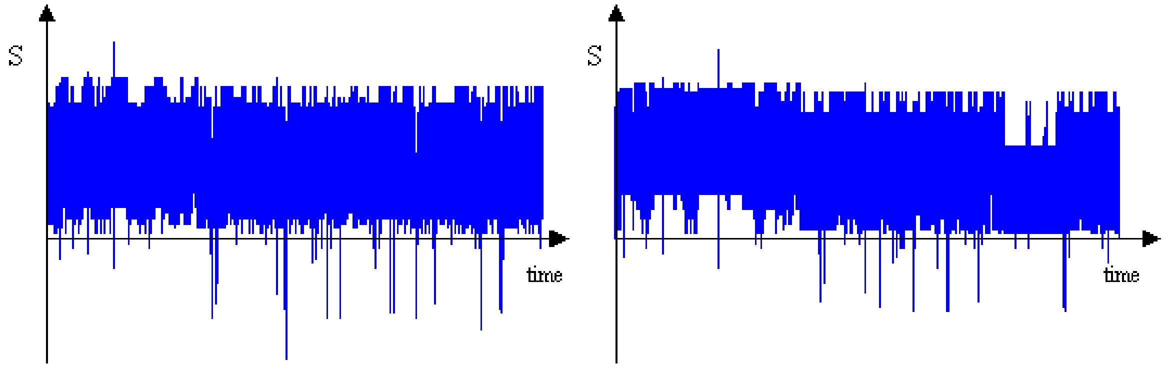

Figure 2 WISPER (left) and WISPERX standardized variable amplitude load signals

Task Group 2: Complex Stress States

Most composite fatigue research is exclusively aimed at determining fatigue behaviour under uni-axial loads. 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 available experimental data indicate a strong dependency of the fatigue behaviour on the complex stress state. Wind turbine rotor blades have increasingly more components which are made of very thick (See TG4) laminates and especially the central load carrying spar and the attachments to the root of the blade are expected to be 'hot spots' for fatigue damage. Useful qualitative research has been performed on the influence of ply-drops and on the behaviour of substructures in static and fatigue conditions in relation to simple coupon tests, but the microscopic stress state was not investigated [8]. Test results on composite rotor blade spar beams are reviewed in [3].

Multi-axial failure theories can be partly derived from uni-axial test data. It is common practice to use uni-directional composites as 'model composites' from which to derive multiaxial failure criteria (e.g. [9]). In OPTIMAT, in addition to this approach, also biaxial specimens will be used. These can be tubes under pressure (see [10]), tubes subjected to simultaneous axial loading and torsion ([11, 12]), or cruciform specimens. Especially the design of a cruciform test specimen for a composite is difficult, since it has to meet a number of stringent requirements (uniform stress distribution in measurement/failure area, repeatable results, large range of tests possible) [13, 14, 15]. Figure 3 shows a picture of the test set-up for cruciform specimens.

The work carried out in this Task Group is, due to its fundamental engineering character, applicable to modelling work generated in most other TGs. Measurements from TG 5 will form an important input to the development of an engineering model and results form TG1 are necessary for validation of the model. Interactions, such as variable amplitude under multiaxial stress conditions, will also be addressed.

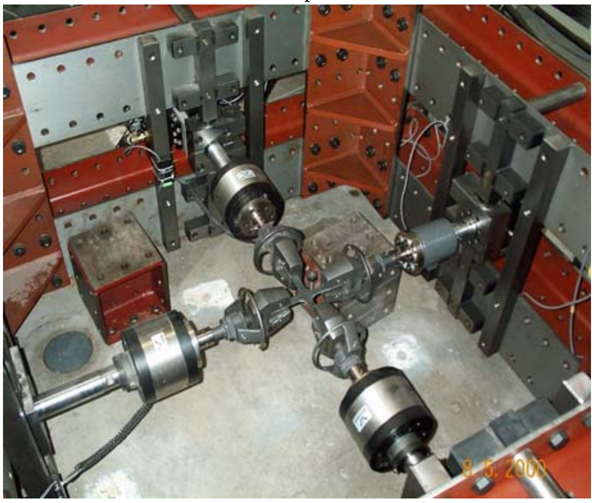

Figure 3 Bi-axial test set-up for tension-tension tests (VUB)

Task Group 3: Extreme Conditions

The erection of wind turbines in deserts, arctic regions and in offshore climates necessitates a deeper understanding of environmental influences. Similar requirements are encountered in another increasing application of composite materials: civil engineering. An annotated bibliography relevant to extreme conditions in fibre composites for civil applications can be found in [16]. For wind energy composites, specific knowledge of the material degradation due to temperature influences and influence of humidity until now is limited to a few scattered investigations. Generally, previous work shows, that moisture absorption degrades the static properties of rotor blade composites. A literature survey on the effect of moisture concludes that static properties are affected most by moisture and that effects on fatigue diminish in the high cycle range [17]. No moisture influence on fatigue could be identified in [18]. The potential of hybrid composites in terms of lower moisture sensitivity was found. This is confirmed by recent research, which shows that the addition of carbon fibres may improve a glass fibre composite's fatigue properties in wet conditions [19].

Ample literature on temperature effects on composites' behaviour in cryogenic or high-temperature applications can be found, but references on the 'moderate' extreme conditions investigated in the current project are scarce. Some results on composite strength and modulus in dry and wet conditions, at temperatures ranging between –20°C and 70°C can be found in [20].
In the current project, static and fatigue tests will be performed at three different environmental conditions, viz. –40°C ('arctic'), 60°C ('desert'), and humidity ('ocean water'). The results of these tests (degradation of global properties such as stiffness and damping, and static and fatigue fracture) will be used to validate constitutive models and model parameter analyses, modelling localised damage in the form of delaminations, weakening in fibre-matrix interfaces and matrix embrittlement. Also, material degradation will be studied at microscopic levels using Scanning Electron Microscopy.
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.
Interactions with other task groups, e.g. residual strength at extreme conditions, are foreseen in the project.

Task Group 4: Thick Laminates and repair

Most wind turbine blade material fatigue research has been carried out on relatively thin specimens (max. 8 mm). Nowadays, highly loaded laminates in the blade structure are in the order of 100 mm thick, and even 300 to 400 mm at the blade root. Fatigue research on thin coupons does not account for the tri-axial stress situation inside a thick laminate, so thin coupon test results may not be safely used in calculating the fatigue life of thick laminates. In fact, the through-the-thickness stress component in combination with the presence of fibres in longitudinal direction, which act as stress raisers, may cause premature damage. On the other hand, the adverse effect of internal flaws has been seen to decrease for thicker laminates [8]. Another potential problem is that, 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 process might differ substantially from the residual stress level in relatively thin coupons.

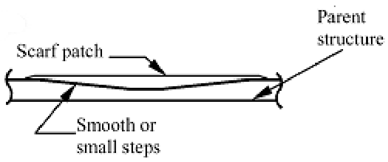

Figure 4 Proposed repair configurations

At present, no recommendations on repair of composite structures are available for wind turbine blades. Blades that are damaged or have production deficiencies in the load-carrying structural parts are being replaced, even if the damage or deficiencies are local. As blades become larger, more material is wasted due to such a localized deficiency. Work carried out in this Task Group is aimed at providing useful guidelines for repair in order to minimize this blade material waste. The repair investigations are aimed at high-loaded, thick glass reinforced plastic components.
Guidelines for composite repair are available for aeronautical applications [21] and marine composites [22]. For the activities in this project, scarf repair will be applied using one-sided access (see Figure 4). The slopes of the repair patch and laminate lay-up will be varied to optimise the strength of the repaired specimens. Tests will be accomplished on specimens of 6.5 and 32 mm thickness.
Repair still being more an art than a science, the industrial partners (blade manufacturers) will each develop and optimise their repair technique, using dedicated tests in tension and bending. Regular communication with certification institutes will facilitate acceptance of a recommended practice on repair.

Due to the thickness of the material, the specimens from this Task Group are the largest in size: approximately 33 mm thickness and a length in the order of 2 meters. A dedicated test bench, with a capacity of 2500 kN (see Figure 5), has been constructed in order to exert the required axial force on the specimen.
Considerable interaction with work carried out in TG 2 is expected.


Figure 5 2500 kN test bench

Task Group 5: Residual Strength and Condition Assessment

An important issue with regards to monitoring the economic potential of a wind turbine (farm) is how to assess, at each moment of operation, the remaining strength of a rotor blade. Currently, condition monitoring of a rotor blade often pertains to manually checking the quality along (critical) sections of the rotor blade, resulting in considerable downtime

Three possible means of quantifying residual strength of a rotor blade are either to use adequate condition monitoring analyses, or to develop an accurate model for residual strength degradation of the material, or a combination of both.

During OPTIMAT, several non-destructive measurement techniques will be implemented in the fatigue- and static tests. Recent relevant research has focussed on acoustic emission techniques, infrared sensors, embedded optical fibres, and accelerometer measurements [23, 24, 25, 26]. For composites containing carbon, electrical NDE methods are subject of investigations [27], but at least for phase I of OPTIMAT, this is not relevant. The project focuses on developing condition-monitoring techniques for practical use in rotor blades.

As has been mentioned previously, residual strength measurements are also a necessary input for development of a residual strength degradation model to use in lifetime predictions for composites under spectrum loading (TG1 and 2).

From previous research, data on condition assessment and residual strength is limited. In the foreseen residual strength programme, residual strength tests will be carried out after constant amplitude fatigue cycling. The tests will be done at three load levels, for R=-1, 0.1 and 10 tests. At each load level, tests will be terminated at 20%, 50% or 80% of the estimated mean lifetime. At each load level and fraction of lifetime, 4 specimens will be subjected to a tensile test and 4 specimens will be subjected to a compressive test to establish the residual strength as a function of load level, R-ratio, and fraction of lifetime, This is schematically shown in Figure 6. The residual strength test programme accounts for a large part of the testing time in OPTIMAT. The results from this Task Group form an important basis for the models generated in TG 1 and 2.

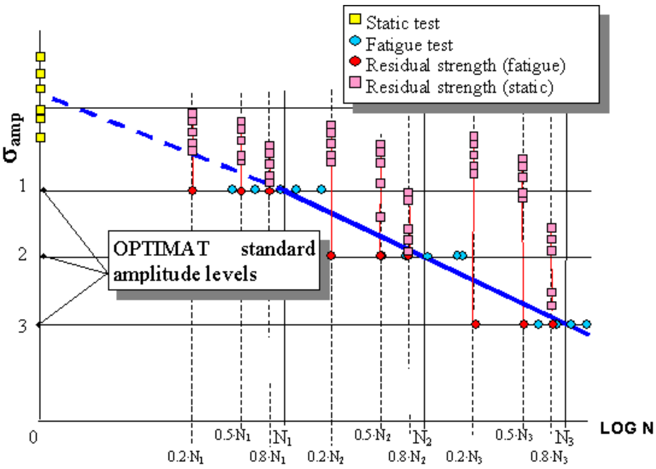

Figure 6 Overview of consistent tests per R-value (ratio of minimum and maximum stress)

Task Group 6: Design recommendations

The main aim of the project is to develop a set of design recommendations based on the results. These recommendations will help to improve composite constructions in a fatigue environment, and allow for an adequate assessment of interactions between factors influencing fatigue life of glass-epoxy rotor blade materials and an alternative material.

The fact that representative delegates from both the certifying bodies and the most important manufacturers take part in this project ensures successful development and implementation of a balanced set of design rules.

Materials considered

In the first phase of the project, only one material will be tested as two main laminates, so as to facilitate comparison of material behaviour under different circumstances. A pure Uni-Directional ('UD') material and a Multi-Directional laminate are manufactured in large batches, from the same constituent fibres and resin, at the same manufacturer using identical processing techniques for each batch (vacuum assisted resin transfer moulding, 4 hr post-cured at 80°C). The UD material consists of a 1250 g/m^2 E-glass reinforcement (PPG 2002 roving) in a $[0°]_4$ lay-up. This material is representative for the laminates used in the outer parts of the main spar. The MD material consists of the same UD roving in combination with an 810 g/m^2 biaxial reinforcement (PPG 2002 roving), in a [[+/-45, 0°]4;+/-45] lay-up. This material is representative for e.g. the spar web. The resin, Prime 20 from SP Systems, is mixed with slow hardener. The fibre volume fraction for both laminates is approximately 54 %.

In the second phase of the project, an alternative material will be subject to similar investigations to the first phase. The choice of material will be tailored to the market demands at the start of phase 2.

Standard geometry

Most importantly, for consistency and for the reliable development of e.g. a residual strength degradation model for variable amplitude loading, selecting a single specimen geometry for different types of tests is favourable. Also for adequate investigation of interaction effects, the number of different specimen geometries has to be limited. The degree of consistency that the OPTIMAT project aims at implies the need for development of a standard testing geometry. The requirements for this geometry are contradictory: it should be used for both compressive and tensile static tests and for fatigue tests, and the failure mode should be acceptable. In this respect, it was decided that 'failure mode and location similar' in different test situations was more important than 'failure mode acceptable according to relevant guidelines'.

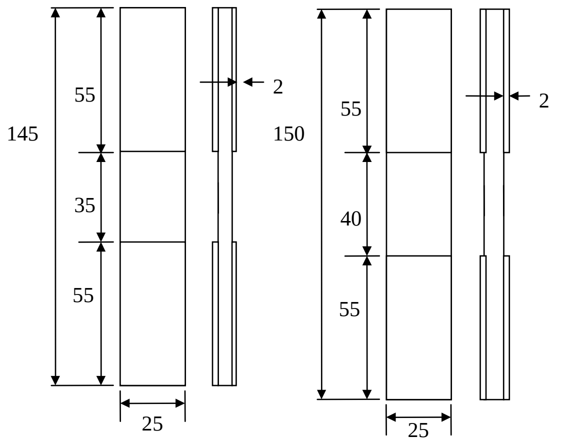

Figure 7 Standard OPTIMAT specimen for UD and MD (right). Dimensions in mm.

Preliminary tests were carried out on candidate laminates and geometries to get a grasp of the failure behaviour of the specimens and to select the 'best' geometry for a standard specimen. More specifically, the performance of dog-bone type specimens and rectangular specimens was compared. Important issues in the preliminary tests were mitigation of Euler buckling, assessment of test frame capability, obtain inconsistent failure modes. The resulting standard geometry, which will be used for the majority of the S-N curve characterization-, residual strength- and variable amplitude tests, is depicted in figure 7.

Previous European projects have made use of an anti-buckling guide (ABG) for compressive (fatigue) tests [3], but in the current project this was considered impractical, as it was feared that ABG interfere with fatigue tests and be rather sensitive to the exact set-up and would require all partners to have to same type of ABG. Furthermore, measurements on the surface of the specimen are hampered by the presence of an anti-buckling guide and if consistency was to be pursued, it should have to be applied in tests other than compressive tests, which creates an extra workload. Therefore, the need for an ABG was discarded by dimensioning the test specimen in such a way that Euler buckling was avoided. Note, that Sutherland, from a comparison of European and US fatigue data in a constant life diagram [28], has theorized that an anti-buckling guide is likely to affect the symmetry of the constant life diagram.

ISO- and special geometries

The competing requirements of the specimen have led to a geometry for which it is unlikely that best measurable material properties are attained in all tests. Therefore, other geometries are necessary for parallel tests. Geometries prescribed by ISO and ASTM are used for tests where best measurable performance of the material is required.

Also, special dedicated geometries are devised to test performance of thick laminates and to assess different repair strategies.

Standard test load levels

In order to minimize errors induced by interpolation of S-N data, standard test load levels were defined. The exact load levels will be determined from the basic S-N curve characterization so that the load levels lead to a mean lifetime of 10^3, $5{\cdot}10^4$ and 10^6 cycles. These stress levels are referred to as level 1, 2 and 3, respectively (see also figure 6). Variable amplitude block tests and residual strength tests will be located on these levels, so as to facilitate model validation with minimal need for interpolation of the S-N data.

In the following, the subjects of the various Task Groups are specified. The Task Groups are here discussed as organizationally separate entities, but in terms of technical content there is expected to be a considerable interaction. A large overlap exists in terms of personnel.

Acknowledgements

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Concluding remarks

The OPTIMAT project is a composite materials research project aiming to improve design guidelines for wind turbine rotor blade materials. It features an integrated and consistent approach to determine wind turbine blade composite characteristics under various conditions, and their interactions.

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 wind turbines, and increase of feasible turbine size.

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 wind energy exploitation with large capacity turbines. This supports the increase in wind energy and by that helps to reach the European Union White Paper target of 40GW of installed power by 2010 [29].

The reduction of the material use, resulting from direct weight saving or from the increased reliability, will lower the impact on the earth resources and environment. Currently, the first test results are being generated, and tests are due to finish in 2004. See the public website for details and updates [30].

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