UPWIND: Rotor Materials and Structures

R.P.L. Nijssen, D.R.V. van Delft, L.G.J. Janssen.

Knowledge Centre Wind turbine Materials and Constructions, 1771 MV Wieringerwerf, the Netherlands; +31(0)227-504927/49 (fax: /48); R.P.L.Nijssen@wmc.eu

This paper outlines the WP 3.1 of the EU 6th framework project UPWIND, which was started in 2006. In this unique integrated project on wind energy in the 6th framework, a large number of material tests will be conducted. These are mainly fatigue tests on relatively small material specimens. In a previous project, OPTIMAT BLADES, a material for wind turbines has been consistently characterised in unprecedented detail. The work carried out within WP3.1 of UPWIND is partly a continuation of this work focussing on a number of issues which require either further investigation or improvements in testing methods and procedures. In addition, new test methodologies will be investigated, such as sub-component testing.

Many uncertainties surround the actual material behaviour, especially in practical applications with large laminate thicknesses, repaired areas, extreme environmental conditions and complex stress states and fatigue loads. 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 itself. A consistent approach to material testing and use in design recommendations is required, covering all major aspects, and their interactions.

The work within UPWIND aims to build on previous work carried out within earlier projects. Specifically it focusses on compression fatigue, the constant life diagram, and behaviour of substructures.

Continued cooperation with industry, and previous experience from OPTIMAT will result in a smaller but more focussed research effort which benefits the industry in a more direct way. The results are expected to lead the way into a more unified approach towards material testing and qualification.

This paper describes results from the first phase of the project and discusses part of the planned research.

1 Introduction

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This paper describes results from the first preliminary phase of the project and discusses part of the planned research. The first part of the experimental work has focussed on the definition of the optimal testing geometry.

2 Material testing is not only testing material

Characteristics measured in tests of small material specimens are sensitive to the specimen and test design. Specimen design can only achieve a limited degree of representation of the actual material behaviour. There are numerous differences between laboratory and actual environment, which influence performance. In addition, the objectives of the test programme also influence the choice of specimen. An important question is, should the test specimen be designed for best performance or for consistency?

2.1 Lab versus reality

In the UPWIND programme [1], a unidirectional (UD) laminate will be investigated. This is a laminate representative of the spar flanges in most wind turbine blades. In addition, results of tests on a unidirectional laminate can be used as input parameters for modelling multi-directional laminates. The most important differences between the laminate in the blade and the test specimens are the limited thickness and width of the specimen, the fact that the laminate in a real blade may be curved in one or two directions, and the manufacturing method. Furthermore, a large number of other differences exist. In a test specimen, fatigue test frequency and loading rate are constant, the environment is controlled (or at least fairly constant) in terms of temperature and humidity. Loading in a laboratory specimen is as uniaxial as possible, where in a realistic blade the stress state is more complex, especially in regions of geometric discontinuity.

In general, the difference in test specimen vs. a comparable amount of material in a blade is expected to lead to a different performance in reality than in the laboratory. In the laboratory, the specimens are tested in an exactly defined set-up. However, the presence of edge effects, load introduction, buckling, etc. can have a detrimental effect. In an actual blade, waviness and residual stresses (because of the high laminate thickness) can reduce the materials performance while buckling is less of an issue. Therefore, it seems logical that it is important to achieve the best possible specimen performance; this will best represent the actual material behaviour.
Conversion factors, which account for the effects of laboratory environment, play an important role and the test programme should involve a means of facilitating the quantification of these factors. The lower they are, the less material is required to be added to the design from design data. Good specimen design is important in view of these considerations.

2.2 Optimised performance versus consistency

In general, the objective of specimen definition is to achieve a test specimen which represents as closely as possible the real-life situation. In practice, this means that the specimen performance should be optimised, as discussed above. The best approach for optimising a specimen is to tailor the specimen to the load type. Specimens loaded in tension should be long and slender, for compression a short, thick gauge length is required, etc. The downside of this is, that special specimens need to be manufactured for each test type, as they are not suitable for loading types other than what they are designed for. Using a long, slender tension specimen in a compression test will result in poor compression strength values because of buckling.

A slightly different philosophy was used in a previous project (OPTIMAT, [2]). In this project, many different ‘interactions’ were investigated. For instance, the influence of humidity on strength and fatigue properties was investigated. Another interaction was the influence of variable amplitude loading: how well can the lifetime of a specimen subjected to a load which varies in amplitude and mean be predicted from constant amplitude data? In the first case, a tensile specimen may be affected by humidity differently than a compression specimen because of the different geometries (surface area). In the second case, a variable amplitude load spectrum contains both tensile and compressive load cycles; which specimen should be chosen for the variable amplitude tests? These are a few examples of where using different specimens would complicate matters because an unknown geometry effect would have to be taken into account. Therefore, in OPTIMAT, a universal geometry was defined which was used in almost all of the tests.
In UPWIND, for the same reasons, use will be made as well of a universal geometry.

2.3 Search for the optimal specimen geometry

In the first phase of the UPWIND project [3], the optimal geometry needed to be found for the specimen. To this end, several plates were manufactured at WMC using the same methods as are planned for the other plates (not all manufactured at WMC). Plates were approximately 300x300 mm and 3 or 4.5 mm thick. The material used was Glass/Epoxy (PPG2002 2400 tex, 963 g/m^2 woven by Saertex (5% off-axis reinforcement) and Hexion laminating/injection resin L135i with 134i and 137i hardener). This is the reference material for both the UPWIND and the INNWIND [4] projects. Plates were manufactured in a double-sided aluminum mould using Vacuum-Infusion, a commonly used manufacturing technique in the wind-blade and ship-building industry, see Figure 1.

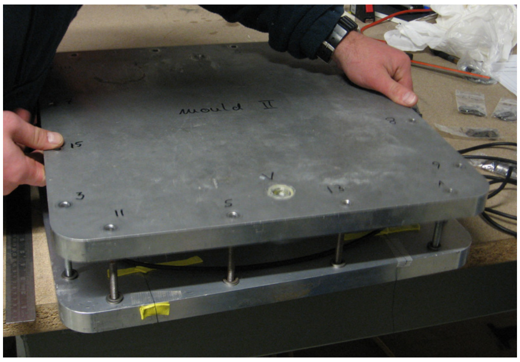

Figure 1: Double-sided VARTM mould for specimen plate manufacturing

After injection and curing in the mould, the plates were post-cured for 10 hours at 70°C. Tab material was applied using ScotchWeld 9323 2-component adhesive, and specimens were cut to the appropriate dimensions using a diamond saw.

The effect of a limited number of parameter variations was studied in a test programme that encompassed more than 100 tests. Static tensile tests and compression tests were done, as well as experiments in R= -1 fatigue (zero mean stress). Tests were done using hydraulic test machines.
The parameters that were varied were tab thickness, gauge length and width, number of layers (4 or 6) in the UD laminate. Four different geometries were tested, which are shown in Figure 2. To the geometries a code is assigned that designates their planform. Geometry R03 was also used for the OPTIMAT standard UD material.

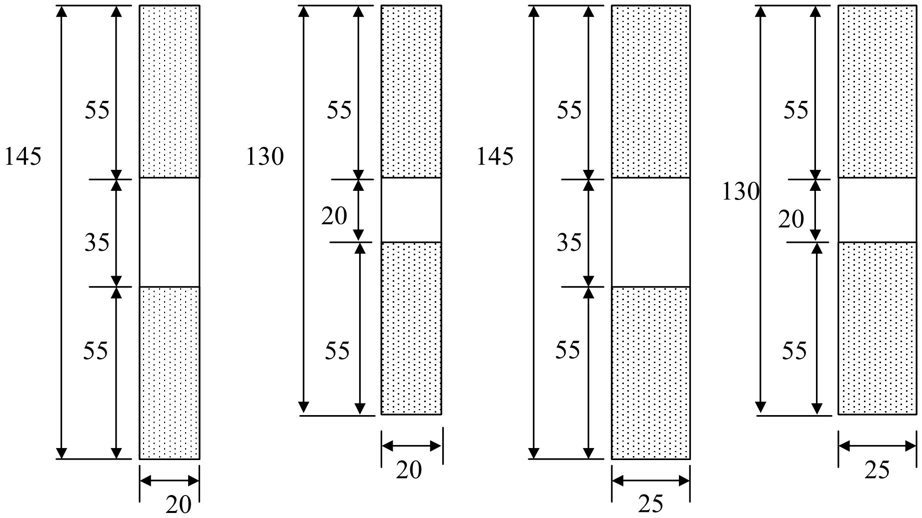

Figure 2: Geometries investigated in preliminary programme of UPWIND. Specimen geometry codes from left to right: R07, R08, R03 and R06

The choice of a UD material means that the specimen geometry should be rectangular. Earlier work demonstrates, that above a certain fraction of on-axis layers, a dogbone geometry is no longer suitable [5]. Different criteria were identified for the specimen.

- consistency with OPTIMAT geometry
- no buckling allowed
- suitable for 100 kN frame
- sufficient gauge length for observations

Consistency with the ISO/ASTM or with OPTIMAT geometries would be an advantage, because this allows more direct comparison with results from other test programmes.
Buckling of the gauge length should be avoided, because it is not a failure mode of interest. However, for high loads it is difficult to prevent buckling. During fatigue, delamination may occur and individual layers may buckle. It is possible to use an anti-buckling device, but this is not recommended. Depending on the exact set-up, usually such a device hampers measurements or observations on the surface. In some cases it might provide resistance against buckling, but induce a Z-shaped bending type.
In a wind turbine blade, the spar cap can be in the order of several centimetres laminate thickness and several meters width. Thickness and width should be as close to these dimensions as possible. The width of the specimen should be as large as possible to dampen the possible effect of partial tows. The thickness should in general be above a certain minimum dictated by the buckling criterion. However, limiting the width and thickness of a specimen is necessary in view of the testing capacity of the most commonly used test frames. In UPWIND, the specimen dimensions are tailored to a maximum load in tension of 100 kN, as most laboratories have test frames up to/around 100 kN maximum load capacity. For integrated projects, with multiple testing partners it is recommended to tailor the specimen cross-sectional area to this test frame capacity.
The gauge length should be sufficiently small to hamper buckling. However, a large gauge length is more suitable for observations and measurements. Typically, a specimen should be equipped with strain measurement equipment such as strain gauges or extensometers. Measuring temperature on the specimen surface is recommended. Advanced full-field optical strain measurements or acoustic measurements might also have to be accommodated for. Balancing buckling and room for measurement is an important aspect of specimen design.

Tab material is generally applied in the region of the grips. The primary role of tabs is to protect the specimen from wear induced by the rough grip surfaces. In addition, they help redistribute possible irregularities in grip pressure and shear loads to the specimen surface. Furthermore, they add cross-sectional area to the specimen, aiming to give the specimen a preference for failing in the gauge area, where (strain) observations are done.

Finally, an important criterion is performance. Tests were done at R= -1, with 1 Hz frequency for the highest load level and 3 Hz for the other load levels. The results available at the time of writing are displayed in Figure 3. The data are plotted in terms of strain. Since strain was not measured for all tests, strain was calculated from the average E-modulus taken from the available strain measurements. The figure also shows a comparison with the standard UD laminate used in the OPTIMAT programme. The strains for this dataset were corrected for fibre volume fraction, since this was higher than in the UPWIND specimens.
These data show, that the 6-layer laminate (geometry R07) does not perform as well as the 4-layer laminate of the same material, notably at high loads. Except for the highest loads, thinner tab material resulted in lower lifetime. Thicker tabs were found to give short lifetimes due to excessive temperature rise (these points are not shown here). At the higher loads, scatter is largest for the 4-layer material. In any case, the influence of the investigated parameters diminishes as life increases. It should be noted, that there was some difference in plate thickness, which seemed to influence the results as well (thinner plates had shorter lifetimes). This could be an increased sensitivity to buckling or inferior behaviour of plates with higher fibre volume fractions.

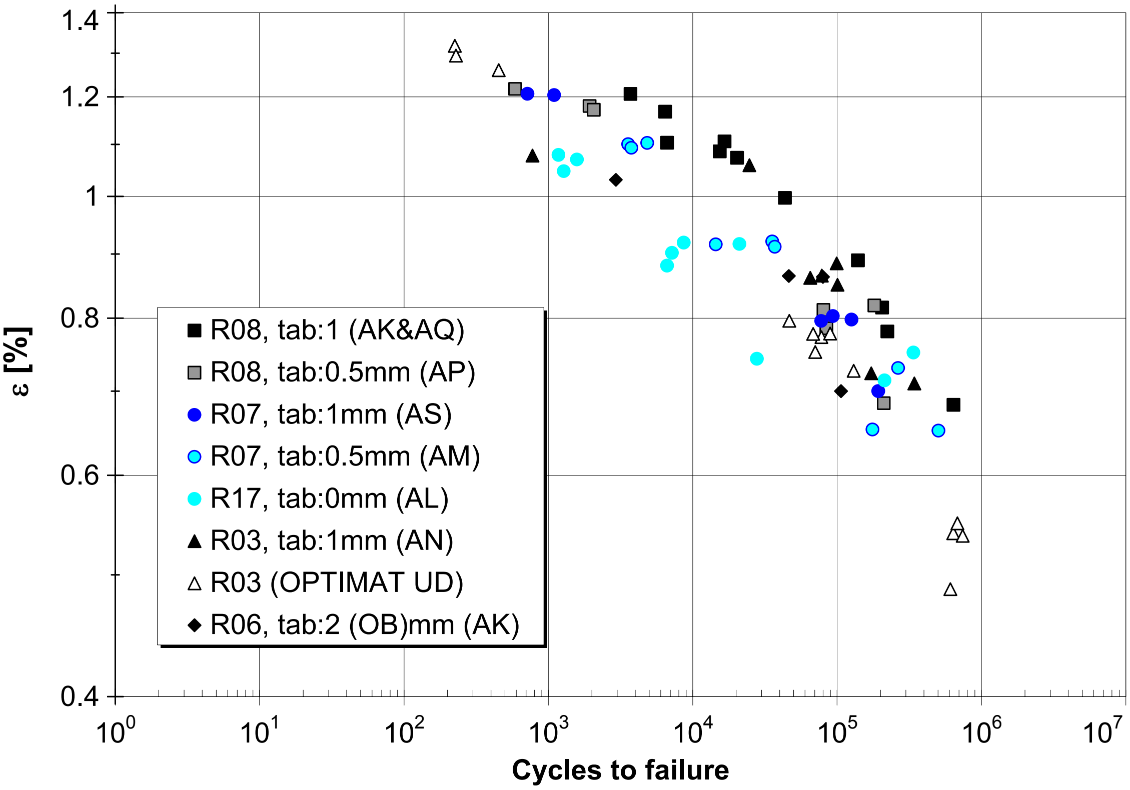

Figure 3: S-N diagram for different preliminary geometries

3 Compression

Special attention is devoted to compression testing methodologies. Compression properties of composites are generally poorer than tensile properties. In fatigue, this is not necessarily true. Experience from the OPTIMAT programme indicates, that the slope of the S-N curve (cyclic load vs. number of cycles to failure) is much smaller than for other load types. Thus, a small decrease in cyclic load leads to a large increase of fatigue life. However, the testing method that is used (including specimen design) influences the results. In addition, the spread in lifetime is much larger than in tension-only or tension-compression fatigue. Many tests are required to get a good description of compression-only fatigue life, and consistent compression fatigue research is typically avoided in view of the expected complications and excessive testing effort. In the UPWIND project, ca. 7 different compression fatigue set-ups will be tested, varying from the 'universal' specimen, to dedicated fixtures and anti-buckling devices. These devices will also be used for R= -1 fatigue and static tests. See Figure 4: using a combined loading fixture, load is introduced through both shear- and end-loading. Figure 5 shows compression strength results. The dark sets were tested using a CLF. The left 10 points are a 4-layer laminate, the right 10 points 6 layers..

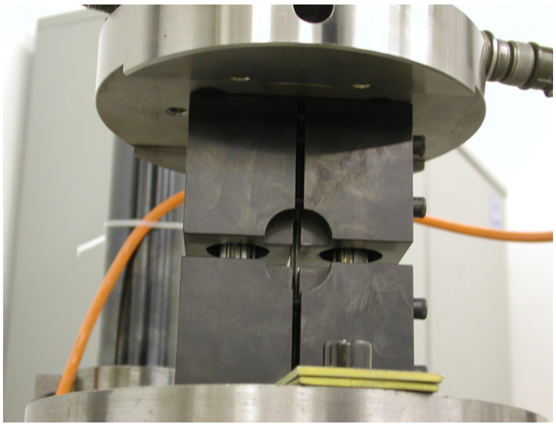

Figure 4: Combined Loading Fixture (CLF)

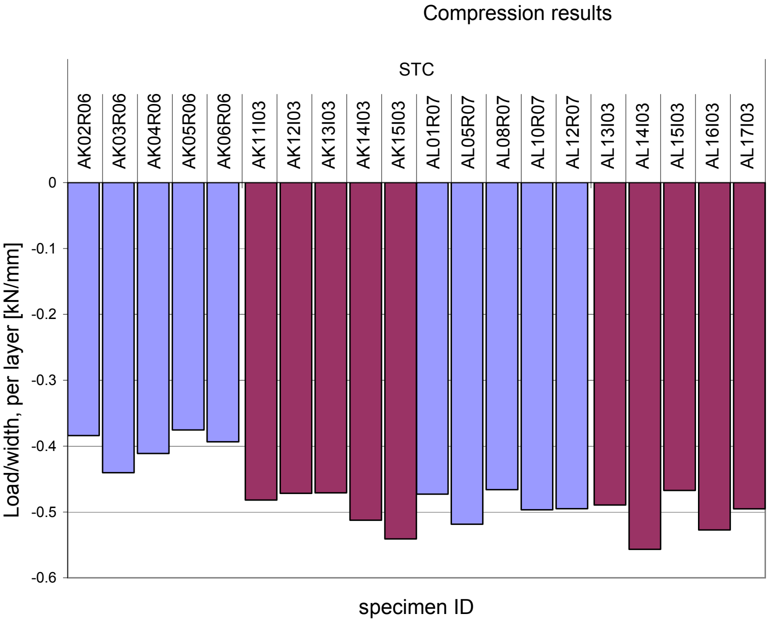

Figure 5: Compression strength results from the preliminary test programme

4 Constant life diagram

The constant life diagram (CLD) is used to predict the number of cycles leading to failure for each possible combination of load amplitude and mean. A well-known example of a constant life diagram is the Goodman diagram. It is an important part of the fatigue life prediction for variable amplitude loading. Previous work has indicated, that the definition of the constant life diagram has a large influence on fatigue life predictions [6]. In the OPTIMAT programme, the constant life diagram has been defined for a single material/lay-up in great detail, but the number of S-N curves was still limited. The type of model which is best suitable for fitting through the available data is a point of discussion. More advanced models have become available which are believed to give better modelling capabilities than existing models [7], [8]. Also, long-life fatigue data are required to provide further detail in the CLD. Typically, 10^6 cycles is the practical limit for testing in view of testing time, but industry and research have indicated a need for tests further into the high-cycle region (10^7 and further, see also Figure 6). In addition, the generality of the CLD-formulation is not evident. For different materials and lay-ups, the CLD may require additional modelling considerations. These are all important challenges for the UPWIND project.

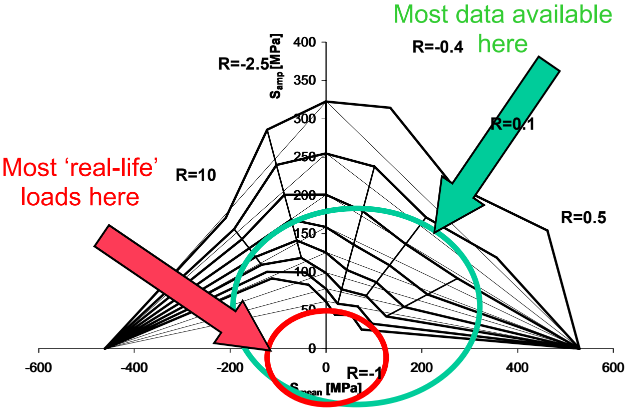

Figure 6: Constant life diagram (OPTIMAT MD), indicating that long life data are required for a more useful description of constant amplitude fatigue life

5 Subcomponents

Blade design and testing is mostly done on the basis of 'bulk' material properties from small specimen tests. In a blade, however, failure modes occur that do not occur in small specimens. For example, the interaction between shear web and flange, and/or attachment to the outer skin may be an important design detail. On a smaller scale, repairs or ply drops [9], or adhesively bonded connections are prone to failure which cannot always be predicted using the models from test data on uniaxial specimens. Both test institutes and the industry are increasingly aware of the need for test methodologies on structural scale, but small enough to allow for larger samples of similar tests and multiple variations. This need can be met through subcomponent tests, where the term 'subcomponent' means anything between a simple test specimen such as described in 2.3 and a full-scale blade.

Typical candidate subcomponents are depicted in Figure 7. This figure shows e.g. a generic I-beam which can be shaped to model different connection methods between web and spar, or different geometries for the end of the web near the blade root. By tailoring the height gradient of the spar, it is possible to obtain a particular combination of shear and peeling stresses. Also, the generic I-beam concept could be used as a platform for different repair techniques.

Smaller specimens, which could be regarded as subcomponents, are also shown. Different geometries can be conceived for testing repairs or adhesive bonds. In some cases, interlaminar shear geometries will be useful, in other cases other set-ups including more pronounced peel stresses should be considered.

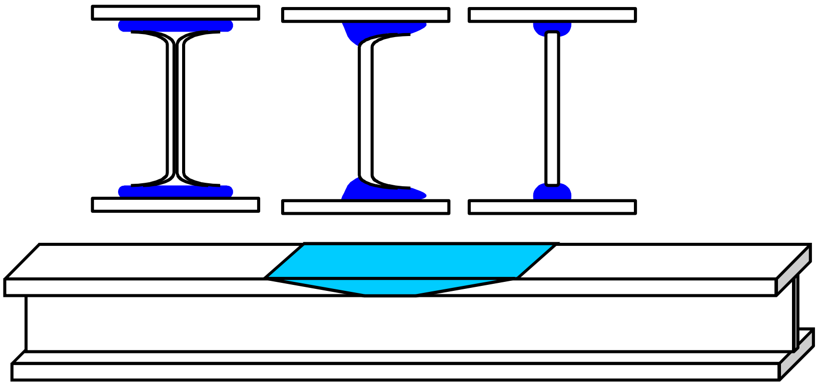

Figure 7: Subcomponents; generic I-beam

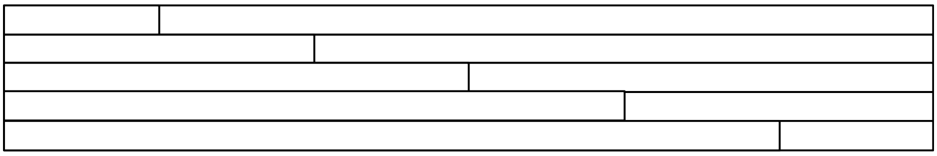

Figure 8: Subcomponents; model repair or adhesive connection

6 References

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