RECENT RESULTS IN CHARACTERISATION AND MODELING OF COMPOSITES FOR WIND TURBINE BLADES

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ABSTRACT

Wind turbine rotor blades are large structures which are designed to withstand extreme loading at low cost. Material and structural characterisation through modeling combined with tests are continuously developed to enable further design optimisation, larger rotors and new design concepts. This paper discusses the latest developments in this research.

INTRODUCTION

Wind turbine rotor blades have developed into low-weight, highly fatigue resistant composite structures with lengths up to 73.5m. This is the result of development of low-cost materials and manufacturing methods, and integrated design of the blades and turbine. Design methods rely on accurate and reliable modeling of material and structural performance to create optimal blade structures.

The main characteristics of blade loading include gravity loading and wind loading. Both are fatigue loads with an extremely large number of load cycles during the blade's design life: up to 10^8-10^9 cycles. Especially gravity loading presents a challenge when increasing the rotor diameter, as adding material to increase strength will also lead to increased loads, and additionally the increased rotor weight will affect the requirements for all components in the turbine. Therefore optimal material use will become a vital aspect in the design of larger rotors.

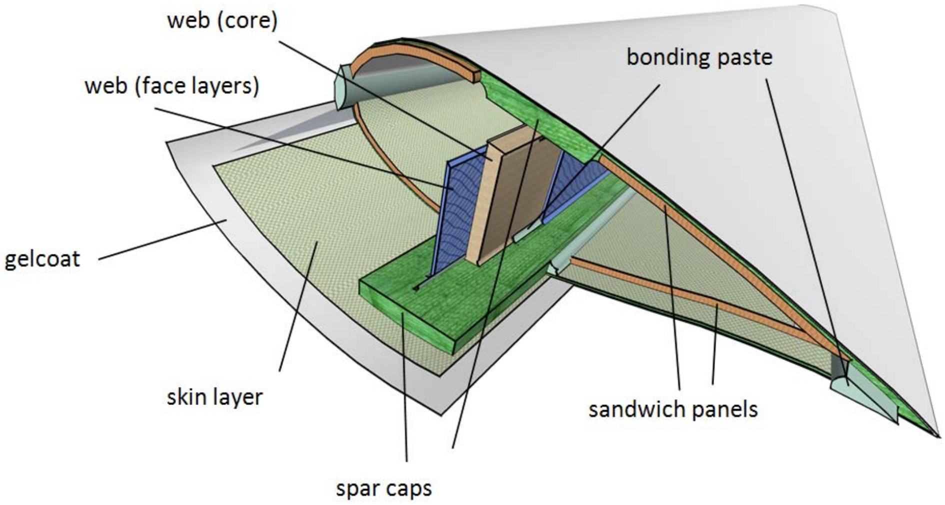

Figure 1: Composite materials in a wind turbine blade

The blade is an integral structure containing a variety of composite materials, see Figure 1. In recent and ongoing projects, material modeling and characterisation are being developed. Current research focusses on the development of variable amplitude fatigue models for UD-dominated materials in the spar caps, e.g. 1. On a fundamental level, this is done taking into account the behaviour of the micro-structure, e.g. 2-3. For understanding the behaviour of thick laminates as used in large rotor blades, modelling and measurement of strain energy and manufacturing-induced strains is necessary. Multi-axial performance of adhesives and bondlines (4) is highly relevant for this application, as well as the introduction of 'new' materials such as pre-pregs and heavy tow carbon.

WHY A WIND TURBINE COMPOSITE IS DIFFERENT FROM OTHER COMPOSITES

A wind turbine blade material can be defined as a summary of its requirements. These are no different from many structural materials, except that in the case of a wind turbine blade the extremes are sought:

- low cost (<10€/kg, lower than aerospace grade materials)
- high stiffness (to maintain tower clearance in upwind rotor designs; due to the extensive use of glass the material stiffness is often limited to <50GPa)
- high fatigue resistance (to withstand, without or with minimal service, $>10^8$ load cycles with strongly varying amplitude)
- high strength (gust loads, etc.; fibre direction, given the high strength-to-stiffness-ratio of most composites, and the severe fatigue requirements, the material strength is almost never a bottle-neck).

Detailed failure frequency and damage type data are not prevalent, but typical fatigue-induced failure modes in a blade are found in bond-lines in the spar structure, in the leading edge and trailing edge of the blades, and in sandwich structures (potentially leading to buckling). For larger wind turbine blades, operating at remote sites (where aerodynamic noise is less of an issue) higher tip speeds are achieved, leading to erosion problems near the tip. The laminate loads in this region are usually not significant, but secondary damage can be a cause for downtime.

Damage in the blade spar laminates is presumably not the dominant failure mode that determines most practical designs. Nevertheless, most of the structural research that is currently available focusses on UD-dominated materials that are representative for the blade spar. This seems contradictory, but on the other hand it makes sense from a test perspective; mechanical characterisation of the main load-bearing laminates is definitely required for design and some of the other failure modes described above are quite sensitive to local geometry and structure.

RESEARCH IN WIND TURBINE COMPOSITE BEHAVIOUR

Test development

It is well-known that testing of composites requires dedicated tooling and methods. Fatigue testing, required for characterisation of wind turbine laminates, is especially complicated. Measurement of fibre-dominated behaviour is difficult, as it is often potentially overshadowed by matrix-dominated behaviour. An example is the fatigue testing, in tension, of a uni-directional composite. In isotropic or matrix-dominated lay-ups, width-tailoring of the specimen, to evoke failure in a known location (viz. the centre of the specimen) is an often employed technique. For fibre-dominated lay-ups this does not work, as matrix failure will result in longitudinal cracking starting from the center of the specimen. Thickness reduction near the center is another option, but often fails due to delamination. This means, that the ‘least-bad’ geometry is simply a prismatic specimen, as depicted in Figure 2. An issue in such a geometry is the influence of the grips and the tendency for tab delamination. The reason why the geometry in Figure 2 has such a short gauge section is, that for consistency in development of fatigue models, the identical specimen geometry is often used for testing at various R-ratios (ratio of minimum to maximum stress) – see section below on variable amplitude fatigue – , enabling comparison of e.g. tension-tension data to compression-compression data with minimal geometry effects. Another advantage is the relative cost-effectiveness of specimen manufacturing, which is a benefit for commonly performed large fatigue test programmes (hundreds of specimens, hundreds of millions of cycles, different materials) for statistically treatable material selection and design input data. For determining the ‘best’ behaviour, geometries tailored to the applied load type should be developed.

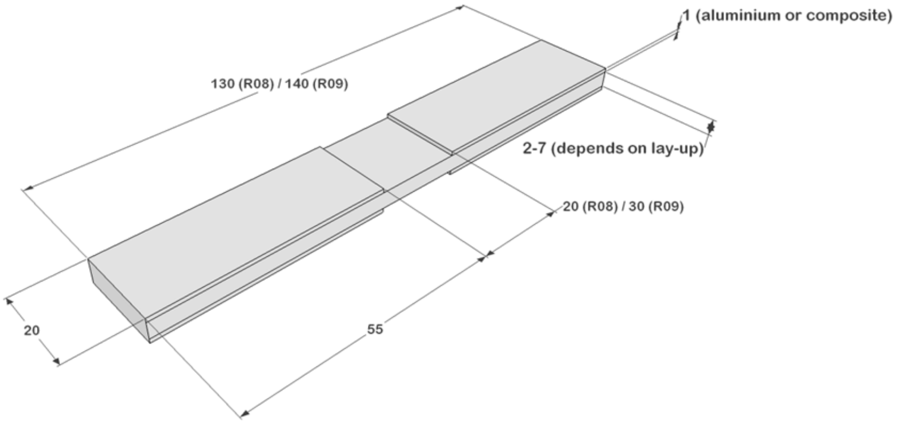

Figure 2: Typical specimen used for testing of UD laminates in fatigue

Test methods for automatic crack length determination in fatigue

A relatively new development in the wind industry is crack growth analysis (rather than ‘bulk’ material properties that is typically characterised with specimens as discussed above). For prediction of fatigue life of load-carrying (UD, spar flange) materials, crack growth analysis and prediction has not been very relevant in the past, as such materials do not fail due to local crack growth, but are (in a sound design) dominated by overall material degradation eventually leading in some cases to local failure. In recent years, however, interest in strain energy release rates / fracture toughness characterisation has been renewed in this industry due to the failure observations mentioned in ‘Why a wind turbine composite is different from other composites’.

A standard test method relevant for this type of evaluation is ASTM 5528, or double cantilever beam (DCB) test, where a pre-cracked specimen is delaminated (the intended crack path being the resin-rich area between two lamina, or a bond-line), and the toughness of the material is evaluated through the instantaneous crack length, loads, and displacement. For wind turbine adhesives, this is frequently used, although resulting values are often not so robust due to high adhesive brittleness. A crucial parameter is the measured crack length, which in quasi-static tests is measured with dedicated gauges, or through visual observation. Problems in these methods are lack of synchronization of the signals and potential for subjective evaluation/limited repeatability (visual method) and crack length resolution and measurement range (gauges). In fatigue, neither method is reliable. A novel development is the use of video-processing of such tests, which solves all of the above issues. The test set-up is shown in Figure 3. The signal of the camera is synchronized with the load-displacement measurements. After (fatigue) testing, a dedicated post-processing tool converts the images from the test to instantaneous crack length and hence fracture toughness values reported in 3.

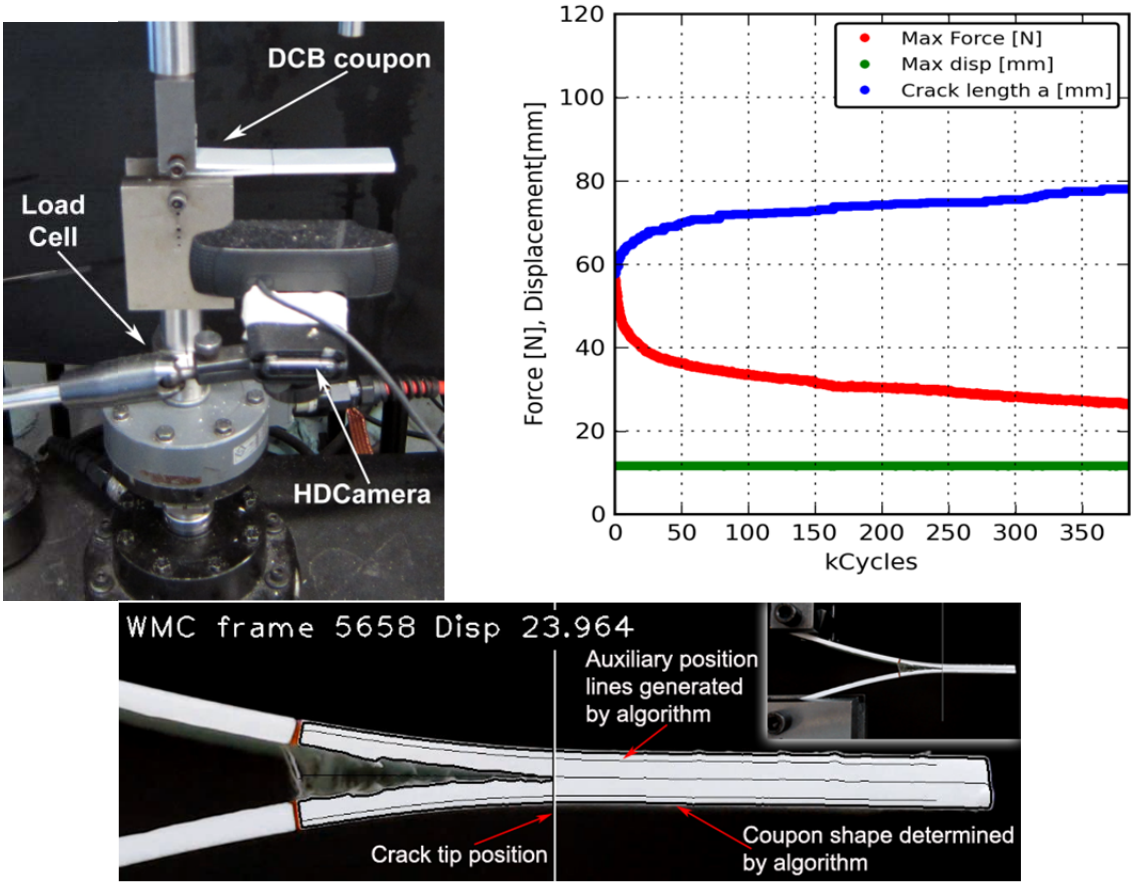

Figure 3: Test frame set-up for automated video crack length tracking; typical results from fatigue measurement; close-up of DCB-specimen with shape elements generated by pattern recognition algorithm

VARIABLE AMPLITUDE FATIGUE

Design for variable amplitude fatigue is currently based on constant-amplitude characterisation of a material. It is likely that non-linear effects of load order, peak loads, etc. might influence fatigue life prediction, but recent work has shown that it is highly likely that the most effective short-term research avenue is the development of a robust and accurate model for constant amplitude fatigue behaviour. Constant amplitude fatigue data are depicted in Figure 4, which shows a Constant Life Diagram (CLD), in this case connecting average fatigue lives obtained through tests at certain R-values (projected data indicated by the markers) with straight lines. Although it is at first glance not evident, the construction of a reliable CLD requires a large amount of costly fatigue tests (which might have to be repeated for different materials), so it would be very useful if a realistic fit could be constructed through a very limited amount of data. In fact, this is usually done by constructing a special case of the CLD, the Goodman diagram, which only uses static strength and tension-compression fatigue data. Such work is done, see e.g. 1, but although this research highlights the CLD formulation as the most influential factor in the VA fatigue prediction, a satisfactorily robust and user-friendly design formulation has not yet been developed.

An indispensible tool for evaluation of variable amplitude fatigue formulations are standardised load sequences, which were primarily developed to compare different materials in variable amplitude loading. An example of relevant VA data and prediction results is shown in Figure 5 for the recently developed NEW WISPER wind turbine reference spectrum.

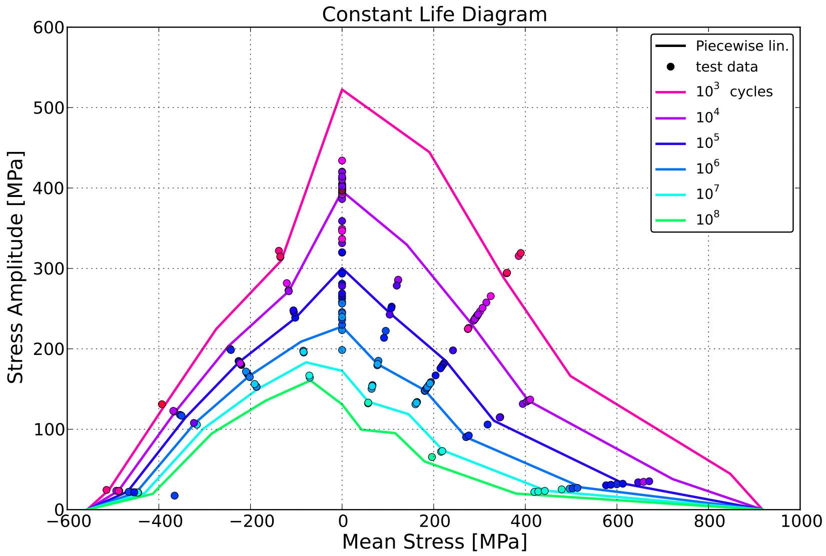

Figure 4. Piecewise linear CLD based on 9 R values from UPwind

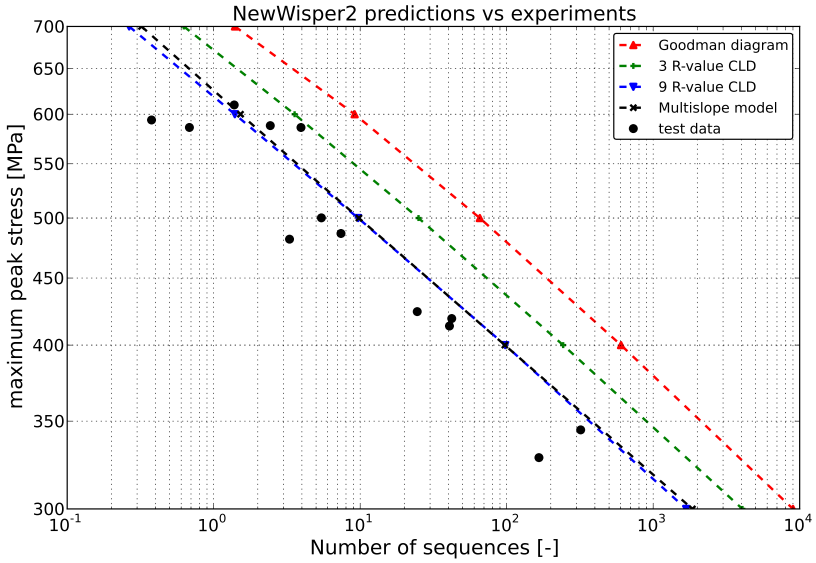

Figure 5. NewWisper2 predictions and experiments

MICRO-MECHANICAL MODELLING

The development of variable amplitude fatigue formulations is characterised above as the most effective short-term research avenue, but an important drawback is that it is based on description of a phenomenon rather than of the underlying mechanisms. A novel approach in wind turbine composite research is micro-mechanical modelling. In this approach, the behaviour (crack growth, fibre-matrix interaction, stiffness, fatigue life) of a small volume of composite is modelled. The internal geometry and boundary conditions of this ‘representative element’ or ‘unit cell’ are such that the failure modes of interest will be reflected and the behaviour of the element can be considered as representative for the macroscopic structure. Thus, (numerical) simulation results from this element can be transferred in a multi-scale analysis from, e.g. a multiple-fibre (MF) element, to a meso-scale (MS) and component scale

(CS) model, as was done in the micro-mechanical simulation of the fatigue behaviour of a uni-directional composite reported extensively in 2.

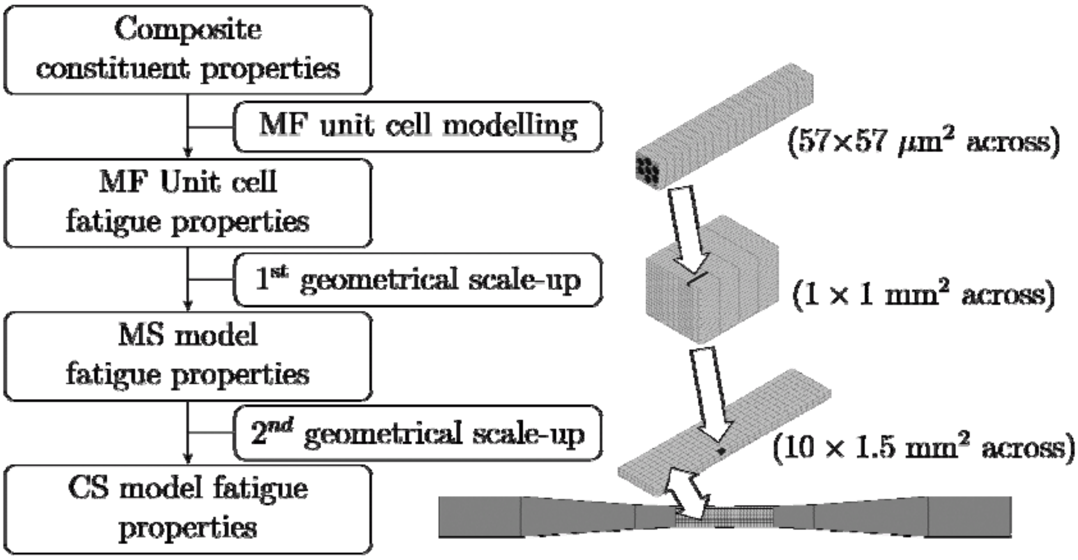

Figure 6: Flow chart of multi-scale micro-mechanical modelling

An indispensible part of such research is the collection of viable input data, preferably on the basic material constituents, i.e. fibre and matrix. In 2, single-fibre fatigue tests were performed. Comparison of the results to tests on fibre bundles, laminated composites, and fatigue tests on neat resin specimens confirms that the matrix (and potentially the interface between matrix and fibres) has a significant influence on composite fatigue performance. One of the complications in setting up a reliable micro-mechanical model is the significant scatter in the experimental load-life results, which hampers extraction of model parameters from the fatigue data 2.

Although micromechanical modelling is not yet at a level where it can be used for fatigue predictions that are in any way reliable, it already provides insight in the failure processes in composites and offers potential for optimization of the composite microstructure to enhance fatigue life. In the long term it has the potential to offer fatigue life predictions for new constituents, material architecture and loading conditions, without the need to resort to extensive fatigue test programs.

THICK LAMINATES

Experimental fatigue data on thick laminates has suggested that their performance cannot be based on that of relatively thin laminates (e.g. 5). This observation has sparked research into the effect of temperature and load frequency during fatigue testing of laminates (e.g. 6); these were shown to be highly influential, which can be explained by the high strains, visco-elastic internal heating and low thermal conductivity of the material. The results of that research are quite interesting for the development of fatigue tests in general, as a basis for finding the maximum fatigue frequency (the higher the frequency, the faster results become available) with acceptable influence of internal heating. Nevertheless, the question remains if the difference between thick and thin specimens depends on the internal heating alone, or whether a ‘scale effect’ exists.

To further investigate this, a study was launched comprising dedicated specimen development, and more extensive thick laminate testing, at different thicknesses and loading conditions. One of the first sets of experiments that was conducted was aimed at quantifying the visco-elastic behaviour of volumes of laminate of different thicknesses, trying to correlate the thermal- (surface heating) to the mechanical (load, displacement) experimental and numerical observations. The influence of manufacturing (notably residual stresses through-the thickness due to shrinkage) is also investigated in this study. An example of the thermo-mechanical model, the test set-up, and infra-red imaging of a specimen during fatigue is shown in Figure 7 (from 7).

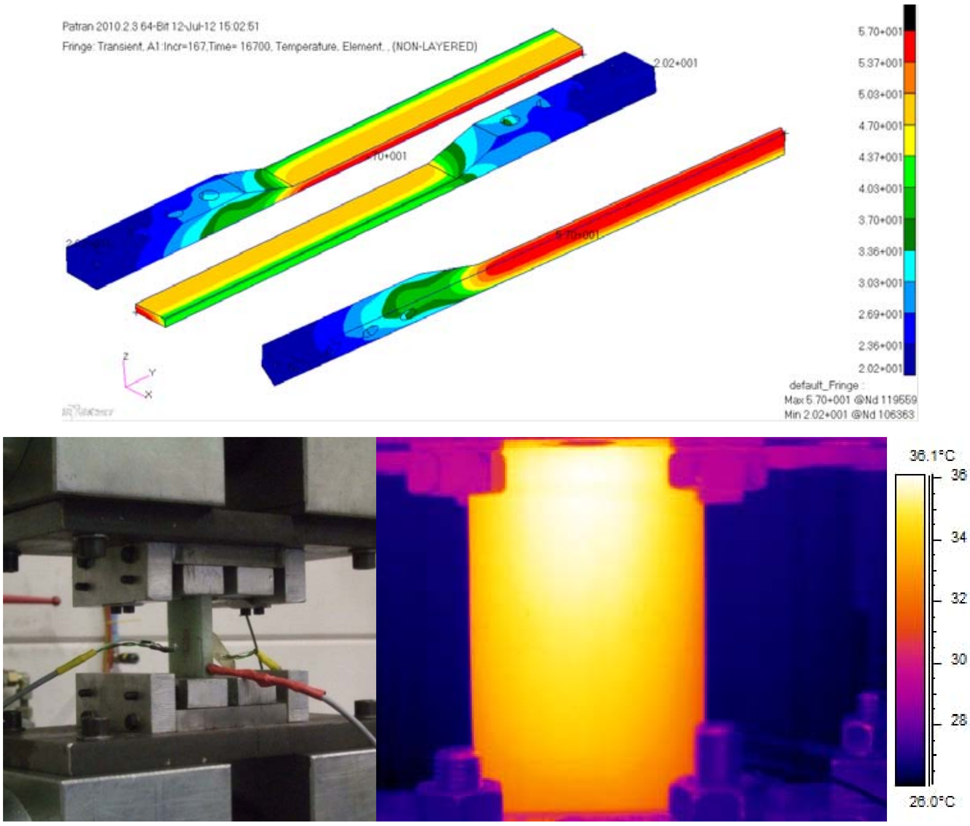

Figure 7: Thick laminate numerical and experimental research: thermo-mechanical model; test set-up; infra-red observation of the self-heating in 30mm thick coupons

CONCLUDING REMARKS

Design of composites for applications like wind turbine blades requires –for an aerospace engineer perhaps counter intuitively- a different approach. Design against fatigue is limited by cost relative to ‘aerospace’ composites. On the other hand, wind turbine blade manufacturers are demonstrating that scale limits can be beaten, and severe design requirements can be met with relatively cost-effective materials and using low-pressure, low temperature production methods.

This niche necessitates research into various aspects of mechanical performance, most of them with an explicit ‘fatigue’ connotation.

Especially for fatigue under various conditions this results in the need for test development and innovations. An example, the development of automatic crack growth registration, was mentioned in this paper. Typically, most of the test development is in specimen geometry and boundary conditions (clamping).

Design against the effects of variable amplitude fatigue of load-carrying composites is currently at the stage that detailed constant life diagrams are indispensable for an accurate life prediction. The formulation of these CLD relies heavily on data, and robust, yet user-friendly formulations are under development, as well as datasets for validation of various new theories. Meanwhile, quantification of the fatigue behaviour continues for ‘standard’ materials as well as for hybrid composites.

In parallel, micromechanical experiments and modelling facilitate better insight into the reasons for the shape and magnitude of the constant life diagram. This is a challenge as fatigue in composites cannot always be regarded as a local phenomenon, and the statistics involved by the tremendous scatter are prohibitive in generating input data on one hand and drawing conclusions from simulations on the other.

Wind turbine rotor blades, especially near the root of the structure uncharted area in terms of laminate thickness. In terms of test development, the interaction of fatigue and visco-elastic heating is a concern. Theoretically, damage development in thick laminates may be thermodynamically quantifiable, and in current research the relation with the hysteretic loss factor and fatigue life is therefore investigated.

This paper shows recent results and methods from ‘wind turbine composite research’. Due to the nature of loads and materials, some of these results are useful outside the realm of wind energy. For instance, many of the issues (fatigue, bondlines) are quite relevant for civil infrastructure.

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