The wind turbine rotor is an important part of the connection between the moving air (containing the wind energy) and the generator (used to capture this energy). The rotor consists of (usually) three blades, which are almost entirely made of fibre-reinforced plastic. These blades experience a large number of load cycles during their economic life. The magnitude of the load cycles is not at all constant. The rotor materials and structure need to withstand all these loads, great and small. Extensive research is devoted to predicting strength and life for rotor blades. For this research, numerous tests are done, exposing small fibre-reinforced coupons (specimens) to realistic loading conditions. Based on this data, fatigue models can be made predicting blade life. But, of course, 'the proof of the pudding is in the eating'. Full-scale blade tests are required to see if reality matches expectations.

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Rotor Structures and Materials

Strength and Fatigue Experiments and Modelling

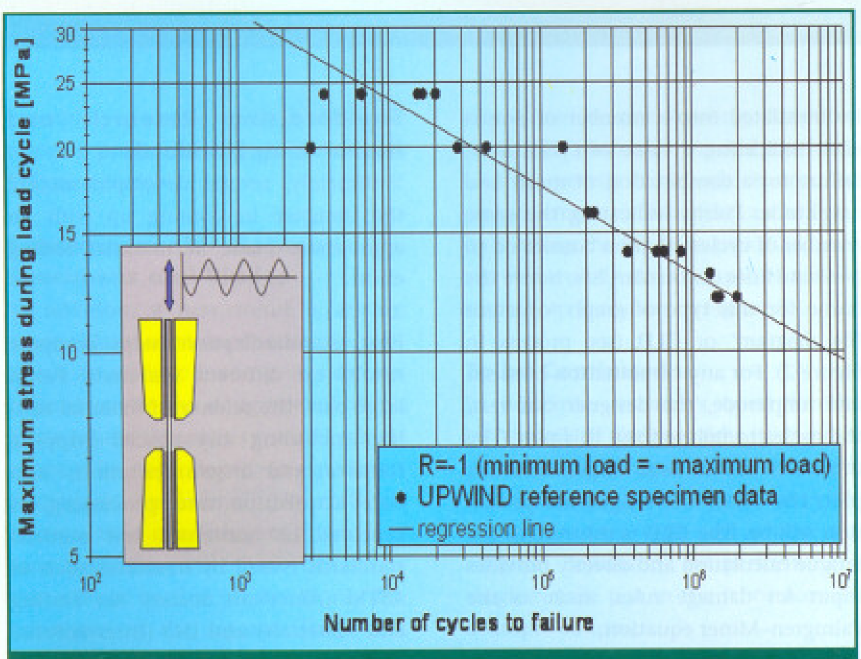

Figure 1. Example fatigue data in S-N diagram

The most important characteristics for the designer of a rotor blade are strength, relationship between cyclic load and fatigue life, and Young's modulus. These are used in design software such as FOCUS and in finite element models to construct rotor blades designed for 20-year life with minimal maintenance and repair. Design properties are obtained from relatively small coupons, doubling as cut-outs from a rotor blade.

Getting it Just Right

There is a lot more to wind turbine design than meets the eye, and it already starts getting complicated with the part 'design properties are obtained ...'. Either overestimation or underestimation of material characteristics can lead to serious problems, as these properties are at the basis of blade design. In the first case this will lead to blades breaking. In the second case this will lead to blades being too heavy.

Testing, one, two...

Extensive testing is necessary to obtain reliable material data. Because the direction in which the fibres are placed in the plastic matrix is tailored to the direction of highest loads, most materials used in a rotor blade are anisotropic (properties depend on the orientation of the material). For obtaining material properties, this means that some tests need to be repeated for a different orientation of the material. As an example, a test on a unidirectional laminate (where most of the fibres are in the direction of principal load) is typically done once in fibre direction and once transverse to the fibre.

In addition, most characteristics for almost all fibre-reinforced materials differ depending on tension, compression and shear. In fatigue, the degree to which the loading contains tension and compression loads matters a lot; at the same time the range of possible loading types in fatigue is literally infinite. To make matters worse, the scatter of material properties needs to be taken into account in the material characterisation. In fatigue tests, typical scatter is of the order of ten; if you test the first coupon (or specimen) of a series at a particular loading amplitude, and it survives x number of cycles, do not be surprised if the second, nominally identical coupon survives 10x cycles to failure (!).

S-N Diagrams

Figure 1 shows example fatigue data in an S-N diagram, which describes fatigue tests at a fixed ratio of minimum to maximum load and plots maximum load versus number of cycles until failure. For wind turbine materials, tests up to 10^6 or 10^7 cycles are not uncommon. Practical constraints hamper investigation of fatigue behaviour in the realm of 10^8 to 10^9 cycles (the range of actual blade load cycles), although a small number of studies have produced results in this cycle range. Since composites do not have a 'fatigue limit' (load below which no failure occurs regardless of number of cycles), careful regression using reliable models is required for justified extrapolation of test data to design lines.

Constant Life Diagrams

Where an S-N curve describes fatigue behaviour for a single loading type (e.g. tension–tension, tension–compression), the designer requires the full fatigue behaviour of the material for all possible loading conditions that the rotor blade material encounters.

This can be plotted in a single graph, which is constructed from a series of S-N curves, where the ratio of minimum to maximum of the load cycle (indicated by 'R') is kept constant per S-N dataset. For each tested loading type this can be translated into a number of points each indicating a value of cycles until failure for a combination of mean and amplitude. Points indicating the same number of cycles are then connected to generate lines of constant life, hence the name for this type of graph 'constant life diagram' or CLD (see process in Figure 2). For any combination of mean and amplitude, the designer can read the cycles to failure from this plot. The more S-N curves used to generate this plot, the better the fatigue life prediction will be. The CLD is the core of the fatigue calculation and directly provides input for damage rules, such as the Palmgren–Miner equation.

Possible Influences ... Did We Forget Any?

Research has shown that around six S-N curves are required for a reliable CLD. All this basically adds up to lots of testing. And then we have not yet considered the influence of loading rate, manufacturing method, laminate thickness, resin, sizing, reinforcement fibres, humidity, temperature, ultra-violet radiation, manufacturing method, multi-axial loading.

...And the coupons we are testing are nowhere near a finished blade (see Figure 3). To offer a more generic approach, several researchers are currently looking into micro-mechanical modelling, trying to predict from interaction between fibre and matrix how any specimen (testing coupon or blade-sized) will perform.

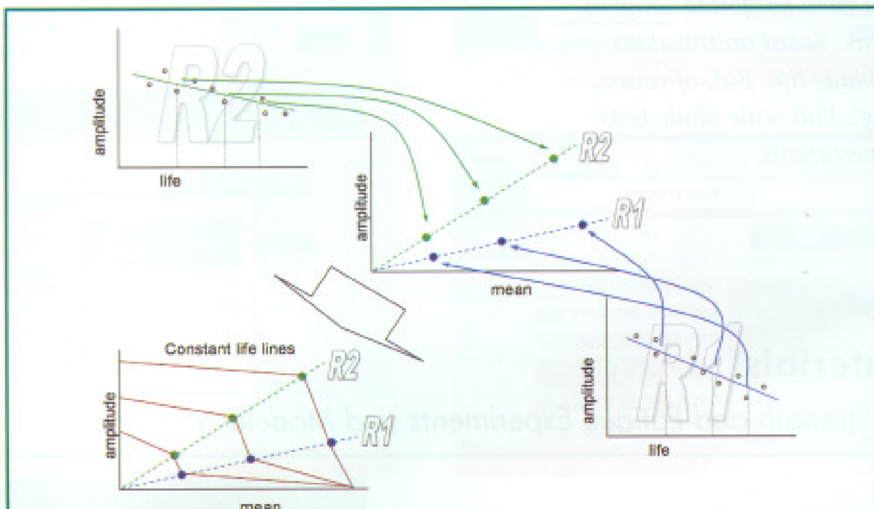

Figure 2. Construction of constant life diagram (CLD), 'R' = ratio of cyclic minimum to maximum

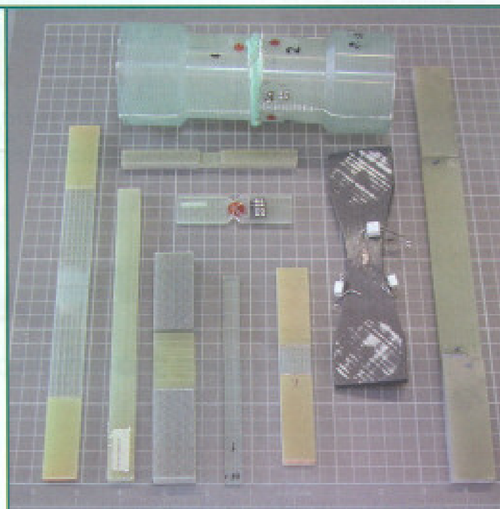

Figure 3. Various specimen geometries and materials

Standardising Research and Researching Standards

Fortunately, several developments aid the designer in coming up with an appropriate blade at minimal testing effort.

First, standardisation helps compare results on different materials. For a large part, the science of material testing, including any special gripping fixtures and instrumentation, and data acquisition and processing, is captured in numerous test method standards issued by institutes such as ASTM (American Society for Testing and Materials) and ISO (International Organization for Standardization). Some testing guidelines for wind turbines have also been made by GL (Germanischer Lloyd), DNV (Det Norske Veritas) and IEC (International Electrotechnical Commission). However, especially for fatigue testing, the standards do not cover all loading types. When multiple standards are available for obtaining a particular property, it is not always clear which one to use.

Efforts continue to be devoted not only to developing test methods where necessary but also to building elaborate material models which attempt to relate strength and life to most of the above-mentioned influences. The finished project OPTIMAT (www.wmc.eu), and current projects UPWIND (www.upwind.eu) and INNWIND (www.innwind.nl) are just some recent examples of large multi-disciplinary research projects that include material fatigue research.

Subcomponents – Between Specimens and Blades

In addition, a new trend is arising where blade subcomponents are subjected to realistic loading. A subcomponent can be any design detail of the blade where failure is expected which cannot be reproduced in specimen testing. As an example, a sandwich construction consisting of foam and face laminates will show behaviour that may be hard to predict if only the behaviour of the separate foam and facings is known. But many other subcomponents can be designed, serving as copies of blade details, or platforms to validate repair methods or condition monitoring techniques. Some representative blade details are shown in Figure 4.

Blade Testing

Finally, the proof of the pudding is in the eating, so all manufacturers choose to perform full-scale mechanical tests on their blades. The blade is fixed at the root and loaded using weights, winches, eccentric rotating masses, or hydraulic actuators (the latter gives most control over load and displacement). A typical test sequence involves a 'slow', static test (in practice consisting of a series of load cases). Then, the blade is subjected to a large number of fatigue loads. This is usually done in one loading direction. To mimic both the wind shear loads and the gravity loads, which occur in phase, a more realistic test can be done by loading the blade in two directions simultaneously. An example of a blade test set-up is shown in Figure 5.

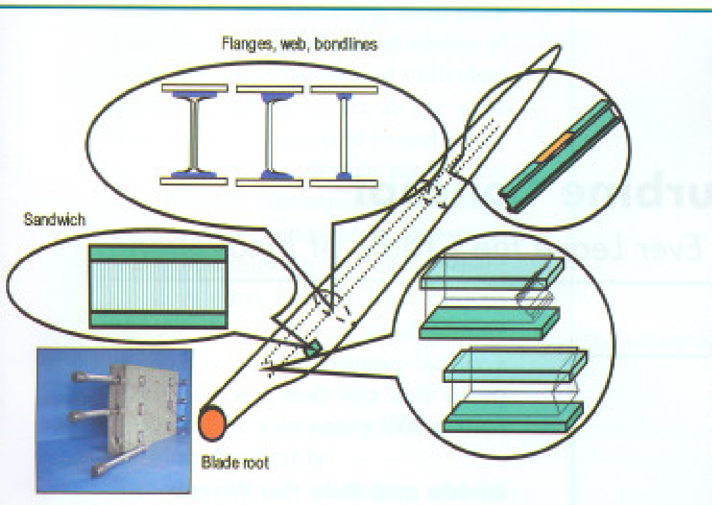

Figure 4. Parts of blade represented in subcomponents

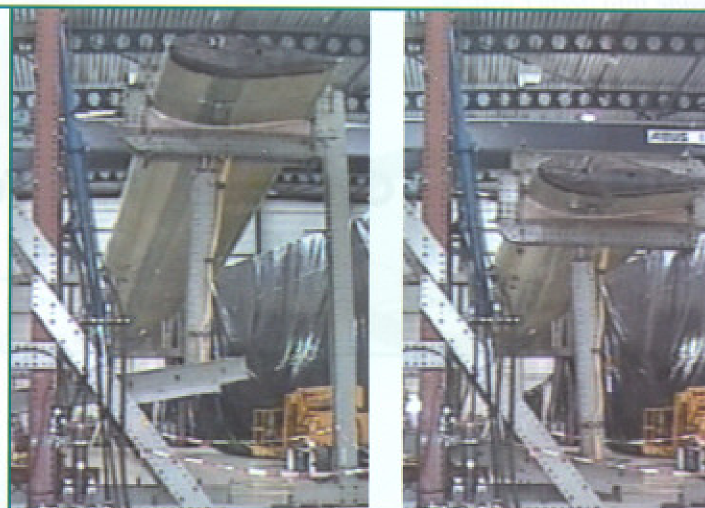

Figure 5. Full-scale mechanical blade test set-up

To be Continued ...

In principle, research's quest for the holy grail of fatigue aims to predict probability of fatigue failure of a rotor blade after any given number of cycles of any loading type and under any external condition, by performing a single tensile test in the laboratory on a simple coupon.

For predicting blade behaviour, it is important to direct investigations both at the material level and on large-scale structures. Material, subcomponent and blade experimental research all fill important requirements in the process of rotor blade design, and researchers are determined to carry out the large number of experiments, validating various models, to quantify all significant influences on fatigue life.

In the current (wind energy) market, ongoing improvements are required to maintain reliability while making design more cost-efficient. As a result – like in the movies – there will be several sequels to current research. New insights and approaches will, we hope, make these projects better than their predecessors (unlike some movie sequels!).

Biography of the Author

Rogier Nijssen is part of the materials research team of WMC (Knowledge Centre Wind Turbine Materials and Constructions). He and his colleagues are actively involved in several industrial and research projects for the wind energy community and blade industry.

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