Fatigue Life of Wind Turbine Structural Components

Betriebsfestigkeitsnachweis von Strukturkomponenten an Windenergieanlagen unter komplexer Belastung

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Summary:

Modern mega watt class wind turbines are exposed to high and complex loads. At the same time the aim is to realize light weight and optimized structures. Compared to other industries the design lifetime of a wind turbine is very long. Applying simulation tools for the predictions of fatigue life is therefore essential.
This paper presents the approaches for fatigue anaylses used in the wind industry and highlights the particular conditions for the design of these dynamically loaded components. At the same time the possibilities and limits of the simulation concepts are discussed.

Keywords:

Wind turbine, machinery structures, fatigue life, material, simulation, stress hypothesis, certification

1 Introduction

The size of modern wind turbines increased continuously over the last years and decades. At the same time the size of the components grew bigger. Today's large size castings pose challenges for designers, component manufacturers and logisticians. Larger components entail increasing cost and the demand for a sturdy sub-structure (e.g. foundation, tower) that is able to carry the dead weight and the aerodynamic loads. In order to reduce material consumption and cost the aim is a light weight and less material expensive design.

In comparison to other industries the design lifetime of a wind turbine is very long. Considering the large size components, full-component fatigue tests are not common practice and rarely seen in the wind industry. Hence simulation of the global loads and the components fatigue behaviour is vitally important. Since the failure of the large parts due to defects can often be an economic disaster, the accuracy of the simulations is very important.

Fatigue failures of structural components under cyclical loading occur in distinct phases – the crack initiation phase, followed by the crack growth phase and then the rupture.

The crack initiation phase is the life of the component up to the formation of a surface crack under fatigue loading. The crack-propagation phase is the remaining part of the life till the crack length reaches the critical length. The later part belongs to the science of fracture mechanics where material properties and micro-structure (grain size, imperfections, etc.) play a major role. The former, the crack initiation life is predicted using methods of damage accumulation which include hysteresis properties of the material involved and stress or strain histories at highly stressed locations. The focus of this paper is on the simulation and prediction of the crack initiation life.

2 Wind turbine components

The load bearing structural components in wind turbines are mostly made of large, complexly shaped spheroidal graphite iron castings and steel fabrications. Structural components that carry a major part of the occurring loads shall be subject to a detailed assessment of static and fatigue strength. For a conventional design of a wind turbine, consisting of hub, main shaft, one or two main bearings and a gearbox and a generator mounted on a main frame (figure 1), the following components will undergo a detailed fatigue assessment: Hub, mainshaft, main bearing housing(s), machine frame, torque arm and planet carrier.

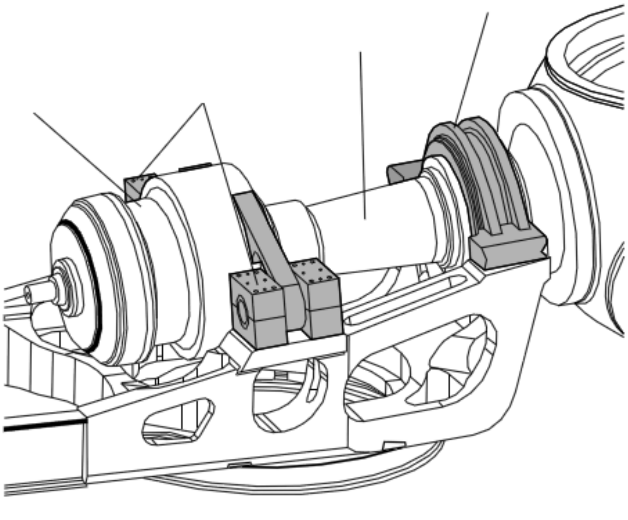

Fig. 1: Convetional 3-point suspension [3]

Also because of remote operations, conservative safety requirements and long life expectancy, a long crack initiation phase is necessary. The unpredictability of loads also makes determination of remaining life during crack propagation phase very difficult. Hence, the prediction of life up to the crack initiation is more relevant to these heavily loaded structural components. Based on this assumption, suitable fatigue analysis procedures are applied on the components to be investigated to determine the crack initiation life.

3 Design Loads

For the strength verification of the above mentioned components usually simulated loads are used. The simulation models commonly used, include the rotor blades and tower in much detail whereas the dynamic properties of e.g. the drive train and the structural components are considered very rudimentarily. Consequently the design loads for a wind turbine are only available at certain pre-defined coordinate systems of the wind turbine, e.g. blade root, hub centre or tower top [1]. Component loads have to be extrapolated from these global loads.

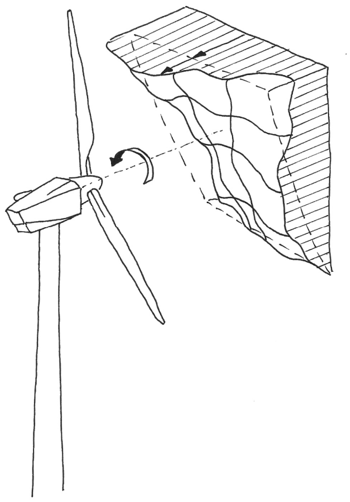

Fig. 2: Three-dimensional turbulent wind applied to wind turbine model.

The loads are calculated by generating a synthetic three-dimensional turbulent wind field that is applied to the wind turbine model (figure 2). The results of the simulation are load times series of forces, moments, accelerations, pitch and yaw angles etc. Forces and moments are the appropriate parameters to be used in the strength verifications.

Basically the loads can be divided in two groups: Normal load conditions and extreme load conditions. The normal condition loads are termed as fatigue loads. Situations as for example power production at different wind speeds, start-up and shut down situations are included in this group. The extreme loads include situations such as emergency shut down, grid loss and fault of the control system. The load cases that have to be analysed and considered in the design process of a wind turbine are specified in the relevant guidelines and standards, e.g. Guideline for the Certification of Wind Turbines (Edition 2010) [1].

From long term observations it was found that the distribution of wind speeds over a longer period of time is best described by the Weibull distribution. Depending on the selected site for a wind turbine the shape of the Weibull distribution may vary. In order to consider the distribution of wind speed over the assumed design lifetime each load case is related to a specific occurrence probability. For the load cases of e.g. normal power production these parameters are derived from the Weibull distribution whereas the occurrence of situations like start-up or shut-down are based on observations and recorded in the relevant guidelines and standards.

The time series of fatigue design load and the probability distribution of the load cases are important data for the verification of the components fatigue strength.

4 Material properties

Complexly fluctuating loads can cause variations in stress directions, usually termed as multiaxiality. The problem is that the limitations of brittle materials, such as high strength cast iron, to withstand multi-axial stresses are a problem rarely known outside the research centres.

Fatigue strength of materials, such as S/N curves for spheroidal graphite cast iron, is experimentally determined on specially prepared laboratory test specimens and usually defined only for uniaxial stress states. The uncertainties involved in quantifying this property are covered using statistical parameters such as probability of failure, scatter, slope and knee of S/N curve, level of confidence and the number of tests. Influence of surface roughness, technical defects, wall thickness and mean stress, notch effects are also appropriately considered as reduction factors to determine the component material strength under fatigue loads for uniaxial stress states [1]. These factors cover all related known risks and a careful combination of these factors is necessary to theoretically optimise load carrying capacity of the component.
This is the generally accepted procedure to derive component S/N curves since it has been financially unviable to conduct accelerated tests on full size components to gain the necessary material data.

An aspect that is disregarded in the determination of material properties is the influence of the manufacturing process. So far the material properties are determined by assuming a homogeneous material free of residual stresses. This involves uncertainties which are taken into account by safety concepts that are described in various standards and guidelines. The potential for more accurate material property assumptions is left unused and an additional, undesired safety margin can be the consequence.

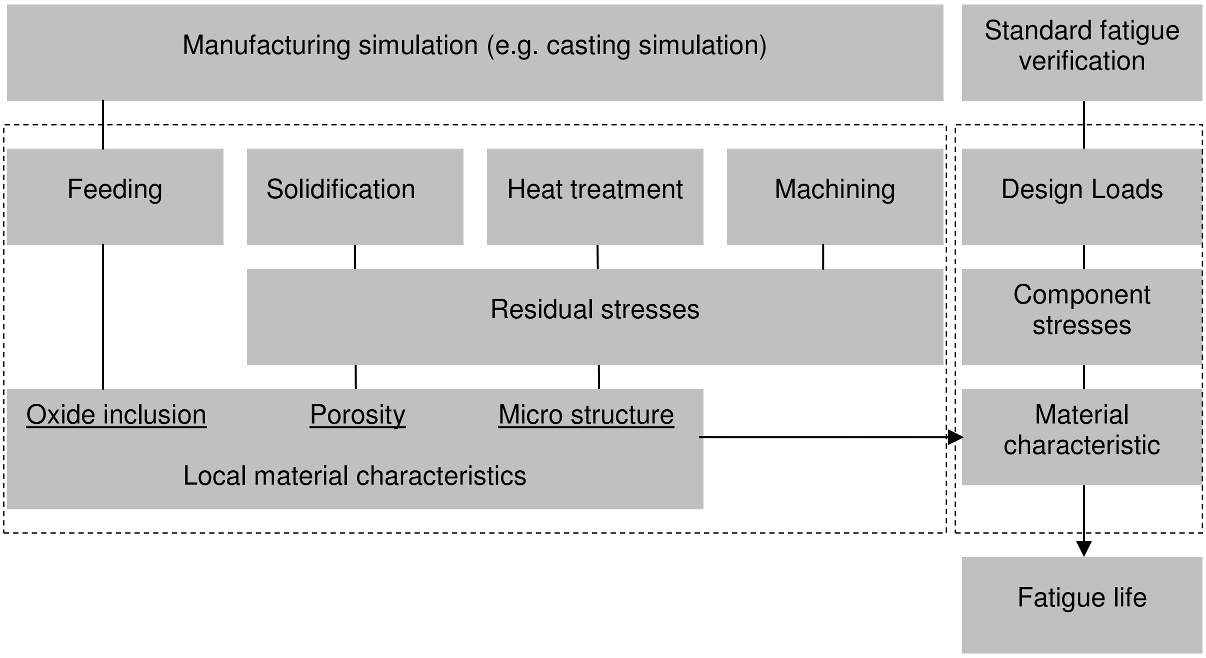

Fig. 3: Integration of the simulation of manufacturing and operation

The research project MABIFF (**Ma**ßgeschneiderte **B**auteileigenschaften durch **I**ntegration von **F**ertigungs- und **F**unktionssimulation – customised component properties by integration of the simulation of manufacturing and operation) deals with this problem. The aim is to integrate the information from e.g. the casting simulation into the strength analysis (figure 3). Parameters that affect the residual stresses and that can be extracted from a manufacturing simulation are the solidification, heat treatment and processing. Local material properties such as micro structure, porosity and oxide inclusion depend on the feeding process and can be gained by an advanced casting simulation.
Results and the practical implementation of the gained knowledge is expected in the near future.

5 Fatigue calculation procedure in wind turbine structural components

The complexity and dynamic of wind loads interacting with a turning rotor are leading to forces and moments that act simultaneously and independently in the three spacial directions. It is not definitely assessable which of the load components are design driving for the structural components that are subject to the fatigue strength verification. Therefore all load components have to be considered equally. At the same time the phase relationship is vitally important. Hence, the conventional approach using load spectra for the fatigue verification will fail in most cases.
Due to the large number of load cycles the wind turbine is exposed to a stress based fatigue approach is appropriate.

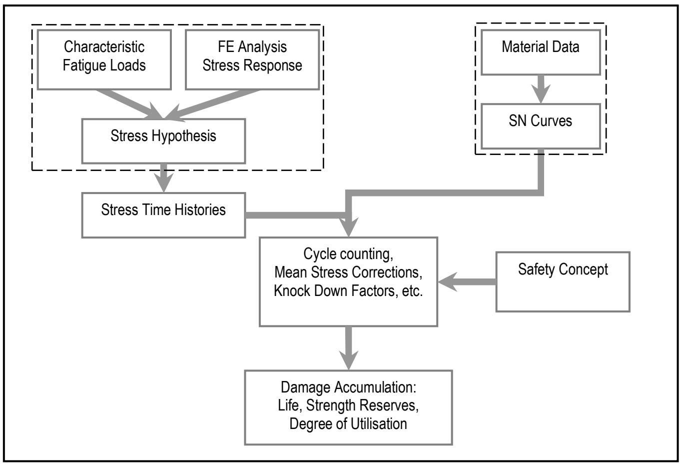

Fig. 4: Fatigue analysis procedure [4]

The analysis can be divided in two parts: the determination of stresses under fatigue loading and the determination of representative fatigue property of the material under consideration.

Figure 4 shows a typical fatigue analysis using the two above mentioned parts. The life of a component is a function of these two parts. The stresses on the component are calculated using appropriate stress hypothesis and then cycle counted to enable a comparison with applicable material data such as stress-life curves (S/N curves). Different safety and reduction factors are considered in these calculations before damage accumulation is carried out to determine the component life and the degree of utilisation.

6 Component stresses

Because of the complexity of the component geometry and varying load scenarios the local stress approach in combination with detailed finite element models and load time series is the method that is mostly used in the wind industry.

The finite element calculations are based on CAD models of component geometries with linear, isotropic material properties and multiple loading points. The load time series are simulated as explained above. Linear superposition of the load-coefficients (unit load stresses or transfer functions) determined from finite element analyses are multiplied with load time series to get local stress tensor time series. This is the generally accepted procedure for linear calculations but if non-linear boundary conditions are to be considered, e.g. contact surfaces of bearings, then modified approaches are necessary.

It is to be noted that reliable fatigue material properties exist predominantly for uniaxial stress states. Several hypotheses also exist to enable conversion of component stresses to an equivalent uniaxial stress. There also exist separate methods such as the critical plane approach to deal with multiaxial stress states.

To help understand this, a mainframe of a multi mega watt class wind turbine is used as an example in this study. Fatigue loads in combination with finite element models of the components were used to compute the stress histories at critical locations. Based on this, a local stress state analysis was performed to analyse the multi-axial behaviour of the stresses at four different locations and investigate the degree of multiaxiality (i.e. change in principal stress directions during a loading sequence).

6.1 Evaluation of stress states

In this paper the detailed evaluation of stress states will be limited to the location 1. The other three locations partly show a similar behaviour.

The stressing is predominantly caused by the rotor weight at low wind speed or in idling situations. If the wind speed increases and/or the blades are turned into the wind the area 1 will be subject to high tensile stresses caused by the tilt moment arising from the shear effects of the rotor and the axial thrust. The shear effects are caused due to the fact that the aerodynamic forces will be higher at the upper end of the rotor than they are close to the ground.

When evaluating the directions of the maximum principal stress at nominal wind speed it turns out that the angle φ is fairly constant at higher stresses but not for the low stresses. This observation applies for lower wind speed as well as for nominal and extreme wind speeds.

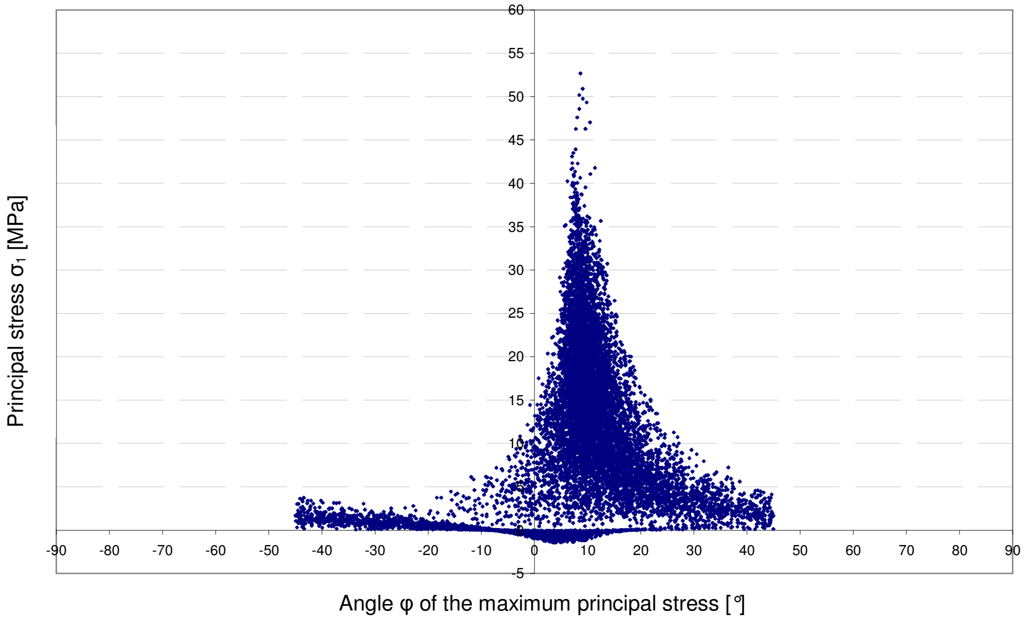

Fig. 5: Direction of the principal stress σ_1 at nominal wind speed [2]

From the analysis of the stress tensor time series it can be concluded that the principal stress is dominated by the normal stress σ_y which predominantly arises from the tilt moment defined at the hub centre of the wind turbine. Since the thrust load will increase at higher wind speeds the mean stress level at location 1 will step up proportional. Based on these observations it is possible to deduce that the stress states causing the largest portion of damage are quasi-uniaxial and show are high mean stress level.

In a second step different hypothesis were applied to calculate equivalent stresses and finally damage. These are the maximum principal stress hypothesis (Tresca), absolute maximum principal stress approach, critical plane approach and a modified shear stress criterion.

The maximum principal stress criterion is not a good choice for the prediction of fatigue life. In case of biaxial and multiaxial stress states it leads to too optimistic results.

For the absolute maximum principal stress approach it has to be noted that it is not physically meaningful because the real local stress-time history at the location is not represented. Furthermore this approach neglects or nullifies the mean stress corrections. Though it is still useful for locating the critical areas and for the most part gives conservative results and thereby covers the uncertainties of combining multiaxial stress states with uniaxial material properties.

The critical plane approach and the modified shear stress criterion proves to be reasonably accurate in predicting fatigue life for both in-phase and out-of-phase loading.To determine the critical plane the multiaxial stress state at a particular point is estimated. Then this multiaxial stress state is resolved to particular planes on the surface to compute the normal and shear stresses acting on the plane. Fatigue damage for these resolved stress histories is computed based on a rainflow counting and an appropriate damage parameter. When all of the calculations for the planes are complete the plane with the highest calculated damage is the critical plane and determines the fatigue life of the structure at that location.

$$\sigma_{V\,MAX} = \max(\sigma_1 , \sigma_2 , \sigma_3)$$ maximum principal stress hypothesis

$$\sigma_{V\,ABS} = \max|(\sigma_1 , \sigma_2 , \sigma_3)|$$ absolute maximum principal stress hypothesis

$$\sigma_n = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2} \cdot \cos(2\varphi) + \tau_{xy} \cdot \sin(2\varphi)$$ critical plane approach

$$\sigma_v = \mathrm{sign}(ABS)\sqrt{\sigma_n{}^2(\varphi) + \left(\frac{\sigma_w}{\tau_w}\right)^2 \cdot \tau_n{}^2(\varphi)}$$ modified shear stress criterion

Fig. 6: Stress hypothesis used for the investigation [2]

Using the first two approaches for calculating the equivalent stress has the disadvantage that the damage in different directions is calculated and added up to a total damage. In this case the difference compared to the latter two approaches is acceptable since the stress state is quasi-uniaxial. When the normal stress hypothesis is applied as a method of the critical plane the mean stress is considered more reliable which makes a difference in the present case of high mean stresses. Due to very low shear stresses the analysis based on the modified shear stress criterion leads to similar results as the critical plane approach.
Generally the main frame has many locations with uniaxial stress states similar to that one presented above. But depending on the specific design of each structure this of course may change.

The situation is different when a rotor hub of a wind turbine is analyzed. At several locations in the hub there exists multiaxial stress states (figure 7).

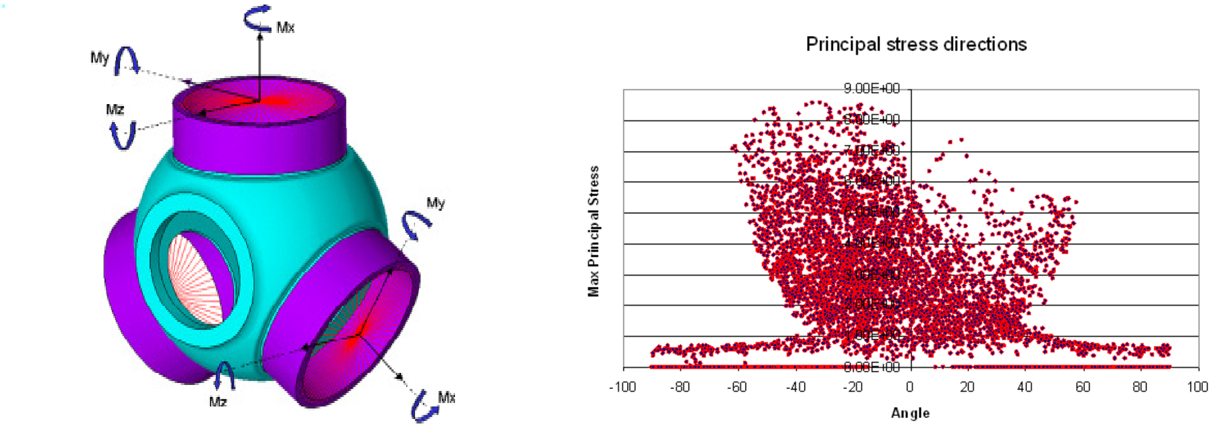

Fig. 7: Rotor hub with an example of multiaxial stress states [4]

The influence of these changing principal stress directions needs to be considered in the procedure for fatigue analysis by applying appropriate stress hypothesis.
The appropriate stress hypothesis is to be selected based on several factors:

- Uniaxial or multiaxial stress state
- Kind of material
- Phase relationships between applied loads
- Tensile, compressive or shear loading
- Type of stress concentration

7 Conclusion

Much effort is put into a reliable prediction of the fatigue life of wind turbine structures. Today it is possible to build complex simulation models and computation time is not an issue any longer.
Still certain conservative assumptions and simplifications are inevitable in order to realize a safe design.
Material behaviour under multiaxial loading is little known and the S/N curves available are for the uniaxial case. For the time being the complex stress state therefore has to be resolved to an equivalent uniaxial stress state.
In a current research project the influence of the manufacturing process on material properties is investigated and the aim is to include the gained knowledge in the simulation of fatigue life. The results will probably help to refine the existing material models which again will lead to a more efficient utilization of the material.
In the simulation of design loads certain dynamic effects in the higher frequency range are neglected. The uncertainties involved are considered by a safety factor for the loads or by a separate dynamic factor. More detailed simulation models could help to obtain reliable component loads.
Working on these issues will contribute to a competitive design and energy supply.

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