On the impact of geometric non-linearities in the fatigue analysis using the example of trailing edge bond lines in wind turbine rotor blades

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1. Introduction

Rotor blades of modern multi-mega-watt wind turbines reach lengths of 80 m and more. Such blades are slender and flexible structures, experiencing huge loads and large deflections. Associated with that, new challenges arise for the design and analysis of rotor blades [1].

This paper is concerned with the 3D finite-element-based fatigue analysis of trailing edge bond lines in large rotor blades. The simulations are based on the reference wind turbine model IWT 7.5 164 [2], which is a 7.5 MW direct driven wind turbine with 80 m long blades.

The focal point of this paper is to examine the influence of geometric non-linearities in the fatigue analysis using the example of trailing edge bond lines, regarding the shear stress proof according to the 2010 edition of the Germanische Lloyd (GL) certification guidelines [3] and a multiaxial stress proof as demanded by the latest DNV GL standard [4]. Both stress proofs for fatigue analysis disregard any potential geometric non-linear behaviour of the blade.

Geometric non-linearities appear whenever the strains in a material exceed more than a few percent and the changing geometry due to this deformation can no longer be neglected [5]. As modern wind turbine blades are subjected to large structural deformations [6] and the accuracy for correct fatigue analysis is crucial for the lifetime prediction of the blades, the geometric non linearity in fatigue analysis is an issue necessary to investigate.

2. Finite element model of the rotor blade and stress calculations

For the analysis a finite element (FE) model of the IWT 7.5 164 reference blade is utilized. It is generated with the Model Creator and Analysis Tool (MoCA) that has been developed at the Institute for Wind Energy Systems at Leibniz University Hannover. MoCA is a parameterized Matlab-based finite element model creator for wind turbine rotor blades that creates three dimensional models for Ansys.The stress post processing is limited to a span-wise region from 41 m to 47 m. A mesh convergence study has been performed to guarantee reliable results. The resulting global FE mesh and a local view of the adhesive are shown in Fig. 1.

Aero-elastic simulations of the wind turbine compute loads on the blade for the simulated wind conditions. To reproduce the bending moments over the blade in FE-analysis it is common to approximate them with the application of substitute forces in bending direction. An example of such a load application on a beam is illustrated in Fig. 2 (b). Here, all forces Q_j acting on a lever to the point r_i produce bending moments that sum up to the desired bending moment $M_{appr,i}$. This method is similar to the testing conditions of a full-scale test shown in Fig. 2 (a).

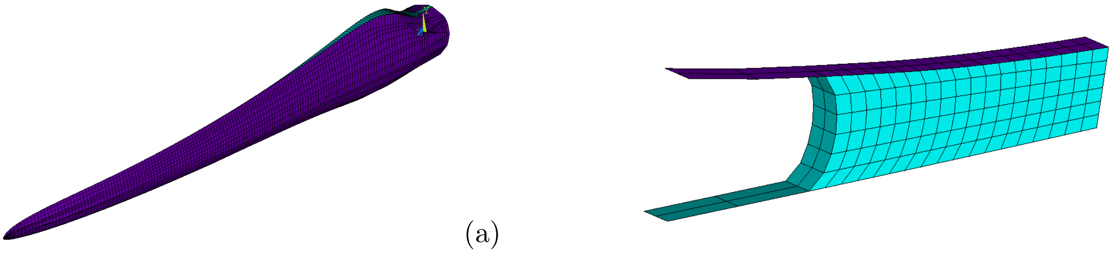

Figure 1. Finite element model of the IWT-7.5-164 reference wind turbine blade: Global mesh (a) and local mesh of the adhesive (b).

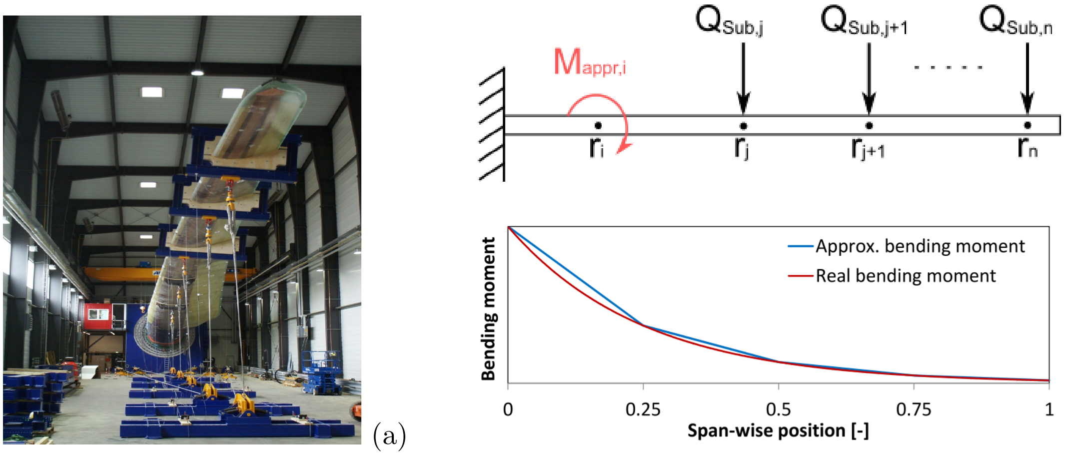

Figure 2. Load application on wind turbine blades for analysis purpose: Loading fixtures in a full-scale test [7] (a), bending moment approximation with substitute loads on a beam (b) and comparison of approximated and real bending moments over the span-wise position on the blade

In both, the FE-analysis and the full-scale test, the forces are adjusted to approximate the real bending moments over the blade as plotted schematically in Fig. 2 (c).

Further, the calculation of the necessary stress-time-series for the fatigue analysis of each element commonly uses the linear superposition principal. Assuming geometric linearity to reduce computational complexity, the linear relation of elements stresses and load magnitude for each load application position on the blade can be calculated with the FE-model. For every times-series of each load component the elements stress-time-series can be calculated using the previously explained stress-load relation. Hence, the overall stress time series on any position of the blade can be derived with the superposition of all stress-time-series for each load component. This principal requires a geometric linear behavior of the mechanical structure in all load conditions of the load-time-series.

3. Comparison of linear and non-linear FE-calculation of the bond line

The highest deviations of linear to non-linear stresses emerge at large deflections, thus high loads. For the example of the trailing edge bond lines the maximum edgewise load is assumed to be the critical load case, as the strains in the bond lines reach their maximum due to the large distance to the principal bending axis. Table 1 shows the load set for maximum edge wise bending during the simulation of the design load case 1.2 according to IEC [8], embodying the normal operation of the wind turbine during power production.

To determine the influence of geometric non-linearities, the stresses in the bond line were

Table 1. Load set for maximum edge wise bending for dlc 1.2.

Span-wise position [m]	Edgewise moment [kNm]	Flapwise moment [kNm]
29	5,632	-2,663
39	3,737	-3,664
51	1,943	-2,948
59	1,011	-1,818

computed performing both, geometric linear (lin) and non-linear (nlin) calculations using the explained load application. In the following the stresses of both calculation methods were compared. The fatigue proof of the trailing edge according to the GL certification guidelines uses the shear stresses in the adhesive to determine the material effort. Fig. 3 shows the mean deviation of the stresses of the linear and nonlinear calculations and the range of the three-fold standard deviation for all FE elements in the corresponding bond line cross section. The relative deviation is related to the linear calculations, as these are state of the art. Disregarding the outer regions of the analyzed bond line, where free edge effects could dominate the stress intensity, the mean value of the deviation is approximately 48 %. Respecting the range of the standard deviation the value can even reach up to 80 %.

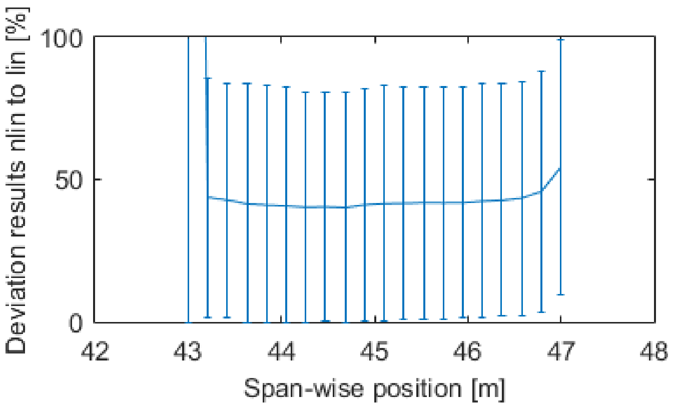

Figure 3. Relative deviation of the non-linear to linear calculated shear stresses in the bond line cross sections (Mean value and three-fold standard deviation).

To estimate the error of the fatigue proof according to the new DNV-GL guideline the Drucker-Prager failure hypothesis is used for the multi-axial stress state. This criterion is developed to model materials with different tensile and compressive strengths [9], which in fact is also the nature of commonly used adhesives (EP and PU) showing a significantly higher compressive than tensile strength [10]. Similar to the previous plot Fig. 4 illustrates the deviation of the computed Drucker-Prager equivalent mean stresses in the bond line cross section with their corresponding three-fold standard deviation range. The deviations for the multi-axial stress proof differ from the shear stress proof. Mean values for the relative difference of geometric linear to non-linear calculation are only about 3 4 %. According to the graph in Fig. 4 the maximum expected values reach up to 9 %, disregarding the outer regions of the bond line.

Further, this paper will suggest a load application method to reduce the non linear effects in FE-analysis of rotor blades. Therefore the blade is evaluated piecewise in span-wise direction,

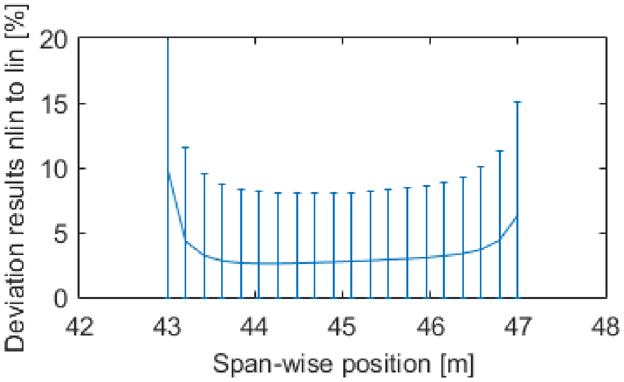

Figure 4. Relative deviation of the non-linear to linear calculated Drucker-Prager equivalent stresses in the bond line cross sections (Mean value and three-fold standard deviation).

applying the real load set with a small offset to the observed region. Thus, no moment approximation is needed. In order to guarantee that for this short span-wise section the moments applied do not change significantly, the evaluation has to be done piecewise. This process has to be repeated to obtain stress relations for the whole blade. The influence of geometric non-linear effects is reduced by using this method.

4. Conclusion

To conclude, this paper states that large wind turbine blades behave geometric non-linearly in extreme load cases within the fatigue load-time-series. Depending on the stress proof the non-linear effects can have a relatively high influence on the results, e.g. up to 80 % with the shear stress proof according to GL [3]. The utilization of the new DNV GL [4] multi-axial stress proof reduces the impact of geometric non linearities to a maximum of 9 % in the analyzed bonding region. Nevertheless, non linearities can occur which is the reason why the superposition principal can theoretically not be applied to calculate the stress-time-series for fatigue analysis. An alternative load application is suggested to reduce the undesired geometric non-linearity.

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