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Comparative study of finite-element-based fatigue analysis concepts for adhesive joints in wind turbine rotor blades

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Micro Abstract
This contribution aims to clarify the need for considering non-proportionality in the fatigue analysis of adhesive joints of wind turbine rotor blades. The comparison covers three different blade configurations (Length: 20 m, 80 m and 86 m) in order to derive generalized conclusions by extracting a correlation between non-proportionality, radial position blade size and design. The results further indicate which type of fatigue analysis has to be performed for reliable life estimations.

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Introduction

Wind turbine blades are subjected to complex loading states consisting of stochastic wind forces and deterministic gravitational forces. As these are generally not in phase, they lead to non-proportional stress histories. A common way of evaluating the annual fatigue damage is to evaluate equivalent stress histories that cannot accurately take non-proportionality into account, which will result in an error of the fatigue damage. The aim of this comparative study is to search for a correlation between blade length or design and the change of fatigue damage in the trailing edge adhesive joint when non-proportional loadings are accounted for or not.

1 Fatigue Analysis of the Three Different Blade Designs

To perform the fatigue analysis we used the in-house tool MoCA (Model Creator and Analyzer) for the generation of 3D finite element models of three different blade designs. The commercial code ANSYS is used as the finite element solver. Figure 1 shows the three blade models and presents the blade lengths of 86 m (DTU 10MW blade [1]), 80 m (IWES IWT-7.5-164 blade [4]), and 20m (demo blade of the SmartBlades2 project [2]). All composite parts are modelled with 4-noded layered shell elements and the adhesive joint with 8-noded solid elments. The mesh density around the trailing edge is locally refined in order to obtain a fine resolution of stresses.

1.1 Non-Proportionality Factor

To evaluate the non-proportionality of the stress histories, a factor proposed by Meggiolaro & Pinho de Castro [3] is employed. The idea behind that is to represent all time steps of the stress histories by concentrated unit masses in the n-dimensional stress space. For the resulting body, the n principle mass moments of inertia $I_1, I_2, ..., I_n$ are calculated and sorted such that $I_1 > I_2 > ... > I_n$. The non-proportionality factor is then defined by

$$\boldsymbol{f_{NP}} = \sqrt{\frac{\boldsymbol{I_2}}{\boldsymbol{I_1}}}, \tag{1}$$

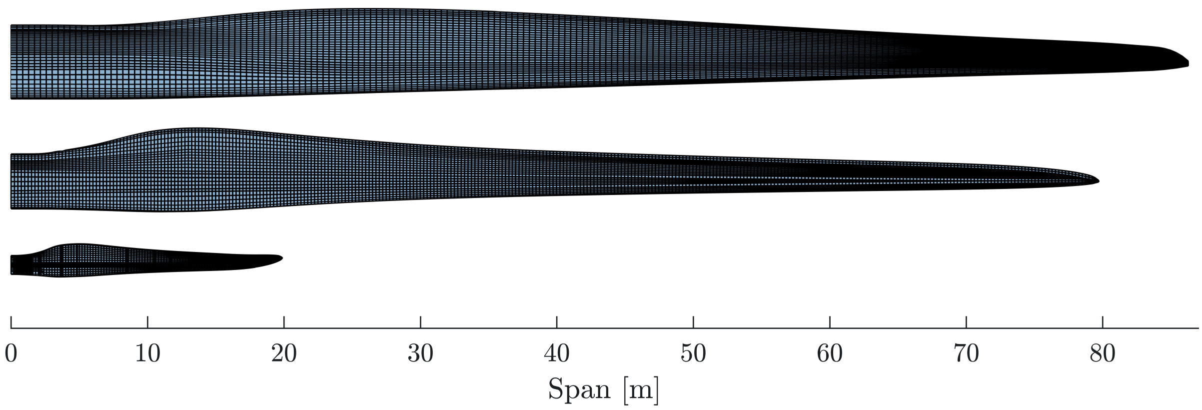


Figure 1. 3D finite element models of the investigated wind turbine blades: DTU 10-MW [1] (top), IWES IWT-7.5-164 [4] (center), and SmartBlades2 demo blade [2] (bottom)

which is the square root of the ratio between the second highest and the highest mass moment of inertia, respectively. For a factor of $f_{NP} = 1$ the stresses are in phase, i.e. proportional, whereas for a factor of $f_{NP} = 0$ they are 90° out of phase, i.e. non-proportional.

1.2 Fatigue Damage Calculation

Two models are applied to calculate the annual fatigue damage. The first one is an equivalent stress approach using the Rankine criterion, where the maximum principle stress is evaluated. In that approach, the direction of the maximum principle stress is changing with time for non-proportional stress histories. Nevertheless, the partial damages of all time instances are accumulated in the framework of a Palmgren-Miner scheme, no matter where the principle stress is pointing to. Hence, this approch does not take into account stress non-proportionality.

The second approach is the so-called critical plane approach, which takes into account stress non-proportionality. On each material plane, the damage due to the normal stress is evaluated and accumulated. Fatigue life is hence predicted on the plane where the maximum damage is calculated. In case of $f_{NP} = 1$, both methods result in the same fatigue life prediction. Fatigue life according to the critical plane approach is longer – and thus less conservative – elsewise.

2 Comparative Study Considering Non-Proportionality

We first analyze the non-proportionality in the trailing edge adhesive joint for the three selected blades. Aeroelastic simulations provide the load histories for all operational wind speeds of the wind turbine. The finite element simulation serves to transfer the loads into stresses. Those are then utilized to calculate f_{NP} in each element. Figure 2 exemplarily shows the results for the IWES IWT-7.5-164 rotor blade in terms of a contour plot. Therein, the maximum non-proportionality factor $f_{NP,max}$ appearing in each cross-section along the rotor radius r is plotted for each operational wind speed v.

With the corresponding Weibull frequency of occurrence distribution for the wind speed, which is plotted on the right-hand side of Fig. 2, the non-proportionality factor in each element can be transformed to a weighted non-proportionality factor defined by

$$\boldsymbol{\overline{f}_{NP}} = \sum_{\boldsymbol{i}} \boldsymbol{f_{NPi}}\, \boldsymbol{h_{Wi}}, \tag{2}$$

where f_{NPi} and h_{Wi} are the non-proportionality factor and the probability of occurence for a particular wind speed i, respectively, and the summation is carried out for all wind speeds at which the wind turbine is operating. In this way, load histories for wind speeds that frequently occur are taken into account to a higher extent than those for wind speeds that rarely appear.

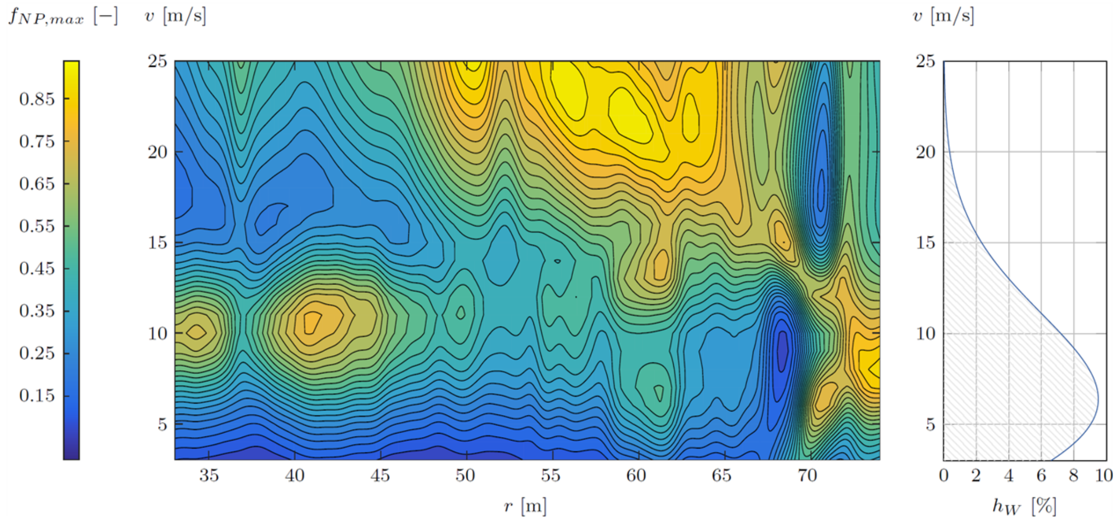


Figure 2. Non-proportionality distribution over the IWES IWT-7.5-164 reference wind turbine blade for all operational wind speeds and its corresponding wind distribution for a reference near shore site.

Figure 3 shows the maximum weighted non-proportionality factor $\overline{f}_{NP,max}$ of each cross-section plotted against the normalized radius r/R, where r is the local radius of each cross-section and R is the radius at the tip of the blade. The distribution does not follow any clear trend. Furthermore, no correlation between the similarly sized blades DTU and IWES can be abstracted neither between the large blades nor the 20 m SB2-blade. The non-proportionality is highly dependent on the dominant normal stress in spanwise direction in the trailing edge adhesive joint, which is mainly provoked by gravitational forces and design philosophy. Thus the missing correlation between the same scaled models can be due to varying amount of load carrying plys in the neighbourhood of the joint, whereas in between the different blade sizes the high mass difference may lead to significantly different material efforts from gravitational forces.

The annual damage is evaluated according to the two methods presented in section 1.2 and related to the non-proportionality factor in the sequel. Figure 4 exemplarily shows the weighted non-proportionality factor and the annual damage using the equivalent stress and the critical plane approach, respectively, for a cross section of the trailing edge of the IWES blade at a radial position of approximately 74 m.

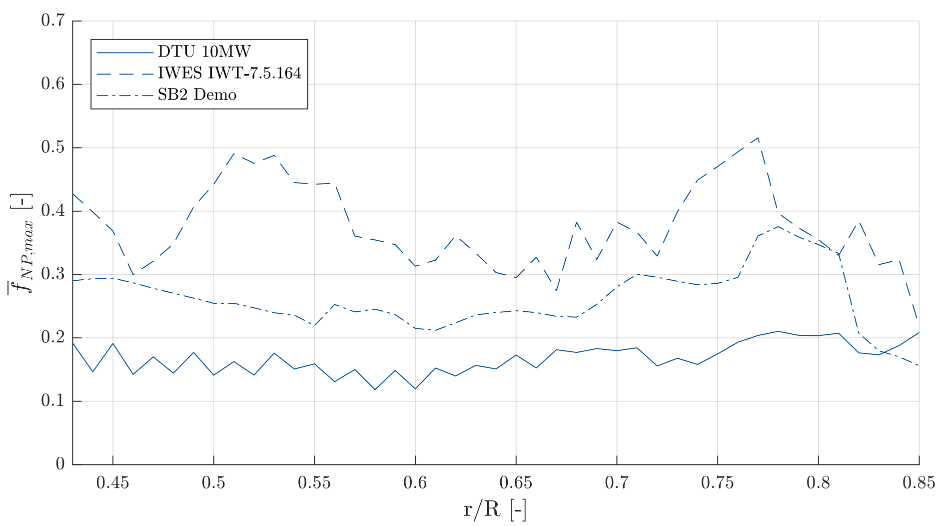
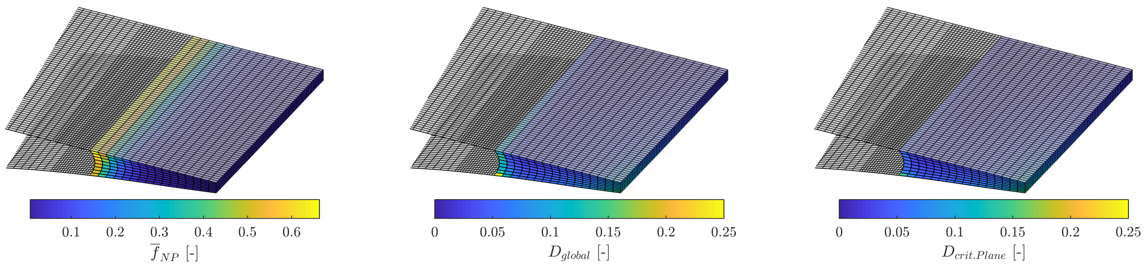


Figure 3. Maximum weighted non-proportionality factor for the three selected blades, plotted against the normalized radial position.

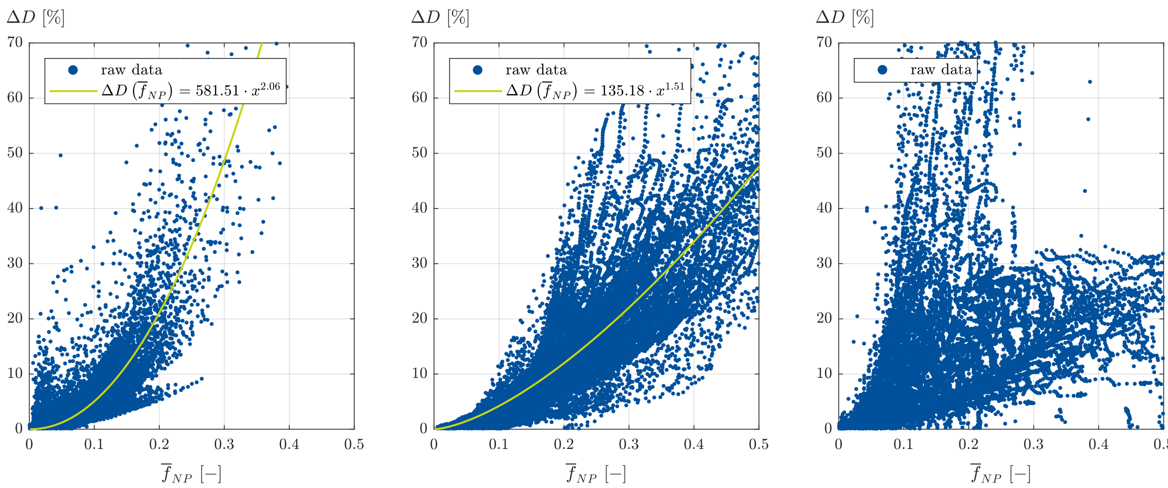


(a) (b) (c)

Figure 4. Contour plots of the trailing edge adhesive joint of the IWES IWT-7.5-164 rotor blade at a radius of 74 m: Weighted non-proportionality factor (a), annual damage according to the Rankine equivalent stress approach (b), and annual damage according to the critical plane approach (c).

The non-proportionality is maximum at the inner edge of the adhesive. Severe damage is observed at both the inner and the outer edges. The differences between both fatigue damage calculation approaches are apparent at locations with high damages and high non-proportionality factors. Considering all selected blades, the distribution of non-proportionality is similar to Figure 4 (a), but high damages are more likely to appear at the outer edges of the adhesive joints.

Figure 5 plots the relative damage difference between the two models against the weighted non-proportionality factor for all three blades. For the large blades, see Fig. 5 (a) and (b), a trendline can be fitted, whereas the plot for the 20 m SB2 demo blade is too chaotic. Qualitatively, it can be concluded that the larger $\overline{f}_{NP}$ is, the larger the damage difference becomes. Hence, it can be concluded that the larger the non-proportionality is, the more important a model becomes that takes into account non-proportional stress states.



(a) DTU 10MW (b) IWES IWT-7.5-164 (c) SmartBlades2 Demo Blade

Figure 5. Relative difference of annual damage between equivalent stress and critical plane approach, related to the equivalent stress approach annual damage for the DTU 10-MW blade (a), the IWES IWT-7.5-164 blade (b), and the demo blade from the SmartBlades2 project (c).

Conclusions

In this work, the presence of non-proportional stress histories and the fatigue damage when applying two different fatigue analysis models, were compared for three different blade designs. The DTU blade (86 m) and the IWES blade (80 m) showed clear non-proportionalities in the inner edge of the trailing edge adhesive joint, which in fact also holds for the SmartBlades2 demo blade (20 m). It has further been shown that in presence of significant stress non-proportionalities, the estimated annual fatigue damage is significantly lower when those non-proportionalities are accounted for in the fatigue analysis procedure.

The different design philosophies of wind turbine blades and their individual performance lead to mechanical behaviours that are hardly comparable, especially for very different blade lengths. However, a comparison of blades with similar lengths may be possible to some extent. It may be justified to generally conclude for any wind turbine rotor blade that trailing edge adhesive joints are prone of significant stress non-proportionalities. In consequence of that, the choice of an appropriate fatigue analysis methodology is of utmost importance, as the wrong model will result in substantial overdimensioning of the rotor blade subcomponents.

References

[1] C. Bak, F. Zahle, R. Bitsche, T. Kim, A. Yde, L. C. Henriksen, M. H. Hansen, J. Blasques, M. Gaunaa, and A. Natarajan. The DTU 10-MW reference wind turbine [sound/visual production (digital)]. Danish Wind Power Research 2013, Fredericia, Denmark, 27/05/2013.

[2] M. Bätge. Design of a 20m blade for the demonstration turbine (Deliverables 1.2.6.2/1.2.6.3). In J. Teßmer, C. Icpinar, A. Sevinc, E. Daniele, J. Riemenschneider, M. Hölling, and C. Balzani, editors, *Schlussbericht Projekt SmartBlades*. German Aerospace Center (DLR), 2016. Updated version from internal report in the SmartBlades2 project, 2017.

[3] M. A. Meggiolaro and J. T. Pinho de Castro. Prediction of non-proportionality factors of multiaxial histories using the moment of inertia method. *International Journal of Fatigue*, 61:151–159, Apr. 2014.

[4] A. Sevinc, M. Rosemeier, M. Bätge, R. Braun, F. Meng, M. Shan, D. Horte, C. Balzani, and A. Reuter. IWES Wind Turbine IWT-7.5-164 (Deliverables 4.2.2.1/4.4.1.1/4.4.2.1). In J. Teßmer, C. Icpinar, A. Sevinc, E. Daniele, J. Riemenschneider, M. Hölling, and C. Balzani, editors, *Schlussbericht Projekt SmartBlades*. German Aerospace Center (DLR), 2016.