Strength analysis of a 5-m composite wind turbine blade under static and fatigue loading conditions

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Abstract. This study focuses on the static and fatigue strength analysis of the existing 5-m RUZGEM composite wind turbine blade with and without defect in the form of debonding. Puck progressive damage analysis is used to investigate the effect of defect introduced to the spar/pressure side interface on the ultimate strength under extreme flap-wise (min) by single-loading point application. In addition, fatigue life according to the Germanischer Liyd (GL) guidelines is determined. For the original blade, collapse is observed after 85% loading, whereas due to defect, failure region changes and the blade collapses after 69% loading. Blade is found to exhibit sufficient resistance against fatigue. However, the inclusion of defect decreases the fatigue life of the blade significantly.

1. Introduction
Wind turbines are environmentally-friendly renewable energy resources, which are designed to operate over a lifespan of 20 years. According to Holmes et al. [1], long-term structural reliability of wind turbine components is vital when high cost of manufacturing, inspection and repair, especially for turbines located in remote regions are considered. Composite blades are important components of a wind turbine, that are subjected to complex loading conditions. During a service time of 20 years, several damage modes caused by extreme gusts in addition to cyclic loading can occur in rotor blades [2, 3].

Static and fatigue strength analysis are needed for validating the design of wind turbine blades. In the literature, there are many studies regarding the static or fatigue strength of blades. However, there are a smaller number of papers, where both static and fatigue strength analysis of wind turbine blades are presented.

For investigating the failure behavior of large-scale composite turbine blades researchers conducted full-scale tests under static loading. Jensen et al. [4] tested a 34-m blade and found that Brazier effect and further delamination buckling is the main reason for the blade collapse. In contrast, according to Overgaard et al. [5], the main failure mechanism which leads to blade collapse is argued to be delamination and its interaction with local buckling. Haselbach and Branner [6] highlight the influence of buckling on the damage onset in the trailing edge and sandwich panel failure during the full-scale test of a 34-m wind turbine blade. In another study, conducted by Chen et al. [7], delamination failure at the root transition were found to be the main failure mechanism for 52.3-m blade collapse. Muyan and Coker [8], investigated the strength characteristics of the 5-m wind turbine blade without any defects.
utilizing progressive damage analysis under extreme flap-wise, edgewise and combined loading conditions.

Regarding the fatigue strength of blades, Marin et al. [9] estimated the fatigue life of a 300 kW wind turbine blade using a simplified procedure proposed by GL standard. They found that an increase in the stress state due to the combined effect of an abrupt change of laminate thickness and existence of a superficial crack leads to a crack generation in the laminate that results in total failure. Castelos and Balzani [10] studied the effect of geometric nonlinearities on the fatigue analysis of the trailing edge bonding in wind turbine blades. They point out that the superposition of stresses for the fatigue may be misleading for modern, flexible rotor blades where geometric nonlinearities must be considered. In addition to this, they propose a novel methodology for calculating stresses with a new load application method that reduces geometric nonlinear behavior of the blade.

Recently, using white light imaging technique and ex situ X-ray computed tomography technique, Mikkelsen [11] investigated the fatigue damage mechanisms in quasi-directional load-carrying laminates of wind turbine blades. He was able to observe the three-stage stiffness degradation during tension/tension fatigue. Moreover, he found that for R=0.1 tension/tension fatigue and R=-1 tension/compression fatigue, damage mechanisms were similar, whereas for R=10 compression/compression case, damage mechanism was different.

For both static and fatigue strength analysis, Montesano et al. [12] introduced a physically based multi-scale damage model, which can account for failures of a 33.25 m rotor blade. The simulation results show the capability of the model to predict the evolution of sub-critical ply cracks between spar webs located near the blade root at maximum chord length. In the follow up work by Zu et al. [13], the multi-scale model is further expanded to include cohesive zone elements to predict structural debonding failure at the spar/skin interface located near the blade root at maximum chord. Structural analysis of large-scale vertical axis wind turbine components is reported by Lin et al. [14]. Strain history is used to evaluate the fatigue damage according to GL Guidelines [15]. Ultimate strength is determined based on Tsai-Wu failure criterion. The study reveals that compressive loads lead to larger fatigue damage than tensile cyclic loads. Highest damage is observed at the blade mid-span.

This study focuses on the static and fatigue strength analysis of the existing 5-m RUZGEM composite wind turbine blade with and without defect in the form of debonding. The main blade components are depicted in Figure 1. Previous study by Muyan and Coker [8], investigated the strength characteristics of the 5-m wind turbine blade without any defects utilizing progressive damage analysis under distributed pressure loading. In this study the investigation is limited to the redistribution of the stresses due to the debonding defect and its influence on the blade static and fatigue strength. The modeling method is not extended to investigate the debonding crack growth. Puck progressive damage analysis is used to investigate the ultimate strength under extreme flap-wise (min) single-loading point application. In addition, blade fatigue life according to GL guidelines is investigated.

![Figure 1. Blade assembly for the 5-meter RUZGEM turbine blade [16].](image-url)
2. Methods

2.1. Static strength analysis method

For this static analysis, Puck’s physically based phenomenological model is implemented in the 5-m composite RUZGEM blade FE Model using ANSYS Parametric Design Language (APDL) [17]. The blade is modelled with plane stress elements. According to Puck’s failure criteria [18] the degradation rules are applied to the elements as explained in detail in the previous work of the authors [8]. In Table 1, the material properties and design allowables of the blade materials for static analysis are listed [16]. Referring to GL Guidelines [15], design allowables are obtained from the knockdown of the experimental strength values by the material safety factor 2.406.

Table 1. Material properties and design allowables of RUZGEM blade for static analysis

| Material Property | Unidirectional Laminate | Steel | Gel Coat | CSM 300 | Divinycell H45 |
|-------------------|-------------------------|-------|----------|---------|---------------|
| Density, \( \rho \) [kg/m³] | 1896 | 7850 | 1200 | 1896 | 200 |
| Thickness, \( h \) [mm] | 0.716 | 5.3 | 0.9 | 0.358 | 5 or 10 |
| \( E_1 \) [GPa] | 24.84 | 210 | 3.98 | 9.14 | 55x10⁻³ |
| \( E_2 \) [GPa] | 9.14 | 0.3 | 0.34 | 0.29 | 55x10⁻³ |
| \( v_{12} \) | 0.29 | 0.4 |
| \( G_{12} \) [GPa] | 2.83 | 15x10⁻³ |
| \( X_1 \) [MPa] | 191.73 | 581.8 | 35.29 | 16.86 | 1.4 |
| \( X_C \) [MPa] | 101.16 | 0.6 |
| \( Y_1 \) [MPa] | 16.86 | 1.4 |
| \( Y_C \) [MPa] | 50.41 | 0.6 |
| S [MPa] | 11.29 | 0.56 |

For the design of the RUZGEM blade, the turbine specifications are obtained from the meteorological data in Ankara, Turkey [19]. Based on this information, the turbine specifications were selected according to the IEC 61400-2 standard [20]. Loads for the structural design were selected as the worst load case scenario for the complete set of IEC extreme loads.

Extreme external loads are given over 28 stations of the blade suction and pressure sides for flap-wise(min) loading. Figure 2 shows the calculated values of the flap-bending moment in sections along the blade span length. These flap-wise moment values are computed from flap-wise loads. In order to simulate testing condition using single load application method, the load which resembles the bending moment over the blade segment 0-3.25 m range is applied at station 3.25-m as shown in Figure 3. The load at this station is distributed among the nodes along the spar width on the suction and pressure sides equally.

As the boundary condition all rotational and translational degrees of freedom at the blade root are fixed. A total number of approximately 35,000 nodes are used in the finite element model, which is determined based on the mesh convergence study. SHELL 181 elements with size 15x15 mm are used for the mesh. This element size correlates to the typical element size for small scale wind turbine blades. Adhesive materials used for the blade connections are modeled using bonded contact with multi point constraint (MPC) algorithm in the FE Model. Geometric nonlinearity is included in the static strength analysis.

FE model of the existing 5-m METUWIND blade with debonding defect is depicted in Figure 4. Debonding defect is a common failure type observed in wind turbine blades [21]. Size of the debonding region is approximately 450x186 mm² as highlighted in blue in Figure 4. The defect is modeled between the spar-pressure side interface and is located approximately 1490 mm away from the blade root. This debonding defect is created by deleting the bonded contact elements (CONTACT174 and TARGET170) in the defect region.
2.2. Fatigue strength analysis method

Fatigue calculation is carried out based on the approach suggested by Germanischer Lyod (GL) Guidelines [15]. This approach suggests simplified and conservative rules by utilizing tensile and compressive strengths of the composite material in the Goodman diagram. Fatigue loading is chosen to be 75% of the extreme flap-wise (min) loading and as stated in [11], the stress ratio is assumed to be R=0.1. According to the recommendations of IEC 61400-23:2002 standard [22], a partial safety factor of 1.2 is included in the fatigue loads Afterwards, cycle mean stress $\sigma_{k,m}$ and cyclic stress amplitude $\sigma_{k,A}$ are generated from FE element simulation. For the computation of stresses geometric nonlinearity is included. Depending on this information, permissible number of cycles, $N_f$ for each element is calculated as follows:

$$N_f = \left[ \frac{R_{k,t} + |R_{k,c}| - 2 \cdot \gamma_{Ma} \cdot \sigma_{k,m} - R_{k,t} + |R_{k,c}|}{2 \cdot (\gamma_{Mb}/C_{ib})\sigma_{k,A}} \right]^m$$

where $R_{k,t}$ and $R_{k,c}$ are the characteristic tensile and compressive strength of the material, respectively. $\sigma_{k,m}$ and $\sigma_{k,A}$ are the mean value and amplitude of the stresses obtained from the blade FE Model under cyclic loading. For this calculation, $\sigma_k$ are calculated as the average resultant axial stresses on laminate level. In expression (1), the values of the material partial safety factors $\gamma_{Ma}$, $\gamma_{Mb}$ constant $C_{ib}$ and slope $m$ are selected according to GL Wind Guidelines [15], $m$ is selected as 10 for glass reinforced epoxy composites. $\gamma_{Ma}$ and $\gamma_{Mb}$ are taken as 2.406 and 1.96 for UD and Triax materials, respectively.

Characteristic strength values for the materials of the RUZGEM blade fatigue analysis are obtained from [23] and are listed in Table 2.

Table 2. Characteristic strength values of the RUZGEM blade materials for fatigue analysis

|                        | Unidirectional Laminate | Triax [0/±45]t |
|------------------------|-------------------------|----------------|
| Characteristic static tensile strength ($R_{k,t}$) [MPa] | 461                      | 301             |
| Characteristic static compressive strength ($R_{k,c}$) [MPa] | 243                      | 287             |
3. Results and discussion
In this section static and fatigue strength of existing 5-m RUZGEM blade is investigated using FE Models with and without defect. First the static strength of the blade with and without defect is presented followed by the fatigue life of the blade with and without defect.

3.1. Static strength analysis
Using progressive damage analysis method, for the extreme flap-wise (min) loading case, the load-displacement curves of the blade with and without defect are obtained as displayed in Figure 5. The load application and the displacement, which is measured at the load application point, is in the flap-wise (min) direction. As seen from the figure, RUZGEM blade without defect and with defect collapses after 85% and 69% of the extreme flap-wise (min) loading, respectively.

Based on the information element failure progression in the damaged blade components (pressure side, internal flange, spar and suction side) are displayed for model without defect and with defect in Figure 6 (a) and Figure 6 (b), respectively. According to the methodology [8], an element fails if fiber-failure (FF) or inter-fiber-failure mode C (IFF(C)) in at least one third of the plies of a laminate is detected. The stiffness of the failed elements is set to zero and they do not contribute to the blade strength anymore. Failed elements are colored in red in the figures. For the model without defect depicted in Figure 6 (a), root transition region is the main damage region which leads to blade collapse. This failure region shows similarity with the findings in [24], where FEA strain were found to be high at the root transition region for the 9-m blade. Chen et al. [7] reports that the root transition was the main failure mechanism region of the 52.3-m blade collapse. The failure region for the blade with defect differs considerably from the blade model without defect as the laminate failure region before collapse is concentrated in defect region as shown in Figure 6 (b).

![Figure 5. Load displacement curves of the blade using progressive damage model (Puck) under extreme flap-wise (min) loading.](image)

![Figure 6. Element failure pattern in the pressure side, spar, internal flange and suction side of the blade (a) without defect (from top to bottom in a row) at 85% of extreme flap-wise (min) loading, (b) with defect (from top to bottom in a row) at 69% of extreme flap-wise (min) loading.](image)
3.2. Fatigue strength analysis

Under fatigue flap-wise (min) loading, average axial stress distribution of the RUZGEM blade without and with defect is depicted in Figure 7 (a) and (b), respectively. Suction side and pressure side are the blade components with the highest stress levels. As seen from the figures, suction side is subjected to tension stresses, whereas pressure side is under compressive stresses. On the suction side, stress concentration location is observed between the spar caps near the maximum chord. This variation of the stress concentration shows similarity with the stress distribution of the 33.25-m blade studied by Montesano et al. [12]. When the stress levels of the blade without defect is compared with the original blade, approximately 16% average compressive axial stress increase is noted in the vicinity of the debonding defect as seen in Figure 7. The increase in the stress level is caused by the local buckling observed at the debonding defect region. In addition, in the model with defect a slight average tensile axial stress increase is observed.

As explained in the methods section, fatigue analysis is conducted according to Germanischer Loyd (GL) 2010 Guidelines [15]. Since the pressure side, the suction side and the spar are the primarily damaged blade components, fatigue analysis results are presented for three components. Fatigue damage locations and the corresponding permissible number of cycles (Nf) are shown for the blade without defect and with defect in Figure 8 and Figure 9, respectively. In Figure 8, the first 60-100 elements with the lowest number of permissible fatigue cycles are marked in black and considered to be damaged due to fatigue. For comparison, in Figure 9, the elements which fall into the same range of permissible cycles are marked in black, as well. Due to flap-wise (min) loading, suction side is loaded under compression-compression cyclic loads. Since the compressive strength of the blade is less than its tensile stress a smaller number of permissible fatigue cycles are found for the pressure side of the blade compared to suction side. The result that compressive loads demonstrated larger fatigue damage than tensile fatigue loads was also reported by Lin et al. [14]. In Figure 8, for the blade without defect, fatigue damage in the pressure side is located at the pressure side along the spar width near maximum chord. Fatigue damage location of the suction side is between the spar webs towards the mid span and accumulates at the ply drop. In Figure 9, for the blade with defect, fatigue damage in the pressure side is located in the vicinity of the debonding defect. Moreover, it is observed that there is a significant increase in the number of damaged elements in the pressure side and spar of the blade compared to model without defect. Similar to the blade without defect, in for the blade with defect fatigue damage location of the suction side is between the spar webs towards the mid-span and accumulates at the ply drop and compared to the original blade a slight increase in the number of damage elements is seen. For the blade with defect, a significant decrease in blade fatigue life of approximately 1.56E+09 cycles are observed.

According to Spera [24] under stochastic loading wind turbine blades undergo up between 10^8-10^9 million load cycles during their service life. Wingerde et al. [26] states that under constant amplitude bending moment fatigue tests for wind turbine blades are conducted for 1-5 million. As the fatigue simulations are performed under constant amplitude bending moment, results show that RUZGEM blade without damage satisfies the desired number of load cycles and is not critical in terms of fatigue strength.

![Figure 7](image_url)  
Figure 7. Average axial stress in the pressure side, internal flange, spar and suction side (from top to bottom in a row) of the blade (a) without defect (b) with defect under fatigue flap-wise (min) loading.
4. Conclusions

In this study, static and fatigue strength analysis of the existing 5-m RUZGEM composite wind turbine blade with and without defect is conducted. The main conclusions are as follows:

• Under extreme flap-wise (min) loading, the blade without defect collapses after 85% loading at the root transition region. When the debonding defect is introduced at the pressure side-spar interface, blade collapses after 69% loading and the laminate failure region changes to the defect region, where debonding is modeled.

• The fatigue analysis results show that the blade without defect satisfies the desired number of load cycles and is not critical in terms of fatigue strength. In the blade FE model with defect, stress redistribution due to the debonding defect is investigated and the debonding crack growth is not simulated. Local buckling in the vicinity of the defect leads to a stress redistribution and an increase of 16% in the average stress level, which further causes a drop in the fatigue life of the blade by approximately 1.56E+09 load cycles.

• As the compressive strength of the blade is less than its tensile stress, compared to the suction side a smaller number of permissible fatigue cycles for the pressure side of the blade are determined.

As a future study it may be useful to investigate the effect of defects by analyzing the blade on ply level using more advanced fatigue analysis models, such as physically based phenomenological fatigue damage model as explained in [27].

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