Interactive comment on “Virtual full-scale testing for investigating strength characteristics of a composite wind turbine blade” by Can Muyan and Demirkan Coker

Anonymous Referee #2
Received and published: 12 May 2020

The authors would like thank the Referee for the valuable comments and detailed remarks regarding the numerical aspects in the manuscript. We believe that in light of the Referee comments our manuscript will become a more accurate and clear study with a greater impact. The comments are individually addressed below, with the Referee’s comments written in red and our response in black.

In the paper, the authors investigate the static strength behavior of a 5 m wind turbine blade by means of finite element simulations. For this purpose, they utilize the well-known Puck failure criteria for the composite parts, both in a linear formulation and a non-linear degradation version. The linear version simply evaluates the strength criteria without stiffness degradation. The non-linear degradation version reduces the material stiffness in each ply whenever the Puck criteria are fulfilled and identifies laminate failure when three plies are failed. The authors analyze static extreme loads in flapwise, edgewise, and combined flap/edgewise directions and compare the results. The topic of full-scale failure analysis of wind turbine rotor blades is generally interesting and important for the wind energy research community. However, the manuscript does not represent a substantial, but rather a minor contribution to scientific progress within the scope of WES. The scientific approach and the applied methods are generally valid, but have weaknesses. At this point, the reviewer refers exemplarily to the incomplete iteration in the degradation model and the missing mesh convergence study (see below). The work is not reproducible, as there is no blade data available. The work can neither be repeated nor be verified by other scientists. The discussion of results is in parts not comprehensible, and does not include enough findings of other authors. The presentation quality is good in general. The text needs some revision due to typos and other minor language errors (that are too numerous to list).

Thank you for the general assessment in this comment regarding the manuscript.

First, we would like to emphasize the importance of the paper for the wind energy community as following:

According to the best knowledge of authors, this paper is the first one in literature concerning the FE Analysis of an existing small scale 5-m blade. It includes an in-depth detailed study of the potential composite failure patterns until collapse load using progressive Puck failure criteria which will be compared with tests that is planned to be conducted as a follow-up of this manuscript in the future.

Next, we would like to address here some of the general comments as follows which will be incorporated in the final revised version of the manuscript:

1. Geometry and material lay-up of the existing 5-meter METUWIND Blade will be shared with the community and will be included in the revised version.

2. Results and discussions will be presented in a more comprehensible and coherent style in the revised version. In some cases, the discussion of the results were already updated in AC1 and in AC2 as our response to RC1.

3. The literature will be extended to include the work and findings of other authors that was missed in our original manuscript and which will be added to the discussion of our results. Below is a list of the additional references that is added to the revised manuscript:

1. Paquette, J. A., & Veers, P. S. (2007). *Increased Strength in Wind Turbine Blades through Innovative Structural Design* (No. SAND2007-2632C). Sandia National Lab.(SNL-NM), Albuquerque, NM (United States).

2. Chen, X., Berring, P., Madsen, S. H., Branner, K., & Semenov, S. (2019). Understanding progressive failure mechanisms of a wind turbine blade trailing edge section through subcomponent tests and nonlinear FE analysis. *Composite Structures*, *214*, 422-438.

3. Chen, X., Qin, Z., Yang, K., Zhao, X., & Xu, J. (2015). Numerical analysis and experimental investigation of wind turbine blades with innovative features: Structural response and characteristics. *Science China Technological Sciences*, *58*(1), 1-8.

4. Chen, X., Zhao, W., Zhao, X. L., & Xu, J. Z. (2014). Failure test and finite element simulation of a large wind turbine composite blade under static loading. *Energies*, *7*(4), 2274-2297.

5. Fagan, E. M., Flanagan, M., Leen, S. B., Flanagan, T., Doyle, A., & Goggins, J. (2017). Physical experimental static testing and structural design optimisation for a composite wind turbine blade. *Composite Structures*, *164*, 90-103.

6. Kim, S. H., Bang, H. J., Shin, H. K., & Jang, M. S. (2014). Composite structural analysis of flat-back shaped blade for multi-MW class wind turbine. *Applied Composite Materials*, *21*(3), 525-539.

7. Montesano, J., Chu, H., & Singh, C. V. (2016). Development of a physics-based multi-scale progressive damage model for assessing the durability of wind turbine blades. *Composite Structures*, *141*, 50-62.

8. Overgaard, L. C., Lund, E., & Thomsen, O. T. (2010). Structural collapse of a wind turbine blade. Part A: Static test and equivalent single layered models. *Composites Part A: Applied Science and Manufacturing*, *41*(2), 257-270.

9. Sørensen, B. F., Jørgensen, E., Debel, C. P., Jensen, H. M., Jacobsen, T. K., & Halling, K. (2004). Improved design of large wind turbine blade of fibre composites based on studies of scale effects (Phase 1). Summary Report.

10. Yang, J., Peng, C., Xiao, J., Zeng, J., Xing, S., Jin, J., & Deng, H. (2013). Structural investigation of composite wind turbine blade considering structural collapse in full-scale static tests. *Composite Structures*, *97*, 15-29.

11. Zuo, Y., Montesano, J., & Singh, C. V. (2018). Assessing progressive failure in long wind turbine blades under quasi-static and cyclic loads. *Renewable Energy*, *119*, 754-766.

4. In the following you may find the italic text, which will be added to the manuscript concerning the findings of other authors. This text will be further extended in the revised version of the manuscript:

Manuscript Line 344-346. Element failure in the trailing edge begins at 110% loading. Similar to the pure flap-wise loading, number of failed elements increase in the trailing edge towards the spar and root as the load is further increased. *"In their study regarding the full-scale testing of a 34-m wind turbine blade, under combined loading Haselbach and Branner (2016) also observed laminate failure along the trailing edge."*

Manuscript Line 256-259. It is worth noting that, IFF(A) and IFF(B) do not lead to the element failure. When IFF(A) or IFF(B) occur, only the transverse, shear moduli and Poisson's ratio are reduced according the degradation rules.

Manuscript Line 279-280. We note FF and IFF(C) initiate in the same location as IFF(A) and/or IFF(B). *"Similar to our findings in Singh (2016)'s study IFF(A) and IFF(B) can be regarded as subcritical ply cracks which are precursor to more critical damage modes such as delamination. Since delamination was modeled within the scope of this study, IFF(C), which is a dangerous failure mode indicating delamination and FF are the critical failure modes which lead to element failure in this study."*

Manuscript Section 3.1 (See Author Comment 2 (Response 8))

At 180% load level trailing edge and the internal flange which is used to bond the pressure and suction sides of the blade are already damaged. As a consequence, towards the blade tip the pressure and suction sides of the blade are detached at this load level. Under these circumstances blade tip structure is weaker and can be damaged more easily. *"Likewise, debonding of suction and pressure sides from the adhesive joints was reported as the main failure mechanism causing a progressive collapse of the blade structure in Yang, Peng, Xiao, Zengi Xing, Jin and Deng (2013)."*

Manuscript Section 3 discussion

"Laminate progression observed under flap-wise, edgewise and combined loading conditions fall into type 4 and type 5 wind blade damages as catagorized in Sorensen et al. (2014)."

In the following, the reviewer lists specific points of criticism that need to be addressed thoroughly in a potential revised version of the manuscript.

- The paper is an application paper rather than a research paper, as the utilized failure models are mainly already published elsewhere. The paper thus lacks novelty in the methodology development. The results are the novel content, but the basis for them, the blade design, is not publicly available due to confidentiality reasons. The added value of the paper for the research community is thus very limited. The fact that the results are neither reproducible nor verifiable is a strong weakness of the paper. A further weakness is the short length of the blade under investigation, which is not representative for modern wind turbines.

Response:

In order to make the results reproducible for other researchers in the community, we will provide material lay-up and geometry in the revised manuscript and supplement. As RÜZGEM (METU Center for Wind Energy) is a partner research institute of EAWE, our policy is to collaborate and share information with researchers in wind energy.

The short length of the blade is attributed to the fact that the blade is constructed mainly for research purposes. Our primary goal is to investigate strength characteristics and failure mechanisms of the 5-meter blade using in-house developed software tools. Furthermore, building of affordable testing facilities are planned so that full-scale blade tests can be conducted and compared with simulations. We would like to point out that research wind turbine blades used by Paquette and Veers (2007) and Chen, Qin, Yang, Zhao and Xu (2014) were also short and only 9-meters and 10.3-meters respectively. Once the simulation results are compared with tests to be conducted in the future and the degree of agreement is assessed, we will be extending our study to the progressive failure analysis of large blades.

- Lines 16-17: The damage evolution is not necessarily linked to stiffness, as it is about stress and strength. It is easily possible to design stiff blades without damage, especially in the small size of the blade studied in this paper. The explanation via stiffness appears repeatedly throughout the text and should be discussed in more detail – or changed by more comprehensible argumentations.

-Section 3.4: The reviewer does not understand why the combined loading is not the most severe one, as it should kind of add up the damage of flapwise and edgewise loading, especially in the linear part of Fig. 24. That holds for the entire section. The explanations have to be improved. Figure 11: The quality of the text in the figure should be improved.

- Conclusions, point 2.: Please add comprehensible explanations for the findings. Otherwise, there is not added value for the research community.

Response:

We agree with the referee comments on the nature of the argument using stiffness and the stiffness argument is removed from the text. More comprehensible explanations in results and discussion section will be provided as explained below:
In combined loading due to the superposition of the loads 'stress state' inside the blade changes. Under pure edgewise loading the leading edge of the blade is subjected to compressive stresses, whereas flap-wise loading induces mainly tensile stresses in this area. In combined loading due to the effect of compressive stresses caused by edgewise loading, tensile stresses caused by flap-wise loading are reduced compared to the stress state in pure flap-wise loading case. This situation leads

to less element failure as depicted in Figure R 1. Figure R 1 shows the evolution of stress exposures IFF(C), FF in the blade at 100% pure flap-wise and combined loading stress states. As seen from the figure, for combined loading failed regions observed in the internal flange are less compared to pure flap-wise loading.

Please note that Figure R **1** is prepared after running the updated FE Model (See Author Comment 2 response 8).

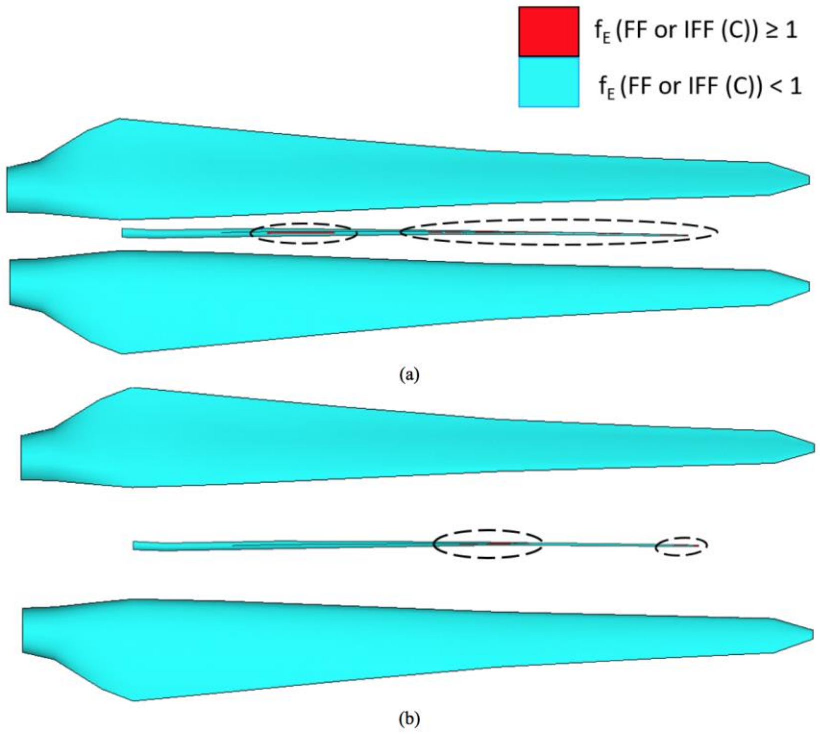


Figure R 1. Failure evolution in the pressure side, internal flange and suction side of the blade (from top to bottom in a row) at 100 % (a) pure flap-wise (b) combined edgewise and flap-wise loading.

- Equations (3) and (4): There are three equations, but only two numbers.

Response:

Thank you for noticing the error. The equations are renumbered as follows:

$$R^A_{\perp\perp} = \frac{S}{2p^{(-)}_{\perp\parallel}}\left[\sqrt{1 + 2p^{(-)}_{\perp\parallel}\frac{Y_c}{S}} - 1\right] \tag{3}$$

$$\tau_{21_c} = R_{\perp\parallel}\sqrt{1 + 2p^{(-)}_{\perp\perp}} \tag{4}$$

$$\text{and } p^{(-)}_{\perp\perp} = p^{(-)}_{\perp\parallel}\frac{R^A_{\perp\perp}}{S} \tag{5}$$

- Line 125 ff.: Why is the degradation model formulated in such a way, that the element fails in case that 3 plies fail? Why 3 plies? That sounds unphysical to the reviewer. Wouldn't a relative number with respect to the overall number of plies be more meaningful? As after the modification of the stiffnesses the load is incremented, the authors do not perform a full iteration for the material degradation in each load step, which also seems unphysical or illogical from a numerical point of view. The authors should explain in more detail why the degradation model is formulated in this form.

Response:

In Passipoularidis, Philippidis and Brondsted (2016) (https://doi.org/10.1016/j.ijfatigue.2010.07.011). laminate failure takes place when IFF(C) is seen in all plies of laminate. Since IFF(C) is an explosive failure mode which indicates high risk of delamination, we wanted to implement a more conservative degradation scheme. As depicted in Figure R 2 our damage model delivers good agreement with experimental results. We agree with the Referee that a relative number with respect to overall number of plies would be more reasonable and we will modify our ANSYS APDL code accordingly. However, for our problem case, the laminate damage initiation and propagation begin at the leading edge and trailing edges where we have 9 plies. We have chosen the degradation scheme “if IFF(C) is observed in three plies or more element failure takes place” for these laminates. Regions with a greater number of plies are not damaged primarily. Therefore, we do not expect to significantly change our results.

Regarding carrying out iterations at each load steps, we have followed the flow chart of the program Subu in the book by Knops (2008) (ISBN 978-3-540-75765-8). According to the algorithm presented in the book, degradation is done per load step. In the revised version of the manuscript we will present our results with increased number of load steps, i.e. min 50 – 100 steps per load case as recommended in Knops (2008).

- Figure 4: The reviewer suggests to change the line formats in order to highlight the own results: Black dots for experiments, red line with dots for the simulation.

Response:

Fig.4 in the manuscript is changed according to the Referee’s suggestion.

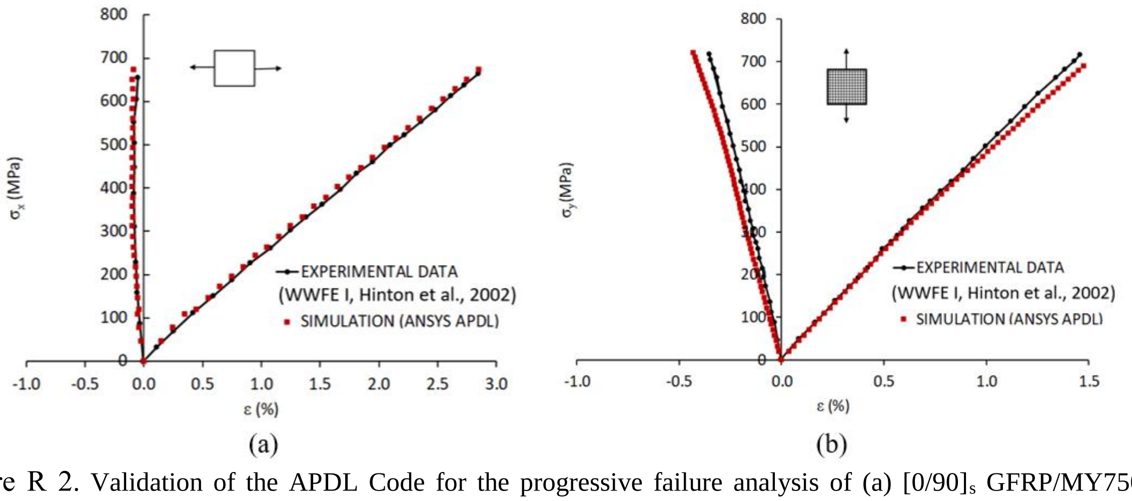


Figure R 2. Validation of the APDL Code for the progressive failure analysis of (a) $[0/90]_s$ GFRP/MY750 laminate under σ_x uniaxial tension (b) $[0/\pm45/90]_s$ CFRP/AS4 3501-6 laminate under σ_y uniaxial tension. (This figure updates Figure 4 in the original manuscript).

- Line 161 ff.: The argumentation on the finite element mesh is weak from a scientific point of view. The mesh is actually quite coarse in some regions of the blade, which should be avoided. The reviewer recommends to perform a mesh convergence study, which should generally be done for finite element simulations, especially in science. The simulation time of 4 hours is nothing spectacular from the reviewer’s point of view, so there is definitely room for further mesh refinement.

Response:

New runs with a finer and corrected mesh was carried out in response to RC1 (See AC2) in which the new mesh is seen in Figure R 3. In addition, a mesh convergence study was carried out based on this final FE model as depicted in Figure R 4 which will be added to the revised manuscript. Mesh convergence is shown for total displacement at blade tip under extreme flap-wise loading and first eigenfrequency as seen in Figure R 4 (a) and (b) respectively. Current model (See Author Comment 2) contains a total number of 61104 elements with an element size 20x20 mm. This element size correlates to the number of elements used in the FE Modeling of small scale wind turbine blades in the literature. For a good compromise between accuracy and computation time in the revised manuscript version simulations with 101970 elements with an element size 15x15 mm will be presented.

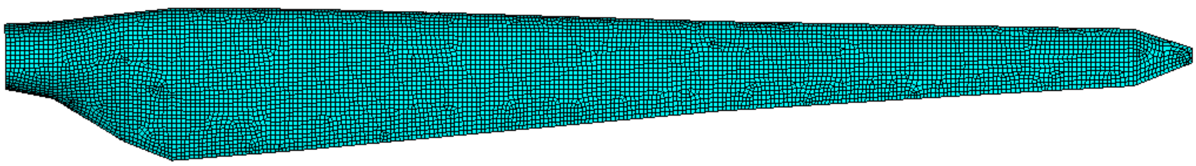
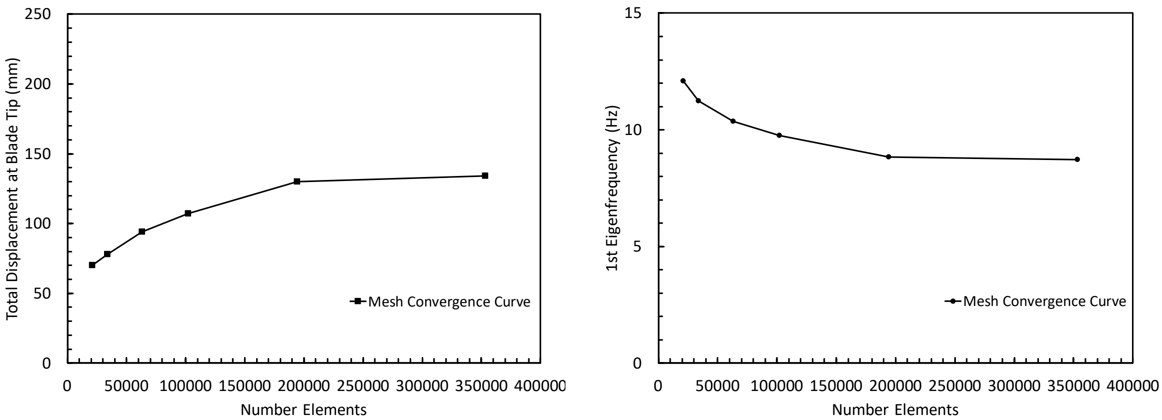


Figure R 3. Mesh density used for the METUWIND Blade FE Model.



(a) (b)

Figure R 4. Mesh convergence study using (a) total number of elements vs total displacement at blade tip (b) total number of elements vs 1. Eigenfrequency.

- Line 168: What is the reason for the limitation of the simulations to geometric linearity?

Response

We decided not to use the nonlinear geometry option in ANSYS, because under 100% flapwise, edgewise and combined loading conditions the total displacement of the blade is relatively small compared to the total blade length. Furthermore, as we are simulating full-scale testing until blade collapses, we wanted to avoid convergence problems at higher load levels and excessive computation time.

- Figure 5: The mesh looks weird in some regions. At the trailing edge, there are strange curves in the first element edges. One is well recognizable at the bottom of Fig. 5 (b). What is the reason for those?

Response:

We agree with the referee's observations. Mesh refinement was made and the mesh quality is improved. Please refer to Author Comment (AC) 2, response number 8 and figure R 3.

- Figures 6-7: What is the coordinate system underlying the moment and force directions? Are the moments extreme for all positions, or just one position along the blade? Is it a mixture of different DLCs and time instances? Which DLC is the basis for the extreme loads?

Response:

This question will be answered by referring to the Loads Report prepared by SMART BLADES GmbH (Weinzierl and Pechlivanoglou, 2013). The forces and moments are given in the blade pitch coordinate system according to GL Guidelines 2010.

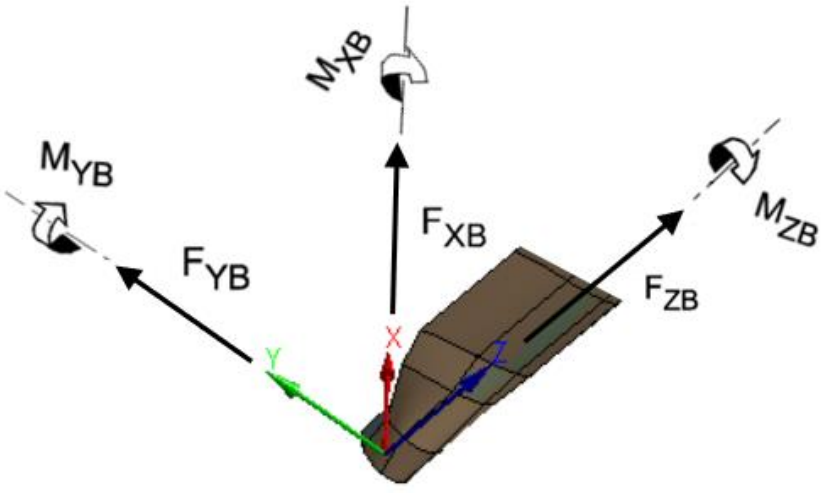


Figure R 5. Blade pitch coordinate system.

Moments are extreme for all positions along the blade. Mixture of extreme load cases and time instances used in the study are listed below in Table R 1:

Table R 1. List of extreme load cases used.

LC_{index}	File name of load case
1	DLC5.1_EWM50_59.50ms_180.0degYAW_0.00degV_final_Trf.out
2	DLC5.1_EWM50_59.50ms_0.0degYAW_-8.00degV_final_Trf.out
3	DLC2.3_EOG1_19.00ms_8.00degH_-8.00degV_Trf.out
4	DLC5.1_EWM50_59.50ms_-135.0degYAW_0.00degV_final_Trf.out
5	DLC2.1_NWP_21.25ms_8.0degV_-45.0degYAW_120.0rpm_final_Trf.out
6	DLC1.2_ECD_11.00ms_0.00degH_-8.00degV_pos_final_Trf.out
7	DLC1.2_ECD_14.00ms_0.00degH_8.00degV_neg_final_Trf.out
8	DLC2.3_EOG1_3.00ms_-8.00degH_-8.00degV_Trf.out
9	DLC2.3_EOG1_3.00ms_-8.00degH_8.00degV_Trf.out
10	DLC2.3_EOG1_5.00ms_-8.00degH_-8.00degV_Trf.out
11	DLC1.4_EDC50_13.00ms_8.00degH_0.00degV_pos_final_Trf.out
12	DLC1.2_ECD_7.00ms_8.00degH_-8.00degV_neg_final_Trf.out
13	DLC2.3_EOG1_3.00ms_8.00degH_8.00degV_Trf.out
14	DLC5.1_EWM50_59.50ms_180.0degYAW_-8.00degV_final_Trf.out
15	DLC1.3_EOG50_3.00ms_-8.00degH_0.00degV_final_Trf.out
16	DLC1.4_EDC50_21.00ms_0.00degH_-8.00degV_neg_final_Trf.out
17	DLC2.1_NWP_21.25ms_0.0degV_180.0degYAW_120.0rpm_final_Trf.out
18	DLC2.3_EOG1_11.00ms_-8.00degH_8.00degV_Trf.out
19	DLC1.2_ECD_13.00ms_0.00degH_0.00degV_pos_final_Trf.out
20	DLC1.4_EDC50_9.00ms_0.00degH_0.00degV_neg_final_Trf.out
21	DLC1.4_EDC50_21.00ms_-8.00degH_-8.00degV_neg_final_Trf.out
22	DLC2.3_EOG1_19.00ms_8.00degH_8.00degV_Trf.out
23	DLC1.2_ECD_14.00ms_0.00degH_0.00degV_neg_final_Trf.out
24	DLC2.1_NWP_21.25ms_0.0degV_-45.0degYAW_120.0rpm_final_Trf.out
25	DLC2.1_NWP_21.25ms_8.0degV_-135.0degYAW_120.0rpm_final_Trf.out
26	DLC2.3_EOG1_7.00ms_-8.00degH_0.00degV_Trf.out
27	DLC1.2_ECD_11.00ms_-8.00degH_-8.00degV_neg_final_Trf.out
28	DLC1.2_ECD_9.00ms_8.00degH_8.00degV_neg_final_Trf.out
29	DLC2.3_EOG1_19.00ms_8.00degH_0.00degV_Trf.out
30	DLC2.3_EOG1_19.00ms_0.00degH_0.00degV_Trf.out
31	DLC1.2_ECD_14.00ms_-8.00degH_8.00degV_neg_final_Trf.out

- Figures 8-9: The load introduction is strange. Why didn't the authors use contact elements (MPCs), which is the standard way for distributed load introduction in 3D structures in ANSYS? The way the authors realize the load introduction may lead to spurious and erroneous local deformations. Please comment on that.

Response:

Our load introduction approach, where the load is distributed along spar width at suction and pressure side and the approach proposed by the Referee are both available in literature. When the short dimensions of the blade are considered, we do not believe that changing our load introduction methodology to MPC will significantly affect our results.

- Figures 10, 20, 24-26: Which load and deflection components are plotted? Which direction of load and deflection? Total load vs. total displacement? Which point exactly is traced in the deflection? It is just stated "a point close to the tip", which is imprecise.

Response:

Please note the following explanations for the figures:

Figure 10:
Total Flap-wise loading component, total deflection in flap-wise direction

Figure 20:
Total resultant combined (Flap-wise+Edgewise) loading component, total deflection

Figure 24:
Total Flap-wise loading component, total deflection in flap-wise direction
Total Edge-wise loading component, total deflection in edgewise direction
Total resultant combined (Flap-wise+Edgewise) loading component, total deflection

Figure 25:
Total Flap-wise loading component, total deflection in flap-wise direction
Total resultant combined (Flap-wise+Edgewise) loading component, deflection component in flap-wise direction

Figure 26:
Total Edge-wise loading component, total deflection in edgewise direction
Total resultant combined (Flap-wise+Edgewise) loading component, deflection component in edgewise direction

The exact location and coordinates of the deflection measurement point close to blade tip is highlighted in green in Figure R 6. Point coordinates are x= 38.493 y=4750. z-31.51 with respect to the coordinate system located at blade root.

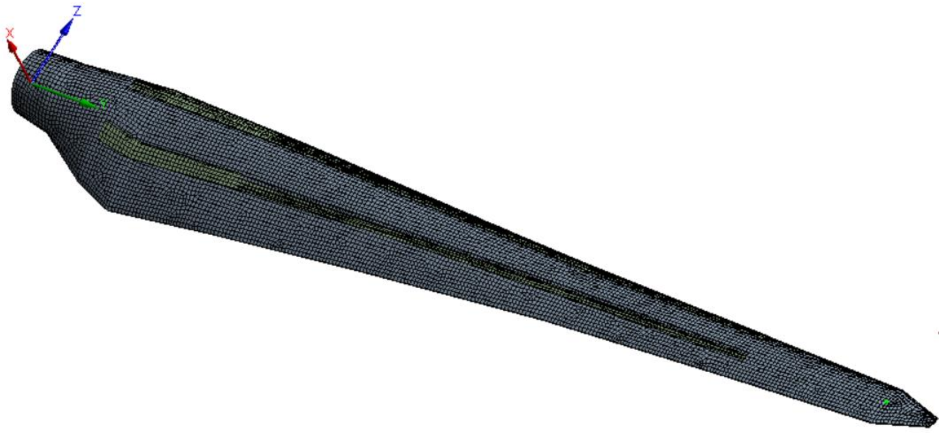


Figure R 6. Location of the deflection measurement point.

- Figure 11: The quality of the text in the figure should be improved.

Response:

As suggested by the Referee, the quality of the Figure text is improved and will be used in the revised version.

- Section 3 in general: The explanations of the results should be more precise. Why is the damage development as it is?

Response

Detailed and precise explanation was done in Authors Comment (AC) 2 response number 8 for extreme flap-wise loading. Similar explanations will be done for edgewise and combined loading conditions in the revised manuscript.

- Line 410: The authors state that the simulations have been carried out "before testing". Are tests planned? If so, it will be interesting to see if the simulations match well with the test.

Response:

In the first part of our project, progressive failure analysis of the existing 5-meter METUWIND blade is carried out as presented in this manuscript. In the second part of our research project, tests for the existing blade seen in Figure R 7 will be conducted following the completion of the test fixture. Afterwards, simulation results from this manuscript will be compared with tests.

Figure R 7. Picture of the 5-meter METUWIND Blade.

- Conclusions, point 3.: This finding is natural, as the fibers have the job to carry stresses and to provide stiffness. The stiffness contribution of the matrix is very limited
– that's the nature of fiber composites.

Response:

We agree with the Referee, and the Conclusion, point 3 will be reworded in the revised version of the manuscript.

- Conclusions, point 5.: How are the authors intending to increase the moment of inertia? By additional material or modifications in geometry?

- Conclusions, point 6.: The authors did not study the adhesives. How do they come to the conclusion that the main failure mechanism is expected to be linked to the adhesive joints?

Response:

Conclusions, point 5 and Conclusions, point 6 will be deleted in the revised version of the manuscript.

- There are numerous language errors. No severe errors that make the paper unreadable, but the entire text needs revision.

<u>Response:</u>

We have corrected numerous language errors in the revised version of the original manuscript (See Author Comment AC1 on WES Discussion page):

https://www.wind-energ-sci-discuss.net/wes-2020-44/wes-2020-44-AC1-supplement.pdf

We will correct language and typo errors in the revised version.

- The reviewer highly recommends to make the blade data publicly available (including geometry and material layup), and also potential test results in the future. Otherwise, the value of the manuscript is, if present, very limited.

<u>Response:</u>

As mentioned in Response to Comment 1 CAD data of the blade components, i.e. suction side, pressure side, internal flange and 'hat shaped' spar will be provided. Moreover, lamination plan of the blade suction side, pressure side, internal flange and 'hat shaped' spar will be shared.