Non-proportionality analysis of multiaxial fatigue stress histories in trailing edge adhesive joints of wind turbine rotor blades

RESPONSE TO REVIEW

Dear Madam or Sir,

We would like to thank the reviewers and editors for the professional, detailed and yet fast review of our manuscript. We are very grateful for your work and the consideration of our manuscript for the Wind Energy Science journal. Besides generally revising the text to eliminate language errors and typos, we thoroughly addressed the comments raised by the reviewers and hope for the reviewers' approval.

Thank you again to the reviewers, as your comments helped to significantly improve the manuscript and to better present its content. We prepared responses to each of your concerns in the supplementary file and look forward to the upcoming steps.

The Authors:
Claudio Balzani
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1 Reviewer #3 / Report #1

Comment #1:

"For final publication, the manuscript should be accepted as is."

> **Response:** Thank you very much for accepting the manuscript.

2 Reviewer #5 / Report #2

General Remarks

"Reliable fatigue design tools are essential for blade design engineers. Generally, physically-based and validated analytical models are preferred over computationallyinefficient models.

In this manuscript, the authors present the derivation of a non-proportionality (NP) factor that indicates the degree of NP in stress histories, meaning the extent to whichstress components are out of phase. They claim that global criteria, such as Beltrami, do not conservatively capture stress exposure when the NP is high, i.e., highly outof phase. To this end, they analyzed the NP along the trailing-edge adhesive joint of two theoretical blade models and one actual built model. They conclude that, undercertain wind speeds, the NP can be significant at specific span-wise positions along the blade. The designer should decide based on the NP whether to use a globalcriterion or a critical plane approach to evaluate fatigue stress exposure.

In the present state the manuscript highlights that there may be an issue when global criteria are used but unfortunately does not prove it, i.e., by demonstrating the impact of NP on damage.

According to the comments listed below, I need to suggest a major revision of the manuscript."

> **Response:** Thank you very much for reviewing the manuscript.
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> To our understanding, the potential non-conservativeness was proven elsewhere (Michael Kuhn et al.: Effects of non-proportionality and tension–compression asymmetry on the fatigue life prediction of equivalent stress criteria, Fatigue & Fracture of Engineering Materials & Structures 46:3161-3178, 2023, https://doi.org/10.1111/ffe.14065). The aforementioned reference was already referred to when pointing this out in the manuscript. However, we added fatigue analyses with a global equivalent stress and a critical plane approach. The applied criteria are simple, but provide good comparability. With these criteria, the global equivalent stress calculation is conservative (but maybe over-conservative), while the critical plane approach seems to be more accurate. However, this result strongly depends on the used criteria, and for other criteria, the claim that global criteria can be non-conservative remains valid. It was proven experimentally, and there is no need to prove it again. Hence, the potential non-conservativeness of global criteria is left in the text with the respective reference.We kindly ask for your agreement.
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> Please find below our response to your further major comments.

Comment MAC.01:

"In order to significantly strengthen the manuscript, I strongly recommend proving the impact of the NP on the damage criterion. This could be achieved by conducting a relative comparison of NP hot spots in the blade models using a global criterion, such as Beltrami, alongside a critical plane criterion that accounts for NP. This would address the most important aspect of your study: whether it has been demonstrated that there is an issue when global criteria are employed without considering NPs in blades. Otherwise, your study appears incomplete, like a cliffhanger, and the reader cannot resolve this independently.Please add the missing calculations to substantially increase the relevance of your study."

> **Response:** We added a comparative fatigue analysis as requested by the reviewer. The Rankine global equivalent stress approach was used for simplicity. The shear stresses in the critical plane approach were neglected to provide clear comparability between the two models.
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> The approaches are described in section 2.4. The results are presented in section 3.4. The results are discussed in section 4. The abstract and other text components have been adapted to the additional content. The highlighted changes can be found in the enclosed LaTeXDiff document.
>
> The criteria applied here do not resemble an issue with non-conservativeness of global equivalent stress criteria. Actually, the global approach in the manuscript appears to be conservative. However, that finding strongly depends on the criteria used. In literature, it was proven that under certain circumstances, there can be an issue with non-conservativeness (see explanations and the reference above) that every user should be aware of. That is the reason why we left this link in the manuscript. It is now included in the discussion in section 4.
>
> At the current stage, a final conclusion on when to use global criteria and when one needs to use a critical plane approach is not possible. Further research is needed in this field. However, the non-proportionality factor could be a useful tool for choosing an appropriate fatigue analysis framework. However, further work on this is reserved for future research.
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> We hope that this sufficiently addresses your comment and kindly ask for your agreement.

Comment MAC.02:

"(Results) You present the NP factor results for the range of r/R = 0.45 to 0.9. However, some interesting areas of the blades were not analyzed, specifically those where high crack densities have been observed in the adhesive in commercial blades in the field (r/R = 0.2 to 0.65) [1] and during full-scale type certification testing (r/R= 0.25 to 0.5) [2]. These areas also include the positions of the largest fatigue stress exposure calculated for a commercial blade design at r/R = 0.35 [3]. Please extend the analysis to include these areas to enhance the representativity of your study."

> **Response:** We agree that transverse cracks normally occur in the vicinity of the maximum chord region. However, there are reasons that the maximum chord regaion was not modelled in this study:
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> - Adhesive joints were not designed in the DTU and the IWES blade. Hence, we tried to model an adhesive joint to the best of our knowledge and belief, but did not re-design the blade structure for fatigue damage in the adhesive. The absolute results of the stress time series in the adhesive are thus not necessarily representative for a commercial blade or a real built blade, as they suffer from an excessive axial normal stress. This excessive normal stress also leads to a reduction of the non-proportionality content in the stress time series. Hence, thoroughly re-designing the blades would result in an increase of non-proportionality and with that to an increase of the risk of unconservativeness of the global approach. However, re-designing the blades is beyond the scope of the manuscript.

- The IWES blade is composed of flatbacks in the transition from normal airfoils to the root section (i.e., in the max chord region). There is no adhesive joint concept specified for that particular blade in the flatback region that could have been modelled for this analysis. Hence, this region was omitted.
- In the SB2-DemoBlade, there were details in the structural design of the trailing edge adhesive joint in the maximum chord region (e.g., balsa wook inserts to limit the adhesive thickness and width) that could not be modelled with the blade modling tool used for this study. Hence, this region wasomitted in the analysis.

Althoug it would be interesting to look into the blades in these regions more thoroughly, the effort to model the blades accurately in the maximum chord region does not seem to be justified for this very first analysis of non-proportionality in trailing edge adhesive joints. Further studies are thus reserved for future investigations.

We added a paragraph at the end of section 2. to make clear why the longitudinal range was limited. The new paragraph reads:

> *"Although transverse fatigue cracks in the trailing edge adhesive normally occurs in the vicinity of the maximum chord length, see section 1.3, the outboard region was primarily selected to provide comparability between the different blades. Moreover,there were structural details in the maximum chord region of the SB2-DemoBlade, such as balsa wood inlays to limit the adhesive thickness, that were not possible to model with the finite element model generator without excessive effort that was considered unjustified."*

We hope that this sufficiently addresses your comment.

Comment MAC.03:

"(Methods) Assuming that you extract the stresses at or close to a corner of the inner adhesive edge, the concave shape of the inner adhesive contour (Fig. 7) seems unrealistic compared to what we observe in the field. As the trailing-edge bond-line is glued blindly, for example, for r/R > 0.37, the adhesive either gets squeezed inside the blade, forming a convex shape [5], or takes on an elliptical "clip" shape for the inner contour. The shape, particularly the fillet angle, can significantly impact the corner stress exposure and the signs of different stress components, as noted in [5]. From Fig. 7, it appears that the fillet angle varies from blade to blade and may also differ from radius to radius.Please use a representative shape along the span and ensure that the fillet angle is consistent across the blades, so that the results are not biased by this variable."

Response: The shape of the adhesive on the interior side can be influenced by including some foam inserts during manufacturing that serve to avoid squeeze-out into the blade. Doing so, the adhesive can also have a concave shape at locations, where the adhesive cannot be postprocessed due to limited availability. It is of course true that manufacturers avoid the additional effort and accept squeeze-out, but it is generally possible, and we have already seen such manufacturing in real blades.

The first row of elements was omitted in the analysis of non-proportionality and fatigue. The stress singularity in the corner, which can be affected by the adhesive shape on the interior side, e.g., by the fillet angle, is thus not included in the analysis, as the stress concentration quickly vanishes along a short geometrical distance. Analysis of the stress singularity is far beyond the scope of this paper. Hence, a more realistic modeling of the adhesive shape is irrelevant for this study.

However, we added the following paragraph to the discussion:

"The increase of $\bar{f}_{NP}$ towards the inner edge of the adhesive, see Figure 7, is caused by the increasing distance to theprinciple edgewise bending axis towards the trailing edge. Consequently, the longitudinal normal stress σ_z from edgewise bending increases towards the trailing edge, which is accompanyied by an increase of its dominance and hence a decrease of non-proportionality. The increase of $\bar{f}_{NP}$ towards the suction side is caused by flapwise bending. Hence, the longitudinal normal stress from flapwise bending increases towards the suction side, increasing the stress non-proportionality. The interior surface of the adhesive was modelled by a concave shape, which may seem unrealistic given what is seen in the field. The trailing edge adhesive joint is a blind bondline, especially in the outboard region of the blade. The adhesive thus becomes squeezed into the inside of the blade, forming a rather convex or clip shape at the interior surface. The corner stress in such configurations was studied in (Rosemeier, 2024). It was shown that the stress concentration due to the geometric singularity in the inner corners of the adhesive is more severe for convex and clip-like shapes. This gives rise to the implication that modeling the correct shape may be important. However, it was also shown that the stress concentration vanishes along a very short distance from the corner. Since the first element row was excluded in the fatigue damage calculation in this paper, which avoids issues with the corner stress concentration, the related effort to model more realistic interior geometric shapes was not justified. Besides, the interior shape of the adhesive can be influenced by applying foam strips during mould closure, which helps to avoid the squeeze-out into the inside of the blade, forming a concave shape, as was modelled here."

We kindly ask for your agreement.

Comment MAC.04:

"(F6) Why do you show the stress histories for all blades at r/R = 0.77 and not for a location with high NP or expected high stress exposure? Wouldn't this be more useful as you focus on NPs as a tool for conservative blade design?"

Response: The aim was to show an excerpt of the stress time series at a location with significant non-proportionality. That's why we chose the position at r/R=0.77, as this position actually shows significant non-proportionality, at least for the IWES and the SB2 demo blades, see Fig. 8. The non-proportionality level in the DTU blade is very low anyways. It was not necessary to pick another position for that blade from our point of view.

A comment was added in the first paragraph of section 3.2 to clarify the choice of radial position for stress time series correlation. The comment reads:

"The radial position was chosen to capture high non-proportionality factors in the IWES blade and the SB2-DemoBlade. The non-proportionality factor in the DTU blade is generally comparably small, and the hotspot is located close to the blade tip, which is a location that is not commonly prone to trailing edge fatigue damage. Hence, there was no need to pick a differentlocation for this blade."

We hope that this sufficiently addresses your comment and kindly ask for your agreement.

Comment MAC.05:

"The structure of the manuscript seems poorly organized. Please: a) Combine C2, C3, and C4 into one Methods chapter. b) Split C5 into one Results chapter (onlyfor results and observations) and one Discussion chapter (for interpretation of results). c) Move interpretations from the Conclusions into the Discussion chapter. d)Shorten the Conclusions to summarize only the most important points and what has already been addressed in previous chapters, and add future work. e) Shorten theIntroduction, as it seems overly lengthy like a review article; I suggest removing sub-chaptering and lengthy explanations, while referring to relevant aspects for thismanuscript. f) Remove repetitions and redundancies throughout the manuscript."

> **Response:** We organized the manuscript. Please find more details in the following.
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> a) We combined the sections 2, 3, and 4 into one Methods section as requested by the reviewer. The previous sections became subsections.
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> b) We splitted the previous section 5 (Results and discussion) into one Results section containing the descriptive part of the results and a discussion section for interpretation of results as requested by the reviewer.
>
> c) We moved interpretations from the Conclusions into the Discussion section as requested by the reviewer.
>
> d) We shortened the Conclusions to summarize only the most important points and what has already been addressed in previous sections and added future work, as requested by the reviewer.
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> e) Shortening the introduction was a good suggestion, as it is indeed a bit lengthy. However, the length of the introduction is a result of previous comments from reviewers who requested to include additional content (especially but not only the fatigue damage subsection) than was included in the original manuscript. Deleting the additional content would violate the previous reviews, which does not seem reasonable. We tried to modify the text here and there to improve conciseness, but could not substantially shorten it. The sub-sections seem useful to structure the introduction. As it is always difficult to handle contradicting reviewers' comments, we kindly ask for your agreement.
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> f) We tried to remove repetitions and redundancies throughout the manuscript as requested by the reviewer. The few remaining redundancies are necessary for a clear storytelling in our point of view.

Comment MAC.06:

"Revise lead-lag, as it is not equal to edge-wise, see [4]."

> **Response:** Lead-lag was replaced by edgewise throughout the manuscript.

Comment MIC.01:

"Check the overall English quality, preferably by a lecturer."

> **Response:** We checked the overall English quality. From our point of view, the manuscript is quite well written. The few potentially remaining language errors may be acceptable.

Comment MIC.02:

"Check the language for consistency, for example, ensure 'velocity' and 'speed' are used appropriately and consistently throughout the manuscript."

> **Response:** We checked the language for consistency and hope we did not miss any inconsistency.