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,

Thank you very much to all 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. Your valuable contributions helped to 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:
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1 Reviewer #1 (Alexander Krimmer)

General Remarks

"The manuscript presents a combined approach to determine the non-proportionality factor for fatigue loads in bond lines of wind turbine rotor blades. It thereby enables to account for both, deviatoric and hydro-static stress contributions. The method is compared to available approaches that are the basis for this combined method and shows very good results. Afterwards the method is applied to three different rotor blade structures available in the literature and the non-proportionality factors are compared and assessed.

To my understanding, there are two fundamental outcomes, that can be highlighted more prominently."

Statement #1:

"Ignoring non-proportionality seems to be making errors on the conservative side."

> **Response:** At first glance, one might actually think that neglecting non-proportionalities results in conservative interpretations. However, this is not the case.
>
> The standard method to perform a fatigue analysis for non-proportional stress time series is the critical plane approach. At many potentially critical planes, a fatigue damage calculation is performed based on local, scalar equivalent stresses, constant life diagrams and linear damage accumulation. Only the stresses acting on the analysed plane are then included in the local equivalent stress criteria. The fatigue damage on the analysed planes is then compared with each other and the plane with the highest fatigue damage is identified as the critical plane. A macroscopic crack will occur on this plane after the fatigue life.
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> In contrast, the approach of global equivalent stresses, in which the complete three-dimensional stress tensor is included, has become established for proportional stress time histories. Here, the time series of the stress tensor are converted into time series of global, scalar equivalent stresses and then into fatigue damage with the aid of a constant life diagram and linear damage accumulation. This means that damage is accumulated at all effective planes, which is not harmful as long as the effective planes do not change over time. However, this is only the case for proportional stress time series.
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> It may be obvious to believe that the use of global equivalent stresses for non-proportional time series is conservative, as damage is accumulated on all effective planes. The result should therefore be significantly greater damage than with the critical plane approach, where the damage is only accumulated on the actual critical plane.
>
> However, it has been experimentally proven for an epoxy resin-based rotor blade adhesive at coupon level that neutral material behaviour occurs. This means that the fatigue life does not depend on the degree of non-proportionality. This behaviour can be reproduced with the critical-plane approach, but not with the global approach. On the contrary,

> it could be shown that the fatigue damage in the case of the global equivalent stress appraoch is not higher for increasing non-proportionality, but significantly lower. In this respect, the global approach not only incorrectly predicted the basic fatigue behaviour (i.e., it did not capture the neutral behaviour), but also significantly overestimated the fatigue life. The prediction was therefore substantially non-conservative.
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> The results mentioned above were published in the following paper, and the reader is asked to refer to it for more details:
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>> Kuhn, M., Manousides, N., Antoniou, A., and Balzani, C.: 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.
>
> This paper does not deal with the fatigue damage calculation itself. It addresses the qualitative classification of stress time series in a trailing edge bondline with respect to non-proportionality and the quantification of these non-proportionalities. The influence on the calculation of fatigue life is currently the subject of research and will be published in due course. We therefore ask for your patience in this regard. However, we included an additional paragraph in the introduction to address this point, which seems to important for the reviewer. The paragraph reads:
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>> "It may be obvious to believe that the use of global equivalent stresses for non-proportional time series is conservative, as damage is accumulated on all effective planes. The result should therefore be significantly greater damage than with the critical plane approach, where the damage is only accumulated on the actual critical plane. However, it has been experimentally proven for an epoxy resin-based rotor blade adhesive at coupon level that neutral material behaviour occurs (Kuhn et al., 2023). This means that the fatigue life does not depend on the degree of non-proportionality (Sonsino, 2020). This behaviour55 can be reproduced with the critical-plane approach, but not with the global approach. On the contrary, it could be shown that the fatigue damage in the case of the global equivalent stress appraoch is not higher for increasing non-proportionality, but significantly lower (Kuhn et al., 2023). In this respect, the global approach not only incorrectly predicted the basic fatigue behaviour (i.e., it did not capture the neutral behaviour), but also significantly overestimated the fatigue life. The prediction was therefore substantially non-conservative."

Statement #2:

"Accounting for the S/N curve exponents of the applied adhesives, the relation between the dominant (z-axis) stresses and the other stresses makes the z-axis stresses by far the dominant design relevant contributions. Therefore it is expected that accounting for the non-proportionality within these three designs may have little to no influence on the final fatigue damage."

> **Response:** This is correct. We agree that the longitudinal normal stress is the dominant stress component. This matches observations in the field and in full-scale blade tests, where tunneling cracks, i.e., cracks in the cross-sectional direction, frequently occur. These cracks cannot be prevented by increasing the width of the adhesive joint, which usually is the primary design variable for adhesive joints. The trailing edge girder needs to be stiffened instead in order to reduce the longitudinal strain and with it the longitudinal stress. To the best knowledge of the authors, this is not yet common practise throughout the industry, and is important to keep in mind. As this is an important finding which

> is common for all three investigated blades, we have added the following phrases to the conclusions:
>
> > "A common finding for all three blades was that the longitudinal normal stress was the predominant stress component. The major goal in blade design with respect to a trailing edge adhesive joint should thus be to avoid excessive longitudinal strain and stress. This cannot be realized by increasing the bondline width, which is the usual design parameter for adhesive joints, but by increasing the stiffness of the trailing edge girder to reduce the longitudinal strain. However, if the longitudinal stress is reduced in this way, the other stress components not affected by the stiffening of the trailing edge girder, will become more significant and the degree of non-proportionality will increase."
>
> The degree of non-proportionality is indeed limited for the blade designs investigated in the paper, but it is finite. There are some spots in the adhesive joint where the non-proportionality is significant, especially after weighting with the wind speed. The evaluation of the stress time series is ongoing and subject of research. We would like to emphasize that it is too early to draw conclusions on the effect of the non-proportionalities on the fatigue life estimate and the choice of the fatigue analysis methodology. This is already included in the last sentence of the conclusions. As argued above, early conclusions can be wrong. Without calculation, it is impossible to say if the non-proportionality is neglible or not, although it may seem obvious.

Further Remarks

"Anyhow, this is a significant learning for future rotor blade designs!

Detailed comments can be found in the attached *.pdf document."

Comment #1:

"I know, it is simple, but in my view it makes sense to state Beltrami here since it is very simple and accounts for compressibility (much more capable then von Mises in my view)."

> **Response:** We included the Beltrami criteria via the following reference:
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> > Beltrami, E.: Sulle condizioni di resistenza dei corpi elastici, Il Nuovo Cimento, 18, 145–155, 1885.

Comment #2:

"I wonder what is the mechanism that causes these. This may affect the influence on the equivalent stress."

> **Response:** You are right that the damage mechanism can influence the equivalent stress. Unfortunately, at the present time, the presence of tension-compression asymmetry (TCA) in an epoxy-based rotor blade adhesive is a matter of macroscopic observation and cannot be clearly explained yet. In the opinion of the authors, speculation is of little use. However, to substantialize our statement that TCA is present in epoxy-based adhesives, we

> included a reference to measurements that were carried out recently in our group, which is the following:
>
> > Wentingmann, M., Manousides, N., Antoniou, A., and Balzani, C.: Yield surface derivation for a structural adhesive based on multiaxial experiments, Polymer Testing, 113, 107 648, 2022.

Comment #3:

"But in fact the extent of shear stresses in trailing edge bond lines is surprisingly low."

> **Response:** This is true and is also reported in this paper. It was stated explicitely in the sentence before that "the normal stress in spanwise direction is dominant in trailing edge adhesive joints", which is substantiated by the stress time series presented in Figure 6 and the respective explanations. Moreover, the ratio between longitudinal normal stress and shear stress depends on the blade design, i.e., if the trailing edge girder is stiff enough, the longitudinal normal stress is decreased significantly, while the shear stress remains the same. We thus did not include an additional comment on the small magnitude of shear stresses, which would have been repetitive and example-specific, and kindly ask for your agreement.

Comment #4:

"To my understanding, this indicates that a structural change of the material is involved."

> **Response:** If you mean some sort of microcrack formation by "structural change", and microcracks being responsible for stiffness and strength degradation in fatigue, then we agree. A microcrack evolving for a particular stress state is relevant for fatigue degradation due to a principle stress perpendicular to the microcrack. It is not necessarily relevant for a completely different stress state at another instance of time in a non-proportional stress history. E.g., if a microcrack forms transverse to the longitudinal direction due to longitudinal stress, it will probably not grow if only normal stresses in the cross-sectional direction occur in the following stress time series, and it will potentially not contribute substantially to further fatigue-related degradation.
>
> Although these may be reasonable thoughts, it is again speculation, as it was not yet proven by experiments and microscopic observations. As the scope of the manuscript is the analysis of the degree of non-proportionality and not the detailed explanation of damage mechanisms due to that non-proportionality, we prefer not to go into detail in this context. This may be subject of future work. We hope this finds the agreement of the reviewer.

Comment #5:

"Why do the shear stresses get a factor of sqrt(2)? This should just be 2, correct?"

> **Response:** In the Voigt notation of the stress tensor, no coefficient is present in the shear stress components. A factor of 2 would occur in the Voigt notation of the strain tensor, if γ was used instead of ε. Bishop actually used the Mandel notation, where a coefficient of $\sqrt{2}$ is present. We corrected this error throughout the manuscript.

Comment #6:

"I feel that this is a very bad term for describing what actually happens. Is there a chance to chose a term that is not already used in a very different meaning in structural mechanics?"

> **Response:** It is a matter of taste, but it may be true that the term results in misunderstandings or confusion of the reader. We have thus introduced the terms *stress body* and *rectangular moment of inertia*, which are both described in a clarifying paragraph, which reads:
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> "The state of stress at a specific point in time can be mapped as a point in the six-dimensional stress space. The collection of these points for a complete stress time series results in a six-dimensional body, which is called *stress body* in the following. The rectangular moment of inertia (RMOI) of the stress body [...]"
>
> The term rectangular body of inertia, or its abbreviation RMOI, are now used throughout the manuscript.

Comment #7:

"This is another hind [sic], that damaging is driving the behavior since non-linearity in composites usually is caused by damaging."

> **Response:** Yes, we agree. However, this paper is about the analysis of the degree of non-proportionality in stress time series, not on fatigue damage analysis, which would certainly be a logical next step. However, discussions on fatigue damage analysis, damage processes or the analysis of material non-linearities are beyond the scope of the manuscript. A discussion on that may be included in a future publication, where we will try to link the degree of non-proportionality with a proper fatigue damage analysis.

Comment #8:

"I assume, that these factors \sqrt(2) and \sqrt(3) are supposed to account for the the [sic] two assumptions of full compressibility and on the other hand incompressibility. But this does not necessarily go in line with equation (8) (see my comment)."

> **Response:** The factor $\sqrt{2}$ comes from the Mandel notation of the stress tensor. The factor $\sqrt{3}$ originates from independency of hydrostatic pressure. There was indeed an inconsistency in notation, both in this paragaph and equation (8), see also the answer to comment #9 below. The errors have been corrected.

Comment #9:

"Is this just due to an inconsistency in writing? Because \sqrt(3)\sigma_13 is not equal \sqrt(3)\tau_13!"

> **Response:** Yes, it was, see answer to your comment #8. The inconsistency has been corrected, both in the text and equation (8).

Comment #10:

"This implies, that hydro-static stresses do not contribute to damaging, correct?"

> **Response:** At this stage, yes, it does. The dependency of hydrostatic stress states is reintroduced later.

Comment #11:

"Maybe rather evolution?"

> **Response:** Yes, evolution has been adapted.

Comment #12:

"of"

> **Response:** The typo has been corrected.

Comment #13:

"As stated above, this underlines that shear stresses (contradicting the design principle of bond lines) do not play a significant role in trailing edge bond line fatigue. Hence, the non-proportionality, that most probably is in favor of the bond line fatigue life (as I deduce from your descriptions), is not driving the design."

> **Response:** We agree that the shear stress is not driving the bondline design in the blades investigated in the manuscript, as the longitudinal normal stress is dominating the time series. However, the stress time series strongly depend on the particular blade design, and for other blades, this may be different.
>
> In any case, it can not necessarily be concluded that non-proportionality is always favorable. It is rather one possible indicator for the choice of the fatigue analysis methodology. As argued above, a global equivalent stress approach works well for proportional loading, but fails for non-proportional loading, as was elaborated in the following paper, which has also been referenced in the manuscript (see also the answer to your general comment #1):

> Kuhn, M., Manousides, N., Antoniou, A., Balzani, C.: 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.
>
> Global equivalent stress approaches give principally wrong fatigue life estimates in case non-proportional stress time series are involved. A comparison of the fatigue life calculated with both methods is not valid in this case. Calculation of the fatigue life with global equivalent stress approaches in presence of non-proportional stress time series may be on the conservative side, or it may not, as was the case in the aforementioned paper. This is not necessarily known a priori. The only thing that is known at the time writing this sentence is that it is wrong.
>
> Again: Fatigue analysis is not the subject of this paper, so we did not include additional comments in this regard here.

Comment #14:

"Question is, what criterion has this bond line been designed to? Because this significantly influences the different means and amplitudes."

> **Response:** Exactly. The influence of each stress component on the non-proportionality factor depends on the blade design, which in turn depends on the design criteria. A trailing edge bondline that is properly designed for longitudinal strain will very likely experience a higher degree of non-proportionality than a blade that is designed only for shear stress, because the longitudinal stress will be lower, increasing the relative influence of shear. And vice versa of course.
>
> To evaluate that was not the scope of this manuscript, but to sensitise that there always is non-proportionality in a rotor blade bondline, that there are methods to evaluate the degree of non-proportionality, and that such methods may serve to select a suitable fatigue analysis framework, i.e., the critical plane or the global equivalent stress approach.
>
> In both approaches, different equivalent stress criteria can be further selected, which is complicating things. But as said: This is beyond the scope of the paper.
>
> In fact, the criteria used in the blade design procedures are not known to the authors, as we did not carry out the design by our own. Hence, we can unfortunately not give information in the paper in this regard.

Comment #15:

"Agree."

> **Response:** Thank you, this is appreciated.

Comment #16:

"... and would still be in favor of the integrety of the bond line if I get all this right."

> **Response:** Not necessarily. See explanations related to your general comment #1 and the additional comment #13. Further research is required in order to draw a general conclusion in this regard – if this is possible at all.

Comment #17:

"Again, isn't the error on the conservative side?."

> **Response:** Again: Not necessarily. A general conclusion is not yet possible. There are rather implications in the paper of Kuhn et al. 2023 that it may be strongly non-conservative in presence of substantial non-proportionality. This requires further investigations.

2 Reviewer #2 (anonymous referee)

General Remarks

"The analysis presented in this paper is well worth investigation and adds new knowledge for wind turbine blade designers. However, a major revision to the paper is required, due to the structure of the paper and some investigations that are missing. The specific changes requested are:"

Statement #1:

"The results in this paper are based on a finite element analysis of a wind turbine blade. However, there are very little details of this model and no validation. Both of these should be added to demonstrate that the authors are starting with an accurate model."

> **Response:** The modeling strategy and the modeling tool were validated in detail using the SB2-DemoBlade in the following reference that was also referenced in the manuscript:
>
> > Noever Castelos, P., Haller, B., and Balzani, C.: Validation of a modeling methodology for wind turbine rotor blades based on a full-scale410 blade test, Wind Energy Science, 7, 105–127, 2022.
>
> The particular parameterization of the blade models were thoroughly verified using models that were internally provided by the blade designers. This information exchange is not citable, since it is based on unpublished data. We ensured that the natural frequencies, mode shapes, the blade masses and the positions of the center of gravity match well. Mesh convergence studies were carried out to guarantee an accurate representation of the global blade response. The mesh was further refined, especially in the evaluation region and at the trailing edge to obtain mesh convergence not only with respect to the aforementioned outputs and additionally deflections, but also with respect to stresses, especially in the trailing edge adhesive. The models used were thus as accurate as possible, and there are no doubts that the results are reliable. We would like to emphasize that we are aware that good models are essential when analyzing model output data. Hence, the procedure described above is regularly exercised whenever we do finite element modeling, at least when we have reference data available, which is not always the case.
>
> We have added some more details on activities related to model quality in the text, which reads:
>
> > "The modeling strategy was validated in detail using the SB2-DemoBlade (Noever Castelos et al., 2022). Mesh convergence studies were carried out with respect to static deflections, natural frequencies, mode shapes, blade mass, and location of the center of gravity for all blades to ensure converged and reliable solutions. Figure 3 shows coarse versions of the blade meshes (the used FE meshes were too fine for visualization) of all three blades, highlighting the size differences."

> Detailed validation is normally not documented in similar publications throughout literature, unless the core of the paper is the finite element modeling itself. In our manuscript, the finite element method is utilized as a state-of-the art tool to calculate stresses in complex structures. The FE modeling itself is not the focus of this paper, but the degree of non-proportionality in the trailing edge adhesive. In our opinion, documenting the blade models in more detail than is done in the revised version of the manuscript, including validation and verificiation, does not provide significant added value, especially given the fact that this would result in several additonal pages of text and figures. Since the paper already consisted of 20 pages in the submitted version (and has even more pages in the revised version), adding this content is – in our opinion – not reasonable. We hope that this finds the reviewer's agreement.

Statement #2:

"From the outset of the paper, the authors acknowledge that "The results do not reveal any correlation between the degree of non-proportionality and the blade size. General conclusions are hard to draw, as the blade response does not only depend on the turbine size, but also on the blade design philosophy." However, a very limited selection of blade (3) are used, two of which are of similar length. Therefore, I would suggest adding more blades to the analysis in order to draw better conclusions for the trailing edge design consideration that is presented in the paper."

> **Response:** We are indeed a bit surprised. We analyzed three different blade designs, which are already two more than usually analyzed in similar research papers. Of course, it would be interesting to see if other blades show similar or dissimilar trends, especially industrial blades (that we don't have access to). We created detailed finite element models, did the analyses, postprocessed the data and documented everything in a detailed and comprehensive fashion. For this paper, three blades are more than enough in our humble opinion.
>
> Moreover, there are multiple factors influencing the stress response in the blade: The choice of the fatigue analysis methodology (global equivalent stress vs. critical plane approach), the choice of the equivalent stress criteria, the quality of the material database, the general design policy of the blade designer, the design targets with respect to aero-elastic performance and cost, the risks the designer is willing to accept, the overall turbine concept, the dynamic behavior not only of the blades but also of the turbine, etc. Hence, stating that a general conclusion is not possible is reasonable and honest. Even if we analyzed three additional blades (that we don't have the data of, by the way), there is a high probability that general conclusions are still not possible. And that is one of the outcomes that is also important to accept: The non-proportionality in a trailing edge adhesive joint (and other adhesive joints and sub-components of the blade) has to be analyzed for every blade and turbine individually.
>
> To clarify the dependency of the outcome on a variety of influencing factors, we have included the following text in the conclusions:
>
> > "A correlation between the degree of non-proportionality and the blade size was not substantiated. The reason is that the stress response in a blade depends on a large variety of influencing factors, such as the choice of the fatigue analysis methodology (global equivalent stress vs. critical plane approach), the choice of the underlying equivalent stress criteria, the quality of the material database, the general design policy of the blade designer, the design targets with respect to aero-elastic performance and cost, the risks the designer is willing to accept, the overall turbine concept, the dynamic response not only of the blades but also of

> > the entire turbine, different inflow conditions of small and large rotor diameters, etc. Hence, the degree of non-proportionality in a rotor blade has to be analyzed for each turbine individually. "
>
> We believe that three blades are enough for a journal paper and kindly ask for your agreement. Additional blades can certainly be subject of follow-up research, and we are looking forward to extend the study presented in this paper in the future.

Statement #3:

"The conclusion largely summarises the work carried out in the paper. A paragraph on the impact of the study should be added to Section 4."

> **Response:** The paper sensitises blade designers that there is always at least some degree of non-proportionality in trailing edge adhesive joints. It is also exlained in the paper by referring to literature with experimental evidence that using a global equivalent stress approach can result to highly non-conservative estimates of the fatigue life of adhesive joints. Hence, the paper can have an impact on the overall structural reliability of wind turbine rotor blades, as the non-proportionality factor can be used as a metric for the choice of an appropriate and reliable fatigue analysis framework, meaning that time-consuming methods such as the critical plane approach needs to be applied only in case the degree of non-proportionality implies that.
>
> We have added the following paragraph to section 4 for clarification:
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> > "The non-proportionality factor as proposed in this paper can be utilized to quantify the degree of non-proportionality in rotor blade adhesive joints, and it can be adapted for other materials and sub-structures as well. The blade designer is then able to select an appropriate fatigue analysis methodology, e. g., the critical plane approach only for spots with a high degree of non-proportionality and the global equivalent stress approach elsewhere. As the wrong choice of the fatigue analysis method can be non-conservative, the non-proportionality factor can thus serve to improve the overall structural reliability of wind turbine rotor blades. "

Statement #4:

"Although much of these details are included throughout the paper, please add a methodology section that clearly outlines the study aim, objectives, materials, methods and overall methodology."

> **Response:** A methodology section has been introduced after the introduction.

Statement #5:

"Section 3 is 8 pages long – please divide it into subsections to make it easier for the reader."

Response: Thank you very much for your comment. We were in fact also struggling with the length of the former section 3 and have divided it into different sections and subsections.

The former section 3 has been re-structured to improve the reading experience. It has been divided into two sections, which are *4 Application examples* and *5 Results and discussion* (number is higher due to the inclusion of the Methodology section). Hence, the *Conclusion* section has become section 6.

The results and discussion section has been divided into the following subsections: *4.1 Non-proportionality in trailing edge adhesive joints*, *4.2 Correlation with stress time series*, and *4.3 Weighted mean non-proportionality*.

In our opinion, the subdivision section 3 improved the readability significantly and thank the reviewer again for the comment.