Dear Julie Teuwen,

We have the pleasure of submitting our revised paper “A Multi-Parametric Composite Approach for the Optimization of Wind Turbine Blades using Double-Double Laminates” (wes-2025-285) for consideration in the journal Wind Energy Science. We are very grateful for the constructive feedback with lots of valuable suggestions from the editorial team and the reviewers which helped to improve our paper. We implemented a simplified fatigue criterion and applied it as constraints to the laminates using strain limits given by DNVGL. Furthermore, we extended our buckling criterion for the sandwich cases taking into account through thickness shear effects according to Kassapoglu 2013. The new results of the CRC-15-240 blade using DD laminates show a mass reduction of 4% (2800 kg) compared to the baseline triaxial configuration, achieved through the substitution of the triaxial skins with a [±37°/ ± 37°] laminate. This configuration strikes a compromise, shifting the skin response from an axially stiff regime toward a softer one that better balances shear and buckling resistance against strain limits.

To address the critical point of matrix-dominated damage mechanisms, we did a first study considering a constraint that enforces a minimum difference between the DD angles (here 30°). It indicates a mass increase of 1*t* compared to the ±37° DD case, while still maintaining a 2*t* mass advantage over the triax configuration. Further research on double-double laminates is needed to better understand their susceptibility to matrix-dominated damage mechanisms which we add to the outlook.

We want to highlight the major changes and extensions:

- We corrected table 2 with the right material properties from the reference Camarena2022.
- We added picture 2 to the manuscript which shows that Tsai’s criterion for homogenization is fulfilled for both Triax and DD in case of four repetitions r.
- We implemented a simplified fatigue criterion and applied it as constraints to the laminates using strain limits given by DNVGL, see section 4.4
- We extended our buckling criterion for the sandwich cases taking into account through thickness shear effects according to Kassapoglu 2013, see section 4.4.
- Based on the new/changed criteria we updated all CRC-15-240 results and adapted the discussion of them.

Furthermore, we have made all necessary changes and have addressed all comments of the referees (printed in black) in the detailed response below.

Our response to the referees are written in green.

Reformulated or added phrases for the revised manuscript are referred to in blue.

Line, figure and table numbers in our answers are according to the revised manuscript. Line, figure and table numbers in the referees’ comments are according to the initial manuscript. New figures and tables are appended to this response. However, the updated figures and tables were omitted, as this would have been almost all figures and tables. The updated versions can be seen in the revised manuscript.

We feel that based on the reviewers comments our paper has been sharpened and improved, especially in terms of clarity, and – in the authors' opinion – should meet the required standards to be published. If any responses are unclear, or if you would like to have additional changes implemented, please let us know.

Sincerely,
Edgar Werthen

- On behalf of all authors –

Referee 1: Alexander Krimmer (= CC1 & RC2)

Dear Dr. Krimmer, thank you very much for taking the time to review our paper. There were some comments both in the manuscript and in the conversation. I have summarized these accordingly. Please find our answers below.

(Line 23) This is a very interesting hypothesis. We would not be able to be competitive if that was the case.

Please excuse the imprecise wording. We reformulated the sentence in the following way:

In practice, blades are often designed using predefined laminate families, which are then treated as homogenized single layers for design and analysis. Following this practice, the blade designs of the International Energy Agency (IEA) Reference Wind Turbines (RWTs) make use of a set of laminates with pre-established angles and thicknesses (fabrics). This is also motivated by manufacturability, because more complex layups significantly increase cost, defect sensitivity, and tapering effort. Standardized families, particularly when produced with fabrics, reduce variability and simplify both production and structural modeling.

(Figure 1) This layout will lead to huge buckling loads. More modern designs go for a main spar cap with one main web and a trailing edge spar cap with a trailing edge web. Those are usually optimized for panel sizes along blade length to reduce buckling criticality of the panels as well as global buckling criticality of the whole trailing edge.

Yes, you are right. Unfortunately, we do not have access to industrial blade design data. We rely on the reference wind turbine designs and have to conduct our research based on these designs, in this case the IEA 15MW reference wind turbine.

(Line 47) Throughout rotor blade design today, we observe that the designs are often driven by fatigue limitations in shells and bond lines. The spar caps therefore are optimized to limit occurring strains in these structural members and are not optimized for their own sake. As a consequence, the buckling loads in the shells are significantly reduced. The remaining buckling criticality results from shear-driven out of plane buckling modes that can usually not be countered efficiently by adapting skin thickness. Therefore, the referenced publications have not been very relevant for daily rotor blade design applications.

Thank you for the comment. According to our understanding of the literature on rotor blade optimisation, predefined layups are used and their thickness distribution is optimised, e.g. that of the shell and the main spar cap. The mechanism you described takes into consideration fatigue as the design driver. We added a simplified fatigue criterion in section 4.4:

Fatigue constraints are applied to the laminates as a simplified maximum strain criterion, based on strain limits considered sufficiently conservative for use without material testing (DNV GL 2015b):

$\frac{R_d}{\gamma_m} = 0.35\%$ tensile strain

$\frac{R_d}{\gamma_m} = 0.25\%$ compression strain with γ_m is the material safety factor and R_d is the design value of the material property. These limits are verified for all four ply orientations of the DD laminate at each optimization step.

We see the same effect that you described, in both cases with and without the simplified fatigue criterion. From our understanding it is a result of the better strength-to-weight ratio of the CFRD UD. The spar cap thickness is increased in our optimization and takes the load from the shell. We consider out-of-plane buckling driven by combined shear and compression and now updated it also to take into account through-thickness shear effects, as stated in section 4.4. Nevertheless, we totally agree that the results will change when taking into account fatigue as a constraint, which we already see it in the new results, coming up with a [±37°/ ± 37°] laminate. This configuration strikes a compromise, shifting the skin response from an axially stiff regime toward a softer one that better balances shear and buckling resistance against strain limits.

We changed the result discussion accordingly and reformulated the conclusion and the outlook section:

Conclusion:

The optimization of the CRC-15-240 blade using DD laminates on the shell resulted in a mass reduction of 4% (2800 kg) compared to the baseline triaxial configuration, achieved through the substitution of the triaxial skins with a [±37°/ ± 37°] DD layup. In general, 0° plies minimize spanwise strain while 45° plies maximize buckling resistance. The optimized [±37°/ ± 37°] configuration strikes a compromise between these two demands, shifting the skin response from an axially stiff regime toward a softer one that better balances shear and buckling resistance against strain limits. This also redistributes axial stiffness from the shell to the spar caps and edge reinforcements, resulting in increased spar-cap thickness. In turn, the optimizer maximizes the structural contribution of the unidirectional carbon fiber, which offers superior strength-to-weight performance in the flapwise direction.

Outlook:

Several additional research directions naturally arise from this work. While the present study focused on preliminary investigations of DD laminates as a novel structural concept, future studies can evaluate its performance with higher-fidelity models and analyses, creating a basis for subsequent detailed design stages:

– Fatigue modeling is a key area for further work. Although DD laminates are relatively new and lack extensive experimental data, their long-term cyclic performance remains uncertain. Future research should integrate fatigue degradation models into the optimization process and support experiments to characterize endurance. These data would allow direct fatigue constraints in the design space and, when needed, guide limits on allowable configurations. Nevertheless, preliminary tension–compression fatigue tests, such as those in Vasconcelos et al. (2025), indicate that DD laminates retain structural integrity under cyclic loading, supporting their long-term use.

– Matrix-dominated damage mechanisms could exhibit for the present DD case with ±37°, since it lacks a third fiber orientation and is therefore not statically determined. A first study considering a constraint that enforces a minimum difference between the DD angles (here 30°), indicates a mass increase of 0.8t compared to the $\pm 37^\circ$ DD case, while still maintaining a 2t mass advantage over the triax configuration. Further research on double-double laminates is needed to better understand their susceptibility to matrix-dominated damage mechanisms.

– Through-thickness shear effects were incorporated into the buckling criterion in a simplified manner ($k = 1$, see sub-section 4.4). A more rigorous treatment should adopt advanced lamination theories such as the First-Order Shear Deformation Theory (FSDT) or Mindlin–Reissner theory, which better capture shear deformation in thicker sandwich laminates. Additionally, the reference plane should be set to the mould surface rather than the mid-plane to improve the accuracy of the predicted bending stiffness.

– Higher fidelity strength criteria such as LaRC03 or Puck describe a physically based failure mechanism and capture specific mechanisms (e.g. matrix cracking).

The vastness is not so much of a problem. As per comment above, the triaxial in the shell is not mainly used for optimizing buckling behavior. With regard to buckling, biaxial would be preferred. Unfortunately, damaging of a biaxial shell laminate would quickly result in growing continuous cracks. This is why the triaxial (in combination with biaxial) is used in our blades only to provide a third fiber direction to provide static determination of the laminate in case of matrix damaging.

Please see also comment above. The critical point that both DD angles have the same value somehow remains and needs to further investigate. As stated above we did A first study considering a constraint that enforces a minimum difference between the DD angles (here 30°). It indicates a mass increase of 0.8t compared to the $\pm 37^\circ$ DD case, while still maintaining a 2t mass advantage over the triax configuration. We adapted the results discussion, conclusion and outlook accordingly.

(Line 63) Symmetry constraints are a problem in aircraft industry. Not so much in wind blades. We drop plies as often as we feel like it. To my understanding, ply drops are the main advantage of double double. Do you see the same advantages if you do not care for ply drop symmetry rules?

In wind turbine blades, symmetry and ply-drop constraints are generally not limiting, as asymmetric laminates and frequent ply drops are standard practice. Accordingly, DD laminates are not introduced here as a solution to symmetry-related manufacturing constraints. Instead, they are used as a direct replacement for conventional fabrics, such as triax and biax, which follow similar manufacturing principles but are typically modeled with fixed stiffness properties. The DD formulation enables continuous angle optimization while remaining consistent with established manufacturing processes.

We reformulated the sentence in the following way (line 63):

A key advantage is tapering: building blocks can be dropped to transition between neighboring panels without symmetry constraints - which is a common practice in the blade’s industry, thereby not introducing any complexity to the current standpoint.

(Line 66) Prepreg is not used in modern rotor blade designs any more.

Yes, we corrected the following sentences (line 65):

From a manufacturing standpoint, Kappel and Tsai (2024) demonstrated DD laminates using prepregs and vacuum infusion, predominantly prepregs with off-the-shelf materials, which can be transferred to wind turbine blade production with new types of fabrics.

(Line 71) This is comparing to a metallic panel and for composites has mainly been limited by ply-drop rules. This is not relevant for wind blades!

Correct, we remove the citation of Kappel (2022)

(Line 117) This is as advertised by Tsai et al in his book. I do not agree! DD is a simplification method of laminate optimization to help application by insufficiently trained composites engineers.

See comments above

(Line 122) This research incorporated very thin plies, as far as I recall. The same homogenization characteristics cannot be expected for wind-dimension laminates.

Please see also my first answer. We added picture 2 (see appendix of this document) to the manuscript which shows that Tsai's criterion for homogenization is fulfilled for both Triax and DD laminates in case of four repetitions r. We already provided you a small Excel tool which you can use to perform the calculations yourself.

We added the following sentences to the manuscript (line 138):

Figure 2 shows that Tsai's homogenization criterion is satisfied for both the Triax and two DD laminates at four repetitions *r*. Since a DD laminate is defined by two angle pairs (±ϕ, ±ψ), a Triax fabric can be interpreted as a DD laminate with [+0,-0,+45,-45] as single repetition r. The criterion depends solely on the number of repetitions, not on individual ply thickness, as the ABD* matrices are normalized by the laminate thickness t_{lam}.

(Line 127) ... assuming sufficiently thin plies. What is the number of necessary repetitions to allow for this assumption? In shells we usually do not see more than five laminae in one skin in our own blades. This definitely does not fulfil whatever requirement in DD.

As shown in picture 2, four repetitions are required to fulfill the Tsai requirement.

(Line 167) What about combinations of biaxials and triaxials, which we usually do have all over the blade?

Our baseline model for the analysis is the IEA-15 RWT, which employs only triaxial laminates in the shell. Therefore, the comparison remains centered around DD and triaxial laminate.

(Line 175) This can only be applied if sufficient homogenization can be assumed. See comments above.

Already discussed above.

(Figure 3) Objection, irrelevant. There are no single purpose laminates in rotor blade shells.

The goal of the study is to show how DD laminates adapt to different load conditions. The pure tension and shear cases are only shown to provide a basis for the reader, when it encounters the cases with combined conditions. This was considered important because under compression and shear combined, the resulting angles might be unexpected at first.

(Line 209, figure 3) To my understanding, the elegance of DD lies in the fixation of two fiber angles (e.g. 10° and 35°) and the combination of two fabrics than resulting in e.g. +/-5° and +/-30°. This fixation is completely ignored throughout the present analysis. Theoretically possible but not practically relevant.

Figure 3 just shows that the DD angles can achieve the same value (part of the elegance), here 0° due to tension loading. These results confirm that the optimization process works correctly. As mentioned above, the section serves as verification study for the reader to understand the DD mechanisms.

(Line 255) For rotor blade optimization it is advantageous to define the mould (and aerodynamic) surface as the reference plane since otherwise the mathematical definition of the blade model is much more complex. It would be preferrable if the reference plane for laminates through laminate optimization would coincide with the aerodynamic surface of the blade.

Yes, you are right. This leads to an overestimation of the bending stiffness which affects the deformations and stresses but in the same manner for all use-cases.

We added/changed the following sentences:

In general, the mould (and aerodynamic surface) should be used as reference plane along the z-axis, to avoid an overestimation of the bending stiffness. For the present study it is imposed to coincide with the mid-plane of the whole stack.

(line 290, figure 12) Is it necessary to elaborate these CLPT fundamentals in this detail? Might be preferable to cite an adequate reference to shorten the paper. In my opinion, the whole work could significantly be shortened if the details on classical laminated plate theory would be referenced from established literature such as VDI2014 or comparable.

Yes, you are right. We shortened section 3.2 significantly and added the VDI 2014 as reference.

(Table 2) Commonly, the 1,2,3 coordinate system is reserved for the ply level while for the laminate level the x,y,z coordinate system is established. It might be helpful to account for this in a short subsection introducing coordinate systems.

We took over the material properties directly from Camarena et al. (2022). There the 1-2 coordinate system is used.

We added the following sentence to introduce the coordinate system:

Every laminate orientation is fixed such that the E1 direction, points towards the blade tip and remains tangential to the shell reference surface.

(Table 2) Matrix dominated and compressive fiber direction properties are totally unrealistic! Assuming these must result in preference for DD. I have never seen a laminate that has higher absolute Yt values than Yc values. Apart from that, e.g. for uniaxial glass a Yt of more than 55 MPa I have never seen! Not to mengtion 196 MPa. Please establish realistic material parameters!

Unfortunately, the conversion of the table with the material properties into LaTeX format was faulty. We again sincerely apologise for this. We corrected table 2 accordingly.

(Line 337) What target does the procedure converge to?

The solver (SNOPT) parameters follow standard definitions, except for the feasibility and optimality tolerances, which are set to 10−4. Please, find it in lines 410 and 415.

(Line 343) This is a very coarse resolution with 25 cross sections if I am right. We usually use between at least 40 to 200 cross sections for our verifications depending on blade length.

The model uses 30 cross-sections. Each cross-section directly determines the number of regions with distinct thickness definitions. Since the solver provides internal loads to be evaluated analytically, a finer discretization is not required. The simulation used a maximum criterion for load selection, keeping the results in the conservative side. Increasing the number of cross-sections to 40–200 would introduce numerous thickness transitions along the span, which was considered impractical for the demonstration purpose of this study.

We added the following sentences to the manuscript (line 330):

The model comprises 30 cross-sections in total. Since internal loads are evaluated analytically, a finer discretization is not required. A maximum envelope criterion is applied for load selection, ensuring conservative results.

(Equation 24): Shouldn't this be D~ as well?

Yes, we corrected it accordingly

(Line 382): Obviously, you are neglecting through thickness shear effects in your buckling analysis. This is to a huge extent driving core thicknesses and therefore mass through resin uptake in core. When taking this into account, your spar cap thickness will most likely be increased significantly by your optimization algorithm.

We extended our buckling criterion for the sandwich cases taking into account through thickness shear effects according to Kassapoglu 2013:

We added the following lines to the manuscript:

To account for through-thickness shear effects in the buckling analysis of sandwich panels, both critical buckling loads (compression and shear) are modified following (Kassapoglou, 2013):

$$N_{x\mathrm{crit}} = \frac{N_{E\mathrm{crit}}}{1 + \dfrac{k N_{E\mathrm{crit}}}{t_c G_c}}$$

where tc and Gc denote the core thickness and transverse shear modulus, respectively, and *k* is the shear correction factor, set to *k* ≈ 1. This choice is conservative for sandwich panels, where the core shear stiffness is low relative to that of the face sheets (Kassapoglou, 2013).

As stated above the results significantly changed. The optimized [±37◦/ ± 37◦] configuration strikes now a compromise, shifting the skin response from an axially stiff regime toward a softer one that better balances shear and buckling resistance against strain limits. This also redistributes axial stiffness from the shell to the spar caps and edge reinforcements, resulting in increased spar-cap thickness. We observed that the influence of transverse shear is comparable across all considered use cases.

(Line 388) This is much steeper than what is expected. Most probably the effect of this constraint is much bigger than that of DD.

Although the constraint of 7.5:1 is lower than the value in the guidelines, this is only active in section 6 (~14m), when the spars and reinforcements are introduced, reducing the function of the shell skin. This effect only created a minimal thickness step between section 7 and 8 (~18.2m), which doesn't interfere with the angles obtained. For your reference, please use figure 18.

(Line 428): Lack of an adequate fatigue criterion leads to high longitudinal strains in the panels resulting in high buckling loads. It seems that fatigue loading is neglected here and therefore optimization for serviceability and extreme loads is carried out. This is why buckling is so dominant which it is not in blades designed for fatigue. Can you please state the resulting core thicknesses to confirm this assumption? (there are only 3 sections with core thicknesses as examples below)

Shell is loaded only heavily in the first section, in the root region. After this region, the thickness drops significantly to its minimum boundary value with the introduction of spars and edge reinforcements. As stated above we added a simplified fatigue criterion which changed the results significantly. If you refer to the foam core thicknesses, we add 4 figures to section 5.2. Here you can see the foam core thicknesses (number 4,6,9 and 11) are in the range between 45mm (max. chord) and 10mm (tip)

(Line 437): The practical problem resulting from this is that fatigue damage of the matrix instantly leads to localizing cracks (no third fiber direction --> not statically determined) that leads to extended cracks along fiber directions within the panels. This is to be avoided in real blades.

Please see comments above

(Line 445) As stated above, I would expect that this is rather due to the applied chamfering ratio boundary condition.

At section 6, where the taper ratio constraint is active, the resulting additional mass coming from it is minimal. This can be visualized in figure 18, where the spar-cap doesn't have any jump in thickness, meaning that it has no direct effect. The optimizer sees this constraint as something to be fulfilled regardless, not as a value driving optimization of angle. The taper ratio is applied to all use cases in the same way.

(Line 464): Why is the minimum allowable for Triax higher than for DD? Shouldn't that be equal to be fair. As well because the 0° is roughly twice the plus/minus in Triax and DD consists of four plies? This is distorting the comparability of the models, to my understanding.

Yes, that is true, we corrected that for the new simulations and all cases have a minimum thickness of 2mm now.

Throughout your paper I have been struggling with the term "spar-cap core" what is that? I tried to understand it as the spar cap itself made from carbon frp. Is that correct? The term is misleading somehow. Meanwhile you do not address shell core materials a lot. Though they are driving rotor blade mass and even more price in reality.

Yes, spar cap core is essentially the spar cap. We corrected that over the paper.

(Line 483): This may as well be preferrable e.g. if aerodynamic TE thickness requirements do not allow for increase of TE reinforcement thickness.

In the new results there is no difference in TE thickness anymore in the first cross-section. From our understanding, such minimal difference wouldn’t be a problem at this stage of design, especially with no constraint directly described by the IEA-15-240. is evident that this effect becomes relevant in the detailed design phase.

(Line 510): Is this incorporating resin uptake throughout infusion?

No, it’s not. The same goes for every optimization case studied, establishing a fair comparison.

(Line 514) The S profile in the pressure side trailing edge panel stabilizes the panel with regard to buckling which has significant influence on resulting core thickness.

Yes, the curvature of the panels is not considered in our analytical (simplified) buckling criterion from HSB-45112-02. We are on the conservative side here for all use-cases.

(Line 521) As indicated above, accounting for fatigue loading would most probably significantly change the layout!

Please see comments above

(Line 532) Isn't this a trivial solution for buckling dominated panels? The "Kreuzzahl" is maximized at +/-45°. This might not be coincidentally.

In general, the variation in angle can be understood from different scenarios. The new results show now a different angle setup as compromise between buckling and max. strain.

(Line 542) It may as well underline the limited capability of DD. What do you mean by "upper skins"? We have never seen compressive loading being critical to skin laminates. Neither in design nor in practice.

DD laminates can easily adapt to different load conditions, and result in different angles. However, in this case, upper skins refer to the suction side of the airplane wing studied. We updated the manuscript and use the word “suction side” now. The related sentence is not present anymore in the manuscript due to the changed results.

I know that I somehow asked this before. How many repeated blocks do you need for the blade apart from the root segment? This seems not to be a viable reasoning for rotor blade structures.

4 repetitions. Please see comments above and figure 2 of the new manuscript.

Why would +/-48° laminates behave significantly different from +/-45° laminates?

We have updated the results and the new configuration is showing a set of [±37°/ ± 37°].

The use of the optimization framework is questionable from my point of view. DD is to my understanding not meant to result in laminates with only two fiber directions. This results in very unstable laminates, especially in the case of matrix damaging. An according design would lack robustness and is therefore to be avoided. Anyhow, this is the superior optimization result in this study with +/-48°. What would be the result if at least three fiber angles would be required? This would be much more realistic with respect to required robustness under field conditions.

As mentioned above and stated now on the outlook, Matrix-dominated damage mechanisms could exhibit for the present DD case with ±37°, since it lacks a third fiber orientation. A first study considering a constraint that enforces a minimum difference between the DD angles (here 30°) would create the third angle you are asking for. The configuration indicates a mass increase of 0.8t compared to the ±37◦ DD case, while still maintaining a 2t mass advantage over the triax configuration. But we fully agree that further research on double-double laminates is needed to better understand their susceptibility to matrix-dominated damage mechanisms.

Referee 2 (=RC1)

We thank the referee for the constructive feedback. Please find our answers below.

While tapering advantages of DD laminates are mentioned, could the authors discuss the practical manufacturability of Double–Double laminates at full blade scale?

Yes, we added the following sentences to the manuscript (line 63):

A key advantage is tapering: building blocks can be dropped to transition between neighboring panels without symmetry constraints - which is a common practice in the blade’s industry, thereby not introducing any complexity to the current standpoint.

The authors may consider citing ”*Riccio A., Caprio F.D., Tsai S.W., Russo A., Sellitto A. Optimization of composite aeronautical components by Re-designing with double-double laminates (2024) Aerospace Science and Technology, 151, art. no. 109304*” in the Introduction, as it presents a recent optimization-driven application of Double–Double laminates that is closely related to the present work.

Yes, of course. We added the following to manuscript (line 70):

Notably, Garofano et al. (2023) compared DD laminates with conventional layups in fuselage structures and reported a 34% weight reduction. Riccio et al. (2024) conducted this comparison for composite aeronautical components and reported mass savings of up to 50%

Could the authors briefly comment on whether ply-by-ply failure checks were considered in selected critical regions to assess potential conservativeness? Additionally, how are interlaminar failure modes, such as delamination or debonding, considered?

We added a simplified fatigue criterion in section 4.4:

Fatigue constraints are applied to the laminates as a simplified maximum strain criterion, based on strain limits considered sufficiently conservative for use without material testing (DNV GL 2015b):

$$\frac{R_d}{\gamma_m} = 0.35\% \text{ tensile strain}$$

$$\frac{R_d}{\gamma_m} = 0.25\% \text{ compression strain}$$

with γm is the material safety factor and Rd is the design value of the material property. These limits are verified for all four ply orientations of the DD laminate at each optimization step.

The updated results show that replacing the triaxial skins of the CRC-15-240 blade with a [±37°/±37°] DD layup, leads to a mass reduction of approximately 4% (about 2800 kg). This configuration represents a compromise that better balances shear and buckling resistance against strain limits. It shifts the shell response from an axially stiff regime toward a more balanced structural behavior while redistributing axial stiffness toward the spar caps and edge reinforcements.

Further interlaminar failure modes or debonding is not modeled since we are using a preliminary design process. We added the following sentences to the outlook:

Several additional research directions naturally arise from this work. While the present study focused on preliminary investigations of DD laminates as a novel structural concept, future studies can evaluate its performance with higher-fidelity models and analyses, creating a basis for subsequent detailed design stages:

– Fatigue modeling is a key area for further work. Although DD laminates are relatively new and lack extensive experimental data, their long-term cyclic performance remains uncertain. Future research should integrate fatigue degradation models into the optimization process and support experiments to characterize endurance. These data would allow direct fatigue constraints in the design space and, when needed, guide limits on allowable configurations. Nevertheless, preliminary tension–compression fatigue tests, such as those in Vasconcelos et al. (2025), indicate that DD laminates retain structural integrity under cyclic loading, supporting their long-term use.

– Matrix-dominated damage mechanisms could exhibit for the present DD case with ±37◦, since it lacks a third fiber orientation and is therefore not statically determined. A first study considering a constraint that enforces a minimum difference between the DD angles (here 30◦), indicates a mass increase of 0.8t compared to the ±37◦ DD case, while still maintaining a 2t mass advantage over the triax configuration. Further research on double-double laminates is needed to better understand their susceptibility to matrix-dominated damage mechanisms.

– Higher fidelity strength criteria such as LaRC03 or Puck describe a physically based failure mechanism and capture specific mechanisms (e.g. matrix cracking).

Given the extensive use of symbols and analytical expressions throughout the manuscript, the authors may consider adding a short Nomenclature section.

Yes, we added a glossary of abbreviations and symbols to the manuscript.

A short clarification on the criteria used to select the PreDoCS discretization shown in Figure 15 would be helpful.

In the spanwise direction, the blade is discretized using a two-zone uniform scheme. From the root (0–23% span), panels are spaced at 2.60 m to capture the highly loaded root region and the transition from the cylindrical base to the main blade with spars. Beyond 23% span, a coarser spacing of 4.50 m is applied up to the tip, reducing computational cost while maintaining geometric continuity and manufacturability, given that taper plays in important role in composite panels design.

We added the following sentences to the manuscript (line 345):

In total the model consists of 30 cross-sections. Since the solver provides internal loads to be evaluated analytically, a finer discretization is not required. The simulation used a maximum criterion for load selection, keeping the results in the conservative side.

The Appendix contains several analytical expressions whose symbols are not fully defined. For completeness and reproducibility, all terms should be clearly introduced when first used.

Yes, as stated above, we added a glossary of abbreviations and symbols to the manuscript.

Referee 3: Alexandros Antoniou (= RC 3)

Dear Dr. Antoniou,

we thank you very much for the constructive feedback. Please find our answers below.

Optimizing the blade mass should be put in the context of a multi-parameter optimization (e.g., fatigue resistance, total blade deflection, root requirements for stiffness for optimal load transition to the pitch bearing and the bolted connections etc.), rather than only on the buckling resistance and static strength of composite panels.

Thank you for your comment. Our goal is to enlarge the design space using a new parametrization for DD laminates. With this, we are exploring new frontiers of composite optimization. Our goal is not to provide an industrial and produceable design. We sharpened the objective section 1.1:

..,the central objective of this study is to enlarge the design space for sandwich composite panels in the context of structural mass optimization for large wind turbine blades. This is achieved by introducing DD laminates in place of the predefined stiffness-fixed triaxial laminates.

According to your concerns, we implemented a simplified fatigue criterion and applied it as constraints to the laminates using strain limits given by DNVGL. Furthermore, we extended our buckling criterion for the sandwich cases taking into account through thickness shear effects according to Kassapoglu 2013. The new results of the CRC-15-240 blade using DD laminates show a mass reduction of 4% (2800 kg) compared to the baseline triaxial configuration, achieved through the substitution of the triaxial skins with a [±37°/ ± 37°] laminate. This configuration strikes a compromise, shifting the skin response from an axially stiff regime toward a softer one that better balances shear and buckling resistance against strain limits. Blade deflections are considered as constraint for all use cases, please see section 4.4. The bolted connection naturally influences the blade design; however, this effect is expected to be similar across all considered use cases.

We changed the result discussion accordingly and reformulated the conclusion and the outlook section:

Conclusion:

The optimization of the CRC-15-240 blade using DD laminates on the shell resulted in a mass reduction of 4% (2800 kg) compared to the baseline triaxial configuration, achieved through the substitution of the triaxial skins with a [±37°/ ± 37°] DD layup. In general, 0° plies minimize spanwise strain while 45° plies maximize buckling resistance. The optimized [±37°/ ± 37°] configuration strikes a compromise between these two demands, shifting the skin response from an axially stiff regime toward a softer one that better balances shear and buckling resistance against strain limits. This also redistributes axial stiffness from the shell to the spar caps and edge reinforcements, resulting in increased spar-cap thickness. In turn, the optimizer maximizes the structural contribution of the unidirectional carbon fiber, which offers superior strength-to-weight performance in the flapwise direction.

Outlook:

Several additional research directions naturally arise from this work. While the present study focused on preliminary investigations of DD laminates as a novel structural concept, future studies can evaluate its performance with higher-fidelity models and analyses, creating a basis for subsequent detailed design stages:

– Fatigue modeling is a key area for further work. Although DD laminates are relatively new and lack extensive experimental data, their long-term cyclic performance remains uncertain. Future research should integrate fatigue degradation models into the optimization process and support experiments to characterize endurance. These data would allow direct fatigue constraints in the design space and, when needed, guide limits on allowable configurations. Nevertheless, preliminary tension–compression fatigue tests, such as those in Vasconcelos et al. (2025), indicate that DD laminates retain structural integrity under cyclic loading, supporting their long-term use.

– Matrix-dominated damage mechanisms could exhibit for the present DD case with $\pm 37^\circ$, since it lacks a third fiber orientation and is therefore not statically determined. A first study considering a constraint that enforces a minimum difference between the DD angles (here 30°), indicates a mass increase of 0.8t compared to the $\pm 37^\circ$ DD case, while still maintaining a 2t mass advantage over the triax configuration. Further research on double-double laminates is needed to better understand their susceptibility to matrix-dominated damage mechanisms.

– Through-thickness shear effects were incorporated into the buckling criterion in a simplified manner (k = 1, see sub-section 4.4). A more rigorous treatment should adopt advanced lamination theories such as the First-Order Shear Deformation Theory (FSDT) or Mindlin–Reissner theory, which better capture shear deformation in thicker sandwich laminates. Additionally, the reference plane should be set to the mould surface rather than the mid-plane to improve the accuracy of the predicted bending stiffness.

– Higher fidelity strength criteria such as LaRC03 or Puck describe a physically based failure mechanism and capture specific mechanisms (e.g. matrix cracking).

Should the presented optimization be only an example case, then it must be made implementing the appropriate mechanics, i.e., considering the out-of-plane shear stiffness, which dominates the stability of large sandwich panels. The analyses are valid within the framework of classical laminate theory for thin plates. However, the core assumptions are not representative of wind turbine blade panels, where transverse shear, core compliance, and face–core interaction govern both stiffness and stability behavior.

We extended our buckling criterion for the sandwich cases taking into account through thickness shear effects according to Kassapoglu 2013:

We added the following lines to the manuscript:

To account for through-thickness shear effects in the buckling analysis of sandwich panels, both critical buckling loads (compression and shear) are modified following (Kassapoglou, 2013):

$$N_{x\mathrm{crit}} = \frac{N_{E\mathrm{crit}}}{1 + \frac{k N_{E\mathrm{crit}}}{t_c G_c}}$$

where tc and Gc denote the core thickness and transverse shear modulus, respectively, and k is the shear correction factor, set to $k \approx 1$. This choice is conservative for sandwich panels, where the core shear stiffness is low relative to that of the face sheets (Kassapoglou, 2013).

From the material volume point of view, it is not profitable for a fabric manufacturer to set up the machines for a limited amount of material production. The wind turbine blade industry serves a cost-driven market. Standardization of fabrics reduces the manufacturing cost and effort, while enhancing alternatives in terms of supply. Moreover, the drapability of the fabric is not to be underestimated. The dry fabric must be laid in the mold and follow the difficult contours. Thus, an arbitrary fiber selection which folds due to its nature, or is “stiff” might be inappropriate for manufacturing purposes.

We understand and agree with the remark. For this reason, we restricted our investigation to the blade shell, given its multipurpose structural role. Furthermore, the shell laminate was constrained to be uniform along the blade span, in line with the considerations regarding manufacturing effort and cost. This choice is analogous to the use of triaxial laminates, especially since we show in the paper that a triaxial fabric can be interpreted as a DD laminate with unoptimized angles, thus not introducing additional manufacturing complexity. We added the following sentences to the manuscript (line 65):

A key advantage is tapering: building blocks can be dropped to transition between neighboring panels without symmetry constraints - which is a common practice in the blade's industry, thereby not introducing any complexity to the current standpoint.

If "tapering" is meant only as a thickness variation, then this comment is not valid. If through "tapering" an angle variation along the blade length, then another counter side of the analysis is that it neglects the increase in the blade manufacturing complexity, which again speaks for increased costs.

Tapering is only a matter of ply drop-off, thickness variation.

Finally, substituting the Triax with a DD material not only affects stiffness, but it also affects the failure mode, which changes from fiber-dominated to matrix-dominated. That increases the risk of a brittle catastrophic failure even with a single crack initiation.

Please see comments above and the updated conclusion and outlook. We addressed that matrix-dominated damage mechanisms could exhibit for the present DD case with ±37°, since it lacks a third fiber orientation and is therefore not statically determined. A first study considering a constraint that enforces a minimum difference between the DD angles (here 30°), indicates a mass increase of 0.8t compared to the ±37° DD case, while still maintaining a 2t mass advantage over the triax configuration. Further research on double-double laminates is needed to better understand their susceptibility to matrix-dominated damage mechanisms.

(Line 50): Concerning your literature survey, what were the optimization criteria behind the referenced papers? For example, does the other research consider major design drivers, like fatigue, to optimize their stacking sequence? A more critical review of the literature should be presented, rather than a list presentation. I cannot imagine designing a blade with 5.8° off-axis spars without having severe fatigue issues.

Indeed, the studies reviewed in this work did not consider fatigue constraints, which is consistent with the scope of the problem we address, namely the development of a framework that enables multiple material descriptions within a sandwich assembly, including the use of DD laminates. Nevertheless, we fully understand and agree with the concern raised. As stated above, we added a simplified fatigue criterion as max. strain and re-run all simulations.

There is only one study about fatigue of DD laminates which we refer to in line 554 Vasconcelos et al. (2025). This shows the need for further research on fatigue of DD laminates as stated in our new outlook section.

(Line 227): The proposed Kirchhoff-Love plate theory does not account for transverse shear, which is the instability driver for thick-composite sandwich structures. How are you coping with that?

Please see also the comment above. We extended our buckling criterion for the sandwich cases to take into account through- thickness shear effects according to Kassapoglu 2013 (FSDT). Furthermore we extended the outlook section with following paragraph:

– Through-thickness shear effects were incorporated into the buckling criterion in a simplified manner (k = 1, see sub-section 4.4). A more rigorous treatment should adopt advanced lamination theories such as the First-Order Shear Deformation Theory (FSDT) or Mindlin–Reissner theory, which better capture shear deformation in thicker sandwich laminates. Additionally, the reference plane should be set to the mould surface rather than the mid-plane to improve the accuracy of the predicted bending stiffness.

(Line 275): By implementing a higher-order shear theory, would your approach still be valid?

It is clear that the CLT underestimates deflections for thick laminate, predicting too high stiffness and also for thick sandwich structures it is only limited suitable. As mentioned above, we extended our buckling criterion for the sandwich cases taking into account through-thickness shear effects using the FSDT. We observed that the transverse shear affects all use-cases (also the reference) in a similar manner.

(Table 7): In what you presented, the multi-parametric framework allows wind blade skins (only thin) to be treated like aerospace composite structures, and when applied to a large blade it naturally converges to slightly off-axis DD laminates that soften the structure in shear and compression, reducing mass by ~10%; in this particular case the optimal solution might remain manufacturable because it collapses to a simple repeated building block. Would this always be the case, or might we end up with variable angles all over blade segments, which makes manufacturing a lot more complicated if not impractical?

The DD angles in this study were enforced to be the same along the blade, following also applications in aerospace industry, which one set of two angles is imposed for the whole designed structure, not to pose impractical manufacturing challenges. We created the DD Local case showing the potential of varying DD angles over the blade shell, which is from its nature not manufacturable.

When substituting Triax plies with DD laminates, how will you cope with the risk of a brittle matrix crack? The whole root will be in severe danger.

As stated in the outlook section, matrix-dominated damage mechanisms could exhibit for the present DD case with $\pm 37^{\circ}$, since it lacks a third fiber orientation and is therefore not statically determined. A first study considering a constraint that enforces a minimum difference between the DD angles (here 30°), indicates a mass increase of 0.8t compared to the $\pm 37^{\circ}$ DD case, while still maintaining a 2t mass advantage over the triax configuration. Further research on double-double laminates is needed to better understand their susceptibility to matrix-dominated damage mechanisms.

In summary, the paper presents an elegant and mathematically rigorous framework for composite panel optimization and introduces interesting methodological concepts with clear potential value for structural design. These might be relevant for more automated manufacturing procedures, like in the aerospace industry, where, additionally, composite structures are substantially thinner. At the same time, these structural assumptions limit its direct applicability to real wind turbine blades, particularly with respect to thick sandwich mechanics, fatigue performance, damage risk, and manufacturing constraints. Addressing these aspects more explicitly and moderating claims regarding industrial relevance would significantly strengthen the paper and clarify its contribution to the wind energy community.

We thank you for your constructive feedback and hope that we could strengthen the paper with the updated results based on the additional integrated criteria for sandwich buckling fatigue and matrix damage.

Appendix:

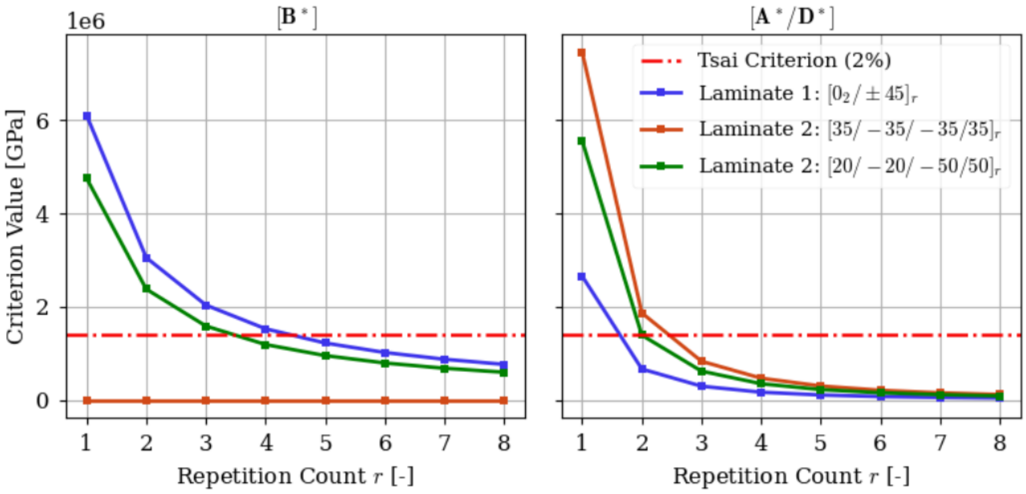

Figure 2. Design space of DD laminates in the V_1^A–V_2^A plane.

Corrected material properties:

Table 2. Mechanical properties of composite and isotropic materials used in the CRC-15-240 blade. Composite values from Camarena et al. (2022).

Property	Uniaxial glass	Biaxial glass	Triaxial glass	Uniaxial carbon	Foam
E_1 [GPa]	43.70	11.02	28.21	157.6	0.1425
E_2 [GPa]	16.50	11.02	16.24	9.1	0.1425
E_3 [GPa]	15.45	16.05	15.84	9.1	0.1425
G_{12} [GPa]	3.495	13.23	8.248	4.131	–
G_{13} [GPa]	3.480	3.488	3.491	4.131	–
G_{23} [GPa]	3.480	3.488	3.491	2.689	–
ν_{12} [-]	0.262	0.6881	0.4975	0.3133	0.3194
ν_{13} [-]	0.264	0.1172	0.1809	0.3133	0.3194
ν_{23} [-]	0.35	0.1172	0.2748	0.4707	0.3194
X_t [MPa]	640.23	46.21	435.63	1285.0	2.083
X_c [MPa]	–370.7	–70.69	–343.1	–878.2	1.563
Y_t [MPa]	38.1	46.21	76.44	38.1	2.083
Y_c [MPa]	–82.18	–70.69	–174.7	–82.18	1.563
S [MPa]	30.17	124.5	85.06	30.17	1.250
R [MPa]	18.97	18.97	18.97	18.97	1.250
T [MPa]	6.21	6.21	6.21	6.21	1.250
ρ [kg/m^3]	1940	1940	1940	1600	130

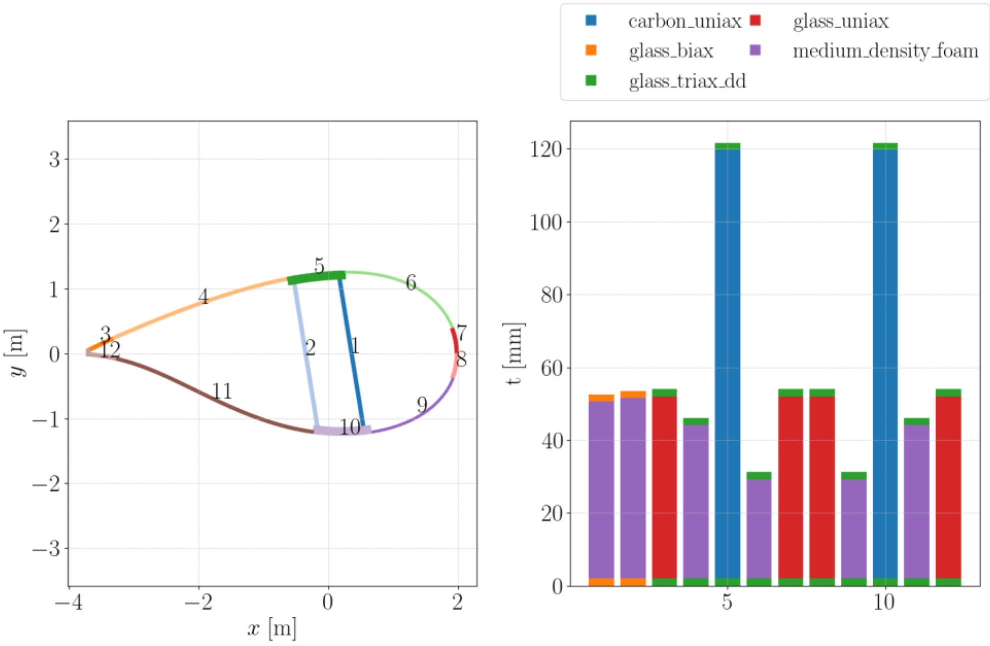

Figure 25. Section at 19% span.