

A Multi-Parametric Composite Approach for the Optimization of Wind Turbine Blades using Double-Double Laminates

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Abstract. As wind turbines scale to meet growing energy demands, blade structures face increasingly demanding performance requirements. This work addresses this challenge by extending the design space of composite blades through the substitution of traditional triaxial laminates with Double-Double (DD) laminates. While triaxial laminates are widely used due to their convenient layup and manufacturability, they are rarely scrutinized in literature and often lead to suboptimal structural performance.

5 To enable this substitution, a multi-parametric composite modeling approach is developed and integrated into a gradient-based optimization framework. This architecture enables the coexistence of discrete and continuous laminate formulations within a single panel, allowing for detailed, skin-wise optimization of sandwich structures. The approach is applied to a modified blade design of the IEA-15-240 Reference Wind Turbine. Results demonstrate that DD laminates provide a more effective design, resulting in significant mass savings in the shell structure.

10 1 Introduction

As wind turbines evolve to support greater energy supply, scaling rotor size has become essential to maximizing power output. The Annual Energy Production (AEP) increases proportionally to the square of the blade radius (Gasch and Tvele, 2012), whereas blade mass scales to the power of around 2.4 with the blade radius (Rosemeier and Krimmer, 2022). This imbalance creates a structural challenge: increasing blade length raises the aerodynamic potential, but also increases mass and loads.

15 Composite materials have been fundamental in counteracting these trends. Beyond a high strength-to-weight ratio, their mechanical response can be tailored to the dominant load paths through ply orientation and stacking sequence. Unlike isotropic metallic alloys, fiber-reinforced laminates enable control of directional stiffness and coupling, improving structural efficiency. As a result, modern blades rely predominantly on composites, which account for approximately 93% of their structural weight (Liu and Barlow, 2017).

20 Although reinforced plastics offer significant potential for weight reduction, they also introduce challenges in design, analysis, optimization, and manufacture. Beyond selecting the fiber composition and matrix material, the layup configuration must be defined, including ply angles, stacking order, and thickness distributions.

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

25 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.

Aligned with industry trends and the demand for a new baseline in the 10–20 MW range, the IEA Wind TCP Task 37 introduced the IEA 15 MW RWT in March 2020—an offshore turbine intended to push the state of the art (Gaertner et al., 2020).
30 To accommodate higher power capture, the blade length and mass were scaled to 117 m and 65 t, respectively. Structurally, the design follows a traditional layout with two main spars and spar caps, complemented by shear webs that extend from 10% to 95% of the blade span. The triaxial glass laminate covers most of the structure, while the shear webs are reinforced with biaxial glass fibers. The internal volume, apart from key load-bearing components, is filled with medium-density foam in a sandwich configuration to limit weight. The trailing and leading edges feature a uniaxial glass laminate, while the spar caps
35 employ uniaxial carbon laminate as the core material. The structural concept is shown in Figure 1.

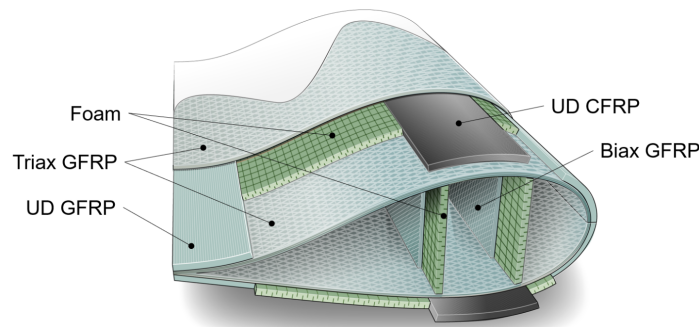


Figure 1. IEA 15 MW structural concept. Source: (Werthen et al., 2023).

Beyond the specific architecture of the IEA 15 MW, the selection of laminate materials reflects a consistent trend across successive reference models—dominated by triaxial laminate applications. Early designs, such as the NREL 1.5 MW, 3 MW, and 5 MW reference wind turbines (Rinker and Dykes, 2018), extensively employed triaxial glass laminates, wrapping both the shell and spar webs. More recent baselines, including the DTU 10 MW (Bak et al., 2013), IEA 10 MW (Bortolotti et al.,
40 2019), IEA 15 MW (Gaertner et al., 2020), and IEA 22 MW (Zahle et al., 2024), retain triaxial laminates primarily on the shell, while the spar webs employ biaxial laminates. Despite this evolution, triaxial materials still represent a substantial share of the overall blade mass.

A typical triaxial layup follows the sequence $[-45^\circ/0^\circ/+45^\circ]$, comprising roughly 50% unidirectional (0°) and 50% off-axis ($\pm 45^\circ$) plies (Camarena et al., 2022). This configuration is attractive for its balanced response under general loading,
45 providing in-plane shear resistance, bending stiffness, and improved buckling performance (Castro, 2018). However, its near-generic character limits the tailoring of stiffness and directional coupling. For this reason, triaxial laminates are often adopted in less optimized industrial contexts due to their simplicity and generality (Samborsky and Mandell, 1996).

Building on the reference models, several studies explored blade optimization under different design settings. Sjølund and Lund (2018) optimized only the thickness of a variety of layers on a 73.5 m blade and achieved a 19.4% mass reduction. Serafeim et al. (2022) tailored spar-cap stiffness by rotating the UD fibers, obtaining a 5.8° off-axis solution and an 8.3% reduction on the DTU 10 MW blade. Hayat et al. (2022) conducted material and thickness optimization of the spar caps (glass, hybrid, carbon), reporting a reduction of up to 26.4%, consistent with the spanwise strategy adopted in the IEA 15 MW baseline. Scott et al. (2022) optimized the IEA 15 MW using thickness laws, material mix, and spar-cap position; however, under frozen loads, they required a 34.7% mass increase to recover stability. Extending stiffness tailoring, Couto et al. (2023) used region-wise laminate optimization with discrete angle sets but remained constrained by the limited orientations.

The vast, discrete design space of composite laminates intrinsically motivates simplifications in their description and design. Most commonly, ply orientations are fixed, and only thickness is scaled (e.g., (Sjølund and Lund, 2018; Hayat et al., 2022; Scott et al., 2022)); in other cases, the space is restricted to a small discrete set of angles, reducing tailoring margin (e.g., (Couto et al., 2023)). A similar pattern appears in aeronautics, where quad-laminates—an extension of triax with an added 90° ply—are widely used; they deliver behavior closer to metallic alloys but at the cost of a more complex design and optimization pipeline (Tsai, 2021).

To address these limitations, Tsai (2021) introduced the Double-Double laminate class. A DD is defined by two angles (Φ, Ψ) forming the four-ply building block $[\pm\Phi, \pm\Psi]_r$ repeated r times. This yields a continuous, balanced parameterization with straightforward homogenization, making design and optimization less complex. A key advantage is tapering: building blocks can be dropped to transition between neighboring panels without symmetry constraints, a common practice in the blade industry, thereby not introducing any complexity to the current standpoint. 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.

Almeida et al. (2025) surveyed the use of DD laminates across applications and discussed their implications. 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%. Zerbst et al. (2025) integrated a DD plate formulation into a gradient-based optimization environment for composite structures called *lightworks* (Dähne et al., 2024) and validated it on a wing-box case. These results highlight the weight-saving potential of DD laminates across aerospace structures and their initial integration into *lightworks*.

Extending this capability to wind-turbine blades requires higher modeling fidelity, as blade panels are typically sandwich structures composed of multiple materials through the thickness. In practice, outer face sheets may follow a continuous DD description, whereas cores remain discrete laminates. Representing such combinations requires a clear parameterization strategy, in which each constituent material defines its own design variables, while consistently contributing to the overall panel response. To support this requirement, a modular and multi-parametric plate formulation is introduced. It allows for the independent parameterization of sub-components and their integration into a unified structural layer. This approach accommodates both continuous and discrete laminates within the same stack and enables replacing conventional triaxial skins with DD laminates. This way, expanding the design space towards more adaptable stiffness behavior.

1.1 Objectives

In light of the above, 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.

To make this substitution viable within sandwich panels, a multi-parametric composite approach is introduced and implemented in the *lightworks* optimization environment. The approach models sandwich structures as modular assemblies of independently parameterized sub-composites, enabling materials with different structural foundations, such as layer-based and continuous formulations, to coexist across the panel thickness.

This work naturally follows as a continuation of the study by Werthen et al. (2023), who employed *lightworks* for large-scale blade optimization using a simplified sandwich representation, in which each component (e.g., a triaxial laminate) was modeled as a single equivalent layer in the stack. In contrast, the present approach expands the formulation to incorporate DD laminates, which is demonstrated on the CRC-15-240 blade, an in-house modified version of the IEA-15-240 reference wind turbine. This constitutes the first application of DD laminates in wind turbine blade design and represents a step forward in advancing composite optimization for the wind industry.

1.2 Structure of the paper

The development of this work is organized into three consecutive phases, each addressing a distinct layer of the proposed methodology. All implementations are subjected to verification and testing, with feedback loops guiding refinements at each stage.

The first phase focuses on DD laminates as replacements for the triax. It includes reviewing the mechanical role and limitations of triaxial laminates, characterizing the stiffness and failure behavior of DD configurations, performing parametric load studies, and implementing a restricted “hard” variant with fixed $\Phi = 0^\circ$ for intermediate optimization tests.

The second phase extends the *lightworks* structural model to support multi-parametric composites. This involves developing a class to handle modular stacking, implementing algorithms for stiffness assembly and load distribution through the thickness, and integrating the formulation into the structural and optimization pipeline.

The third phase applies the methodology to the CRC-15-240 blade, demonstrating the practical use of the multi-parametric framework and DD laminates in large-scale optimization. This involves adapting auxiliary tools to the framework and analyzing outcomes in terms of mass reduction, design-space expansion, and material property distribution along the span.

The subsequent sections of this study are organized as follows. Section 2 investigates DD laminates in comparison to triaxial laminates. Section 3 introduces the multi-parametric approach and demonstrates it through a single-panel case. Section 4 applies the methodology to the CRC-15-240 blade, detailing the optimization setup. Section 5 presents a comparative assessment of results. Finally, Section 6 summarizes the key findings.

2 Characterization of DD and Triaxial Laminates

115 The DD laminate concept, introduced by Tsai (2021), represents a significant advancement in the efficient design of composite structures. Based entirely on the Classical Laminate Theory (CLT), its formulation requires no additional assumptions and, notably, removes the need for mid-plane symmetry, traditionally imposed to avoid bending-extension coupling, simplifying design and manufacturing constraints.

120 A typical DD laminate is composed of repeated Building Blocks (BBs), each containing four plies arranged in two balanced angle pairs of Φ and Ψ . Among the possible stacking options, the configuration $[\Phi / -\Psi / -\Phi / \Psi]$ has been shown to yield superior homogenization characteristics (Tsai, 2021), and is therefore adopted throughout this work. The complete laminate is formed by repeating this block r times through the thickness, resulting in the configuration $[\pm\Psi / \pm\Phi]_{rT}$, where the subscript T denotes the total stack, following the Nettles convention (Nettles, 1994).

2.1 Homogenization

125 The main advantage of DD laminates lies in their potential for homogenization: as the number of building blocks increases, the bending and extensional stiffness matrices ($[\mathbf{D}]$ and $[\mathbf{A}]$) approach proportionality, while the coupling matrix ($[\mathbf{B}]$) tends toward zero. The resulting structure exhibits a layer-position-independent response with minimal coupling between in-plane and out-of-plane behaviors.

As reported in Zerbst et al. (2025), the normalized matrices exhibit characteristic dependencies on r . These trends indicate 130 that with increasing r , the off-diagonal terms of $[\mathbf{B}^*]$ decay as $1/r$, while specific coupling terms in $[\mathbf{D}^*]$ vanish at a rate of $1/r^2$. To formalize this, Tsai (2021) elaborated two conditions to be met for assumed homogenization:

$$\forall i, j \in \{1, 2, 6\} : |A_{ij}^* - D_{ij}^*|, |B_{ij}^*| < \alpha \cdot \text{TSAI} \quad (1)$$

where α is a prescribed fraction of the Tsai modulus, defined as the trace of the ply stiffness matrix $[\mathbf{Q}]$ ($\text{TSAI} = \text{Tr}[\mathbf{Q}]$). Acting as a threshold to define acceptable levels of coupling and stiffness mismatch, Tsai (2021) recommends $\alpha = 0.02$.

135 Once these conditions are met, the laminate behavior can be approximated using only the extensional stiffness matrix $[\mathbf{A}]$, and the bending stiffness $[\mathbf{D}]$ can be derived as:

$$[\mathbf{A}] = \sum_{k=1}^4 \left([\bar{\mathbf{Q}}]_k \frac{t_{\text{lam}}}{4} \right), \quad [\mathbf{B}] = \mathbf{0}, \quad [\mathbf{D}] = \frac{t_{\text{lam}}^2}{12} [\mathbf{A}], \quad (2)$$

where $[\bar{\mathbf{Q}}]_k$ denotes the transformed reduced stiffness matrix of the k -th ply in the building block, dependent on $\pm\Phi$ or $\pm\Psi$.

Figure 2 shows that Tsai's homogenization criterion is satisfied for both the Triax and two DD laminates at four repetitions 140 r . Since a DD laminate is defined by two angle pairs $[\pm\Psi / \pm\Phi]$, a Triax fabric can be interpreted as a DD laminate with $[0/0 / -45 / +45]$ as a single repetition r . The criterion depends solely on the number of repetitions, not on individual ply thickness, as the $[\mathbf{ABD}^*]$ matrices are normalized by the laminate thickness t_{lam} .

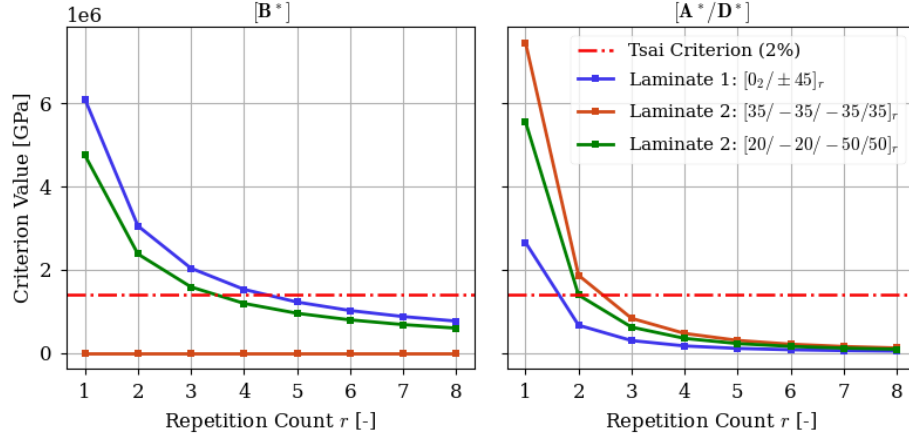


Figure 2. Homogenization criterion values for Triax and two DD laminates as a function of repetition count r .

2.2 Design Space

According to Tsai and Melo (2015a), any laminate can be described through lamination parameters: a continuous stiffness
 145 representation grounded in invariant theory. To characterize the design space of DD laminates relative to conventional triaxial configurations, their formulation is briefly recalled.

The general formulation of the lamination parameters (V_x^A, V_x^B, V_x^D) can be expressed as follows, in accordance with Zerbst et al. (2025):

$$V_x^A = \frac{1}{t_{\text{lam}}} \sum_{k=1}^N (z_k - z_{k-1}) W_x, \quad (3)$$

$$150 \quad V_x^B = \frac{1}{t_{\text{lam}}^2} \sum_{k=1}^N (z_k^2 - z_{k-1}^2) W_x, \quad (4)$$

$$V_x^D = \frac{4}{t_{\text{lam}}^3} \sum_{k=1}^N (z_k^3 - z_{k-1}^3) W_x, \quad (5)$$

where z_k is the distance from the k -th ply to the laminate mid-plane, and W_x are trigonometric functions of the ply angle θ :

$$W_x = \begin{cases} \cos(2\theta_k), & x = 1, \\ \sin(2\theta_k), & x = 2, \\ \cos(4\theta_k), & x = 3, \\ \sin(4\theta_k), & x = 4. \end{cases} \quad (6)$$

For a homogenized DD laminate, this formulation simplifies considerably. All coupling-related lamination parameters
 155 $V_{1,2,3,4}^B$ vanish, and due to the proportional nature of $[\mathbf{A}]$ and $[\mathbf{D}]$, the bending parameters equal the extensional ones ($V_x^A =$

V_x^D). The resulting formulation thus reduces to four unique values, among which only V_1^A and V_2^A (and their bending counterparts) vary with the fiber angles Φ and Ψ :

$$V_1^A = \frac{1}{2}[\cos(2\Phi) + \cos(2\Psi)] = V_1^D, \quad (7)$$

$$V_2^A = \frac{1}{2}[\cos(4\Phi) + \cos(4\Psi)] = V_2^D, \quad (8)$$

$$160 \quad V_3^A = 0 = V_3^D, \quad V_4^A = 0 = V_4^D, \quad V_{1,2,3,4}^B = 0. \quad (9)$$

Thus, the entire design space of a DD laminate can be visualized in the V_1^A – V_2^A plane, where each admissible combination of the angle pair $\{\Phi, \Psi\}$ maps to a specific point. Figure 3 illustrates the full DD design space, as mathematically described in Zhao et al. (2023).

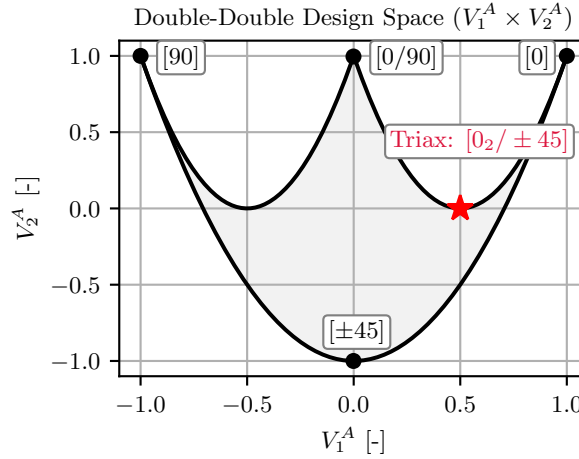


Figure 3. Design space of DD laminates in the V_1^A – V_2^A plane.

An important aspect to highlight is the role of the lamination parameter V_2^A . Laminates with $V_2^A \geq 0$ are classified as hard
165 laminates due to their greater resistance to normal stresses, whereas those with $V_2^A < 0$ are called soft laminates, exhibiting improved shear and buckling performance.

A typical triaxial laminate can be interpreted as a particular case of the DD configuration, though with a stacking arrangement $[\pm 0 / \pm 45]$ that is not optimal for homogenization (Tsai, 2021). Owing to its position along the vertical axis of the design
170 improving its shear and buckling resistance. Despite their practicality, triaxial laminates are ill-suited to optimization: they are fixed at a single point in the lamination-parameter space, enforcing a predefined normal–shear compromise. As a result, their capacity to adapt to specific load cases is limited, unless the optimal solution coincidentally aligns with the same fiber orientations.

2.3 Strength Criterion

175 For discrete laminates, strength evaluations are typically performed at the ply level (i.e., Tsai-wu criterion). However, when employing a continuous homogenized formulation, ply-level evaluation becomes inconsistent with the design representation. In this context, a laminate-level failure criterion is essential to maintain continuous formulation without layup reconstruction.

One laminate-level alternative is the strain-based omni-envelope criterion proposed by Tsai and Melo (2015b). This method is derived from the classical quadratic failure criterion in stress space and reformulated in strain space. The general form of the failure condition is expressed as:

$$H_{ij}\varepsilon_i\varepsilon_j + H_i\varepsilon_i = 1 \quad (10)$$

where H_{ij} and H_i are material-dependent coefficients derived from strain invariants. These coefficients depend on the stiffness matrix and ply orientation, and their derivation is detailed in Kappel (2023).

The omni-envelope extends the ply-level criterion by superimposing the strain-space envelopes of unidirectional plies across all fiber orientations present in the laminate, following the Tsai-wu criterion (Kappel, 2022). The result is a global strain envelope that represents the union of all individual failure surfaces. Zerbst et al. (2025) discusses its use for DD laminates using *lightworks*.

2.4 Design Space Exploration under In-Plane Loads

Under distinct loading conditions, DD laminates adjust their angles to optimize the response in relation to a specific objective (e.g. mass), exploring the full design space capacity previously shown in Figure 3. This analysis considers only strength constraints, provided by the omni-envelope criterion, and disregards any stability assessment. The focus remains exclusively on material-level response.

The exploration includes pure and combined loading conditions involving uniaxial (n_x) and shear loads (n_{xy}): a scenario similar to the wind turbine blade application explored in this study. The load cases are summarized in Table 1.

Table 1. In-plane load combinations used for design space exploration.

Case #	Name	n_x [N m ⁻¹]	n_{xy} [N m ⁻¹]
1	UD Tension	$+1.0 \times 10^6$	0
2	UD Compression	-1.0×10^6	0
3	Pure Shear	0	2.0×10^5
4	Tension + Shear	$+1.0 \times 10^6$	5.0×10^5
5	Compression + Shear	-1.0×10^6	5.0×10^5

195 Under axial tension and compression (Cases #1 and #2), the optimized DD laminate aligns both fiber angles with the load direction, defined here as $\Phi = \Psi = 0^\circ$, since the fibers act as the primary load carriers. Figure 4 illustrates the resulting

mass distribution across different angle combinations: while the DD laminate converges to the optimal alignment, the triaxial configuration remains fixed, with one angle aligned with the load and the other offset by 45° , resulting in a mass increase. The compressive case exhibits nearly identical behavior, differing only in allowable limits due to the material's higher tensile

200 strength.

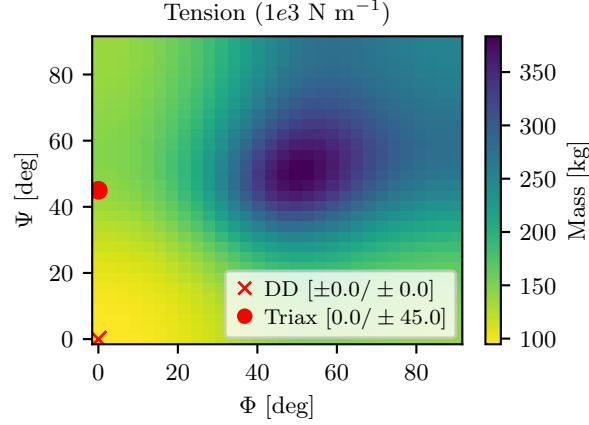


Figure 4. Optimized mass distribution for the DD laminate under axial tension.

When subjected to pure shear (Case #3), the optimal stacking shifts toward intermediate angles, with 45° emerging as the dominant orientation, as shown in Figure 5. This response reflects classical shear mechanics, where maximum shear stress (τ_{12}) is resolved along $\theta = 45^\circ$ planes, producing a corner-driven deformation mode that is best resisted by fibers oriented in those directions. Once more, the triax shows mass increase due to additional non-optimized 0° plies.

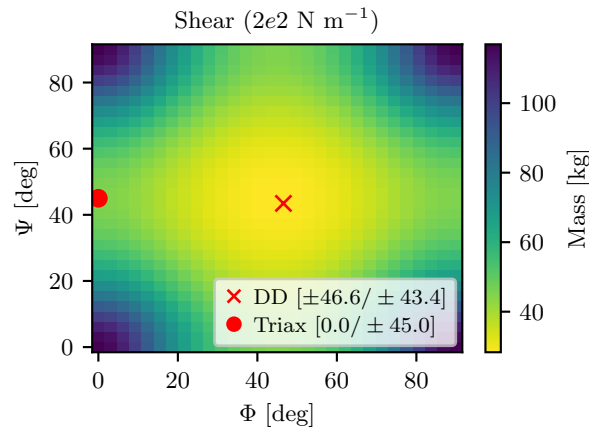


Figure 5. Optimized mass distribution for the DD laminate under pure shear loading.

205 In the tension–shear case (Case 4#), shown in Figure 6, the optimal fiber angles shift toward lower values, corresponding to the hard-laminate region. The solution remains offset from the $(0,0)$ coordinate, with both Φ and Ψ lying between 0° and 45° . This trend is consistent with the pure tension and pure shear responses previously observed in Figure 4 and Figure 5.

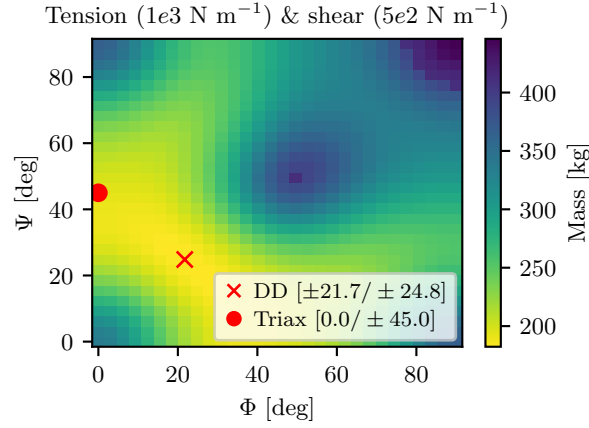


Figure 6. Optimized mass distribution for the DD laminate under combined tension and shear loading.

Conversely, the compression–shear interaction (Case 5#), illustrated in Figure 7, produces a markedly different result. The optimized angles shift toward higher values, which increases the off-axis orientation and, as a consequence, generates larger
 210 transverse normal stress σ_2 .

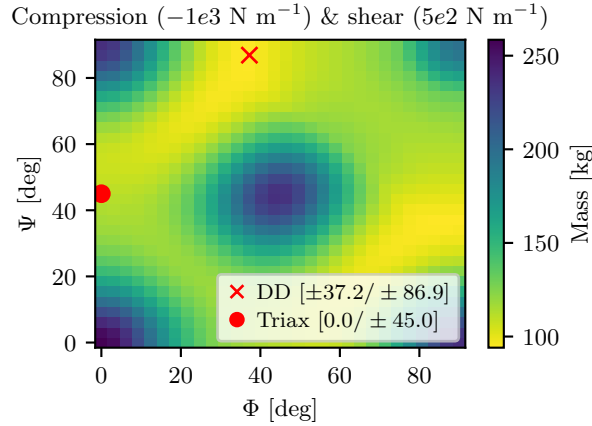


Figure 7. Optimized mass distribution for the DD laminate under combined compression and shear loading.

This behavior follows directly from the Tsai–Wu interaction terms, shown in Figure 8: the shear strength is coupled with the transverse normal stress, such that moderate compression in the 2-direction increases the effective shear strength. Physically,

this corresponds to the fibers being laterally constrained by the matrix, which delays shear-driven failure. However, once σ_2 becomes sufficiently large, the quadratic compression term dominates, and the allowable shear strength drops again. This mechanism explains why the proportion n_x/n_{xy} is critical for determining the optimal angle shift in this case.

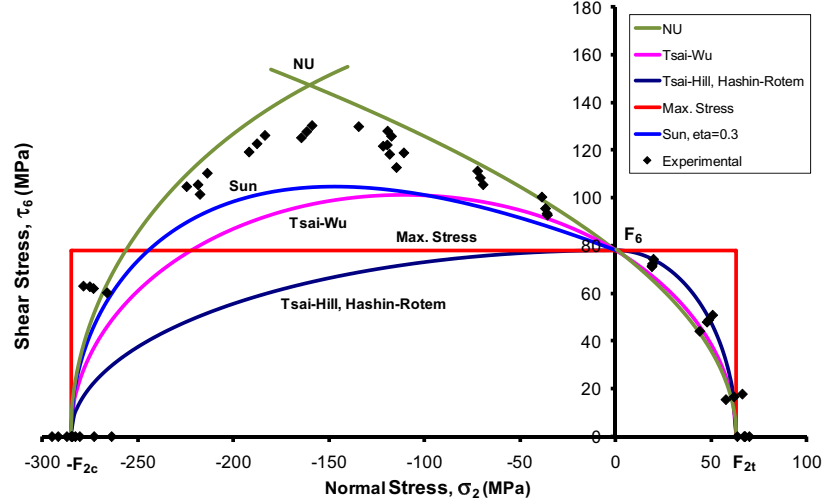


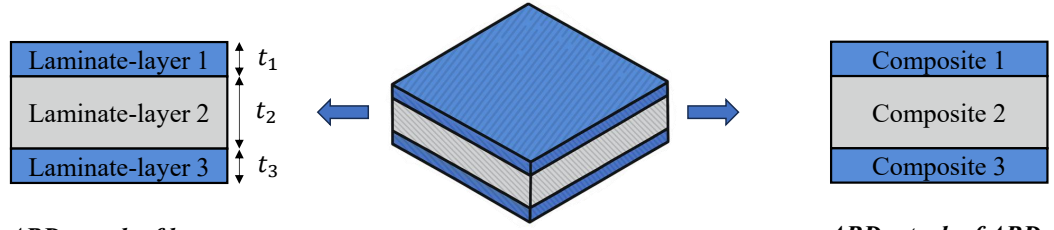
Figure 8. Tsai–Wu τ_{12} – σ_2 failure envelope. Source: Daniel et al. (2011).

These results underscore that stiffness-based tailoring, even in its simplified form, captures design freedoms that are unexplored by triaxial laminates, whose fixed fiber arrangement constrains their ability to adapt to varying loads.

3 Multi-Parametric Composites

Conventional structural models in structural optimization, such as those used in previous large-blade studies, describe each panel through a set of homogenized layers (e.g. Sjølund and Lund (2018); Hayat et al. (2022); Scott et al. (2022); Werthen et al. (2023)). While efficient, this approach simplifies the internal composition of sandwich structures into equivalent layers within a laminate, typically limited to three homogenized materials.

The multi-parametric formulation introduces a modular description of composite panels (Figure 9). Each panel is decomposed into a stack of independently parameterized sub-composites, each retaining its own material model and design variables. This structure allows, for example, Double–Double laminates to coexist with unidirectional or foam components within the same stack. Design variables are defined at the composite level, enabling independent control of each sub-component’s parameters, such as fiber angles and thickness, without constraining them to a single, homogenized behavior. Whereas conventional models assemble stiffness from individual laminate layers, the new approach computes and superimposes the stiffness of each composite sub-component, maintaining analytical consistency while expanding the design space available for optimization.



ABD: stack of layers

ABD: stack of ABDs

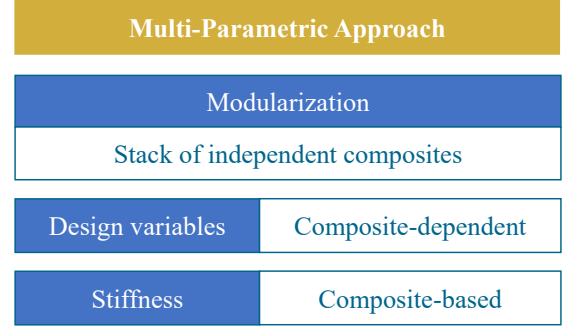
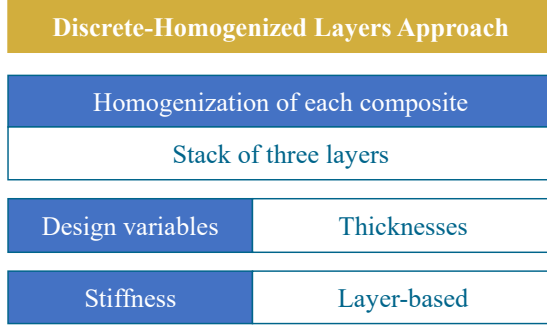


Figure 9. Conceptual comparison between the discrete-homogenized and multi-parametric formulations.

230 3.1 Stiffness Superposition

To enable a generalized treatment of stiffness for any combination of composite formulations, the stack must be interpreted as a sequence of materials, each characterized solely by its stiffness matrix, thickness, and position across the panel's thickness. This abstraction enables the creation of a global stiffness matrix $[\mathbf{ABD}]_{\text{global}}$ from various combinations of materials, regardless of whether the underlying model is discrete or continuous. As long as each material supplies its individual stiffness matrix $[\mathbf{ABD}]_{\text{local}}$ and total thickness, the modular integration remains intact.

The core principle enabling stiffness superposition is the analytical shift of the reference plane for each component, from its original mid-plane, as defined in Classical Laminate Theory, to a common reference shared across all material blocks. This alignment allows for the consistent transformation of stiffness contributions, enabling their direct summation into a global stiffness matrix. The entire process is fully grounded in the CLT without introducing any additional assumptions.

240 Figure 10 illustrates the concept of an arbitrary reference plane shift for a single laminate.

For such a shift, the position of any point along the thickness can be expressed as:

$$z^{\text{new}} = z^0 + \Delta z, \quad (11)$$

where z^0 is the coordinate with respect to the original reference plane, Δz is the signed offset between the planes, and z^{new} is the transformed coordinate relative to the new reference.

245 Using this definition, the transformed stiffness matrices $[\mathbf{A}^{\text{new}}]$, $[\mathbf{B}^{\text{new}}]$, and $[\mathbf{D}^{\text{new}}]$ can be defined as:

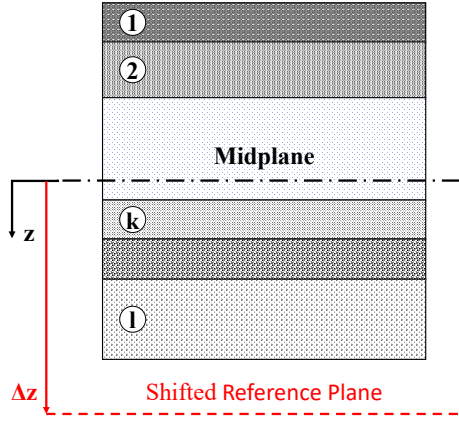


Figure 10. Plane shift from the original mid-plane.

$$[\mathbf{A}^{new}] = \sum_k [\bar{\mathbf{Q}}_k] [z_{k-1}^{new} - z_k^{new}], \quad (12)$$

$$[\mathbf{B}^{new}] = -\frac{1}{2} \sum_k [\bar{\mathbf{Q}}_k] [(z_{k-1}^{new})^2 - (z_k^{new})^2], \quad (13)$$

$$250 \quad [\mathbf{D}^{new}] = \frac{1}{3} \sum_k [\bar{\mathbf{Q}}_k] [(z_{k-1}^{new})^3 - (z_k^{new})^3]. \quad (14)$$

By substituting Equation 11 into Equations 12, 13 and 14, and expanding each term, the transformed stiffness matrices can be written as functions of the original matrices (0) and the shift Δz . The resulting transformations are shown below, while their derivations are provided in Appendix A:

$$\begin{aligned} [\mathbf{A}^{new}] &= [\mathbf{A}^0], \\ [\mathbf{B}^{new}] &= [\mathbf{B}^0] + \Delta z [\mathbf{A}^0], \\ [\mathbf{D}^{new}] &= [\mathbf{D}^0] + 2\Delta z [\mathbf{B}^0] + \Delta z^2 [\mathbf{A}^0]. \end{aligned}$$

(15)

255 Once the $[\mathbf{ABD}]$ formulation is derived with respect to an arbitrary reference plane, the superposition of multiple composites can be consistently established. Figure 11 illustrates a generic stack composed of multiple material blocks, each contributing to the overall stiffness, given the plane shift to a common one.

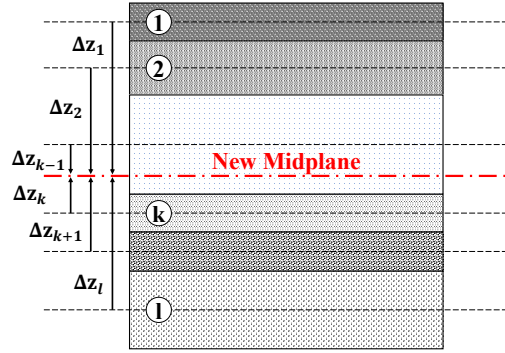


Figure 11. Superposition of different composite blocks.

In general, the mould (and aerodynamic) surface should be used as the reference plane along the z -axis to avoid overestimation of the bending stiffness. In the present study, the reference is set to coincide with the mid-plane of the whole stack, consistent with the plate formulation in which loads and deformations are defined relative to the mid-plane. The resulting superposition is given in Equations 16, 17, and 18.

$$[\mathbf{A}] = \sum_k [\mathbf{A}_k^0] \quad (16)$$

$$[\mathbf{B}] = \sum_k ([\mathbf{B}_k^0] + \Delta z_k [\mathbf{A}_k^0]) \quad (17)$$

$$[\mathbf{D}] = \sum_k ([\mathbf{D}_k^0] + 2\Delta z_k [\mathbf{B}_k^0] + \Delta z_k^2 [\mathbf{A}_k^0]) \quad (18)$$

265 3.2 Load Distribution

In the context of structural assessment, stability and strength evaluations operate at distinct hierarchical levels. Stability is assessed at the panel level, based on the global geometry, stiffness matrix, and applied loads. Once the governing criterion is defined, the procedure follows a fixed analytical pipeline dependent solely on these macroscopic parameters. Strength evaluation, in contrast, is performed at the material level to capture the behavior of each constituent composite. This requires distributing the global load state across the components of the stack so that each sub-composite is assessed independently, based on its local strain field and failure criterion.

From the solver, each panel receives a set of membrane forces and bending moments, which serve as input loads for subsequent evaluations. For strength assessment, these loads are converted into strain quantities through inversion of the $[ABD]$ matrix, following the plate stiffness relation described in VDI (2014).

275 4 CRC-15-240 Blade Optimization

The blade analyzed in this study is based on the structural layout of the IEA-15-240 Reference Wind Turbine. This reference configuration features a blade span of approximately 117 meters and a total mass of 65 t. Structurally, the blade comprises two main spars, along with leading edge (LE) and trailing edge (TE) reinforcements, all extending from 10% to 95% of the span.

Internally, the structure combines triaxial glass fiber laminates in the outer shell with core materials that vary along span and
280 circumference. UD Carbon laminates are used in the spar caps to provide high bending stiffness with minimal added mass, while UD Glass layers reinforce the leading and trailing edges under edgewise loading. Foam cores occupy the space between spar caps and edge reinforcements beyond the root, improving buckling resistance and bending stiffness. The shear webs are also built as sandwich panels, using biaxial glass face sheets bonded to foam. Figure 12 illustrates this composition at four representative cross-sections along the blade span.

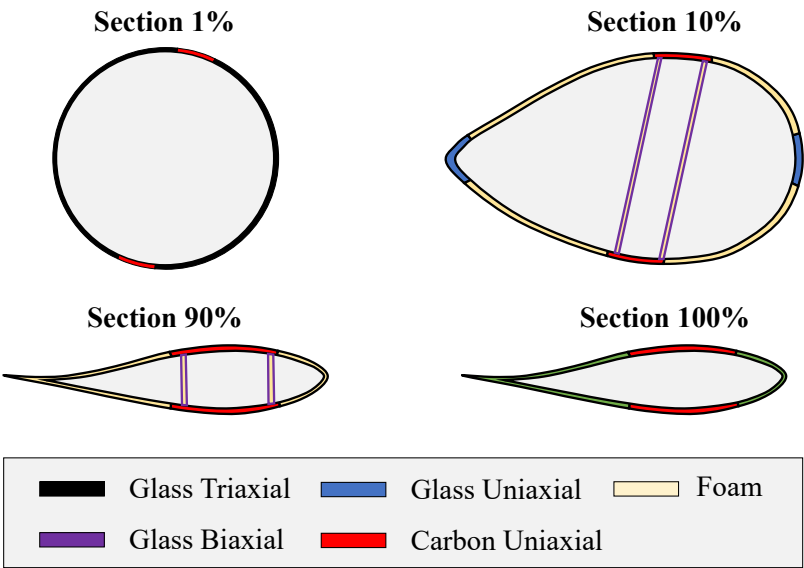


Figure 12. Cross-section schematics for different spanwise locations in the CRC-15-240 blade.

285 The IEA-15-240 material dataset provides a solid reference basis but contains a few undefined parameters, including Poisson’s ratios for biaxial and triaxial glass laminates, as well as some missing properties for the unidirectional carbon material. To enable a comprehensive structural assessment, the CRC-15-240 blade utilizes the material definitions from the IEA-22-240

Reference Wind Turbine (Zahle et al., 2024), which provides an updated dataset developed by Camarena et al. (2022). For all laminates, the material coordinate system is defined such that the E_1 direction is oriented spanwise, tangential to the shell reference surface. The values used in this study are summarized in Table 2.

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

Moreover, panel-level analyses of the baseline model reveal localized instability near the blade tip, where spar caps taper and the leading and trailing edge reinforcements are discontinued, as reported by Scott et al. (2022). To mitigate this effect and increase bending stiffness in these regions, the CRC-15-240 model introduces foam cores where the reinforcements are absent, thereby maintaining a continuous sandwich configuration along the blade span.

The following sections describe the complete simulation and optimization framework employed for the CRC-15-240 blade. Simulation Setup details the aeroelastic analyses, load processing procedures, and the solver–optimizer integration environment. Structural Model Initialization introduces the spanwise and circumferential discretization of the blade. Loading and Boundary Conditions summarizes the design load cases and the procedure for extracting the load envelopes. Coupling and Constraints specifies the structural requirements imposed during the optimization process. Finally, Parametrization and Optimization Setup presents the parametrization strategies adopted in the analysis and provides an overview of the optimization workflow.

4.1 Simulation Setup

The simulation and optimization of the CRC-15-240 blade are conducted using a modular pipeline that integrates aeroelastic simulation, load processing, structural modeling, and gradient-based optimization. The overall workflow is shown in Figure 13, illustrating the data exchange between the main tools involved.

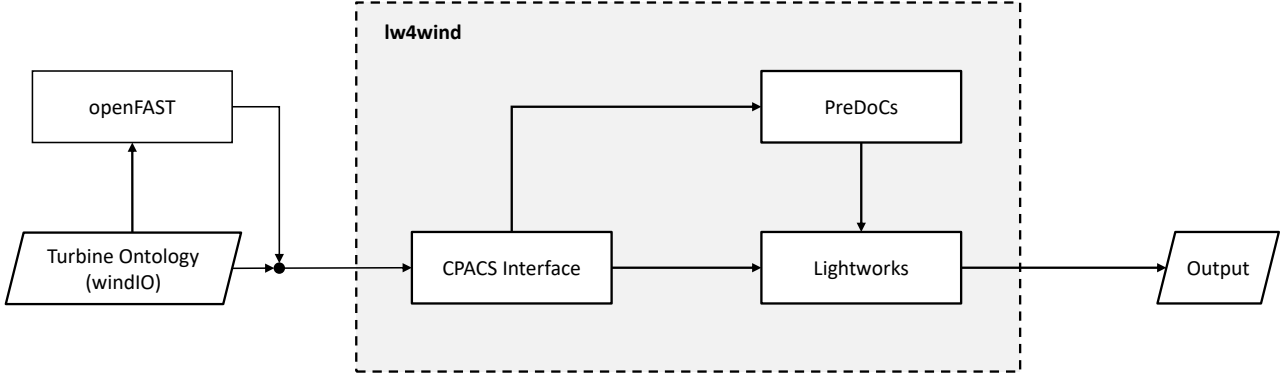


Figure 13. Simulation methodology.

At the core of this process lies the `lw4wind`¹ environment, which manages communication between all modules. The simulation begins with an aeroelastic analysis in OpenFAST, generating time series of aerodynamic and inertial loads along the blade span. These results are then embedded into a WindIO file (Bortolotti et al. (2022)), an ontology scheme that defines the storage of wind turbine engineering parameters in a hierarchical yaml structure.

After load embedding, the pipeline proceeds to the structural modeling stage. The WindIO file is parsed through the CPACS interface, which performs the format conversion and initializes the structural solver *PreDoCS*. This stage defines the spanwise structural representation of the blade and sets up the optimization problem.

PreDoCS (Preliminary Design of Composite Structures, (Werthen et al., 2024)) performs the structural analysis of the blade as a continuous anisotropic beam governed by Timoshenko theory. During initialization, the blade span is discretized into cross-sectional stations, for which section properties and fully coupled 7×7 stiffness matrices are assembled. The solver computes the spanwise displacement field under applied external loads, from which internal loads are recovered using the cross-sectional stiffness relations described by Jung and Nagaraj (2002).

Once initialized, *lightworks* takes over the local structural representation, mapping each beam section to a detailed set of composite panel models. During optimization, *PreDoCS* and *lightworks* operate in parallel: *PreDoCS* provides the individual panel load states, while *lightworks* evaluates local stiffness, strength, and stability responses. Following convergence, the optimization results are post-processed.

¹Short for “*Lightworks* for Wind”

4.2 Structural Model Initialization

After conversion of the blade geometry to the CPACS format, the model is segmented into structural panels. Circumferentially, each cross-section is divided into regions following WindIO conventions, which define the structural layout illustrated in Figure 12 for different span positions.

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 an important role in composite panels design. 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.

In addition to spatial control, the sections are aligned with the blade's actual load axis, which follows the curved blade geometry. The resulting model is visualized in Figure 14.

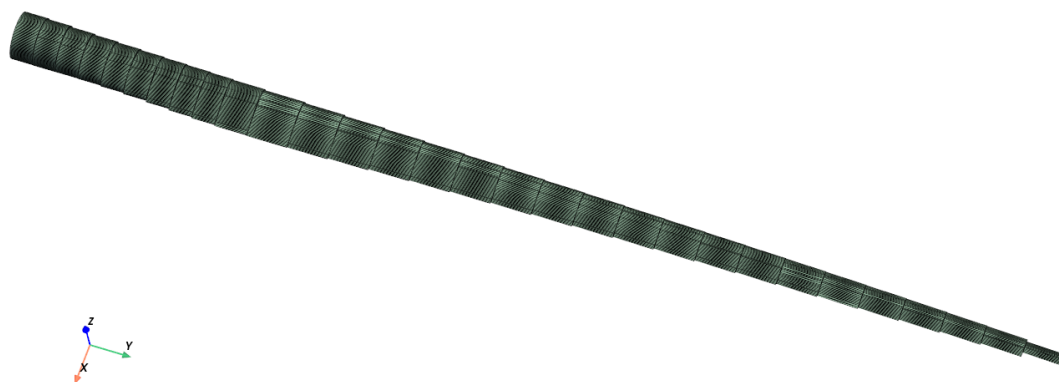


Figure 14. Structural discretization of the CRC-15-240 blade in *PreDoCS*.

4.3 Loading and Boundary Conditions

The loads used in this analysis represent the transient response of the nominal IEA-15-240 reference model. Aero-servo-elastic simulations are performed in OpenFAST using the ElastoDyn module, which applies an Euler–Bernoulli beam formulation with two bending modes: flapwise and edgewise deflections (Rinker et al., 2020). Building upon the structural analysis of the scaled 22 MW blade presented by Werthen et al. (2023), a reduced subset of design load cases is defined in accordance with the guidelines of DNVGL-ST-0376 (DNV GL, 2015a). The selected load cases are summarized in Table 3.

Table 3. Design load cases and corresponding wind speeds used in the simulation.

DLC number	Description	Mean wind speeds (m/s)
DLC 1.5	Extreme wind shear (vertical, positive and negative horizontal wind shear)	10.6 (rated)
DLC 1.6	Power production, NTM	10, 13, 18, 21
DLC 6.1	Extreme wind, 50-year storm, yaw misalignment of $\pm 8^\circ$	50

340 For each load case, time series of aerodynamic and inertial loads are post-processed to extract the critical design conditions. Following the DNVGL-ST-0376 guideline (DNV GL, 2015a), envelopes of all force and moment components are generated by evaluating their minimum and maximum values, including additional bending moments computed in the flap–edgewise plane at 30° intervals from 0° to 180° . The corresponding time steps associated with the maximum flapwise and edgewise tip deflections are also included.

345 4.4 Coupling and Constraints

The model is subject to five categories of constraints: coupling, strength, stability, taper, and deflection. A safety factor of 1.5 is applied to all evaluated constraints, whereas coupling relations are enforced directly and therefore excluded from this factor, following the definitions adopted by Werthen et al. (2023).

Coupling relations are applied to ensure consistent material behavior across the blade. Intra-panel coupling enforces sym-
350 metry through the sandwich thickness, mirroring the outer composite about the mid-plane while maintaining the uniqueness of the core. Inter-panel coupling links corresponding composites between the upper and lower shells, ensuring material symmetry despite their geometric differences. These relations remain fixed throughout the optimization.

Strength constraints are applied at the composite level and depend on the specific class of each material. For those modeled as single-ply laminates, the Tsai-Wu criterion (Amabili, 2018) is employed, widely used in structural analysis and optimization
355 studies due to its computational efficiency and limited material parameter requirements. For DD laminates, the Omni-Envelope criterion is adopted, as detailed in subsection 2.3. Finally, the foam cores, due to their isotropic behavior, are evaluated using the von Mises criterion.

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):

$$360 \quad \frac{R_d}{\gamma_m} = 0.35\% \quad (\text{tensile}), \quad (19)$$

$$\frac{R_d}{\gamma_m} = 0.25\% \quad (\text{compression}) \quad (20)$$

where 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.

Stability constraints are evaluated at the panel level to account for local buckling under axial compression and in-plane shear. Assuming an orthotropic and symmetric laminate, the critical buckling load per unit width under compression is given by (Structural Analysis Working Group I, 2009, HSB-45112-02) as:

$$N_{x,cr} = k_x \left(\frac{\pi}{b} \right)^2 \sqrt{\tilde{D}_{11} \tilde{D}_{22}}, \quad (21)$$

and, for shear-dominated buckling, by (Structural Analysis Working Group I, 2009, HSB-45111-08) as:

$$N_{xy,cr} = k_s \left(\frac{\pi}{b} \right)^2 \sqrt[4]{\tilde{D}_{11} \tilde{D}_{22}^3}. \quad (22)$$

Here, $\tilde{D}_{11}$ and $\tilde{D}_{22}$ denote the laminate's effective bending stiffness terms, while k_x and k_s are the buckling coefficients for compression and shear, respectively. These coefficients are interpolated from the provided curves, assuming simply supported boundary conditions for all panel edges to yield conservative estimates.

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):

$$N_{x/xy,cr,new} = \frac{N_{x/xy,cr}}{1 + \frac{k N_{x/xy,cr}}{t_c G_c}}, \quad (23)$$

where t_c and G_c 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).

Since both axial and shear loads act simultaneously, the overall stability assessment combines the two modes through the interaction criterion proposed by (Peters, 1954):

$$R_x + R_s^2 \leq 1, \quad (24)$$

where R denotes the ratio between the applied and critical load for each mode.

Tapering constraints prevent abrupt thickness variations between adjacent panels. All materials satisfy the DNVGL-ST-0376 requirements (DNV GL, 2015a), except for the shell face sheets, which show a localized acute thickness drop near the root-mid-span transition where spars and reinforcements are introduced. Following Tsai (2021), a specific constraint is applied to the DD laminates, allowing taper ratios up to 7.5:1.

Deflection constraints are added to all use cases to limit the maximum allowable blade tip displacement under extreme load cases. These constraints ensure the tower clearance of the blades.

4.5 Parametrization and Optimization Setup

Each panel in the blade is initialized with a multi-parametric scheme that enables multi-layer sandwich configurations composed of distinct sub-components, allowing each layer to be parametrized independently. Glass unidirectional, biaxial, and unidirectional carbon laminates are modeled as transversely isotropic single plies, while the foam core is treated as isotropic. These composites are optimized solely by their thicknesses across different panels.

The main innovation is the substitution of the triaxial glass laminates with Double–Double laminates, moving from a ho-
 395 mogenized $[0_2/\pm 45]$ stacking to a configuration composed of unidirectional glass plies, which can be tailored in thickness and
 stiffness through the ply angles (Φ, Ψ) . To ensure consistent comparison, the baseline case also employs the DD formulation
 with fixed angles $[0/\pm 45]$, equivalent to the nominal triaxial stacking and part of the DD design space (Figure 3). This substi-
 tution removes inconsistencies in material properties and strength criteria, allowing all configurations to be assessed within a
 unified modeling approach.
 400 Building upon this baseline, a series of simulation cases is defined with increasing levels of design freedom regarding the
 DD skin parametrization. The different optimization scenarios are shown in Table 4.

Table 4. Comparison of DD laminate configurations and variable definitions.

Config.	Description	Number of variables	Remarks
Triax	DD laminate with fixed 0° , 45° an- gles	1 thickness per section	Basis case, mimicking triax lami- nates
DD-Hard	DD laminate with fixed 0° , and Ψ variable	1 thickness per section and 1 global angle	DD with hard behavior restriction
DD	DD laminate with variable Φ and Ψ	1 thickness per section and 2 global angles	Classic DD
DD-Local	DD laminate with individualized set of angles per cross-section	1 thickness per section and 2 angles per section	Idealistic case, stiffness benchmark case

In all cases except DD-Local, the fiber angles are uniform across all panels, meaning each panel adopts the same globally
 optimized orientation. Only the laminate thicknesses vary along the blade span. The locally optimized case is introduced to
 explore the potential of angle tailoring per cross section along the blade in response to localized structural demands. While not
 405 directly manufacturable, this configuration provides insights into the maximum achievable performance through local stiffness
 adaptation.
 An overview of the materials employed in the CRC-15-240 blade and their corresponding parametrization strategies is
 presented in Table 5.

Table 5. Material models and parametrization strategies in the CRC-15-240 optimization.

Material	Region	Parametrized Properties	Remarks
UD Glass	LE/TE reinf. core	Thickness	Transversely Isotropic
UD Carbon	Spar cap	Thickness	Transversely Isotropic
Biaxial Glass	Web face sheet	Thickness	Transversely Isotropic
Foam	Web/Shell core	Thickness	Isotropic
Glass DD	Shell face sheet	Thickness, Φ , Ψ	Orthotropic

Table 6. Optimization formulation scheme.

	Constraint/Variable	Description	Bounds
Minimize	m	Mass of ...	
On the basis of	n_x, n_{xy}	Panel loads (Axial forces, shear)	
With respect to	Φ in [deg]	First double double angle	[0, 90]
	Ψ in [deg]	Second double double angle	[0, 90]
Subject to	$g_{stability}$	Panel buckling	≤ 0
	$g_{strength}$	Strength Omni-FPF	≤ 0
	$g_{fatigue}$	Max. strain in fiber direction	≤ 0

The optimization aims to minimize the total structural mass of the blade, subject to strength, simplified fatigue, stability, taper, deflection, and coupling constraints. The problem is solved using the Sparse Nonlinear OPTimizer (SNOPT), a gradient-based sequential quadratic programming algorithm that solves large-scale constrained problems through iterative quadratic approximations. Preliminary tests showed that SNOPT achieved more robust convergence than the Interior Point Optimizer (IPOPT) and the Method of Moving Asymptotes (MMA). The solver parameters follow standard definitions, except for the feasibility and optimality tolerances, which are set to 10^{-4} . For the usage of gradients, a check of the robustness of the results against varying initialization and perturbations has to be performed. Optimizations are started from different DD angle combinations like described in Zerbst et al. (2025). The mass optimum could be achieved with a reliability of over 90%. The overall optimization framework is summarized in Table 6.

5 Results

The optimization outcomes for all design cases are summarized in Table 7. The triaxial and DD-Hard configurations yield nearly identical masses which indicates that the 0° plies dominate the overall stiffness, while the second angle exerts only a minor influence. In contrast, introducing full angular freedom in the DD case results in a mass reduction of 4% (2800 kg) relative to the triaxial baseline, highlighting the relevance of full directional control of the fiber orientations. The DD-Local case, which permits section-wise variation of Φ and Ψ , achieves an additional improvement of 1.38% (1000 kg) compared to the DD case.

The optimized fiber orientations show a general shift toward softer laminates in the direction of $\pm 45^\circ$, reflecting a compromise between spanwise stiffness and buckling resistance. This trend is illustrated in Figure 15, which maps each configuration onto the lamination parameter design space.

The Triax configuration remains fixed, while the DD-Hard model slightly increases the second angle to reduce axial stiffness along the span. Despite this adjustment, both configurations exhibit similar stiffness behavior, positioned within the “hard”

Table 7. Comparison of mass and optimized angles for each design case.

Parameter	Triax	DD-Hard	DD	DD-Local
Mass [t]	75.5	75.35	72.7	71,7
Φ [deg]	0	0	37.0	–
Ψ [deg]	45	48.6	37.0	–

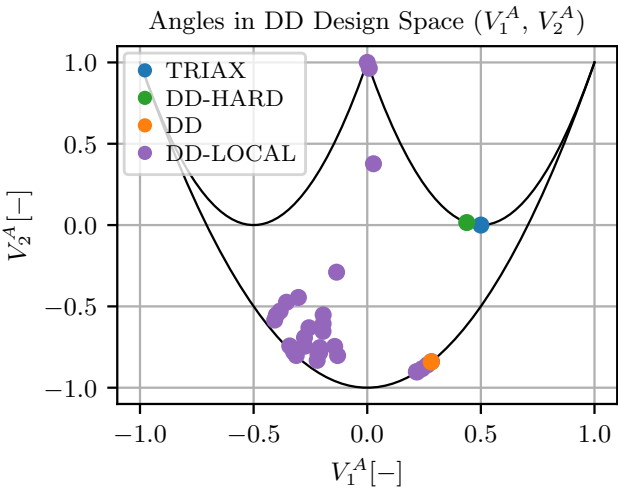


Figure 15. Case-related stiffness in LP design space

430 region identified by Tsai (2021). This explains the marginal difference in their optimized masses, as the limited variation of approximately 3.5° in the second angle produces only minimal changes in stiffness.

In contrast, the DD case, where both angles are freely optimized, is driven toward the softer region of the lamination parameter space, near the $\pm 45^\circ$ boundary of the feasible domain. This reflects a structural preference for combining spanwise stiffness with shear and buckling resistance, with Φ and Ψ converging to approximately 37° . The DD-Local case follows a
435 similar trend for most panels, though softer angles are adopted in the trailing edge panels of the rear shell to prevent local buckling, and 90° orientations appear near the maximum chord region (at 27 m), contributing edgewise bending stiffness in this region.

The spanwise mass distribution for all configurations is presented in Figure 16. The influence of laminate stiffness tailoring is evident: shell stiffness directly governs the structural mass profile. The Triax and DD-Hard cases exhibit nearly identical
440 distributions.

Nevertheless, the total mass difference between the Triax and DD cases amounts to 2800 kg. The root region, marked by a significant mass drop, accounts for approximately 70% of the total reduction (1960 kg), while the remaining 30% (840 kg) is

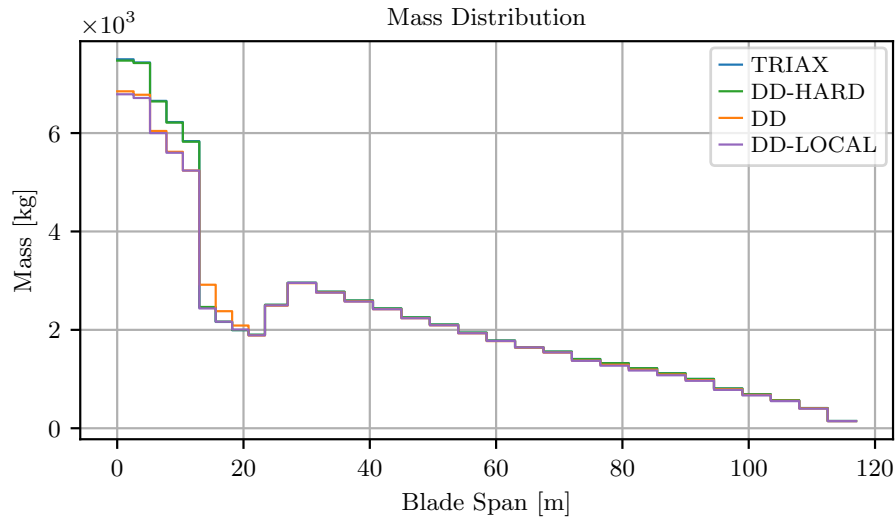


Figure 16. Spanwise distribution of mass.

distributed along the mid-span and tip. This concentration of mass reduction near the root highlights its dominant role in the optimization, driven by the region’s structural simplicity and exposure to high loads. It consists solely of two spar-cap cores
445 and two face-sheet layers, making it highly sensitive to stiffness adjustments.

Between the DD and DD-Local models, a distinct trend emerges: the DD-Local configuration achieves a lower mass between the root and max. chord. This behavior reflects the additional flexibility of the DD-Local setup, which allows localized stiffness adaptation.

This is further evidenced by Figure 17: in the cylindrical root region, the DD-Local angles cluster around 37° , coinciding
450 with the globally optimized DD solution. Since this region contributes the largest share of mass savings, it dominates the global optimum for the DD case — when a single angle pair is enforced across the entire blade, the optimizer converges to the value that minimizes mass in the most weight-critical zone. Beyond the root, where spars and reinforcements assume the primary load-bearing role, the DD-Local case adapts its angles to local structural demands and diverges from the one-angle solution.

Figure 17 shows that in the cylindrical root region, the DD-Local angles cluster around 37° , coinciding with the globally
455 optimized DD solution. Since this region contributes the largest share of mass savings, it explains the global optimum for the DD case: a single angle pair enforced across the entire blade naturally converges to the value that is most beneficial in the most weight-critical zone. Beyond the root, where spars and reinforcements assume the primary load-bearing role, the DD-Local case adapts its angles to local structural demands, and the two solutions diverge. Nevertheless, 37° remains the most effective uniform configuration overall.

460 Given that the DD-Hard configuration shows limited gains relative to the triaxial baseline, it confirms that restricting $\Phi = 0^\circ$ leaves little room for stiffness tailoring. As DD-Hard and DD-Local serve as boundary references — the former a near-triaxial

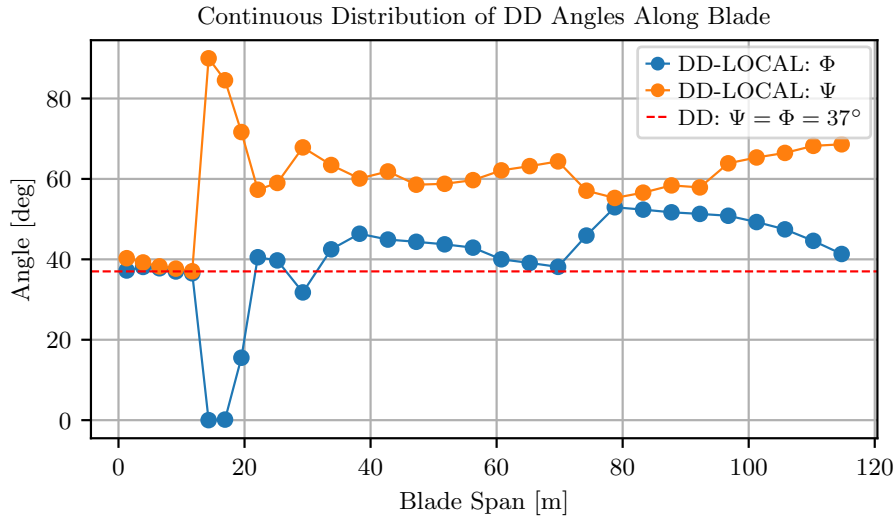


Figure 17. Spanwise distribution of fiber angles for the DD-Local case.

constraint, the latter an idealized stiffness benchmark — the following analysis focuses on the Triax and DD cases as the most meaningful comparison.

5.1 Comparative Analysis of Triaxial and DD Configurations

465 The thickness profiles provide a direct physical interpretation of how laminate architecture influences mass distribution. Figure 18 compares the spar-cap and shell-skin thicknesses for the Triax and DD configurations. Near the root, within the cylindrical section, the $[0_2, \pm 45]$ layup exhibits a 7% greater shell-skin thickness than the $[\pm 37, \pm 37]$ configuration. Conversely, the DD layup requires a 2%–6% greater spar-cap thickness through the transition region toward maximum chord. This trade-off highlights how laminate orientation affects not only its own stiffness but also the material demand in adjacent structural

470 components.

After the cylindrical sections, the shell skin thickness shows a progressive loss of structural relevance, as spars and edge reinforcements assume the primary load-bearing function. A marked reduction occurs at the 6th section (6th step in Figure 18), limited by the tapering ratio 7.5. For the triaxial skin, the thickness decreases from 37.3 mm to 5.5 mm over the local span; for the DD configuration, it decreases from 32.7 mm to 8.2 mm, both matching the allowable slope. By the 9th section, both skins

475 attain their minimum allowable thicknesses of 2.0 mm.

Given the root section’s significant mass contribution and the strong influence of DD angles, this region is analyzed in more detail. The stiffer the laminate is in the direction of load application, the greater the expected concentration of membrane forces. This effect is evident in Figure 19, where axial loads N_x concentrate within the spar-cap region due to the thick unidirectional CFRP layers.

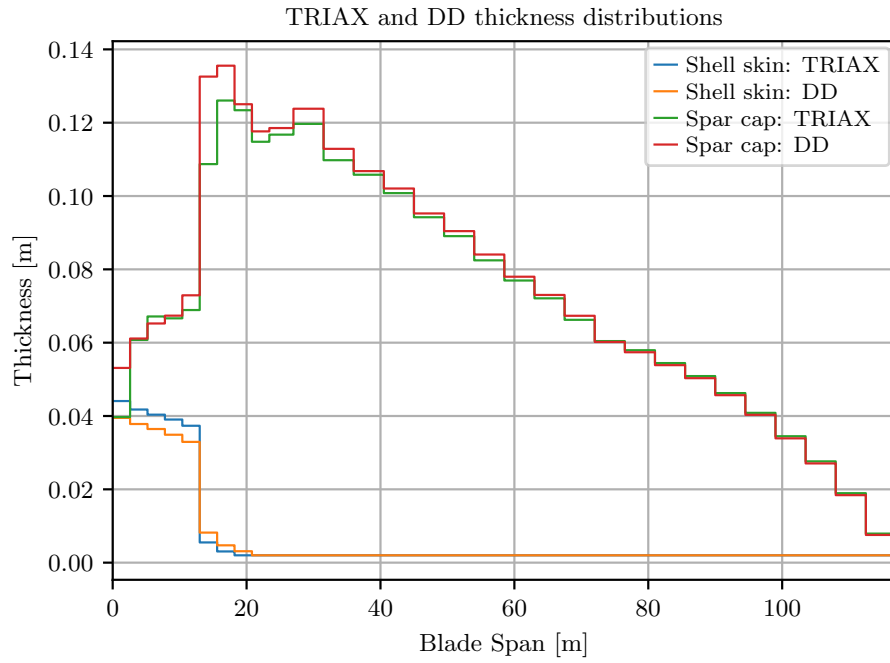


Figure 18. Thickness distribution of spar cap and shell skin

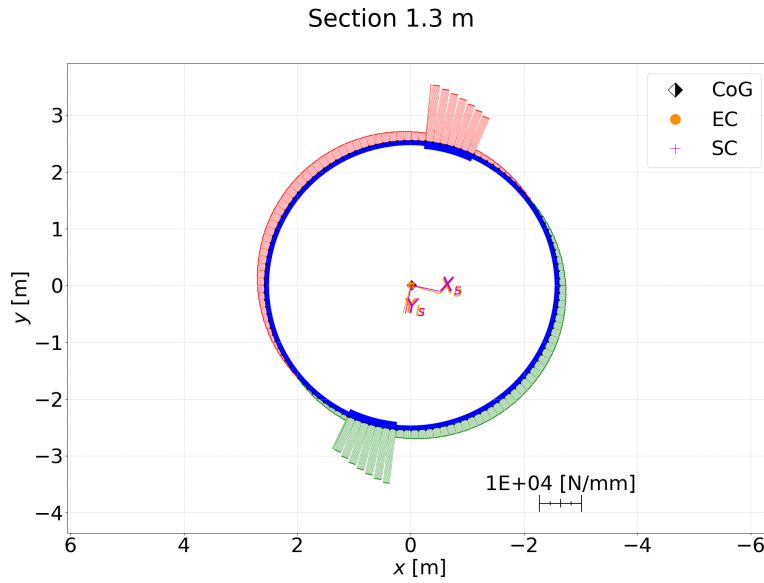


Figure 19. Axial force distribution (N_x) for the critical minimum edgewise moment case (Triax and DD).

480 However, the triaxial laminates contain a larger portion of 0° plies, which concentrate excessive axial stiffness in the face sheets. Considering the superior strength-to-weight ratio of CFRP and the structural role of the spar cap, this behavior contradicts the most efficient stiffness distribution. As shown in Figure 20, the spar cap remains far from the constraint threshold of 0, while the shell operates at its limits. Consequently, the optimizer first increases the spar-cap thickness to relieve part of the load carried by the shell, which acts as a sinking component. In addition, the 0° -dominated layup provides poor buckling
 485 resistance, further requiring local thickening of both the spar-cap and shell face sheets.

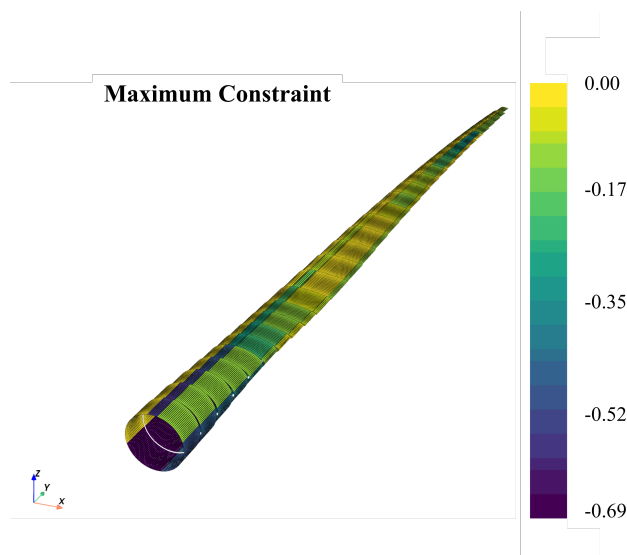


Figure 20. Constraint contour distribution for the Triax case.

In terms of trailing and leading edge reinforcements, as shown in Figure 21, they follow a similar overall trend for both the Triax and DD configurations. Reinforcements are generally thinner in the Triax case, primarily due to the additional axial stiffness provided by the 0-degree plies in the skin. In contrast, the DD configuration lacks this axial reinforcement from the skin, and the UD core must compensate for this, resulting in thicker reinforcements.

490 Given the redistribution of loads between shell skins, spar-cap cores, and LE/TE reinforcements, spanwise variations in blade stiffness can occur. As shown in Figure 22, some minor change in flapwise stiffness occurs near the root, where the DD is softer due to its reduced spar-cap thickness. Beyond this region, the spar-cap thicknesses in both configurations converge, leading to similar stiffness trends along the remaining span. In contrast, the edgewise stiffness distribution exhibits a larger root-region offset, even though both configurations converge along the span. In edgewise bending, the spar cap contributes less
 495 to stiffness, shifting the dominant role to the reinforcements and shell skins. The Triax skin, with its higher axial stiffness, therefore provides greater support, particularly at the root and near the tip where LE and TE reinforcements terminate. In these regions, the skin dominates the edgewise response.

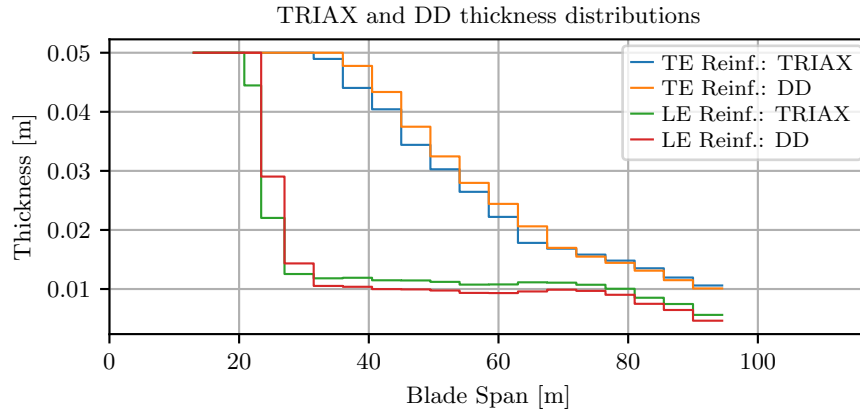


Figure 21. Thickness distribution of TE and LE reinforcements

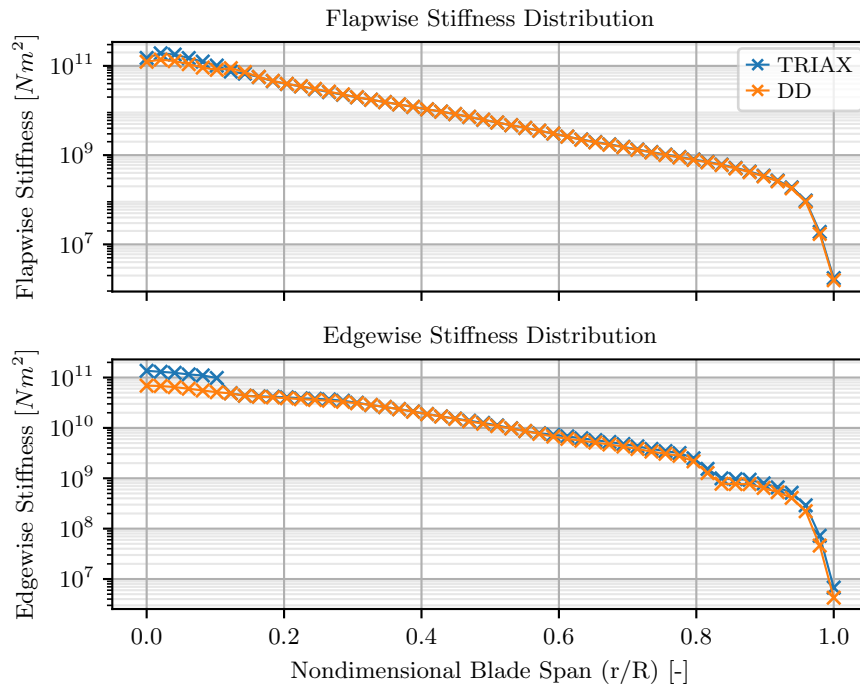


Figure 22. Flapwise (upper) and edgewise (lower) stiffness distributions for both configurations.

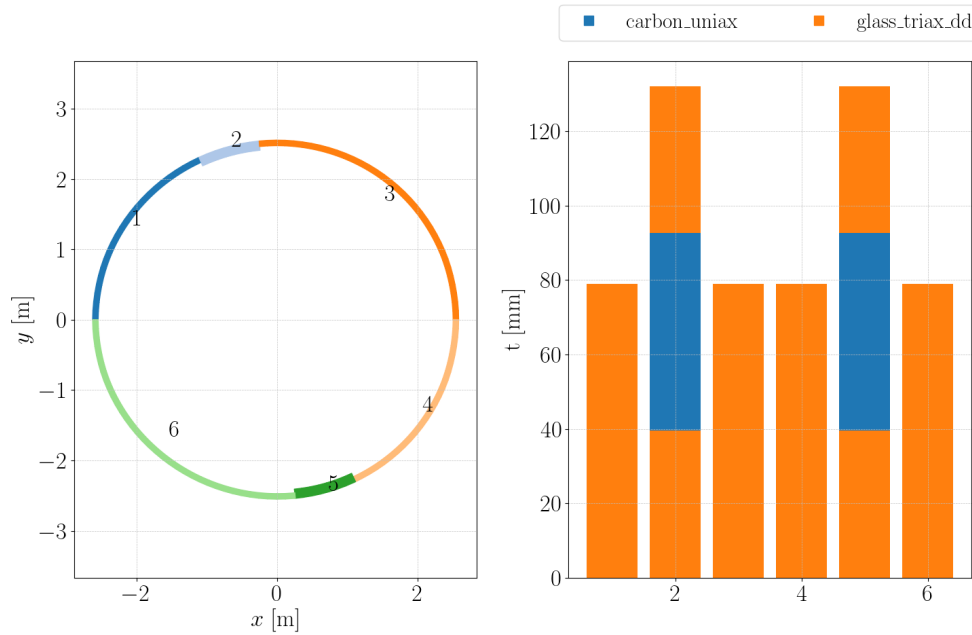


Figure 23. Section at 1% span.

5.2 In-Depth Analysis of the Optimized DD Blade

Near the root (Figure 23), the configuration reveals a structurally simple yet heavily reinforced section. The high material density in this region reflects its critical role in load transfer, particularly through the spar cap and shell skin. The skin plays a dominant role in this area and benefits the most from optimization, as previously discussed.

Progressing outward, Figure 24 illustrates the transition in structural composition with the introduction of foam cores, UD Glass reinforcements, and the shear webs. Among the layups originating from the root, only the spar cap maintains the same thickness distribution trend. In contrast, the shell skin rapidly decreases in thickness and structural relevance, in line with the shift toward spar- and reinforcement-dominated load paths. The foam core has its highest thickness value at 19 % of the span shown in Figure 25.

The section at 83 % span, shown in Figure 26 illustrates the increasingly simplified structural layout of the blade as it approaches the tip. The introduction of foam at the leading and trailing edges reflects a modification incorporated into the CRC-15 blade to enhance local bending stiffness in a region where the UD glass is already tapered out. Notably, the foam cores are not reduced to their minimum allowable thickness, indicating their structural relevance in mass saving.

A key characteristic of the IEA-15-240 design is its material symmetry between the pressure and suction sides. Although the outer geometry is aerodynamically asymmetric, each upper-surface structural panel has a mirrored counterpart on the lower

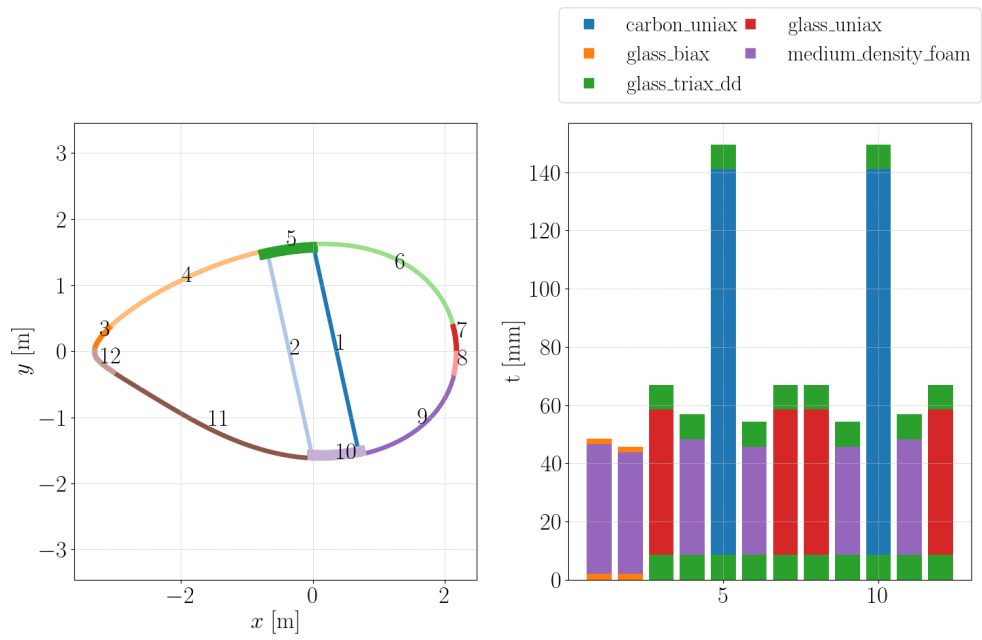


Figure 24. Section at 12% span.

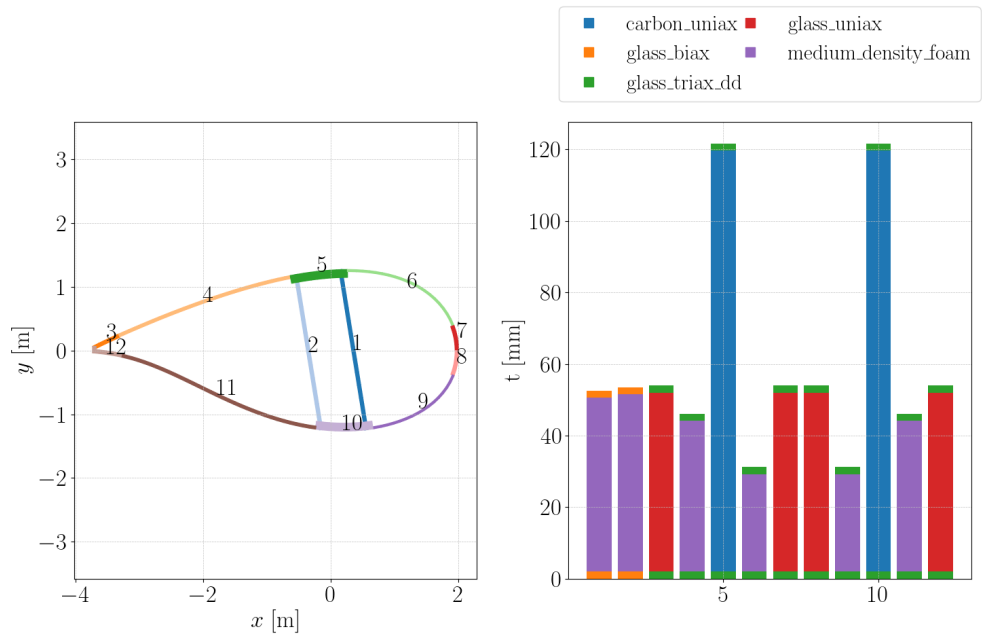


Figure 25. Section at 19% span.

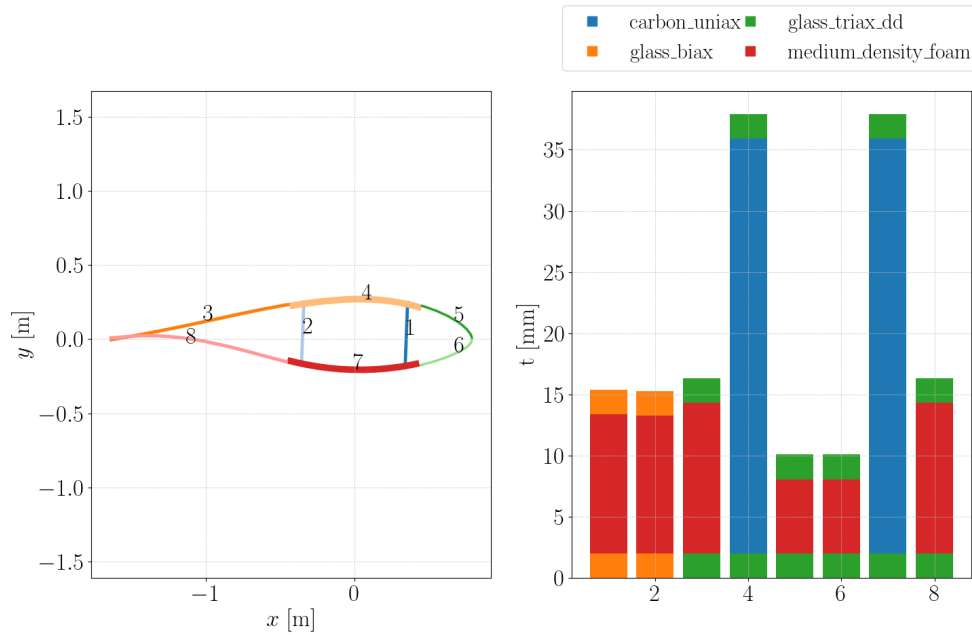


Figure 26. Section at 83% span.

surface. Under asymmetric operational loading, particularly flapwise bending, the suction side experiences higher compressive stresses and therefore buckling can become a critical factor in some areas, as reported in Ullah et al. (2020).

515 In the CRC simulations, the suction side governs structural sizing along the span due to the dominant compressive demand from bending. The spar caps are constrained by the peak flapwise moment, while the leading and trailing edges are governed by combined flapwise–edgewise load cases. The leading edge is placed in compression under the 150-degree moment orientation, whereas the trailing edge is compressed under the 30-degree orientation, which reverses the tension–compression distribution between the two regions.

520 In the CRC simulations, the suction side governs structural sizing along the span due to the dominant compressive demand from bending. The spar caps are constrained by the peak flapwise moment, while the leading and trailing edges are governed by combined flapwise–edgewise load cases. The leading edge is placed in compression under the 150° moment orientation, whereas the trailing edge is compressed under the 30° orientation, reversing the tension–compression distribution between the two regions.

525 Maximum strain is the primary sizing mechanism across most of the suction side, with compression-induced buckling becoming critical on the quarter-cylindrical shell at the leading edge and in some trailing edge panels toward the rear of the blade. The tailored $\pm 37^\circ$ laminate finds a better compromise between these two failure modes than the triaxial layup: by reducing axial stiffness in the skin, it redistributes load more effectively toward the spar caps and edge reinforcements, which are better suited to carry it.

This work introduced a multi-parametric panel approach and incorporated it into the blade-optimization workflow, enabling sandwich panels to be represented as modular assemblies with independently parameterized materials. The formulation was verified through stiffness, load-path, and tapering consistency tests, establishing its suitability for applying continuous composite descriptions. This capability enabled the examination of DD laminates as viable replacements for conventional triaxial skins in a large-scale optimization setting.

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 $[\pm 37^\circ / \pm 37^\circ]$ DD layup.

In general, 0° plies minimize spanwise strain while 45° plies maximize buckling resistance. The optimized $[\pm 37^\circ / \pm 37^\circ]$ 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.

Beyond the spar caps, the suction-side shell emerged as the dominant sizing region. This area experienced the highest stress levels, particularly in compression, which were identified as the primary failure mode.

From a stiffness perspective, the aeroelastic response was only moderately affected. The most significant variations occurred near the blade root, where local mass reductions reached approximately 70%. Despite these changes, all flapwise and edgewise displacements remained within the operational limits defined in Gaertner et al. (2020), confirming the structural viability of the optimized design.

From a manufacturing standpoint, the optimized DD skins integrate seamlessly into existing blade production practices. In a manner consistent with triaxial laminates, they can be assembled as repeating blocks, but with two selected fiber angles arranged according to the DD stacking pattern. This configuration remains fully compatible with current fabrics and vacuum-infusion processes and introduces no additional layup complexity. Consequently, the DD concept offers a practical approach to achieving weight savings while maintaining the established workflow used for conventional triaxial skins.

6.1 Future Work

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 subsection 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).
- A **fully coupled aeroelastic analysis** integrated into the optimization pipeline would enable more accurate prediction of stiffness-induced load redistribution. The current formulation assumes fixed aerodynamic loading and therefore does not capture secondary effects arising from skin softening or stiffness variation.

Appendix A: Derivation of Plane-Shifted Stiffness Matrices

Extension Stiffness:

$$\begin{aligned}
 [\mathbf{A}^{\text{new}}] &= \sum_k [\bar{\mathbf{Q}}_k] [z_{k-1}^{\text{new}} - z_k^{\text{new}}] \\
 &= \sum_k [\bar{\mathbf{Q}}_k] [(z_{k-1}^0 - \Delta z) - (z_k^0 - \Delta z)] \\
 &= \underbrace{\sum_k [\bar{\mathbf{Q}}_k] [z_{k-1}^0 - z_k^0]}_{\mathbf{A}^0} \\
 &= [\mathbf{A}^0]
 \end{aligned}$$

Bending–Extension Stiffness:

$$\begin{aligned}
[\mathbf{B}^{\text{new}}] &= -\frac{1}{2} \sum_k [\bar{\mathbf{Q}}_k] [(z_{k-1}^{\text{new}})^2 - (z_k^{\text{new}})^2] \\
&= -\frac{1}{2} \sum_k [\bar{\mathbf{Q}}_k] [(z_{k-1}^0 - \Delta z)^2 - (z_k^0 - \Delta z)^2] \\
&= -\frac{1}{2} \sum_k [\bar{\mathbf{Q}}_k] [(z_{k-1}^0)^2 - 2z_{k-1}^0 \Delta z + \Delta z^2] \\
&\quad + \frac{1}{2} \sum_k [\bar{\mathbf{Q}}_k] [(z_k^0)^2 - 2z_k^0 \Delta z + \Delta z^2] \\
&= \underbrace{-\frac{1}{2} \sum_k [\bar{\mathbf{Q}}_k] [(z_{k-1}^0)^2 - (z_k^0)^2]}_{\mathbf{B}^0} \\
&\quad + \underbrace{\Delta z \sum_k [\bar{\mathbf{Q}}_k] [z_{k-1}^0 - z_k^0]}_{\mathbf{A}^0} \\
&= [\mathbf{B}^0] + \Delta z [\mathbf{A}^0].
\end{aligned}$$

Bending Stiffness:

$$\begin{aligned}
[\mathbf{D}^{\text{new}}] &= \frac{1}{3} \sum_k [\bar{\mathbf{Q}}_k] [(z_{k-1}^{\text{new}})^3 - (z_k^{\text{new}})^3] \\
&= \frac{1}{3} \sum_k [\bar{\mathbf{Q}}_k] [(z_{k-1}^0 - \Delta z)^3 - (z_k^0 - \Delta z)^3] \\
&= \frac{1}{3} \sum_k [\bar{\mathbf{Q}}_k] \left\{ (z_{k-1}^0)^3 - 3\Delta z (z_{k-1}^0)^2 + 3\Delta z^2 z_{k-1}^0 \right. \\
&\quad \left. - \Delta z^3 - [(z_k^0)^3 - 3\Delta z (z_k^0)^2 + 3\Delta z^2 z_k^0 - \Delta z^3] \right\} \\
&= \underbrace{\frac{1}{3} \sum_k [\bar{\mathbf{Q}}_k] [(z_{k-1}^0)^3 - (z_k^0)^3]}_{\mathbf{D}^0} \\
&\quad + 2\Delta z \underbrace{\left(-\frac{1}{2} \sum_k [\bar{\mathbf{Q}}_k] [(z_{k-1}^0)^2 - (z_k^0)^2] \right)}_{\mathbf{B}^0} \\
&\quad + \Delta z^2 \underbrace{\sum_k [\bar{\mathbf{Q}}_k] [z_{k-1}^0 - z_k^0]}_{\mathbf{A}^0} \\
&= [\mathbf{D}^0] + 2\Delta z [\mathbf{B}^0] + \Delta z^2 [\mathbf{A}^0].
\end{aligned}$$

List of abbreviations

AEP	Annual Energy Production. 1, 34
BB	Building Block. 1, 5, 34
CLT	Classical Laminate Theory. 1, 5, 34
DD	Double-Double. 1, 3–10, 19–21, 25, 29, 32–34
DD-Hard	DD laminate with fixed 0° , and Ψ variable. 1, 34
DD-Local	DD laminate with individualized set of angles per cross-section. 1, 34
IEA	Internation Energy Agency. 1–3, 34
RWT	Reference Wind Turbine. 1, 2, 34
Triax	DD laminate with fixed 0° , 45° angles. 1, 34
UD	Unidirectional. 1, 8, 34

590 List of symbols

G_c	Shear modulus of the sandwich core. 1, 34
$N_{x,cr}, N_{xy,cr}$	Critical buckling load for compression and shear. 1, 34
R	Ration between applied and critical load for the related mode. 1, 34
T	Total stack, following the Nettles convention (Nettles, 1994). 1, 5, 34
$TSAI$	Tsai modulus is the trace of the ply stiffness matrix ($TSAI = \text{Tr}[Q]$). 1, 34
V_x^A, V_x^B, V_x^D	Lamination parameters in accordance with (Zerbst et al., 2025). 1, 6, 34

W_x	Trigonometric functions of the ply angle θ_k . 1, 6, 34
$[\mathbf{A}]$	Extensional stiffness matrix. 1, 5, 34
$[\mathbf{B}^*]$	Coupling stiffness matrix normed by the laminate thickness. 1, 5, 34
$[\mathbf{D}]$	Bending stiffness matrix. 1, 5, 34
$[\mathbf{Q}]$	Ply stiffness matrix. 1, 5, 34
Φ	First double-double angle. 1, 5, 34
Ψ	Second double-double angle. 1, 5, 34
α	Fraction of the Tsai modulus. 1, 34
ϕ	First double-double angle. 1, 34
ψ	Second double-double angle. 1, 34
ρ	Density. 1, 34
σ_1	Normal stress. 1, 34
σ_2	Transverse normal stress. 1, 10, 34
τ_{12}	Shear stress. 1, 9, 34
θ	Ply angle orientation. 1, 6, 34
$\tilde{D}_{11}$	Effective bending stiffness term of the laminate. 1, 20, 34
b	Buckling/panel width. 1, 34
g	Constraint e.g. for stability, strength etc.. 1, 34
k	Shear correction factor. 1, 34
kx and ks	Buckling coefficients for compression and shear according to (Structural Analysis Working Group I, 2009). 1, 20, 34
m	Mass of.... 1, 34
n_x	Uniaxial load. 1, 8, 34
n_{xy}	Shear load. 1, 8, 34
r	Number of repeats. 1, 5, 34
t_c	Thickness of the sandwich core. 1, 34
t_{lam}	Thickness of the laminate. 1, 5, 34
z_k	Distance of the k -th ply to the laminate mid-plane. 1, 6, 34

Data availability. The raw data required to reproduce these findings are available under the following repository:
<https://doi.org/10.5281/zenodo.17965770> (Werthen, 2025).

Author contributions. EW and GNR developed the methodology and software code, did the analyses and wrote the manuscript. SD and LT supported the implementation of the approach into the *lightworks* framework. DZ and CH revised the manuscript and provided scientific supervision.

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