

Highlights

Coupled Internal Wing-Box Layout- and Composite Optimization via Parametric CAD Modeling and Lamination Parameters

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- Coupled layout and composite optimization exploits coupling effects to reduce mass.
- Load tailoring redirects forces to favorable regions through structural coupling.
- Layout coupling yields larger gains with lamination parameters than with thickness alone.

Coupled Internal Wing-Box Layout- and Composite Optimization via Parametric CAD Modeling and Lamination Parameters

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ABSTRACT

Conventional preliminary wing design workflows typically follow a sequential approach. The shape and internal layout of the wing are fixed first, followed by structural optimization of local stiffness properties of composite materials based on predefined load cases. However, this decoupled strategy neglects the critical coupling effects between the internal structural layout and local stiffness distributions of composite materials, often yielding suboptimal weight performance. Existing frameworks for layout design primarily rely on topology optimization, bi-level approaches that separate layout and structural optimization, or formulations that assume fixed local stiffness. This work proposes an integrated, parametric CAD-based optimization framework that directly modifies the internal structural layout like ribs and spars through explicit geometric parameters while simultaneously optimizing structural composite design variables, including skin thicknesses and lamination parameters. The methodology is evaluated on an established rectangular wing box benchmark. Results demonstrate that co-optimizing the rib and spar layout together with skin thicknesses and lamination parameters increases the mass savings to 15.20% compared with structural optimization using a fixed layout. Furthermore, configurations with variable directional stiffness yield internal layouts that differ from those obtained under fixed stiffness assumptions, highlighting the benefit of capturing layout and local stiffness coupling effects.

1. Introduction

The demand for more efficient and environmentally sustainable aircraft has led to increasingly lightweight optimized structural wing designs [1]. Besides the aerodynamic shape, the wing structure is particularly important as it contributes significantly to both the overall aircraft mass and its aerodynamic performance [2].

Structural optimization enables a large number of design variables (DVs) and structural constraints to be considered simultaneously [3]. The use of composite materials further expands the available design space. Their mechanical properties can be tailored not only through thickness variations but also through fiber orientation [4]. This additional design freedom can provide further lightweight potential compared with structures restricted to isotropic materials [5]. Therefore, composite stiffness design plays an important role in aircraft structural optimization [4].

The wings structural ribs and spars layout is usually defined prior to structural optimization, such that the optimization primarily modifies material properties rather than the underlying structural topology [6, 7]. The resulting optimum consequently depends on the selected structural layout. Furthermore, material level tailoring cannot exploit performance improvements that require changes to the arrangement of ribs and spars. This limits the achievable structural weight reduction potential [8, 9]. In contrast, simultaneous optimization enables direct trade-offs between geometric

and composite DVs, which may be missed when the design spaces are optimized sequentially [10, 5].

Topology optimization has been widely applied to the conceptual design of internal aircraft wing-box structures [11]. It offers a high degree of geometric freedom by determining efficient material distributions within a defined design space [12]. However, results often require post-processing before they can be used in subsequent design stages. The resulting material distributions therefore require interpretation and geometric reconstruction before they can be represented as manufacturable, parametric computer-aided design (CAD) models [13]. CAD-based optimization provides an alternative approach in which the overall structural layout is defined through a parametric CAD model [14, 15]. Structural components are preserved, while their shape or arrangement is modified through geometric DVs [15]. This representation is compatible with structural composite optimization, because the individual structural panels remain explicitly defined [14]. Geometric layout variables can therefore be considered alongside structural DVs such as panel thicknesses and lamination parameters (LPs) within one common optimization framework. LPs provide an alternative representation of the stiffness properties of composite laminates [16].

Composite structural optimization is a well established field and approaches for it have been investigated extensively [4]. Optimization of internal structural layouts has likewise received considerable attention, particularly through topology optimization [17]. CAD-based shape optimization is also well established, with applications in aerodynamic optimization of external aircraft geometries [18, 19], as well as for modifications of internal wing box layouts for aircraft wings [20, 15]. However, the simultaneous consideration of

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CAD-parameterized internal layout variables and composite design is rarely published. One notable study optimizes the external wing shape while accounting for composite materials, but the internal structural layout is defined mainly by general design rules and therefore offers only limited geometric design freedom. In addition, the composite design is restricted to predefined ply shares [21]. A fully coupled optimization of the internal structural layout and composite design has the potential to enable greater structural performance and to broaden the available design space.

The objective of this study is to extend an existing structural optimization framework [22] by incorporating CAD-based internal layout variables into the gradient-based optimization process. The extended framework enables automatic updates of the internal wing box layout, regeneration of the structural analysis model, and evaluation of sensitivities with respect to geometric DVs. The design space includes internal wing box layout variables, like rib and spar positions and orientations, as well as composite DVs, including skin thicknesses and composite stiffness. The performed optimizations are subject to strength and stability constraints, as well as composite and wing-box feasibility constraints. To investigate the interaction between structural wing layout and the influence of tailored composites, several optimization cases with different levels of geometric degrees of freedom (DOFs) are compared using a simplified rectangular wing box test case. The resulting designs are evaluated in terms of structural mass and optimal internal layout to estimate the potential of combined structural and geometric optimization. By integrating geometric DVs into the structural optimization, a mass reduction of 15.2% is achieved compared with optimization using a fixed internal layout.

2. Geometric and composite design framework

This work employs a gradient-based optimization framework named *lightworks* [22]. It was initially designed for the structural optimization of wing-like configurations using structural parameters, importantly skin thickness and LPs following the formulation of Tsai and Pagano [16]. Central to the *lightworks* framework is a parametric panel-meta-model that contains the wing box architecture through composite stacking, material assignments, and geometric information. Each panel is treated as one optimization region.

The structural optimization problem is generally stated as a nonlinear constrained minimization:

$$\begin{aligned} \min_{\mathbf{x}} \quad & f(\mathbf{x}) \\ \text{subject to} \quad & \mathbf{c}_i(\mathbf{x}) \leq 0, \quad i = 1, \dots, m, \\ & \mathbf{x}^L \leq \mathbf{x} \leq \mathbf{x}^U \end{aligned} \quad (1)$$

where $\mathbf{x}$ denotes the vector of DVs. The objective function $f(\mathbf{x})$ represents the total structural mass of the wing box.

Structural feasibility is enforced through a set of inequality constraints. These include material strength criteria, which are evaluated at finite-element level and buckling stability limits for compression and shear loadings, which are assessed for each panel. Arbitrary combinations of LPs do not necessarily correspond to physically realizable composite laminates. Therefore, when LPs are included in the design space, a laminate compatibility constraint is imposed to ensure physical realizability [23].

The resulting optimization problem is solved using a gradient-based approach due to the high dimensionality of the design space. The Sparse Nonlinear Optimizer (SNOPT) [24] is employed, which implements a sequential quadratic programming method tailored for large-scale problems.

The initial framework was extended to employ a CAD-based parameterization process to define the geometric design space. The approach is based on a parametric CAD model whose geometric parameters are treated as additional DVs alongside the structural DVs. Changes to these geometric DVs automatically update the underlying CAD model.

2.1. Geometry update workflow

The geometry update workflow implements an automated pipeline that translates parametric DVs into the objective function and constraints functions while generating a complete FE-model suitable for structural analysis. This workflow is illustrated in Figure 1.

A Python-based geometry processor generates the geometry directly from the provided geometric DVs. The *pythonOCC* library is employed to construct any arbitrary CAD model. Afterwards, the CAD geometry is exported to *Gmsh* [25] for structural mesh generation.

During the initial setup, the resulting discretized model is integrated with additional data, including applied loads, boundary conditions, and region-specific stiffness properties, to assemble a complete FE-model. This model serves as the computational foundation for structural analysis during the optimization process. The FE-solver employed in this study is the *B2000++* solver [26].

Any changes to the geometric DVs automatically regenerate the CAD model and trigger the remeshing process. To maintain a consistent element count across iterations, the number of nodes on each geometric curve is stored and reused during subsequent updates, while only the nodal positions are modified. This allows for efficient updating of the FE mesh without the need to rebuild the entire model.

2.2. Treatment of design variables

The optimization framework distinguishes between two categories of DVs that define the total design vector $\mathbf{x}$:

$$\mathbf{x} = [\mathbf{x}_{\text{struct}}, \mathbf{x}_{\text{geo}}] \quad (2)$$

where $\mathbf{x}_{\text{struct}}$ represents classical structural optimization parameters, and $\mathbf{x}_{\text{geo}}$ describe geometric DVs.

Structural DVs directly modify the properties of the FE- and panel-meta-model, such as shell thicknesses, or composite stiffness properties, which influence the calculated

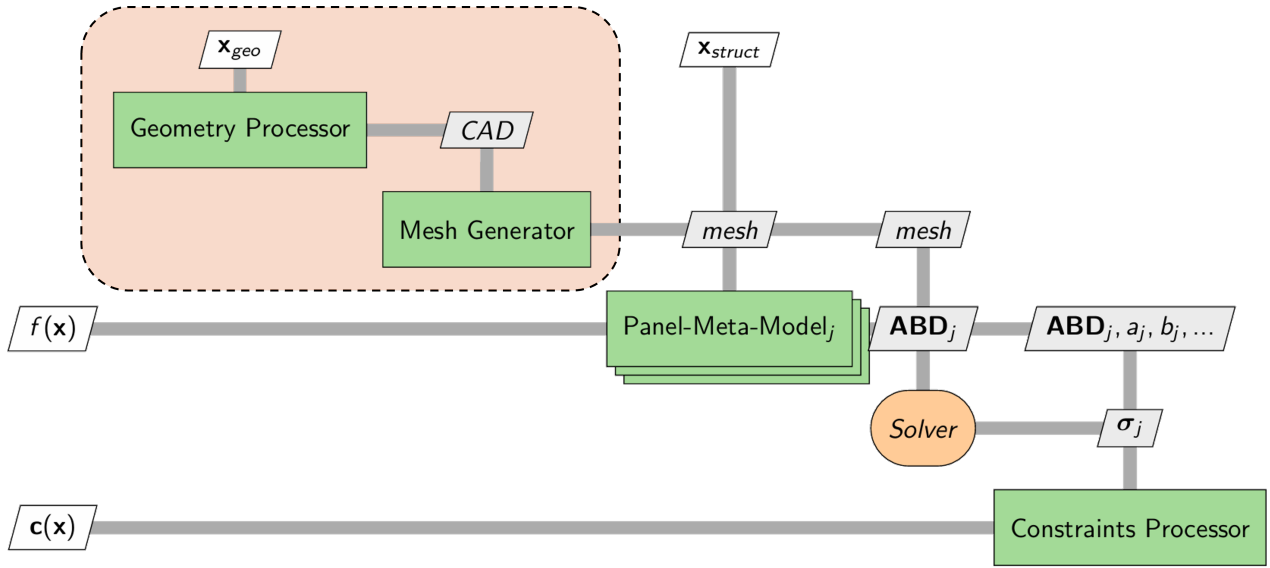


Figure 1: XDSM diagram illustrating the dependencies between the DVs, the objective function, and the constraint functions. Components introduced in the this study are highlighted.

stiffness matrix for each optimization region. In contrast, geometric DVs control the parametric CAD geometry and subsequently modifying the underlying FE-mesh. Alterations in $\mathbf{x}_{\text{geo}}$ propagate through the model generation pipeline to modify global stiffness distributions, panel dimensions, and mass distribution.

2.3. Sensitivity computation

Lightworks relies on gradient-based optimization algorithms, which require computation of first-order sensitivities for both the objective and constraint functions with respect to all DVs. Let $\mathbf{x}$ define the vector of n DVs, $f(\mathbf{x})$ represent the scalar objective function, and $\mathbf{c}(\mathbf{x}) = [c_1(\mathbf{x}), \dots, c_m(\mathbf{x})]^\top$ define the vector of constraint functions. The required sensitivity information is defined through the objective gradient:

$$\nabla_{\mathbf{x}} f = \frac{\partial f}{\partial \mathbf{x}}, \quad (3)$$

where $\frac{\partial f}{\partial x_i}$ represents the partial derivative of f with respect to the i -th DV. Additionally, the sensitivities of the constraint functions are captured by its Jacobian matrix:

$$\mathbf{J}_{\mathbf{c}}(\mathbf{x}) = \frac{\partial \mathbf{c}}{\partial \mathbf{x}}. \quad (4)$$

The evaluation of sensitivities distinguishes between structural- and geometric DVs, each requiring a designated numerical differentiation methodology.

For structural DVs, gradients are computed using the complex-step (CS) method. This approach is adopted primarily for its superior numerical accuracy. Unlike finite differences (FD), it avoids cancellation errors through subtractions and yields exact derivatives up to machine precision for analytic functions [27].

In contrast, sensitivities with respect to geometric parameters are evaluated via FD. This distinction is required by external software used in the current implementation, which do not support the use of complex numbers.

3. Numerical wing box optimization setup

To evaluate the proposed methodology, a representative wing box test case is utilized. The model provides a simplified wing box configuration that allows the interaction between geometry and structural parameters to be investigated. This chapter describes the baseline configuration, the DV definitions, the objective and constraint functions, and the compared optimization cases.

3.1. Baseline wing box

The selected benchmark case has been established in earlier studies of composite optimization problems [22, 28, 29, 30, 31]. The test geometry is a rectangular structure, illustrated in Figure 2, which can be regarded as a reduced-scale wing box.

The upper and lower shells are subdivided into nine distinct optimization regions, divided by four uniformly spaced rib and spar segments, with the ribs defined in the x - z plane and the spars in the y - z plane. Each one consist of three discrete panels. All structural surfaces are modeled as unstiffened laminates, meaning no additional stringers are included into the design.

The spar and rib panel composites are designed using a shear carrying stacking sequence defined as $[(\pm 45^\circ)_2]$. The upper and lower shell panels add axially oriented plies, specified as $[4(0^\circ)/4(\pm 45^\circ)/2(90^\circ)]$, to efficiently resist bending

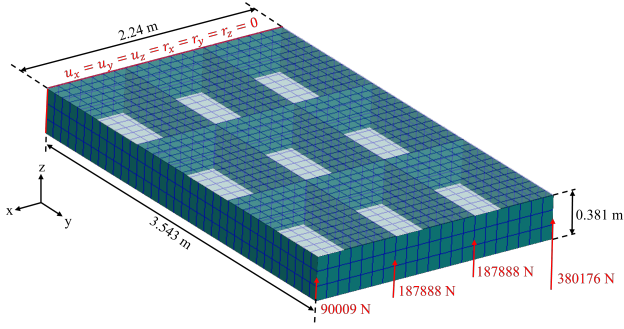


Figure 2: Rectangular wing-box benchmark geometry, including the FE mesh, applied loads, and boundary conditions.

Table 1

Mechanical properties of the T300/5208 pre-preg material.

Property	Value
E_{xx}	181 GPa
$E_{yy} = E_{zz}$	10.3 GPa
$\nu_{xy} = \nu_{xz}$	0.27
ν_{yz}	0.42
$G_{xy} = G_{xz}$	7.17 GPa
G_{yz}	3.78 GPa
ρ	1760 kg/m ³
$X_t = X_c$	1500 MPa
$Y_t = Y_c$	246 MPa
S	68 MPa

moments. To enable a continuous design space for gradient-based optimization, these discrete ply sequences are represented via a set of continuous LPs.

Each individual ply is composed of T300/5208 carbon-epoxy pre-preg material [29]. The complete set of mechanical and physical properties for the unidirectional plies is summarized in Table 1.

The panel-meta-model is discretized using a FE-mesh composed entirely of quad shell elements, resulting in a total of 1512 elements and 1628 nodes. A fully clamped boundary condition is enforced at the root. Asymmetric concentrated forces are applied at the tip and are combined to form a single bending–torsion load case. The resulting FE-mesh is illustrated in Fig. 2.

3.2. Design variables

As mentioned earlier, the DVs are grouped into two classes. The first class contains conventional structural DVs, namely one thickness variable for each design region and a set of LP used to describe the composite laminate. The second class consists of geometric DVs. In principle, any parameter used to define the parametrized CAD model can be selected as a DV.

3.2.1. Structural optimization variables

LPs provide a continuous formulation for describing the in-plane, coupling, and bending stiffness characteristics of

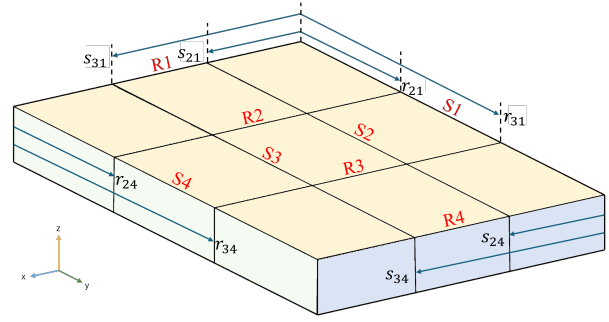


Figure 3: Wing box component notations and geometric DVs.

composite laminates. Unlike discrete representations that rely on individual ply angles and thicknesses, LPs define the stiffness properties into a compact, continuous set of 12 variables. Symmetric and balanced quad laminate as assumed in this study, can be fully described using only five LPs in addition to the total thickness [32]. Such laminates consist of plies oriented at 0° , $\pm 45^\circ$ and 90° , arranged symmetrically with equal numbers of $+45^\circ$ and -45° plies. In the context of gradient-based optimization, LPs offer significant advantages over discrete DVs. Their properties ensures continuous design spaces and enables the application of efficient gradient-based methods [33]. The calculation of the stiffness matrix components from the LPs is described in Appendix A.

The initial structural DVs employed are summarized in Table 2. Only those parameters that are relevant for the optimization cases are listed. All remaining LPs are initialized to zero and held constant throughout the optimization processes.

3.2.2. Geometric design variables

The geometric DVs serve as the parametrization for the internal wing box structure. By modifying the underlying CAD geometry, these variables directly modify the nodal coordinates of the discretized model. They influence mass distribution, global stiffness characteristics and panel dimensions.

The rectangular wing box configuration is defined by eight DVs, as illustrated in Figure 3. Each internal component is parameterized using two positional coordinates, which determine both the longitudinal placement of the structural elements and their implicit orientation within the wing box.

The optimization initiates from a symmetric configuration, where the first and second positional parameters are initialized at 1/3 and 2/3 of the total chord or span length. To maintain geometric feasibility during design updates, all geometric DVs are constrained within bounds corresponding to 1%–99% of the chordwise or spanwise length. In addition, geometric constraints are imposed to prevent crossing between rib and spar components, as described in further detail in Chapter 3.3.4.

Table 2

Initial structural DV values and boundaries of relevant parameters.

	Thickness [m]	$V_{1,A}$	$V_{2,A}$	$V_{1,D}$	$V_{2,D}$	$V_{3,D}$
Upper shell / Lower shell	0.01	0.2	0.2	0.344	0.296	0.24
Ribs / Spars	0.0055	0	-1	0	-1	0.068
Boundaries	0.0001, 0.6	-1, 1	-1, 1	-1, 1	-1, 1	-1, 1

3.3. Objective and constraints

The structural optimization problem is restricted by a set of constraints that contain material strength limits, buckling stability criteria, laminate layup design rules, and geometric feasibility requirements. These constraints ensure that the resulting wing box configuration remains structurally viable under loading conditions while satisfying laminate and geometric feasibility.

3.3.1. Objective function

The objective of the optimization process is the minimization of the total structural mass of the wing box. Although the DVs are restricted to the thickness and stiffness parameters of the upper and lower shell components, the objective function accounts for the mass contribution of all panels, including ribs and spars. This captures the global weight implications of local geometric modifications in the objective function. The total structural mass f is expressed as a summation over all individual panels:

$$f = \sum_{i=1}^n \rho_i A_i t_i, \quad (5)$$

where ρ_i denotes the material density of the i -th panel, A_i represents its surface area, and t_i corresponds to its thickness. Through this formulation, both geometric parameters and material distributions directly influence the objective function.

The complete optimization problem can be stated as:

$$\begin{aligned} \min_{\mathbf{x}_s, \mathbf{x}_g} \quad & f(\mathbf{x}_s, \mathbf{x}_g) \\ \text{s.t.} \quad & \mathbf{x}_{s,i}^l \leq \mathbf{x}_{s,i} \leq \mathbf{x}_{s,i}^u, \quad i = 1, \dots, n_s, \\ & \mathbf{x}_{g,j}^l \leq \mathbf{x}_{g,j} \leq \mathbf{x}_{g,j}^u, \quad j = 1, \dots, n_g, \\ & \mathbf{c}_{s,k}(\mathbf{x}_s, \mathbf{x}_g) \leq 0, \quad k = 1, \dots, m_s, \\ & \mathbf{c}_{g,l}(\mathbf{x}_g) \leq 0, \quad l = 1, \dots, m_g. \end{aligned} \quad (6)$$

where f denotes the objective function to be minimized. The vectors $\mathbf{x}_s$ and $\mathbf{x}_g$ represent the structural and geometric DVs, respectively, with lower and upper bounds defined by $\mathbf{x}_{s,i}^l, \mathbf{x}_{s,i}^u$ and $\mathbf{x}_{g,j}^l, \mathbf{x}_{g,j}^u$. The terms $\mathbf{c}_{s,k}$ and $\mathbf{c}_{g,l}$ correspond to the structural constraints, including strength, buckling, LP feasibility constraints, and geometric constraints.

3.3.2. Structural constraints

To prevent strength failure, this study employs a LP-based failure criterion as proposed by Khani et al. [34]. Traditional failure criteria rely explicitly on individual ply

orientations and stacking sequences, making them incompatible with LP formulations where such discrete ply information is not available. Consequently, the proposed criterion evaluates strength constraints at the finite element level, resulting in one independent constraint per element. A more detailed description of the strength criterion used in this study is provided in Appendix B.1.

Buckling assessment is conducted at the element level. To maintain a conservative design approach, the most critical local element load is applied to the entire panel. This assumption implies that the full panel is subjected to the peak load in both compression and shear. The calculations follow the approach analogous to that of Dähne et al. [22], with the additional consideration of compression in the transverse fiber direction. A detailed description is provided in Appendix B.2.

To ensure that the optimized LP designs correspond to physically realizable composite layups, it is necessary to impose explicit feasibility constraints on these DVs. In general, not all combinations of LPs correspond to physically realizable laminate stacking sequences. The LP design space must therefore be restricted to the feasible region. Following the methodology proposed by Werthen and Dähne [23], the feasible region of LPs is characterized by a set of hyperplanes derived from a convex hull formulation. A more detailed description is given in Appendix B.3.

3.3.3. Buckling length evaluation

Modifying the geometric parameters affects the shape of the panels. As the applied buckling constraints are formulated for orthogonal panels, an equivalent buckling length must be determined for skewed panels to satisfy the orthogonal reference model.

The buckling length evaluation in this study follows the methodology prescribed in the HyperSizer documentation published by Collier Research Corporation [35]. It idealizes a skewed flat panel as an orthogonal rectangular plate. It determines equivalent longitudinal and transverse buckling directions from the panel geometry and material orientation, then calculates representative X- and Y-buckling spans from the panel area distribution about its centroid.

$$\begin{aligned} Y &= 2 \left[\min \left(c_y^+, Y^+ - c_y^+ \right) \right. \\ &\quad \left. + \min \left(c_y^-, Y^- - c_y^- \right) \right], \\ X &= 2 \left[\min \left(c_x^+, X^+ - c_x^+ \right) \right. \\ &\quad \left. + \min \left(c_x^-, X^- - c_x^- \right) \right]. \end{aligned} \quad (7)$$

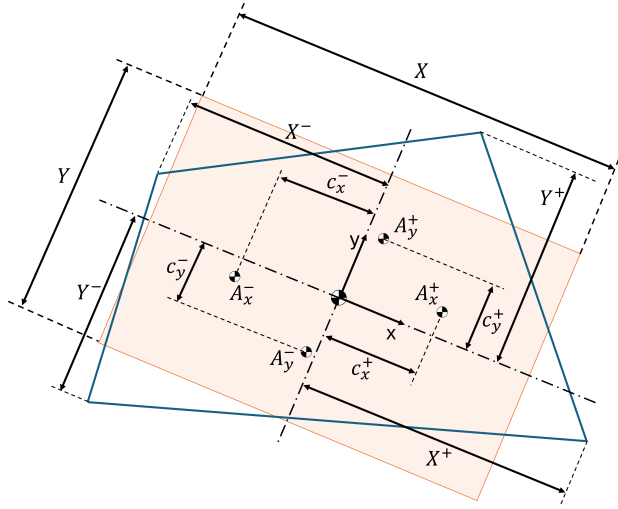


Figure 4: Buckling length calculation parameters for the blue panel, with the red panel representing the calculated equivalent orthogonal buckling length

Here, Y^+ and Y^- define the distances from the panel centroid to the outermost boundaries of the panel in the positive and negative transverse directions, respectively. The values c_y^+ and c_y^- denote the distances from the panel centroid to the centroids of the two subregions obtained by dividing the panel along the material orientation axis passing through the panel centroid. Analogously, X^+ , X^- , c_x^+ and c_x^- represent the corresponding distances in the fiber 0° direction of the panels composite, as illustrated in Figure 4. The highlighted rectangular plate results from transforming the skewed panel using the equations described above.

3.3.4. Geometric constraints

To guarantee geometric feasibility and prevent degenerate configurations during the optimization process, geometric constraints are applied on the geometric DVs. These constraints are use-case dependent and are tailored to the specific structural requirements of the model topology. In the present use case, it is mandatory to maintain separation between adjacent ribs and spars, to avoid overlap.

While the outer boundaries of the geometry are enforced through standard parameter bounds, internal spacing is regulated by explicit geometric constraints. To ensure a physically realizable design throughout the search space, a minimum separation distance equivalent to 2% of the local chord or spanwise length is chosen between any two adjacent members. This condition is mathematically formulated as:

$$R_{\text{geom}} = i_{3j} - i_{2j} \geq 0.02, \quad (8)$$

$$(i, j) \in \{(r, 1), (r, 4), (s, 1), (s, 4)\}.$$

The parametric positions are defined in Figure 3.

Table 3 provides a summary of each constraint group, including the discretization level at which they are evaluated,

the total number of constraints per optimization case, and their corresponding mathematical formulations.

3.4. Study overview

The objective of this study is to compare pure structural optimization with combined geometry–structural optimization. This comparison provides insight into the potential of incorporating geometric DVs with respect to structural efficiency and weight reduction, relative to conventional structural optimization approaches and how composite tailoring influences the optimal structural wing internal layout.

To investigate the interaction between laminate design and geometric configuration, two optimization cases are established, each considering a different set of structural DVs. Each case comprises four stages where the complexity of the geometric DVs is incrementally increased to evaluate the influence on the final structural mass of each geometric DOF.

Case 1: Thickness and geometric optimization focuses on thickness parameters with fixed layups. The design space is initially constrained to laminate thickness variations, serving as the baseline for structural optimization. This case isolates the performance gains achievable through geometric adaptation alone.

Case 2: Thickness, stiffness, and geometric optimization expands upon Case 1 by incorporating LPs as continuous DVs alongside thickness optimization. This coupled approach enables simultaneous optimization of laminate stiffness and structural layout, allowing the structure to adapt both its local stiffness characteristics and global geometry for more favorable load paths and panel dimensions.

Within both cases, the optimization runs follow a continuous progression of geometric freedom:

1. **Baseline optimization (Stage 0):** Optimization is restricted to structural DVs
2. **+Rib positioning (Stage 1):** Continuous translational variables for the ribs, without rotation.
3. **+Spar positioning (Stage 2):** Additional continuous translational variables for spars, without rotation
4. **+Rotational DOFs (Stage 3):** Additional rotational DOFs for ribs and spars.

Table 4 summarizes the variable configurations and total DOFs for each optimization run across both cases.

To ensure a controlled comparison, both cases employ identical objective functions and constraint formulations. This isolates the influence of internal layout by varying only two parameters: the geometric DOF and their corresponding geometric constraints per stage. All other computational settings within the optimization process remain constant across all stages, ensuring that any performance differences can be directly attributed to variations in geometric parameters.

The optimized designs are evaluated against their respective baseline configurations. Performance is quantified by the relative mass reduction achieved by each stage.

Table 3

Summary of constraint groups, evaluation levels, and counts per computational case.

Constraint group	Evaluated on	Number	Formula
Strength	Element level	1512	$c_{\text{strength}} = R_{\text{strength}} - 1 \leq 0$
Buckling	Panel level	1512	$c_{\text{buckling}} = R_{\text{buck,comb}} - 1 \leq 0$
LP	Skin level	$49 \times 18 = 882$	$c_{\text{LP}} = R_{\text{LP}} \leq 0$
Geometry	Model level	$n_g/2$	$c_{\text{geom}} = R_{\text{geom}} - 0.02 \leq 0$

Table 4

Summary of DV configurations and DOFs for each optimization stage.

Case	Stage		$N_{\text{thickness}}$	N_{LP}	n_{geom}
Case 1	Stage 0	Thickness	18	0	0
	Stage 1	+ Ribs parallel	18	0	2
	Stage 2	+ Spars parallel	18	0	4
	Stage 3	+ Rotations	18	0	8
Case 2	Stage 0	Thickness + LP	18	90	0
	Stage 1	+ Ribs parallel	18	90	2
	Stage 2	+ Spars parallel	18	90	4
	Stage 3	+ Rotations	18	90	8

4. Results

This chapter presents the results of the investigated optimization cases obtained with the proposed methodology. The final optimized wing box designs are first evaluated by comparing their objective values and deviations from the structural-only optimized configuration. The resulting changes in the structural layout, thickness distribution, and laminate DVs are then analyzed and compared across the optimization stages. Finally, the optimization trajectories and design spaces are examined to assess the convergence behavior of the objective function and convexity.

4.1. Influence of geometric design variables on the objective function

The progression of mass reductions achieved through successive addition of geometric DVs of both cases is summarized in Figure 5. For Case 1, the baseline design employs a fixed internal architecture, yielding an optimized mass of 428.38 kg. When all geometric parameters are simultaneously optimized, the final configuration achieves a total mass reduction of 6.23% compared to the thickness-only optimized baseline. In Case 2 the initial reference mass starts at 343.13 kg. The relocation and rotation of rib and spar components results in an overall mass saving of 15.20% over the original stiffness-optimized reference design. All optimized configurations satisfy structural feasibility requirements and are mainly governed by buckling constraints. They converged to optimal values without encountering boundary constraints across every optimization stage.

Each additional geometric DOF led to a further reduction in the optimal weight. In Case 2, the mass reduction of each added DOF was greater than in Case 1, highlighting the benefit of coupling internal layout optimization with composite tailoring. This coupling provides the optimizer with greater flexibility to explore the design space as with fixed stiffness distribution. Adding rotational DOFs expands

the optimization design space compared to using straight components alone. It enables more independent control over the buckling lengths of individual panels as well as more favorable load distributions. This allows for further mass reduction, even when the total structural area increases. In this case, the overall contribution to the optimal mass of the geometric DVs is smaller than that of the LPs. Nevertheless, the observed geometric effects are sufficiently significant to consider their inclusion in structural optimization workflows.

Table 5 summarizes the final optimization results, including the objective function values, the number of iterations required for convergence and the maximum constraint violation in the final design.

4.2. Optimized internal layout configurations

The relocation of internal structural components induces two distinct effects that govern the structural buckling response. The first is a direct geometric effect, where component displacement alters the effective buckling lengths. The second is an indirect load transfer effect, as positioning of components modifies the distribution of reaction forces across the structure. In this case, these two mechanisms exhibit opposing behaviors, requiring a compromise during the layout optimization process. Both effects are discussed in greater detail in Appendix D. The notation for all internal components is provided in Figure 3.

The baseline configuration of Case 1 exhibits a nearly uniform chordwise distribution of structural thickness, with spanwise thickness gradually tapering from the root to the tip. A notable exception to this trend is observed in the lower shell, where panel mass is concentrated toward the tip region as illustrated in Figure 6.

When the rib position parameter is introduced as a DV, rib placement is shifted toward the tip. This geometric modification enables redistribution of structural material, by influencing critical buckling loads through changes of the

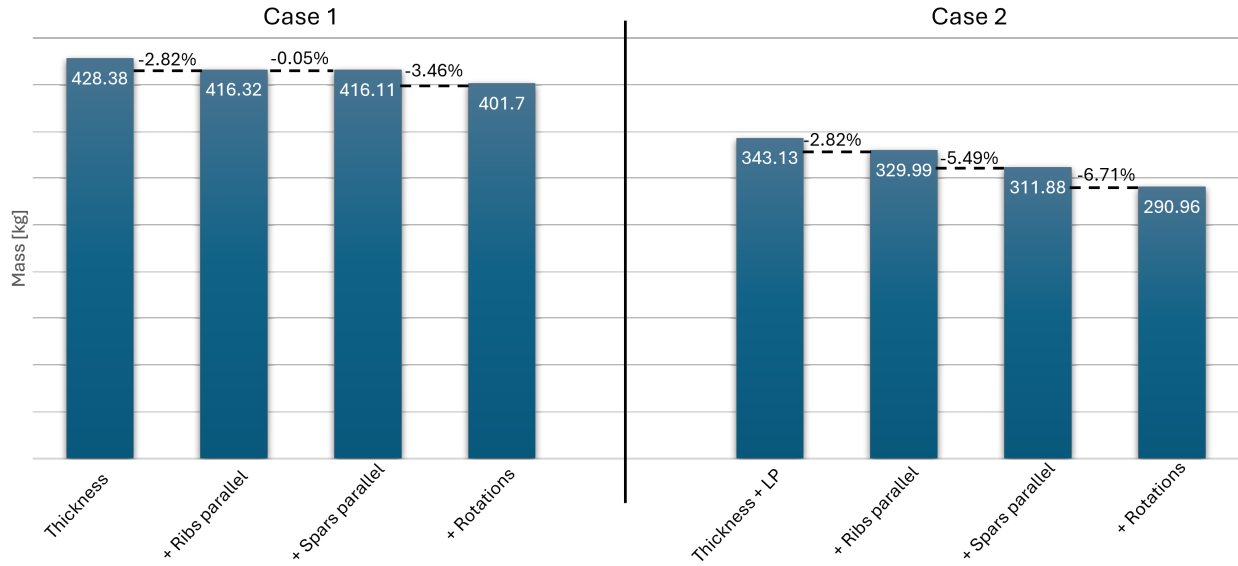


Figure 5: Final objective values with relative mass savings across all design stages.

Table 5

Optimization results across all design stages.

Stages	Iterations	Objective [kg]	Max. constraint	Critical criteria
Stage 0 Thickness	49	428.38	9.22×10^{-7}	US buck
Stage 1 + Ribs parallel	26	416.32	6.73×10^{-5}	US buck
Stage 2 + Spars parallel	30	416.12	9.96×10^{-6}	US buck
Stage 3 + Rotations	26	401.70	7.26×10^{-5}	US buck
Stage 0 Thickness + LP	35	343.13	9.78×10^{-5}	US buck
Stage 1 + Ribs parallel	147	329.99	2.03×10^{-8}	US buck
Stage 2 + Spars parallel	184	311.88	5.75×10^{-6}	LS buck
Stage 3 + Rotations	201	290.96	5.28×10^{-8}	US buck

panel buckling lengths. This results in a more uniform thickness distribution across the lower shell and mitigating the initial tip heavy mass concentration present in the baseline configuration.

Introducing additional spar DVs does not further improve the objective, as the 33% and 66% positions are already close to the optimum. The additional rotational degree of freedom primarily allows the optimizer to adjust the effective buckling length more freely between adjacent panels. It reduces the buckling length in highly loaded regions, while allowing larger buckling lengths in less loaded regions.

The fixed layout optimization of Case 2 exhibits a thickness distribution that gradually tapers from the root to the tip in the spanwise direction, as well as from S1 to S4 in the chordwise direction, as shown in Figure 7. This distribution is consistent with that reported by Dähne et al. [22]. In contrast to the fixed layout optimization of Case 1, this design yields a notably thinner lower shell near the tip. This reduction is due to the effective redistribution of structural loads through fiber orientation rather than relying solely on material volume.

When rib positioning parameters are introduced, the design differs from that of Case 1. The rib R3 is shifted

toward the tip and R2 toward the root. The global thickness distribution and primary stiffness orientations remain relatively close to the previous design. Similar to Case 1, the rib placement primarily affects the effective buckling lengths.

A key distinction from Case 1 is the significant influence of spar placement on the final objective. The optimizer positions the spars slightly closer together and moves them toward S1. This relocation is attributed to the asymmetric load distribution, with higher loads appearing at the leading edge. By repositioning the spars, these highly loaded regions are reinforced. As a result of this redistribution, the middle chord panels are now more suitable for carrying the loads than the outer chord panels. This selective load-carrying behavior is achieved by aligning the fiber directions within the designated regions with the direction of the resultant reaction forces. Conversely, panels intended to carry less loads are assigned fiber orientations perpendicular to the primary force direction. This orientation in secondary regions effectively redirects structural loads toward the optimally positioned panels. A more comprehensive explanation of the correlation between the load path and load carrying panels is provided in Appendix C.

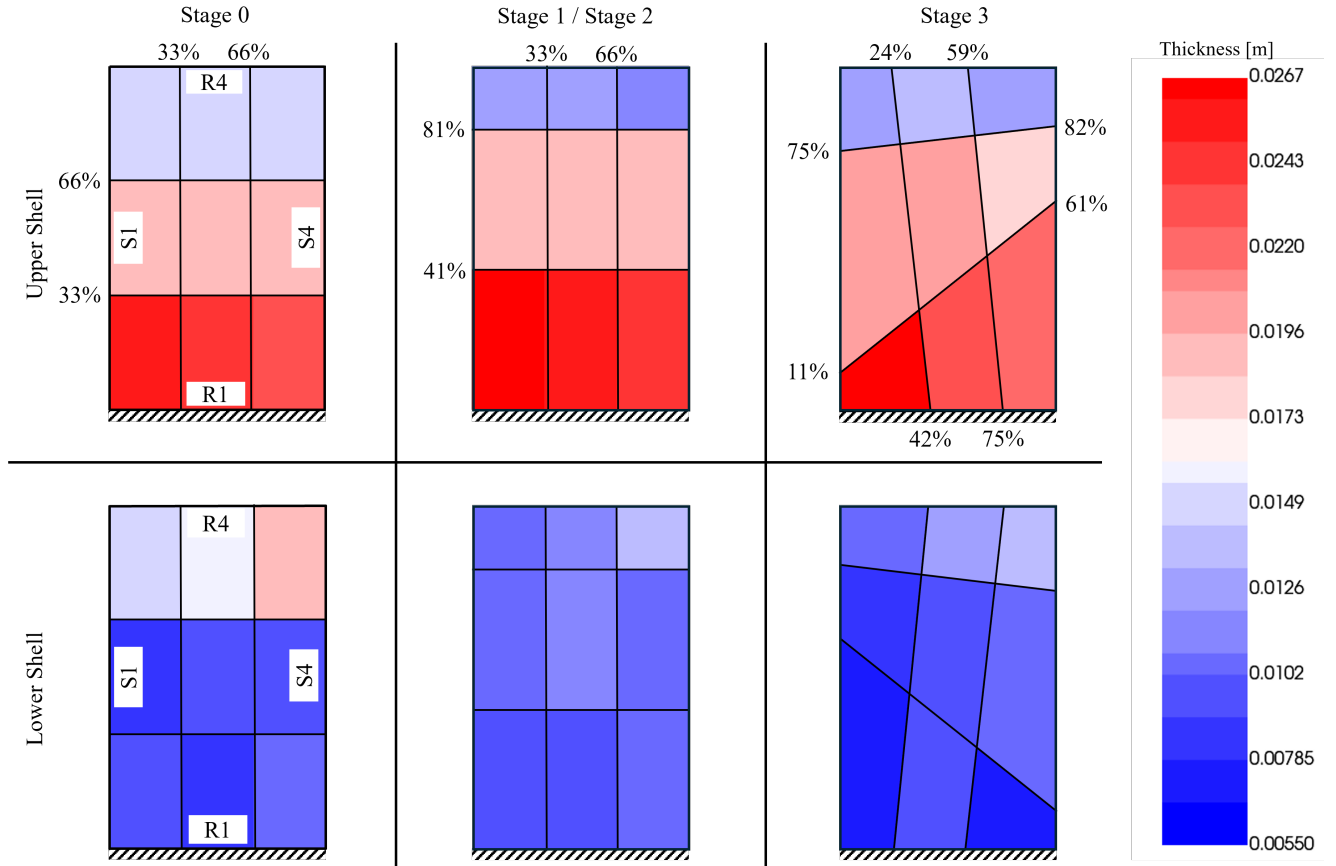


Figure 6: Thickness distribution and structural layout across the design stages of Case 1.

The additional rotational DOF enables distribution of loads more evenly across the middle chord panels. This effect is evident from the strain energy distribution presented in Appendix C.

The integration of local stiffness optimization with geometric DVs allows for more effective tailored load paths according to specific loading conditions. In contrast to local stiffness optimization alone, the combined approach provides greater design flexibility, enabling the selection of particular panels as primary load-bearing areas.

4.3. Optimization convergence

Figure 8 illustrates the convergence trajectories of the objective functions and maximum constraint violation across all optimization stages. As shown, every configuration successfully satisfied the imposed constraints.

The number of iterations required to reach optimality varied significantly depending on the problem formulation. In Case 1, the fixed layout optimization demanded more iterations than the other stages. The introduction of additional geometric DOFs accelerated convergence toward the optimum. For Case 2, the fixed layout optimization exhibited iteration counts comparable to those observed in Case 1. Conversely, increased parametric complexity consistently correlated with a higher iterative cost to reach optimality.

The convergence behaviors were evaluated to assess the convexity of the design spaces and the robustness of the optimization algorithm. Figures 9-12 show the design spaces for both cases and all design stages as well as the path the optimization algorithm took to reach the optimum. These plots were generated by varying the axis-defined parameters in increments of 0.05, while maintaining all other geometric DVs at their optimal values. The resulting masses of the structural optimizations were plotted, optimizing only structural DVs.

Figure 9 presents the design space for Stages 1 and 2 of Case 1. The parameter space exhibits strong convexity, enabling the optimizer to precisely locate the optimal layout. Notably, for the baseline spar arrangement, the initial benchmark layout already corresponds to the global optimum. Consequently, introducing an additional DOF for spar positioning does not yield further mass reduction, despite the positional parameters employ a clear influence on the objective function.

Figure 10 shows the corresponding design space for Stage 3 of Case 1 for each internal component. Similar to the straight arrangement, the design spaces remain convex, and the optimizer converges to the global optimum with high precision.

For Case 2, the design spaces exhibit slightly different topologies as illustrated in Figures 11 and 12, attributed to

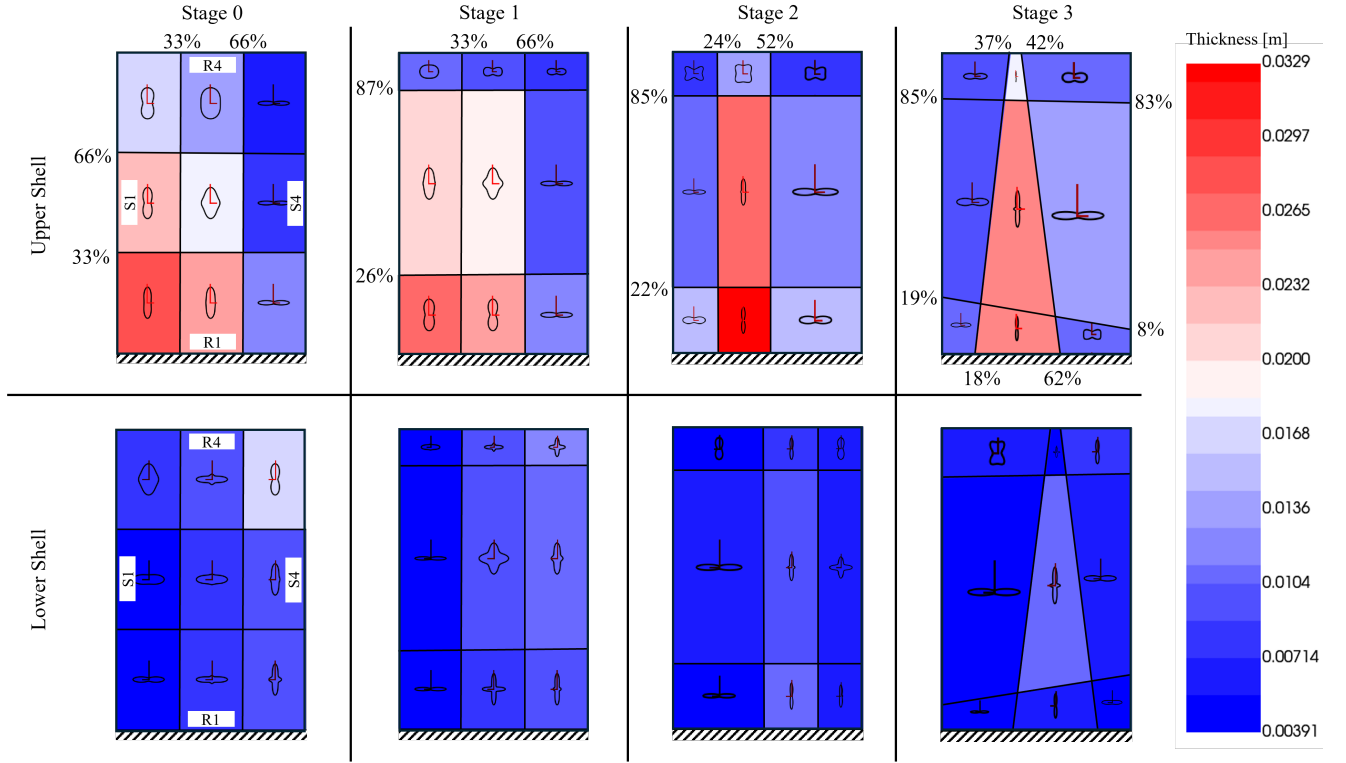


Figure 7: Thickness distribution and structural layout across the design stages of Case 2. Composite designs are illustrated using polar plots of the D-stiffness matrix.

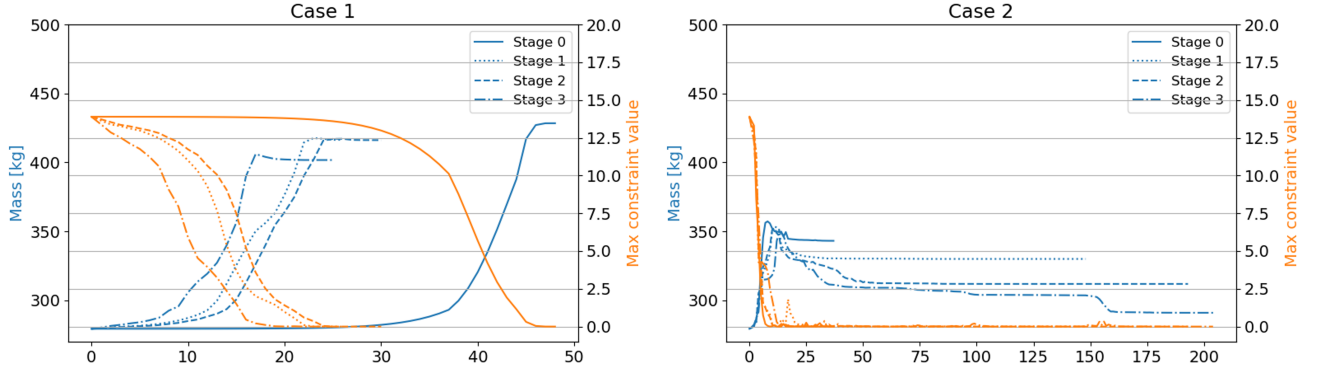


Figure 8: Convergence of the objective function and maximum constraint violation of all optimization stages.

the added local stiffness DOF. In Stage 1, the design space reveals two distinct local minima, one of which corresponds to a lower mass. The optimization algorithm successfully identifies the global optimum when starting from the initial layout. Furthermore, compared to Case 1, the objective function exhibits a steeper and more localized minimum around the optimal design point. The optimal spar position shifts slightly toward S1, making the initial benchmark spar layout suboptimal. This shift illustrates why introducing an adjustable spar parameter in Case 2 enables additional mass reduction, contrasting with Case 1 where the initial spar layout was already optimal.

For Stage 3 of Case 2 (Figure 12), the design space keeps its overall convex characteristics, and the optimizer again converges to the global optimum with good precision.

These plots demonstrate that the resulting layouts correspond to optimal configurations and that a gradient-based optimization algorithm is able to identify them through adjustments of geometric DVs. Furthermore, the used geometric DVs show convex design spaces for the considered use case and are therefore well suited for gradient-based optimization algorithms.

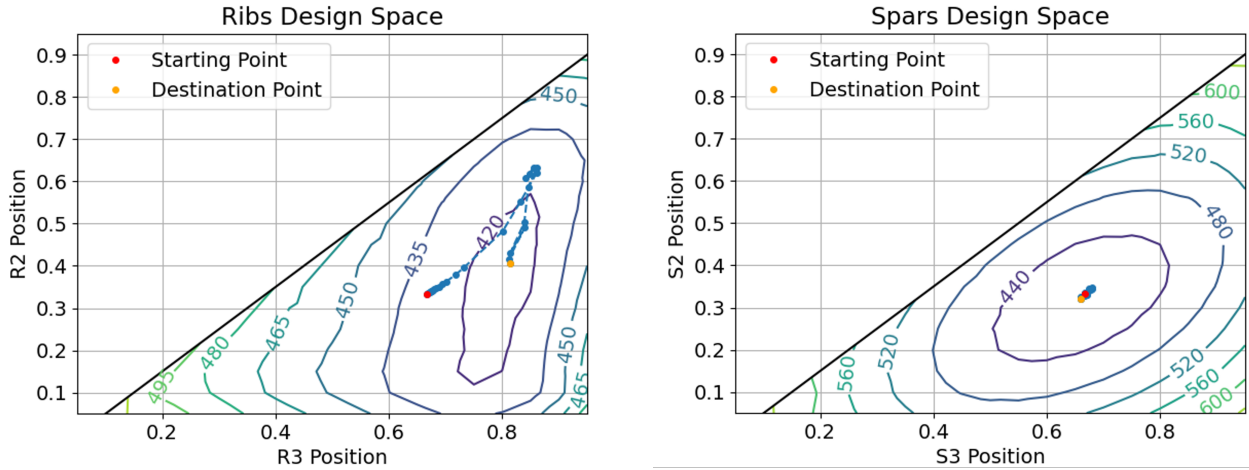


Figure 9: Design spaces of Case 1 for Stage 1 (left) and Stage 2 (right).

5. Conclusion

This study investigated the effects of coupling structural composite optimization with geometric DVs of the internal wing layout by integrating geometric parameters directly into a structural optimization framework. The proposed methodology was evaluated on a benchmark rectangular wing box configuration. The results demonstrate that incorporating geometric parameters results in further reductions in the objective function compared to optimizing structural parameters alone. When the LPs are optimized simultaneously with the geometric variables, the fully coupled design space can be exploited efficiently, leading to results that differ from those obtained through fixed stiffness optimization. Each additional geometric DOF contributes to an improvement in the objective, while the design space remains smooth for gradient-based algorithms to identify the global optimum.

These results highlight the advantage of optimizing the internal wing structure together with structural variables, such as thickness and LPs. Traditional bi-level design approaches, where the internal structure is fixed prior to structural optimization, lead to suboptimal designs. Therefore, coupling the internal wing structure with composite design enables a higher potential in mass reduction.

The proposed methodology not only demonstrates the strong coupling between the internal wing structure and composite design but also provides the sensitivity data required for a tightly coupled MDO. In this framework, any geometric parameter, including those defining the outer wing geometry, can serve as a DV, with structural sensitivities computed with respect to these external parameters. Such interdisciplinary interactions are typically neglected in loosely coupled MDOs, often leading to suboptimal designs. By integrating these interdisciplinary sensitivities to a global optimization algorithm, the proposed approach enables simultaneous handling of multiple disciplines through such interdisciplinary gradients.

The results in this study primarily validate the proposed methodology rather than representing a comprehensive aircraft wing design. While the framework is capable of consider an arbitrary number of geometric DVs, its computational scalability and parameter coupling in high dimensional configurations require further investigation. The efficiency of the selected optimization algorithm when applied to large sets of geometric parameters remains unverified.

Furthermore, only a monodisciplinary structural optimization was performed in this study. However, the geometric DVs defining the internal structural layout can have a notable influence on the deflection behavior of a wing, particularly for high aspect ratio configurations. These deflections affect the internal loads acting on the structural panels. Consequently, incorporating an external load evaluation process into the optimization process is expected to enable further mass reductions compared with structural optimization alone. By introducing this additional discipline, the optimization algorithm would be able to exploit aeroelastic load alleviation through the strategic positioning of internal structural components, thereby reducing the loads acting on structurally critical regions and potentially achieving additional weight savings.

Immediate efforts will focus on showing the potential of the proposed approach using realistic wing configurations under representative flight conditions. The design space will be expanded by increasing both the number of geometric parameters and structural DVs to assess scalability and feasibility. Furthermore, the effects of the internal structural layout on load alleviation will be investigated, together with its automated optimization while accounting for load alleviating effects.

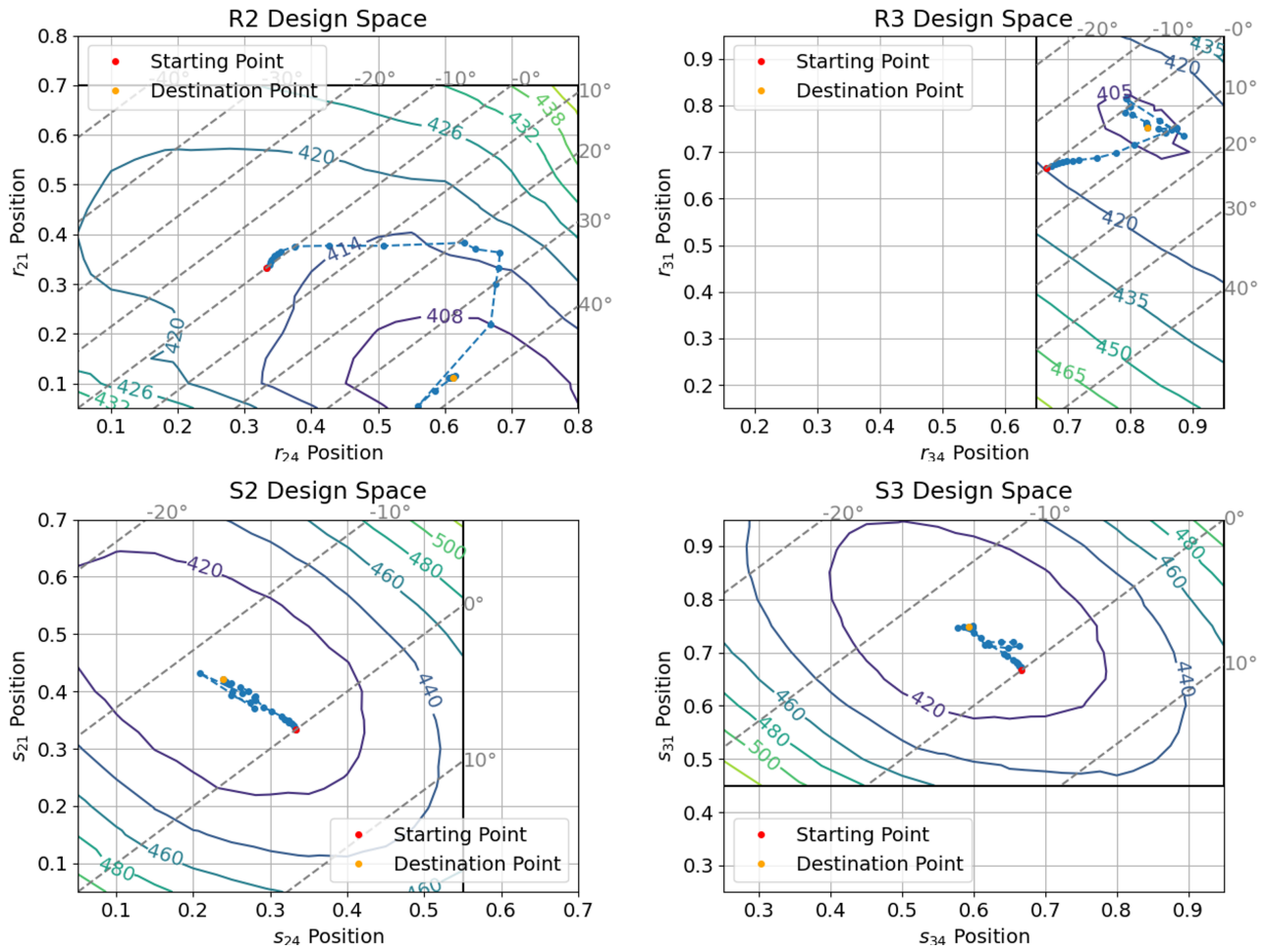


Figure 10: Design spaces of Case 1 for Stage 3 of each internal component.

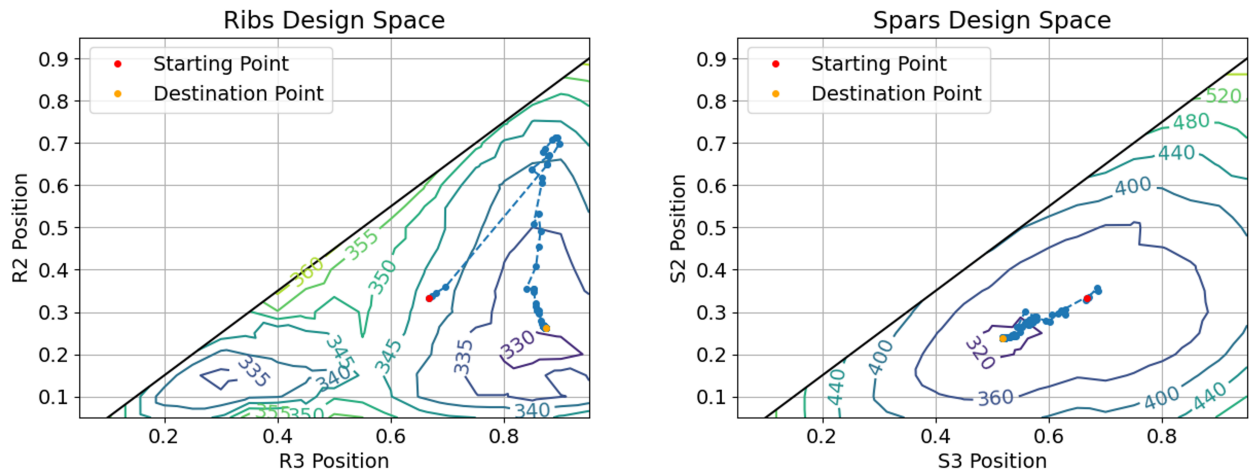


Figure 11: Design spaces of Case 2 for Stage 1 (left) and Stage 2 (right).

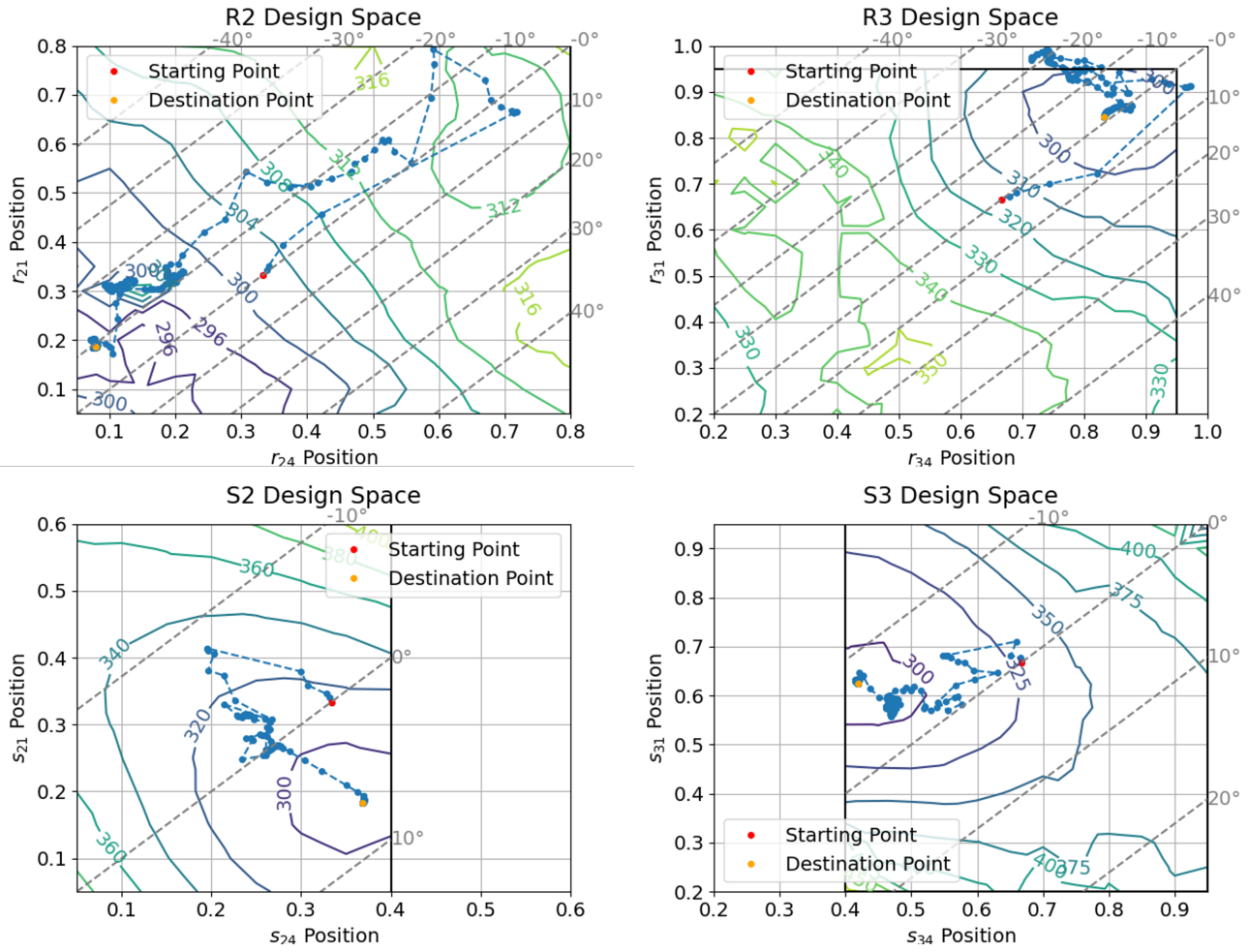


Figure 12: Design spaces of Case 2 for Stage 3 of each internal component.

CRedit authorship contribution statement

Lennart Tönjes: Conceptualization, Methodology, Software, Investigation, Validation, Visualization, Writing – original draft. **Sascha Dähne:** Conceptualization, Software, Validation, Writing – review and editing. **David Zerbst:** Conceptualization, Validation, Writing – review and editing. **Christian Hühne:** Writing – review and editing, Supervision, Funding acquisition. All authors have read and approved the final manuscript.

Declaration of Competing Interest

The authors have no competing interests to declare that are relevant to the content of this article.

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Data Availability

The CPACS files containing the geometric and structural definition of the use case presented in this study are publicly available in the zenodo repository [36].

Code availability

The code used in this study is part of an internal research framework and is not publicly available.

A. Calculation of stiffness matrix components from lamination parameters

The LPs V_x^A , V_x^B , and V_x^D , corresponding to the in-plane, coupling, and bending stiffness matrices respectively, can be computed based on the ply orientation angles, laminate thickness, and their through-thickness positions within the laminate stack.

$$V_x^{(s)} = \frac{c_s}{t_{\text{lam}}^s} \sum_{k=1}^N (z_k^s - z_{k-1}^s) W_x(\theta_k), \quad (9)$$
$$s \in \{1, 2, 3\}, \quad x = 1, \dots, 4.$$

where t_{lam} is the laminate thickness and z_k the distance of the k -th ply from the laminate mid-plane. The trigonometric orientation functions are collected in

$$\mathbf{W}(\theta_k) = \begin{bmatrix} W_1(\theta_k) \\ W_2(\theta_k) \\ W_3(\theta_k) \\ W_4(\theta_k) \end{bmatrix} = \begin{bmatrix} \cos(2\theta_k) \\ \sin(2\theta_k) \\ \cos(4\theta_k) \\ \sin(4\theta_k) \end{bmatrix}. \quad (10)$$

The specific sets of LPs used for the in-plane, coupling, and bending stiffnesses are

$$\begin{aligned} V_x^A &:= V_x^{(1)} \quad (c_1 = 1), \\ V_x^B &:= V_x^{(2)} \quad (c_2 = 1), \\ V_x^D &:= V_x^{(3)} \quad (c_3 = 4). \end{aligned} \quad (11)$$

With the LP the independent stiffness components can be calculated as

$$\mathbf{A} = [A_{11} \quad A_{22} \quad A_{12} \quad A_{66} \quad A_{16} \quad A_{26}]^T,$$

$$\begin{aligned}\mathbf{B} &= [B_{11} \ B_{22} \ B_{12} \ B_{66} \ B_{16} \ B_{26}]^T, \\ \mathbf{D} &= [D_{11} \ D_{22} \ D_{12} \ D_{66} \ D_{16} \ D_{26}]^T.\end{aligned}\quad (12)$$

With the material parameter vector

$$\mathbf{U} = [u_1 \ u_2 \ u_3 \ u_4 \ u_5]^T \quad (13)$$

the laminate stiffness can be expressed as

$$\begin{aligned}\mathbf{A} &= t_{\text{lam}} \mathbf{M}(\mathbf{V}^A) \mathbf{U}, \\ \mathbf{B} &= \frac{t_{\text{lam}}^2}{4} \mathbf{M}_B(\mathbf{V}^B) \mathbf{U}, \\ \mathbf{D} &= \frac{t_{\text{lam}}^3}{12} \mathbf{M}(\mathbf{V}^D) \mathbf{U},\end{aligned}\quad (14)$$

where $\mathbf{V}^A, \mathbf{V}^B, \mathbf{V}^D$ denote the corresponding sets of LPs and

$$\mathbf{M}(\mathbf{V}) = \begin{bmatrix} 1 & V_1 & V_2 & 0 & 0 \\ 1 & -V_1 & V_2 & 0 & 0 \\ 0 & 0 & -V_2 & 1 & 0 \\ 0 & 0 & -V_2 & 0 & 1 \\ 0 & V_3/2 & V_4 & 0 & 0 \\ 0 & V_3/2 & -V_4 & 0 & 0 \end{bmatrix}, \quad (15)$$

while the coupling matrix uses

$$\mathbf{M}_B(\mathbf{V}) = \begin{bmatrix} 0 & V_1 & V_2 & 0 & 0 \\ 0 & -V_1 & V_2 & 0 & 0 \\ 0 & 0 & -V_2 & 0 & 0 \\ 0 & 0 & -V_2 & 0 & 0 \\ 0 & V_3/2 & V_4 & 0 & 0 \\ 0 & V_3/2 & -V_4 & 0 & 0 \end{bmatrix}. \quad (16)$$

B. Structural constraints

B.1. Strength failure criterion

The failure condition is governed by a quadratic strain-based equation:

$$C_{ij}\varepsilon_i\varepsilon_j + RC_i\varepsilon_i + R^2C_0 = 0, \quad i, j \in \{I, II\}, \quad (17)$$

where the strength margin is quantified by the ratio:

$$R_{\text{strength}} = \frac{\varepsilon_{\text{crit}}}{\varepsilon_{\text{applied}}} \leq 1. \quad (18)$$

The coefficients C_0, C_i , and C_{ij} are expressed in terms of the material invariant parameters u_k as follows:

$$\begin{aligned}C_0 &= -\frac{1}{4} \frac{u_6^2}{u_4} - 1, \\ C_I &= -\frac{1}{2} \frac{u_3 u_6}{u_4} + u_5, \\ C_{II} &= -\frac{1}{2} \frac{u_3 u_6}{u_4} + u_5,\end{aligned}\quad (19)$$

$$C_{II} = -\frac{1}{4} \frac{u_3^2}{u_4} + u_2 + u_1,$$

$$C_{III} = u_1 - \frac{1}{4} \frac{u_3^2}{u_4},$$

$$C_{III} = -\frac{1}{4} \frac{u_3^2}{u_4} + u_2 + u_1.$$

In addition to strength constraints, the structural integrity of the laminate panels is evaluated against buckling instability. Both compressive loads along the principal material axes and shear loads are assessed to ensure stability under the defined loading condition.

B.2. Buckling criterion

Compressive buckling resistance along the primary material direction is determined in accordance with HSB 45111-08 [37]. The critical buckling load, $n_{x,\text{cr}}$, is expressed as:

$$n_{x,\text{cr}} = k_x(\bar{\alpha}, \beta) \cdot \frac{\pi^2}{b^2} \sqrt{D_{11} D_{22}}, \quad (20)$$

where k_x denotes the elastic buckling coefficient dependent on panel geometry and laminate anisotropy, a and b represent the panel buckling length in both principal directions, and D_{ij} are the components of the transformed bending stiffness matrix. The auxiliary parameters $\bar{\alpha}$ and β characterize the normalized aspect ratio and coupling effects:

$$\begin{aligned}\bar{\alpha} &= \frac{a}{b} \left(\frac{D_{22}}{D_{11}} \right)^{1/4}, \\ \beta &= \frac{D_{12} + 2D_{33}}{\sqrt{D_{11} D_{22}}}.\end{aligned}\quad (21)$$

For compression applied orthogonally to the fiber direction, the bending stiffness matrix is rotated by 90° , effectively exchanging the principal stiffness terms ($D_{11} \leftrightarrow D_{22}$). The same fundamental formulation is then applied to determine the transverse critical buckling load, $n_{y,\text{cr}}$.

Shear buckling resistance is evaluated following HSB 45112-02 [37], yielding the critical shear load as:

$$n_{s,\text{cr}} = k_s(\beta) \left(\frac{\pi}{b} \right)^2 \sqrt[4]{D_{11} D_{22}^3}, \quad (22)$$

where $k_s(\beta)$ is the shear buckling coefficient, which primarily depends on the laminate anisotropy parameter β .

To account for the multiaxial loading conditions, a modified quadratic interaction criterion is employed to evaluate the combined effects of compression in the principal fiber direction, transverse compression, and shear buckling as stated in 45113-01 [37]. The combined buckling index is defined as:

$$R_{\text{buck,comb}} = \frac{n_x}{n_{x,\text{crit}}} + \frac{n_y}{n_{y,\text{crit}}} + \left(\frac{n_{xy}}{n_{xy,\text{crit}}} \right)^2 \leq 1, \quad (23)$$

where n_x and n_y represent the applied compressive loads in the principal material directions and n_{xy} denotes the applied shear load. Stability is ensured provided $R_{\text{buck,comb}} \leq 1.0$.

B.3. Hyperplane approach to restrict LP design space

In this approach, each hyperplane defines a boundary that restricts the parameter space to physically realizable designs. A single feasibility hyperplane is mathematically expressed as

$$R_{LP} = h_{m1}V_{1A} + h_{m2}V_{2A} + h_{m3}V_{1D} + h_{m4}V_{2D} + h_{m5} \leq 0. \quad (24)$$

where h_{mi} ($i = 1, \dots, 5$) are the hyperplane coefficients. For a given parameter set to be considered feasible, it must satisfy this inequality for all bounding hyperplanes defining the convex hull [23].

The number of required hyperplanes depends on the specific class of laminate under consideration. Under the present study's assumption of symmetric, balanced quad laminates, the convex hull of the feasible parameter space is fully defined by exactly 49 distinct hyperplanes per parameter set. Consequently, the optimization framework incorporates 49 linear inequality constraints per skin to guarantee that every solution corresponds to a valid and realizable composite stacking sequence.

C. Load-path visualisation using element strain energy

To evaluate the mechanical response of the wing boxes layout and interpret the reasons behind the optimizer's design choices, element strain energy is used as a diagnostic metric. Strain energy quantifies the elastic deformation stored within specific structural regions, thus showing which regions are more load carrying than others. For anisotropic composite laminates, interpreting the design choices also requires consideration of the directional orientations of the force resultants.

The elemental strain energy is computed from the in-plane force resultants and their corresponding strain components over the element area. The directional contributions are expressed as:

$$\begin{aligned} U_x &= \frac{1}{2} N_x \epsilon_x A_e \\ U_y &= \frac{1}{2} N_y \epsilon_y A_e \\ U_{xy} &= \frac{1}{2} N_{xy} \gamma_{xy} A_e \end{aligned} \quad (25)$$

where N_x , N_y , and N_{xy} denote the axial and shear force resultants, ϵ_x , ϵ_y , and γ_{xy} represent the corresponding strain measures, and A_e is the elemental area. For visualization and comparative analysis, these directional components are

combined into a single scalar quantity representing the strain energy per unit area:

$$U_e = \frac{1}{2} (N_x \epsilon_x + N_y \epsilon_y + N_{xy} \gamma_{xy}). \quad (26)$$

To capture the directional characteristics of the load transfer, the generalized angle of the force resultants, θ_N , is computed as:

$$\theta_N = \frac{1}{2} \text{atan2}(2N_{xy}, N_x - N_y). \quad (27)$$

Figure 13 illustrates the distribution of element strain energy and the orientation of the force resultants across all optimization stages for Case 2. The force resultant field exhibits a consistent pattern for all optimization stages. The root region is governed by axial loading, whereas the tip region experiences increasing shear deformation induced by load introduction and torsional effects.

In the baseline and Stage 1 configurations, the leading-edge panels carry the highest strain energy. However, in Stages 2 and 3, the load path migrates toward the mid panels, with the leading- and trailing-edge panels carrying minimal energy. When compared with the overall fiber orientation distribution shown in Figure 7, a clear correlation can be observed. Laminates contributing significantly to the structural stiffness align closely with the principal direction of the force resultants, whereas low-energy panels exhibit misaligned fiber orientations.

D. Sensitivities of geometric design variables

The sensitivity of the buckling response to geometric DVs can be separated into two distinct physical effects. A direct geometric effect, which modifies the effective buckling lengths and consequently the critical buckling load, and a structural effect, which alters the internal load redistribution captured by the FE analysis. Because these influences are physically separable, their individual contributions can be quantified through the buckling sensitivities with respect to the geometric parameters. The total sensitivity gradient is expressed as the sum of the direct geometric contribution and the structural contribution.

$$\begin{aligned} \frac{dc_{\text{buck}}}{dx_g} &= \left(\frac{\partial c_{\text{buck}}}{\partial x_g} \right)_{\text{geom}} + \left(\frac{\partial c_{\text{buck}}}{\partial x_g} \right)_{\text{struc}} \\ &= \left(\frac{\partial c_{\text{buck}}}{\partial \mathbf{P}} + \frac{\partial c_{\text{buck}}}{\partial \mathbf{N}} \frac{\partial \mathbf{N}}{\partial \mathbf{P}} \right) \frac{\partial \mathbf{P}}{\partial x_g} \end{aligned} \quad (28)$$

Figure 14 illustrates the distribution of these sensitivities for Case 1, where the laminate stackings are kept constant. The results demonstrate that different structural components have distinct influences on the buckling constraint depending on their local position. Specifically, rib R2 primarily affects the root panels through its direct influence on the local buckling length. Shifting this rib toward the midspan increases the effective buckling length in the root region, thereby decreasing the critical buckling load. Conversely,

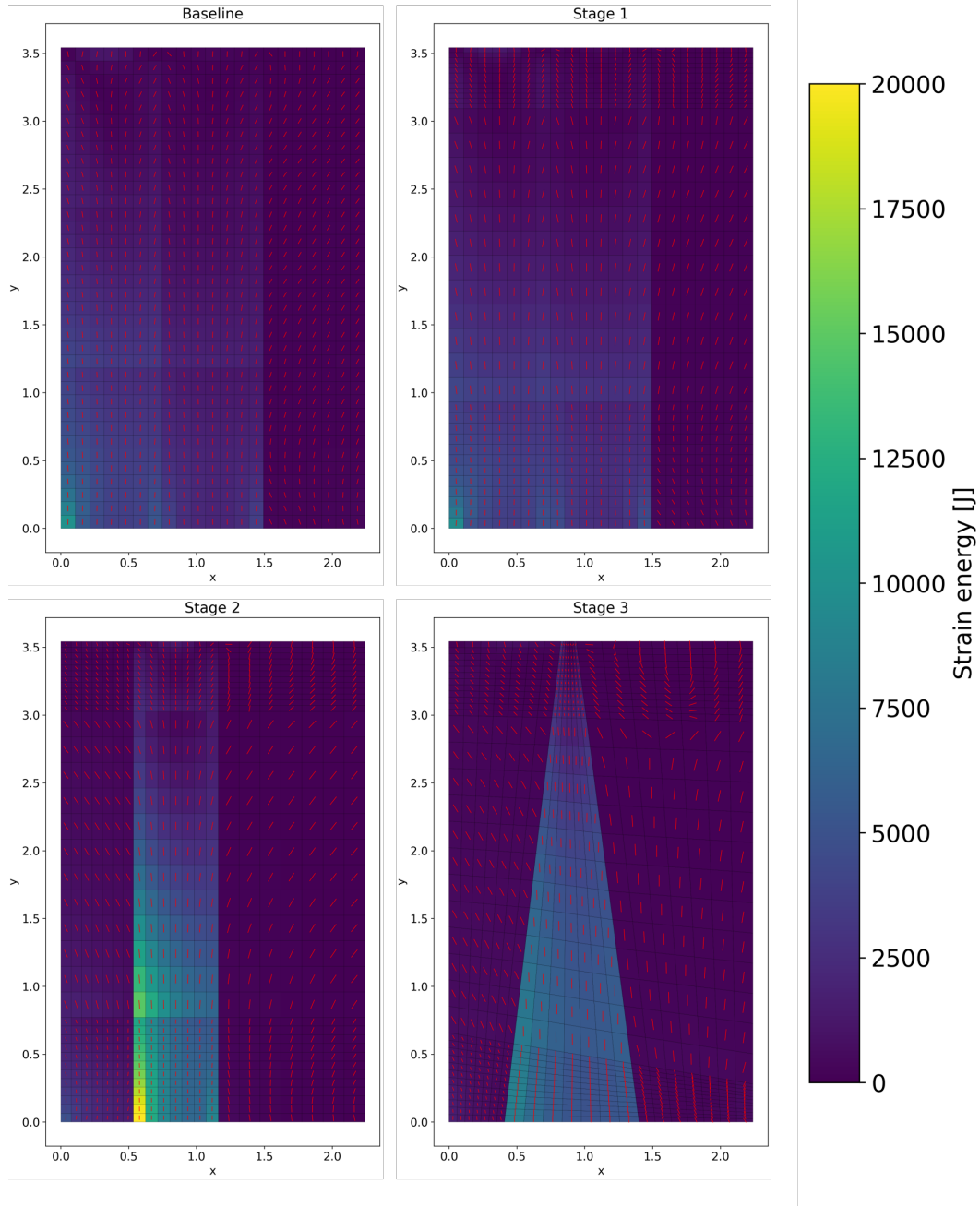


Figure 13: Distribution of element strain energy and force resultant orientation θ_N across all optimization stages for Case 2.

this relocation reduces the internal loads, which decreases the buckling effect in that area.

In contrast, rib R3 exhibits minimal direct geometric influence on the buckling response. Its sensitivity is mainly influenced by load redistribution. The spars, on the other hand, do not affect load redistribution. Their sensitivity is entirely geometric, where critical areas are particularly sensitive to design changes of the spars.

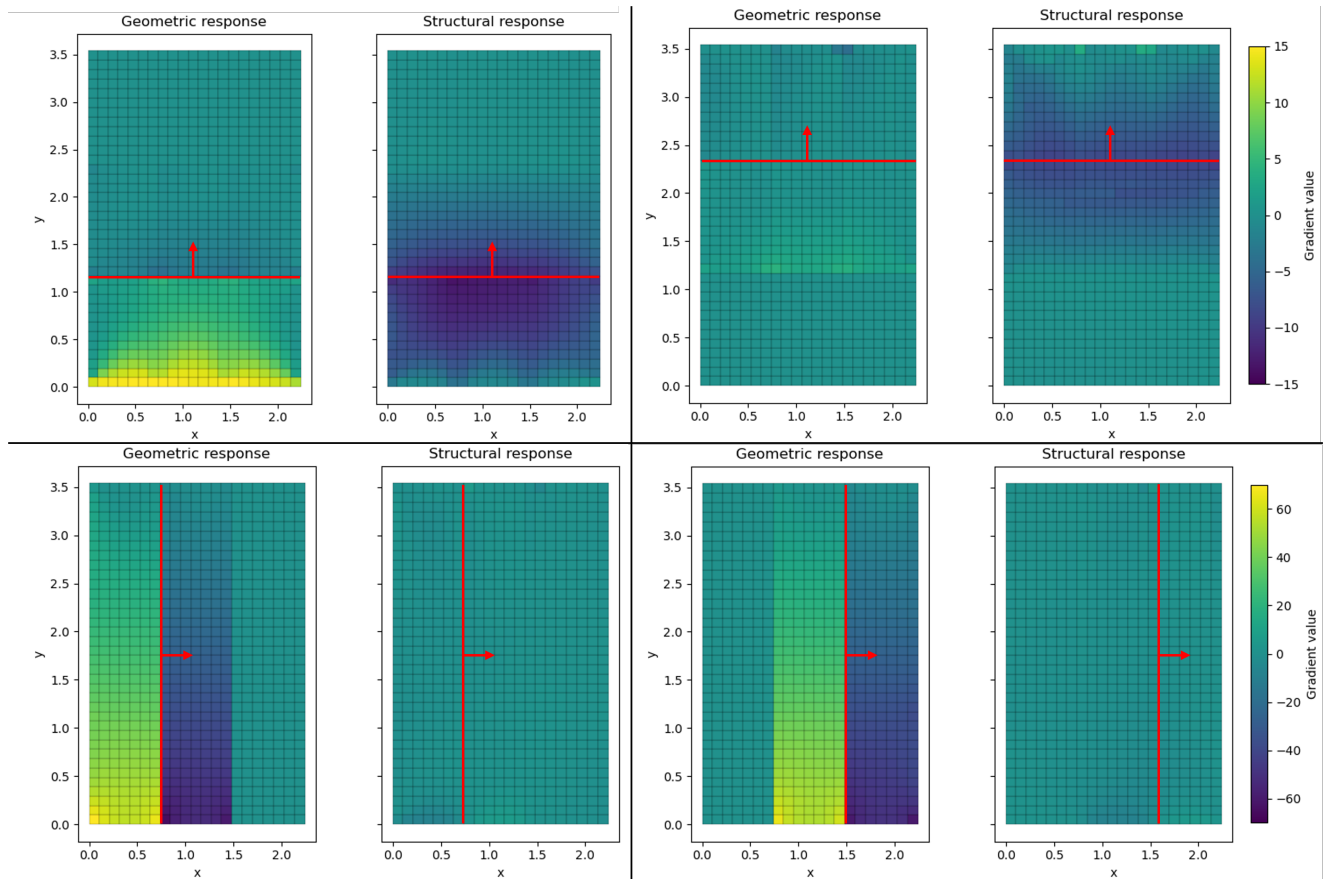


Figure 14: Geometric and structural influence of each internal component visualised by sensitivity magnitudes.

References

- [1] E. Carrera, G. Palaia, K. Abu Salem, The green transition in commercial aviation, *Rendiconti Lincei. Scienze Fisiche e Naturali* 36 (2025) 785–829. URL: <https://link.springer.com/article/10.1007/s12210-025-01345-1#citeas>. doi:10.1007/s12210-025-01345-1.
- [2] N. Bons, J. R. R. A. Martins, F. Odagui, A. P. C. Cuco, Aerostructural wing optimization of a regional jet considering mission fuel burn, *ASME Open Journal of Engineering* 1 (2022) 011046. doi:10.1115/1.4055630.
- [3] G. Kennedy, J. Martins, A parallel finite-element framework for large-scale gradient-based design optimization of high-performance structures, *Finite Elements in Analysis and Design* 87 (2014) 56–73. doi:10.1016/j.finel.2014.04.011.
- [4] S. Nikbakt, S. Kamarian, M. Shakeri, A review on optimization of composite structures part i: Laminated composites, *Composite Structures* 195 (2018) 158–185. URL: <https://www.sciencedirect.com/science/article/pii/S0263822317336279>. doi:https://doi.org/10.1016/j.compstruct.2018.03.063.
- [5] T. R. Brooks, J. R. R. A. Martins, G. J. Kennedy, High-fidelity aerostructural optimization of tow-steered composite wings, *Journal of Fluids and Structures* 88 (2019) 122–147. doi:10.1016/j.jfluidstruct.2019.04.005.
- [6] M. Sensmeier, B. Stewart, J. Samareh, Rapid Generation and Assessment of Aircraft Structural Topologies for Multidisciplinary Optimization and Weight Estimation, 2006. URL: <https://arc.aiaa.org/doi/abs/10.2514/6.2006-1981>. doi:10.2514/6.2006-1981. arXiv:https://arc.aiaa.org/doi/pdf/10.2514/6.2006-1981.
- [7] S. Grihon, L. Krog, D. Bassir, Numerical optimization applied to structure sizing at airbus: A multi-step process, *International Journal for Simulation and Multidisciplinary Design Optimization* 3 (2011) 432–442. doi:10.1051/ijsmdo/2009020.
- [8] D. Locatelli, S. B. Mulani, R. K. Kapania, Wing-box weight optimization using curvilinear spars and ribs (sparibs), *Journal of Aircraft* 48 (2011) 1671–1684. URL: <https://doi.org/10.2514/1.C031336>. doi:10.2514/1.C031336. arXiv:https://doi.org/10.2514/1.C031336.
- [9] B. K. Stanford, Shape, sizing, and topology design of a wing-box under aeroelastic constraints, *Journal of Aircraft* 58 (2021) 1406–1415. URL: <https://doi.org/10.2514/1.C036315>. doi:10.2514/1.C036315. arXiv:https://doi.org/10.2514/1.C036315.
- [10] J. Sobieszczanski-Sobieski, Multidisciplinary optimization for engineering systems: Achievements and potential, in: H. W. Bergmann (Ed.), *Optimization: Methods and Applications, Possibilities and Limitations*, Springer Berlin Heidelberg, Berlin, Heidelberg, 1989, pp. 42–62.
- [11] B. K. Stanford, P. D. Dunning, Optimal topology of aircraft rib and spar structures under aeroelastic loads, *Journal of Aircraft* 52 (2015) 1298–1311. doi:10.2514/1.C032913.
- [12] M. P. Bendsøe, N. Kikuchi, Generating optimal topologies in structural design using a homogenization method, *Computer Methods in Applied Mechanics and Engineering* 71 (1988) 197–224. URL: <https://www.sciencedirect.com/science/article/pii/0045782588900862>. doi:https://doi.org/10.1016/0045-7825(88)90086-2.
- [13] A. Nana, J.-C. Cuillière, V. Francois, Automatic reconstruction of beam structures from 3d topology optimization results, *Computers & Structures* 189 (2017) 62–82. URL: <https://www.sciencedirect.com/science/article/pii/S0045794916308835>. doi:https://doi.org/10.1016/j.compstruc.2017.04.018.
- [14] M.-P. Schmidt, C. B. W. Pedersen, Gradient-based optimization of cad models addressing heterogeneous parameters and

- composite materials, *Structural and Multidisciplinary Optimization* 68 (2025) 209. URL: https://link.springer.com/article/10.1007/s00158-025-04155-z?utm_source=chatgpt.com#citeas. doi:10.1007/s00158-025-04155-z.
- [15] K. Amadori, C. Jouannet, P. Krus, Aircraft conceptual design optimization, *International Congress of the Aeronautical Sciences ICAS*, 2008 4 (2008).
- [16] Stephen W. Tsai, Nicholas J. Pagano, Invariant properties of composite materials, 1968. URL: <https://api.semanticscholar.org/CorpusID:136436586>.
- [17] J.-H. Zhu, W.-H. Zhang, L. Xia, Topology optimization in aircraft and aerospace structures design, *Archives of Computational Methods in Engineering* 23 (2016) 595–622. URL: https://link.springer.com/article/10.1007/s11831-015-9151-2?utm_source=chatgpt.com#citeas. doi:10.1007/s11831-015-9151-2.
- [18] D. Agarwal, S. Marques, T. T. Robinson, Aerodynamic shape optimisation using parametric cad and discrete adjoint, *Aerospace* 9 (2022) 743. URL: https://www.mdpi.com/2226-4310/9/12/743?utm_source=chatgpt.com. doi:10.3390/aerospace9120743.
- [19] H. Hajdik, A. Yildirim, J. R. Martins, Aerodynamic shape optimization with cad-based geometric parameterization, in: *AIAA SCITECH 2023 Forum*, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2023. doi:10.2514/6.2023-0726.
- [20] C. Ledermann, P. Ermanni, R. Kelm, Dynamic cad objects for structural optimization in preliminary aircraft design, *Aerospace Science and Technology* 10 (2006) 601–610. URL: <https://www.sciencedirect.com/science/article/pii/S127096380600085X>. doi:https://doi.org/10.1016/j.ast.2006.07.001.
- [21] T. F. Wunderlich, S. Dähne, L. Reimer, A. Schuster, Global aero-structural design optimization of composite wings with active manoeuvre load alleviation, *CEAS Aeronautical Journal* 13 (2022) 639–662. URL: <https://link.springer.com/article/10.1007/s13272-022-00585-3#citeas>. doi:10.1007/s13272-022-00585-3.
- [22] S. Dähne, E. Werthen, D. Zerbst, L. Tönjes, H. Traub, C. Hühne, Lightworks, a scientific research framework for the design of stiffened composite-panel structures using gradient-based optimization, *Structural and Multidisciplinary Optimization* 67 (2024). doi:10.1007/s00158-024-03783-1.
- [23] E. Werthen, S. Dähne, Design- and manufacturing constraints within the gradient based optimization of a composite aircraft wingbox, in: *Proceedings of the 6th Airframe Structural Design Conference*, Bristol, United Kingdom, 2018. Conference held 9–11 October 2018.
- [24] P. E. Gill, W. Murray, M. A. Saunders, Snopt: An sqp algorithm for large-scale constrained optimization, *SIAM Review* 47 (2005) 99–131. doi:10.1137/S0036144504446096.
- [25] C. Geuzaine, J.-F. Remacle, Gmsh: A 3-d finite element mesh generator with built-in pre- and post-processing facilities, *International Journal for Numerical Methods in Engineering* 79 (2009) 1309–1331. doi:10.1002/nme.2579.
- [26] SMR SA, B2000++ and B2000++ Pro Summary, 2018. URL: <https://www.smr.ch/products/b2000/>, finite Element Analysis Environment.
- [27] J. Martins, P. Sturdza, J. Alonso, The complex-step derivative approximation, *ACM Transactions on Mathematical Software* 29 (2003) 245–262. doi:10.1145/838250.838251.
- [28] D. Zerbst, L. Tönjes, S. Dähne, E. Werthen, E. Kappel, C. Hühne, Equivalent plate formulation of double-double laminates for the gradient-based design optimization of composite structures, *Composite Structures* 354 (2025) 118786. doi:10.1016/j.compstruct.2024.118786.
- [29] M. P. Scardaoni, M. Montemurro, A general global-local modelling framework for the deterministic optimisation of composite structures, *Structural and Multidisciplinary Optimization* 62 (2020) 1927–1949. doi:10.1007/s00158-020-02586-4.
- [30] B. Liu, R. T. Haftka, M. A. Akgün, Two-level composite wing structural optimization using response surfaces, *Structural and Multidisciplinary Optimization* 20 (2000) 87–96. doi:10.1007/s001580050140.
- [31] D. Liu, V. V. Toropov, O. M. Querin, D. C. Barton, Bilevel optimization of blended composite wing panels, *Journal of Aircraft* 48 (2011) 107–118. doi:10.2514/1.C000261.
- [32] S. Dähne, C. Hühne, Gradient based structural optimization of a stringer stiffened composite wing box with variable stringer orientation, in: A. Schumacher, T. Viator, S. Fiebig, K.-U. Bletzinger, K. Maute (Eds.), *Advances in structural and multidisciplinary optimization*, Springer, Cham, 2018, pp. 814–826. URL: https://link.springer.com/chapter/10.1007/978-3-319-67988-4_62#citeas. doi:10.1007/978-3-319-67988-4_62.
- [33] S. Setoodeh, M. M. Abdalla, Z. Gürdal, Design of variable-stiffness laminates using lamination parameters, *Composites Part B: Engineering* 37 (2006) 301–309. URL: <https://www.sciencedirect.com/science/article/pii/S1359836806000023>. doi:https://doi.org/10.1016/j.compositesb.2005.12.001.
- [34] A. Khani, S. T. IJsselmuiden, M. M. Abdalla, Z. Gürdal, Design of variable stiffness panels for maximum strength using lamination parameters, *Composites Part B: Engineering* 42 (2011) 546–552. doi:10.1016/j.compositesb.2010.11.005.
- [35] Collier Research Corporation, Buckling Spans, https://hypersizer.com/help_7.0/Content/FE-Shell/shell-buckling_span.php, 2014. HyperSizer Version 7.0. Accessed: 2026-06-25.
- [36] S. Dähne, D. Zerbst, Cpacs for rectangular box wing, 2023. URL: <https://doi.org/10.5281/zenodo.7972946>. doi:10.5281/zenodo.7972946.
- [37] *Luftfahrttechnisches handbuch 1th: Handbuch strukturberechnung hsb / hrsg. vom industrie-ausschuß struktur berechnungsunterlagen iasb ; 3*, 1969. URL: <https://www.tib.eu/de/suchen/id/TIBKAT%3A225343789>.