REDESIGN OF AN AERONAUTICAL COMPOSITE STIFFENED PANEL WITH THE DOUBLE-DOUBLE DESIGN APPROACH

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Abstract

The tailorability of composite structures represents a fundamental aspect of their appeal and utility across a spectrum of industries, as unlike traditional materials, they offer unparalleled flexibility in design and manufacturing, allowing engineers to precisely tailor material properties to meet specific performance requirements. The heart of composite tailorability lies in the ability to control material composition, fiber orientation, stacking sequences, and resin systems during the manufacturing process. Such customization level enables engineers to optimize structures for several applications, balancing factors such as strength, stiffness, weight, durability, and cost-effectiveness. The concept of Double-Double laminates makes it possible to introduce an alternative approach to the design of composite laminate structures, for which to carry out a proper and effective optimization in terms of laminate thickness and plies orientation. The aim is to minimize the use of plies to the minimum required to provide strength to the structure, while ensuring a reduction in the total mass of the component. In this paper, the Double-Double design and the feasibility study of a composite stiffened panel, typically adopted in aircraft structures, has been investigated. This investigation has delved deeper into the implementation of the Double-Double approach in the aviation field and its potential impact on component performance. The findings of the study revealed promising results, demonstrating that the new Double-Double design, optimized to meet the material strength requirements, yielded a remarkable reduction in total mass. Specifically, the optimized design achieved a mass reduction of up to 26.48% compared to the initial design configuration. This substantial decrease in weight not only contributes to improved fuel efficiency and operational performance but also aligns with the aerospace industry's ongoing efforts to enhance sustainability and reduce environmental impact.

Keywords: Composite Structures, Aircraft Component Design, FEA, Double-Double Design, Composite Laminates Optimization

1. Introduction

Composite materials are subject to continuous evolution and research, offering increasingly attractive properties for all kinds of applications in several engineering fields. Layered composites are the preferred option when building structures that are focused on lightweight and the ability to meet specific stiffness and strength requirements. This is achieved by strategically stacking plies, each consisting of fibers oriented in particular directions, thus enabling a fine tailoring of the structure's properties. Such customized configurations allow engineers to optimize the performance, ensuring an effective resistance to a variety of loading and boundary conditions [1-3].

The advantages of composite materials in terms of lightness and mechanical performances over traditional metal alloys are particularly beneficial in the manufacturing of components in the aerospace field, where composite laminate structures have been in increasing use in the recent decades [4]. The lightweight nature of composite materials coupled with their high mechanical performance places composite materials as the ideal option for producing extremely high-performance airframe structures able to reduce the total mass of the aircraft and, consequently, fuel consumption and emissions [5, 6].

Nevertheless, in such a promising framework, the lack of a complete knowledge about mechanical behavior of composites as for metals and the prevalence of historically entrenched design rules hinder the full exploitation of their benefits, despite their well-known mechanical potential and the availability of powerful and effective optimization methods. Since the beginning of the use of fiber-reinforced composite materials in the aviation industry, several design rules have been adopted and rooted over the years, informally establishing a standard for the industrial production [7]. Fiber-reinforced laminated composites are mainly limited to the use of only four angles (0, ±45 and 90) for plies orientation and referred as QUAD laminates. The hand lay-up process initially imposed such lay-ups due to manufacturing capabilities and easiness. Then, the certification of conventional laminates and the wide availability of experimental mechanical reference data increasingly extended their use. However, this limitation is now easy to overcome with the introduction of new production technologies such as Automated Fiber Placement (AFP) [8]. Others of the most relevant rules impose the mid-plane symmetry requirement to avoid the laminate's out-of-plane warpage and that laminates must be balanced to maintain the in-plane isotropy [9]. Additionally, the '10% rule' mandates at least a 10% contribution of each orientation to the total number of plies while the inter-ply angle should be set to 45 degree or less to minimize interlaminar stresses [10].

Such issues and rules negatively affect the performance of composite structures by making them heavier than necessary and not allowing the full potential of composites to be exploited. Moreover, tapering and optimization processes result more difficult.

The design of composite laminate structures can be performed by means of three approaches in order to enhance the mechanical performance of the structure and ensure lightness: optimize the employed base materials [11], optimize the design of the components through topological optimization processes [12], or optimize the lay-up and the number of plies adopted in the laminate [13]. However, the former approach is of major concern in the base materials development and not always feasible for the structures' design depending on possible limitations in the materials development capabilities. The latter approach can be pursued only in cases where the design of components is not primarily fixed by specific constraints imposed by employment or interaction with preexisting components. The last approach is the most easily employable, but previously mentioned limitations restrict the possible permutations in orientations and minimization of the plies number, partially thwarting the process.

In this context, the concept of Double-Double laminates arises as an alternative approach to the conventional design of composite laminated structures to make the structures perform better by carrying out an optimization process of the orientation and number of plies in the laminate according to the loads acting on the structure [14-16]. The Double-Double laminates, introduced by Prof. Stephen W. Tsai, differ significantly from Quads as they overcome most of the limitations imposed by manufacturing and simultaneously ensures a reduction in the total mass of the structure by minimizing the number of adopted plies to the minimum required to withstand the acting loads. Additional and unnecessary plies introduced to meet laminate symmetry and balancing requirements or mitigate warping phenomena are avoided.

In this work, the design approach offered by Double-Double laminates is employed in the redesign of a composite stiffened panel adopted as a typical representative aircraft component to investigate the benefits of Doble-Double approach in the design process of structures for aviation applications and their manufacturability in the new proposed design. Over the years, multiple configurations of composite stiffened panels have been targeted in the investigation of component design, manufacturing and repair approaches [17-20] and in the study of typical phenomena of interest in the aircraft structures [21-24]. The redesign is aimed to define a structure that is lighter than the starting configuration but able to provide suitable mechanical performance in terms of strength. The mass reduction allowed by the procedure has been evaluated as benefits.

In section 2, an overview on the Double-Double laminates concept is proposed, along with an explanation of the workflow for the Double-Double design generation for components. Section 3 proposes the Finite Element model description of the adopted composite stiffened panel, while results of the DD design generation process are given and discussed in the Section 4.

2. Double-Double laminates overview

Double-Double laminates are based on double bi-axial [±Φ, ±Ψ] angle plies and made up by stacking thin 4-plies sub-laminates one upon the other until imposed structural requirements are met. The laminate features are tailored according to the structure needs [25, 26]. Unlike the typical QUAD approach which involves 8-plies-based building blocks, the DDs adopts base sub-laminates with only 4 plies which allow an earlier achievement of the laminates' homogenization. In the QUAD laminates, the plies' orientations generally take only four typical values. On the other hand, in Double-Double laminates, the values of Φ and Ψ angles, which provide the orientations of the plies, can take on any value between 0° and 90° without any limitation. These values are optimized with respect to the stress state experienced by the structure in order to minimize the number of sub-laminates required to support the acting loads and minimize the mass. Optimization results simple as DDs have only four permutations for the stacking sequence. Indeed, the use of infinite orientations and the small number of permutations make layup optimization simple. Moreover, they do not need to be symmetrical due to the natural achieved homogenization obtained by stacking identical sub-laminates.

According to huge number of introduced simplification, the Double-Double approach is intended to provide an alternative method to the use of conventional laminates in the design of composite laminate structures that is closer to the design standards of metal structures. Once the DD angles in the sub-laminate are optimized according to the loading condition, the laminate thickness is modified discretely by adding or removing sub-laminates as needed, as with metals.

The Double-Doubles concept and their usage in such a way to design composite components as metal components lays its foundation in another intuition introduced by Prof. S.W. Tsai in [27-29]. The so-called Tsai's Modulus represents the trace of the stiffness matrix [A] of a composite laminate, which is the sum of the elements on the main diagonal. Tsai identified a correspondence between the mathematical and physical meanings of the trace of the stiffness matrix [A], demonstrating that it can represent the only parameter needed to accurately define the stiffness features of the layers and that of the complete laminate. The value of Tsai Modulus for a certain composite is always the same regardless of the laminate lay-up and is an intrinsic property of the material. The Modulus can therefore be used to compare and rank different composites. It introduces a huge simplification in the description of mechanical properties and comparison of fiber-reinforced composite materials, in an equivalent way to the role of stiffness modulus for metallic materials.

2.1 Double-Double laminates generation workflow

The identification and optimization of the Double-Double design for a composite laminate component in terms of thickness and plies orientation to meet a strength requirement can be easily accomplished by means of the Lam-Search Optimizer tool and the DD-Design tool, following the workflow shown in Figure 1 and previously presented in [25, 30].

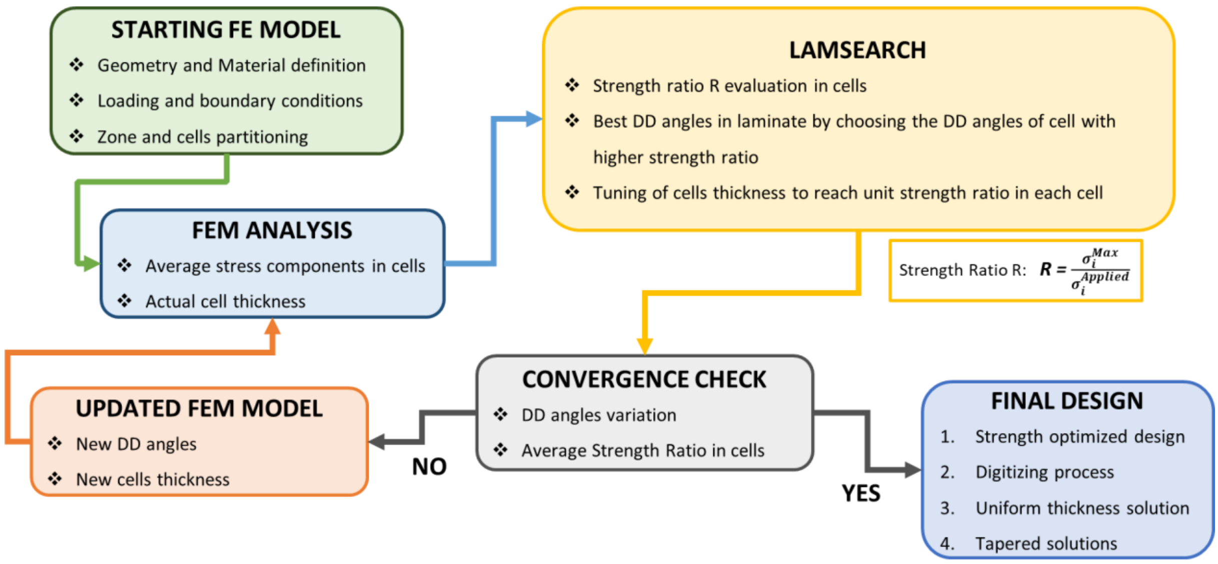

Figure 1 - Workflow for the Double-Double design determination on structures by means of the Lam-Search optimizer tool and FE analyses

The former is a sophisticated Excel-based optimization tool designed to identify the optimal Φ and Ψ angles for the Double-Double design. It conducts a thorough optimization of the laminate's thickness profile, tailored to the applied loads on the structure to ensure compliance with strength criteria. An intralaminar failure criteria among several available in the tool are used to evaluate the strength features of the structure. The latter is an interface tool between Lam-Search and Ansys Mechanical APDL Finite Element Analysis software that allows the automatic connection of the two tools during the process.

Based on the tool's assumptions, partitioning into zones could be contemplated to precisely delineate the optimal Double-Double design within each zone, thereby addressing various sections of a complex structure. Each zone necessitates a partitioning of up to 49 cells, as per the specifications of the Lam-Search Optimizer Tool. Each cell groups part of the elements constituting the structure. The input of the process comprises a finite element (FE) model of the structure, incorporating cell partitioning. This FE model encompasses property definitions, mesh configurations, boundary conditions, and all requisite steps for conducting linear analyses.

The DD-Design tool can be called as input directly into Ansys Mechanical APDL and allows setting the parameters of the DD laminate design process via pop-ups. During the process, the DD-Design tool feeds instructions to Ansys Mechanical APDL to perform linear static Finite Element analyses on the defined structure, extrapolate the in-plane strain and stress components recorded on the on elements and the average values on the cells, and provide them to Lam-search. Then, Lam-Search processes the received data, determines the best Φ and Ψ angles and thickness profile on the structure according to the chosen intralaminar failure criterion. The DD-Design tool provides the new design to the FE software to perform a new analysis and proceed with the optimization process, which ends when the imposed convergence criteria are met. In each iteration, Lam-Search automatically assesses every potential angle combination, arranges them, and selects the optimal angles [±Φ, ±Ψ] to minimize safety margins. This is done by analyzing the strength ratio R, given in Equation (1), according to the adopted failure criterion.

$$R = \frac{\sigma^{allowable}}{\sigma^{applied}} \tag{1}$$

Lam-Search uses the computed cells' average stresses to determine the Strength Ratio R in every cell. Within each zone, the cell with the lowest R-value became the controlling cell and its Φ and Ψ angles form the optimal Double-Double angle combination. The thickness distribution is adjusted proportionally according to the difference in R-values between each cell and the controlling cell.

The convergence criteria are identified in achieving in each cell of each zone an R-value approximately equal to 1 and obtaining the same Φ and Ψ angles for each zone in two subsequent iterations. Thus, the structure is optimized in the lay-up and thickness distribution of the laminate with respect to a strength criterion to minimize mass.

3. Stiffened panel Finite Element model description

The composite laminated stiffened panel adopted for the present work has been modelled in the FEM Ansys Mechanical APDL software according to the typical geometry features and dimensions commonly assumed in the literature for studying the mechanical behaviour of such type of structures and their related phenomena. Specifically, the panel consists of a rectangular 500 mm x 450 mm outer skin and two T-shaped reinforcing stringers, neglecting any eventual curvature. A detailed representation of the complete structure and the main dimensions of the components are provided in Figure 2.

A shell-based formulation has been employed in modeling the panel through the use of Shell181 elements for discretization. Such four-node elements are suitable for analyzing thin to moderately-thick shell structures and have six degrees of freedom at each node. They are suitable for layered applications for modeling composite shells and the accuracy in modeling composite shells is governed by the first-order shear-deformation theory.

The reason for choosing shell modelling is justified and mandated by the need to have a formulation for which automatically the DD-Design tool could update the design of the structure in terms of stacking sequence and thicknesses at each iteration without re-generating the model based on the outputs provided by the Lam-Search Optimizer Tool. The shell formulation allows the design of the structure to be simply updated by changing the number, thickness, and orientation of the plies in the appropriate sections used to define the initial design.

A representation of the discretized structure is given in Figure 3. An element size of 6 mm has been selected, encouraging the matching of nodes on the skin and stringer surfaces in the contact zone.

Since the skin and stringer have been modeled as separate entities, an approach using Conta173 and Targe170 elements has been preferred for the creation of the bonding constraint of the stringers to the skin, without providing for any debonding phenomenon.

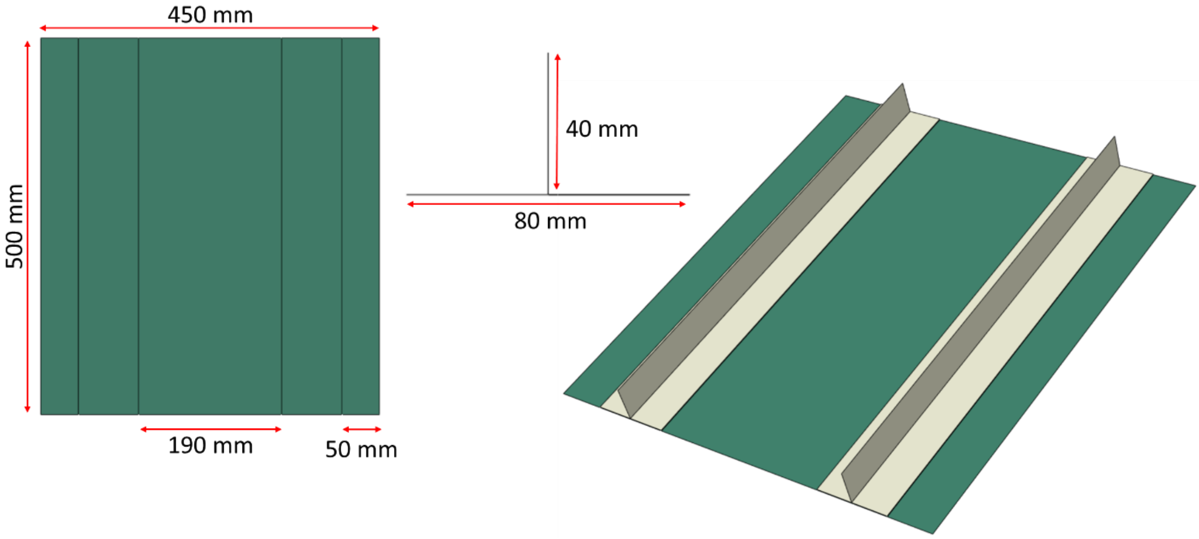

Figura 2 – Stiffened panel geometrical description and main dimensions

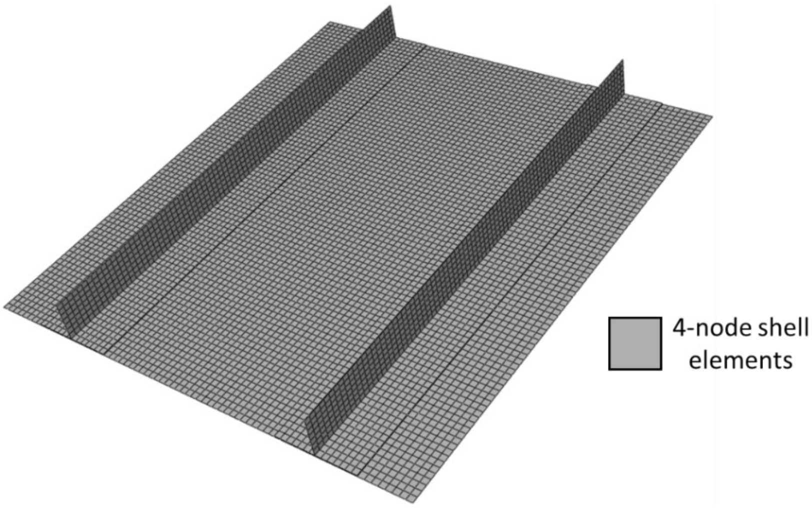

Figura 3 – FE discretization of the modelled panel

A distinct stacking sequence has been chosen and assigned through the Ansys Mechanical APDL section features to the individual parts of the structure as detailed in Table 1. The sequences have been established based on typical sequences used for such components, through the use of plies oriented in the only 0°, ±45° and 90° angles, as typically in QUAD laminates. The properties of the adopted carbon fiber-reinforced composite material are shown in Table 2. This material has been taken from the materials database already present within Lam-Search, which collects the mechanical properties of typical carbon fibre-reinforced composites typically used in several engineering fields and can be extended with user-defined materials. The implementation of linear static analysis requires the only definition of the lamina elastic properties and strengths for the possible failure modes, in order to verify the fulfilling of the imposed strength criterion.

Stacking Sequences	Web Stringer	[+45,90,0,0,-45,0,0,-45,0,0,90,+45]s	Tk = 3 mm
	Foot Stringer	[+45,90,0,0,-45,0]s	Tk = 1.5 mm
	Skin	[+45,90,-45,-45,+45,90,0,-45,+45,0]s	Tk = 2.5 mm

Table 1 – Adopted stacking sequences for components in the starting QUAD configuration of the panel (Note: Tk = thickness)

T700 CPLY64 CFRP composite	
E_1 = 140800 MPa	*v_{13} = 0.34*
E_2 = 9300 MPa	*X_T = 2944 MPa*
E_3 = 9300 MPa	*X_C = 1983 MPa*
G_{12} = 5800 MPa	*Y_T = 60 MPa*
G_{23} = 4060 MPa	*Y_C = 220 MPa*
G_{13} = 5800 MPa	*S_T = 93 MPa*
v_{12} = 0.34	*S_L = 93 MPa*
v_{23} = 0.38	*Thickness = 0.125 mm*

Table 2 – Mechanical properties of the T700 CPLY64 composite

The determination of the best Double-Double design for a component is tailored to the applied loading condition so as to minimize the mass and keep the structure in safe with respect to the strength of the material. In the present case, the selected loading condition is intended to simulate a simplified combination of loads acting on such a panel when employed in the structure of a composite fuselage section. Specifically, a constant pressure distribution equal to 0.1013 MPa on the inner surface is applied to simulate pressurization on the fuselage structure, while concentrated forces are applied to a pilot node at the front of the panel, as shown in Figure 4. A 392 kN load and a 1.41 kN load have been applied longitudinally and perpendicular to the skin, respectively, and are intended to simulate the action exerted on the panel by the unmodeled components of the structure. The pilot node is constrained to nodes on the panel's forward end by rigid connections, while nodes on the rear end have been constrained.

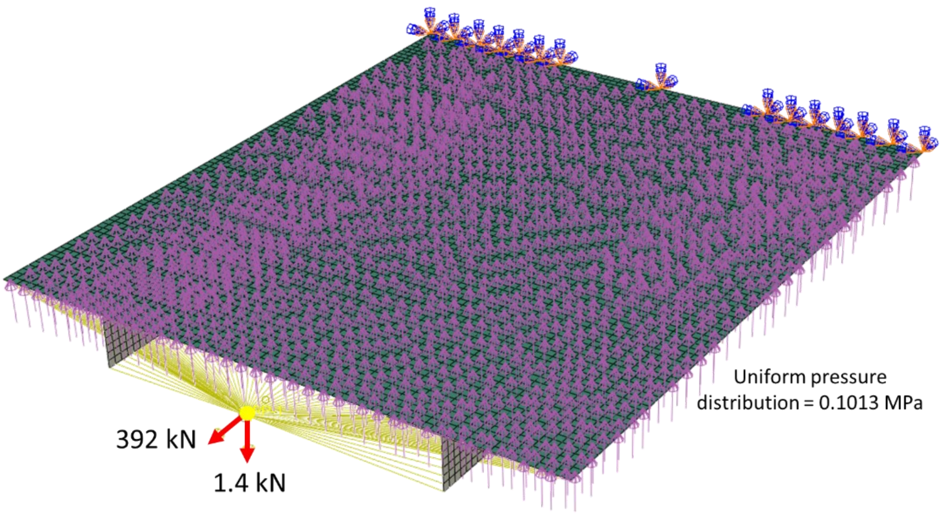

Figure 4 – Loading and boundary conditions applied on the panel

According to the prescription of the DD design determination and optimization process through the Lam-Search Optimizer tool, the composite panel structure have been subdivided into three different zones, in order to obtain the best and most characteristic Double-Double design for each part of the panel.

Particularly, Zone 1 has been associated with the panel's skin, while Zone 2 and Zone 3 have been assigned to the web and foot of the two stringers, respectively, as detailed in the Figure 5. Furthermore, cells have been created in each of the zones by grouping the elements that discretize the structure, as required by the procedure. 28 cells are defined in Zone 1 while 14 cells are defined in each of Zones 2 and 3. The assigned cell numbering for all zones is shown in Figure 6.

In compliance with the basic procedure's principle, an optimal combination of Φ and Ψ angles valid for all cells in the zone is defined for each zone; then, thickness of cells is defined according to the value of the strength ratio R with respect to the controlling cell.

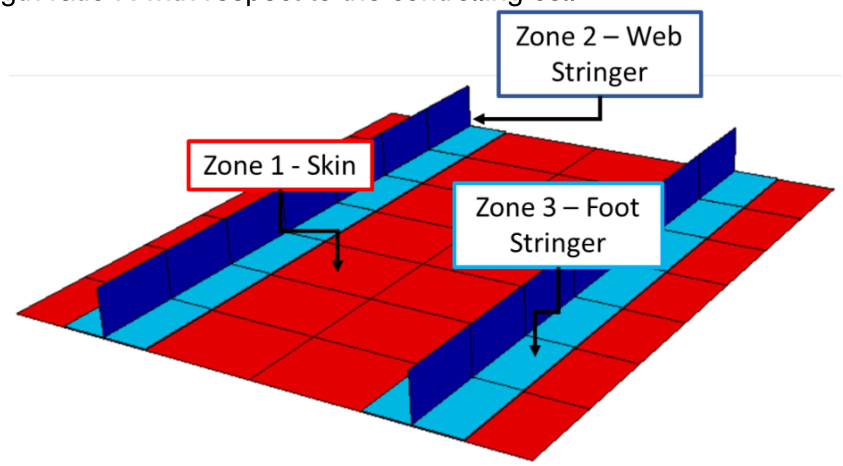

Figure 5 – Zone partitioning for the Double-Double design determination

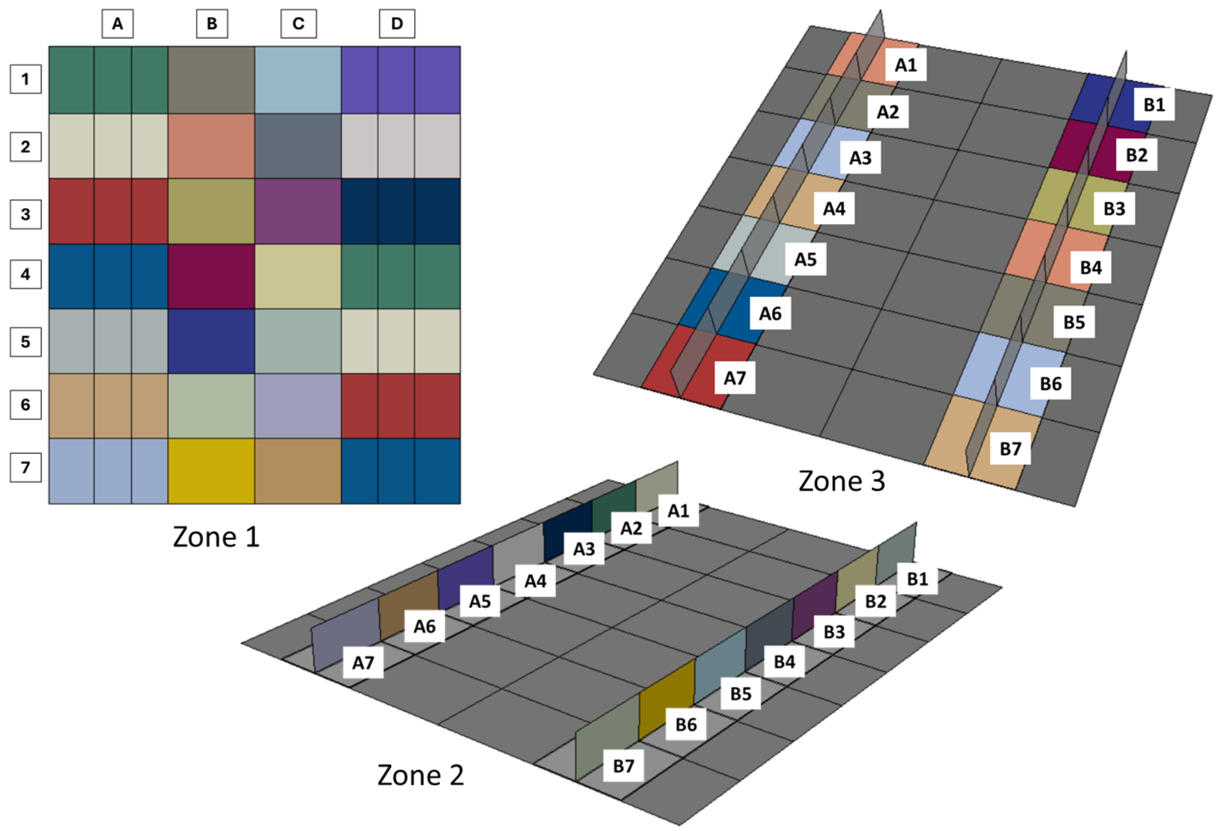

Figure 6 - Cells partitioning in the three defined zones for the Double-Double design determination

4. Double-Double design determination

The redesign began with the initial setup of the stiffened panel. According to the workflow in Figure 1, an iterative procedure has been employed to determine the most effective Double-Double design for the structure. This implied systematically adjusting the thickness and lay-up of cells within each zone while conducting linear static finite element analyses considering the loads described in Figure 4. A concurrent redesign has been executed for all three zones, reaching the optimal [±Φ, ±Ψ] DD lay-ups and thickness distributions simultaneously.

A preliminary linear static analysis has been performed on the initial design of the panel, referred to as Iteration 0. The numerical outcomes in terms of strain components contour plots for the panel can be found in Figure 7.

Complying with the procedure guidelines, the in-plane strain components for each of the cells in the three zones have been determined by averaging the strain components of the elements contained in each cell, as for Equation (2). Then, the in-plane stress components in the cells have been computed by multiplying by the thickness-normalized laminate stiffness matrix [A]*, as for Equation (3). Instructions and operations are automatically supplied by the DD-Design tool and implemented in in the Post1 module of Ansys Mechanical APDL.

$$\varepsilon_{11_{cell_j}} = \frac{1}{n} \cdot \sum_{i=1}^{n} abs\left(\varepsilon_{11_i}\right) \tag{2}$$

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix} = [A]^* \cdot \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \end{Bmatrix} \tag{3}$$

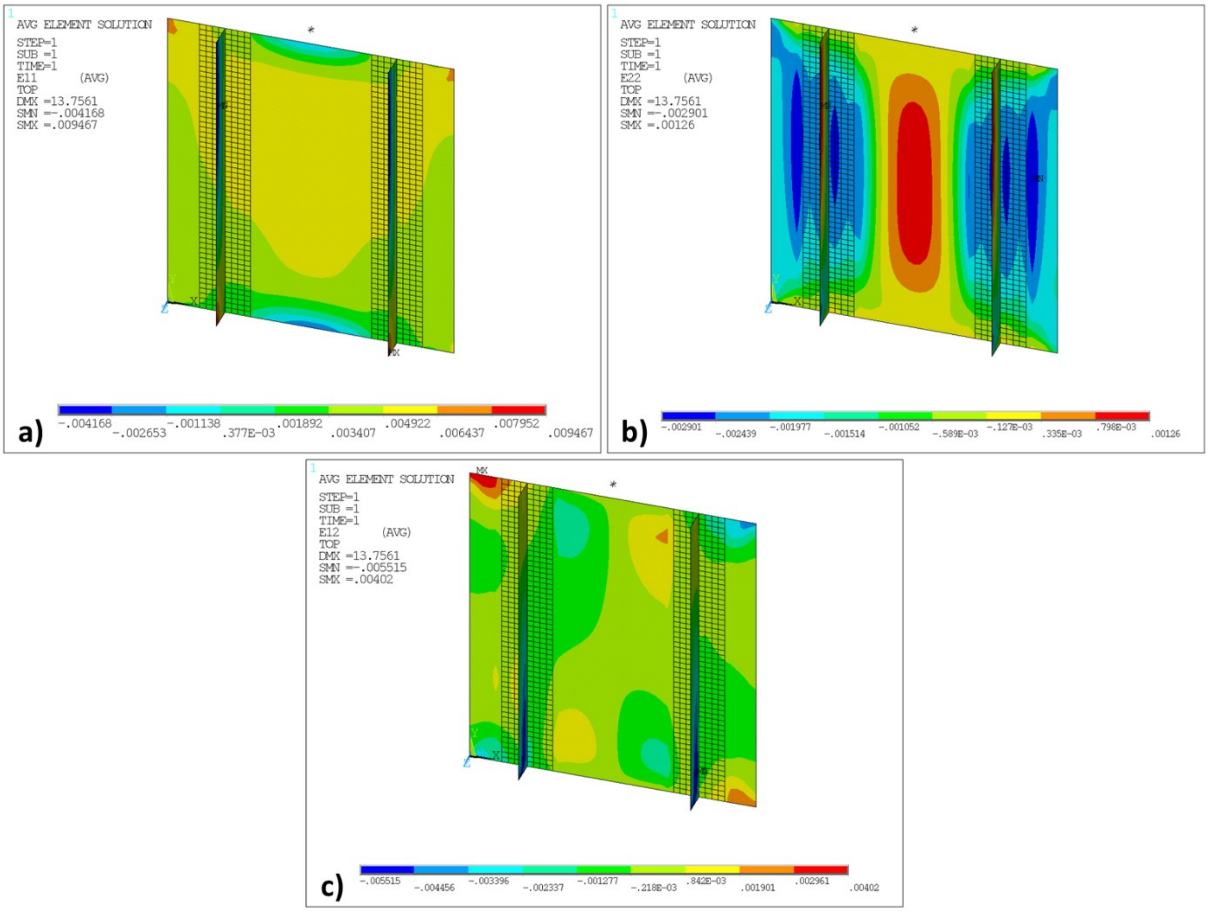

Figure 7 – In-plane strain components distribution at element level: a) ε_{11}; b) ε_{22}; c) ε_{12};

The stress components for all cells in a zone are given to Lam-Search Optimizer tool as input data to determine the best Double-Double design. When multiple zones are considered, the same procedure is individually run for each zone.

Iteration 0 identified [±7.5, ±37.5], [±15, ±15] and [±15, ±22.5] as the best Double-Double lay-ups for Zones 1 to 3, respectively. The Strength Ratio R values obtained for each cell through the Tsai-Wu failure criterion allowed the thickness distribution in the cells to be recalculated, as shown in Figure 8. The R-values greater than 1 suggest that the starting cell thicknesses can be reduced since they are higher than required for the structure's strength. As a result, the mass of the whole structure is reduced from 1.284 kg to 0.355 kg.

The new proposed design is provided by the DD-Design tool to Ansys Mechanical APDL to update the FE model and verify its strength performance through a new linear static analysis, constituting Iteration 1. Iteration 1 changed to [±7.5, ±52.5], [±15, ±15] and [0, ±37.5] the best Double-Double lay-ups for Zones 1 to 3, respectively. However, some of the Strength Ratio R values in the cells resulted smaller than 1, suggesting that the thicknesses in these cells need to be increased to meet the material strengths. Cells' thickness recalculation for Iteration 1 is given in Figure 9, and the mass increased from the initial 0.355 kg to the current 0.544 kg.

The outlined steps have been iterated until the prescribed convergence criteria occurred simultaneously. Specifically, each zone was required that there was no change in the angles for two subsequent iterations and that the average value of R in the cells was in the range of 1±0.05. In the present study, the iterative procedure achieved convergence after six iterations, and a summary of the results obtained for all zones in each iteration is provided in Figure 10 and Figure 11.

ZONE 1 R VALUES IT0

	A	B	C	D
1	3.58	3.94	3.94	3.57
2	4.12	4.14	4.14	4.11
3	3.83	3.41	3.41	3.82
4	3.69	3.17	3.17	3.69
5	3.68	3.34	3.35	3.68
6	3.52	3.93	3.93	3.53
7	2.90	3.19	3.19	2.91

ZONE 1 STARTING THICKNESS IN CELLS

	A	B	C	D
1	2.50	2.50	2.50	2.50
2	2.50	2.50	2.50	2.50
3	2.50	2.50	2.50	2.50
4	2.50	2.50	2.50	2.50
5	2.50	2.50	2.50	2.50
6	2.50	2.50	2.50	2.50
7	2.50	2.50	2.50	2.50

$$Tk_{new} = Tk_{starting} * R$$

ZONE 1 THICKNESS IN CELLS AFTER IT0

	A	B	C	D
1	0.70	0.63	0.63	0.70
2	0.61	0.60	0.60	0.61
3	0.65	0.73	0.73	0.65
4	0.68	0.79	0.79	0.68
5	0.68	0.75	0.75	0.68
6	0.71	0.64	0.64	0.71
7	0.86	0.78	0.78	0.86

ZONE 2 R VALUES IT0

	A	B
1	2.25	2.24
2	2.81	2.81
3	3.89	3.90
4	5.16	5.17
5	6.33	6.16
6	7.29	7.30
7	7.17	7.20

ZONE 2 THICKNESS IN CELLS AFTER IT0

	A	B
1	1.33	1.34
2	1.07	1.07
3	0.77	0.77
4	0.58	0.58
5	0.47	0.49
6	0.41	0.41
7	0.42	0.42

ZONE 3 R VALUES IT0

	A	B
1	4.88	4.87
2	3.87	3.89
3	3.13	3.17
4	3.13	3.14
5	3.18	3.12
6	3.19	3.20
7	2.98	2.98

ZONE 3 THICKNESS IN CELLS AFTER IT0

	A	B
1	0.31	0.31
2	0.39	0.39
3	0.48	0.47
4	0.48	0.48
5	0.47	0.48
6	0.47	0.47
7	0.50	0.50

Figure 8 - Lam-Search optimizer tool output at Iteration 0

ZONE 1 R VALUES IT1

	A	B	C	D
1	0.68	0.50	0.49	0.67
2	0.55	0.62	0.49	0.54
3	0.59	0.66	0.55	0.57
4	0.58	0.65	0.63	0.57
5	0.56	0.52	0.64	0.54
6	0.57	0.52	0.61	0.53
7	0.69	0.56	0.54	0.66

ZONE 1 THICKNESS IN CELLS AFTER IT1

	A	B	C	D
1	1.02	1.27	1.28	1.04
2	1.11	0.98	1.22	1.12
3	1.11	1.11	1.33	1.15
4	1.16	1.22	1.25	1.18
5	1.21	1.43	1.17	1.25
6	1.25	1.22	1.04	1.33
7	1.25	1.40	1.45	1.30

ZONE 2 R VALUES IT1

	A	B
1	0.96	0.99
2	0.97	1.00
3	1.02	1.04
4	1.19	1.21
5	1.61	1.52
6	2.08	2.21
7	2.02	1.98

ZONE 2 THICKNESS IN CELLS AFTER IT1

	A	B
1	1.39	1.35
2	1.10	1.07
3	0.76	0.74
4	0.49	0.48
5	0.30	0.32
6	0.20	0.19
7	0.21	0.21

ZONE 3 R VALUES IT1

	A	B
1	0.90	0.75
2	0.93	1.05
3	0.72	0.93
4	0.81	0.78
5	1.03	0.75
6	0.78	0.79
7	0.67	0.72

ZONE 3 THICKNESS IN CELLS AFTER IT1

	A	B
1	0.34	0.41
2	0.42	0.37
3	0.67	0.51
4	0.59	0.61
5	0.46	0.64
6	0.60	0.59
7	0.75	0.70

Figure 9 - Lam-Search optimizer tool output at Iteration 1

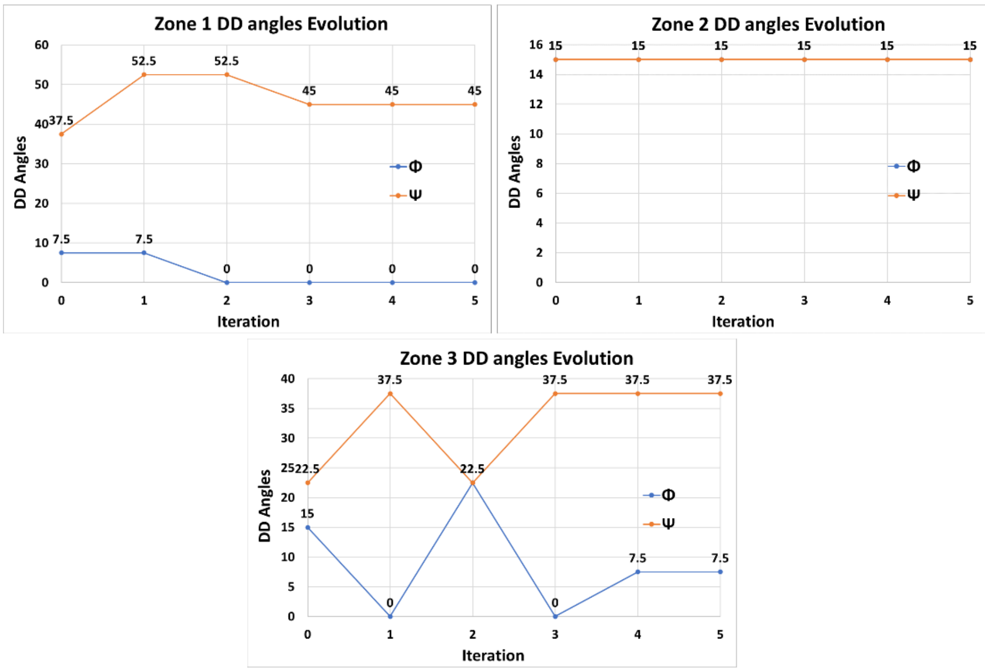

Figure 10 – Double-Double angles evolution in zones across iterations

ZONE 1 R VALUES IT0	A	B	C	D
1	3.58	3.94	3.94	3.57
2	4.12	4.14	4.14	4.11
3	3.83	3.41	3.41	3.82
4	3.69	3.17	3.17	3.69
5	3.68	3.34	3.35	3.68
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ZONE 1 R VALUES IT1	A	B	C	D
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3	0.59	0.66	0.55	0.57
4	0.58	0.65	0.63	0.57
5	0.56	0.52	0.64	0.54
6	0.57	0.52	0.61	0.53
7	0.69	0.56	0.54	0.66

ZONE 1 R VALUES IT2	A	B	C	D
1	1.15	1.11	0.92	1.19
2	1.09	1.05	0.89	1.07
3	1.15	1.02	0.96	1.10
4	1.11	1.00	0.98	1.11
5	1.05	0.91	1.03	1.08
6	1.08	0.88	1.06	1.04
7	1.11	0.97	1.22	1.03

ZONE 2 R VALUES IT0	A	B
1	2.25	2.24
2	2.81	2.81
3	3.89	3.90
4	5.16	5.17
5	6.33	6.16
6	7.29	7.30
7	7.17	7.20

ZONE 3 R VALUES IT0	A	B
1	4.88	4.87
2	3.87	3.89
3	3.13	3.17
4	3.13	3.14
5	3.18	3.12
6	3.19	3.20
7	2.98	2.98

ZONE 2 R VALUES IT1	A	B
1	0.96	0.99
2	0.97	1.00
3	1.02	1.04
4	1.19	1.21
5	1.61	1.52
6	2.08	2.21
7	2.02	1.98

ZONE 3 R VALUES IT1	A	B
1	0.90	0.75
2	0.93	1.05
3	0.72	0.93
4	0.81	0.78
5	1.03	0.75
6	0.78	0.79
7	0.67	0.72

ZONE 2 R VALUES IT2	A	B
1	1.01	1.01
2	1.01	1.01
3	1.01	1.01
4	1.01	1.02
5	1.14	1.13
6	1.77	1.72
7	1.52	1.37

ZONE 3 R VALUES IT2	A	B
1	1.93	1.53
2	1.71	1.82
3	1.69	1.64
4	1.62	1.66
5	1.69	1.75
6	1.42	1.73
7	1.42	1.65

ZONE 1 R VALUES IT5	A	B	C	D
1	0.98	0.96	0.99	1.00
2	0.97	1.01	1.01	0.99
3	0.99	1.00	1.00	0.98
4	1.00	1.00	0.99	0.99
5	0.99	1.02	0.99	0.99
6	0.97	1.00	0.99	0.98
7	1.03	0.99	0.98	0.98

ZONE 1 R VALUES IT4	A	B	C	D
1	0.99	0.95	0.98	1.02
2	0.99	1.03	1.04	1.00
3	1.03	1.01	1.02	0.97
4	1.02	1.02	1.01	1.00
5	0.98	1.04	1.00	1.02
6	1.00	1.01	1.01	1.01
7	1.07	0.97	0.98	1.01

ZONE 1 R VALUES IT3	A	B	C	D
1	1.09	0.85	0.87	1.10
2	1.04	1.06	0.94	1.02
3	1.02	1.01	0.98	1.01
4	1.02	0.99	0.98	1.01
5	1.03	1.00	1.04	1.00
6	1.03	0.94	1.09	1.01
7	1.18	0.88	0.89	1.03

ZONE 2 R VALUES IT5	A	B
1	1.00	1.00
2	1.00	1.00
3	1.00	1.00
4	1.00	1.01
5	0.99	0.88
6	1.01	0.98
7	1.01	1.01

ZONE 3 R VALUES IT5	A	B
1	1.12	1.03
2	1.17	1.23
3	1.01	0.96
4	0.97	0.98
5	0.93	1.04
6	1.22	1.27
7	0.97	1.09

ZONE 2 R VALUES IT4	A	B
1	1.02	1.02
2	1.01	1.02
3	1.01	1.01
4	1.00	1.00
5	0.98	0.81
6	0.99	0.95
7	1.07	1.09

ZONE 3 R VALUES IT4	A	B
1	1.13	1.07
2	1.24	1.30
3	1.04	1.00
4	0.94	1.01
5	0.98	1.09
6	1.24	1.32
7	0.98	1.09

ZONE 2 R VALUES IT3	A	B
1	1.01	0.99
2	1.01	0.99
3	1.01	0.99
4	1.01	0.98
5	1.04	0.80
6	1.11	1.03
7	1.07	0.99

ZONE 3 R VALUES IT3	A	B
1	1.22	1.00
2	1.16	1.40
3	0.93	1.25
4	0.98	1.11
5	1.20	1.08
6	1.18	1.16
7	0.93	1.05

Figure 11 – Summary of the strength ratio R values evolution among iterations

Across iterations, the angles Φ and Ψ for all zones and the thicknesses in cells have been re-calculated and optimized according to the obtained strength ratio values so that the strength criterion was met in all cells with respect to applied loads and the total mass of the structure was minimized. The best mass-optimized Double-Double design obtained at the end of the iterative procedure considering the strength requirement resulted in [0, ±45], [±15, ±15] and [±7.5, ±37.5] for Zones 1 to 3 respectively, while the distribution of R-values and thicknesses among cells are shown in Figure 12. The total mass of the structure resulted as 0.491 kg.

BEST DOUBLE-DOUBLE ANGLES		
ZONE 1	Φ	0
	Ψ	45
ZONE 2	Φ	15
	Ψ	15
ZONE 3	Φ	7.5
	Ψ	37.5

ZONE 1 THICKNESS IN CELLS AFTER IT5				
	A	B	C	D
1	0.84	1.49	1.67	0.78
2	1.01	0.84	1.38	1.05
3	0.94	1.07	1.40	1.09
4	1.01	1.21	1.29	1.06
5	1.16	1.49	1.10	1.15
6	1.15	1.45	0.90	1.29
7	0.86	1.71	1.40	1.23

ZONE 2 THICKNESS IN CELLS AFTER IT5		
	A	B
1	1.33	1.32
2	1.05	1.05
3	0.73	0.73
4	0.48	0.48
5	0.26	0.49
6	0.10	0.11
7	0.12	0.14

ZONE 3 THICKNESS IN CELLS AFTER IT5		
	A	B
1	0.11	0.24
2	0.14	0.09
3	0.41	0.26
4	0.41	0.34
5	0.25	0.30
6	0.24	0.18
7	0.60	0.34

Figure 12 – Best Double-Double design in the considered zones at the of the iterative process

4.1 Influence of manufacturing requirements on the best Double-Double design

Upon completing the iterations, the final design of the panel, optimized for minimum mass, exhibits an infeasible continuously varying thickness distribution among cells. In composite laminates, the total thickness can only assume discrete values which are multiples of the single ply thickness.

As a result, the continuously varying thickness distribution in cell must be conservatively switched to discrete values throughout a digitizing operation. This process entails the assignment of multiple values of the base sub-laminate thickness to each cell, thus reducing the benefits of mass reduction, as in Figure 13a. According to the adopted ply, the thickness of each sub-laminate is set to 0.5 mm. Furthermore, several tapered designs can be suggested within the capabilities of the procedure. A decrease in the mass saving is recorded in the digitized and tapered solutions, showed in Figure 13b-d, as compared to the proposed best Double-Double design. However, an increase in structure's uniformity and ease of manufacturing is afforded. The Tapered 1 solution designates the maximum thickness among cell thicknesses as the uniform thickness for all cells in a zone, while the Tapered 2 and Tapered 3 solutions provide uniform columns and uniform rows with max thickness, respectively. The trend of the mass change during the different steps of the optimisation process is shown In Figure 14.

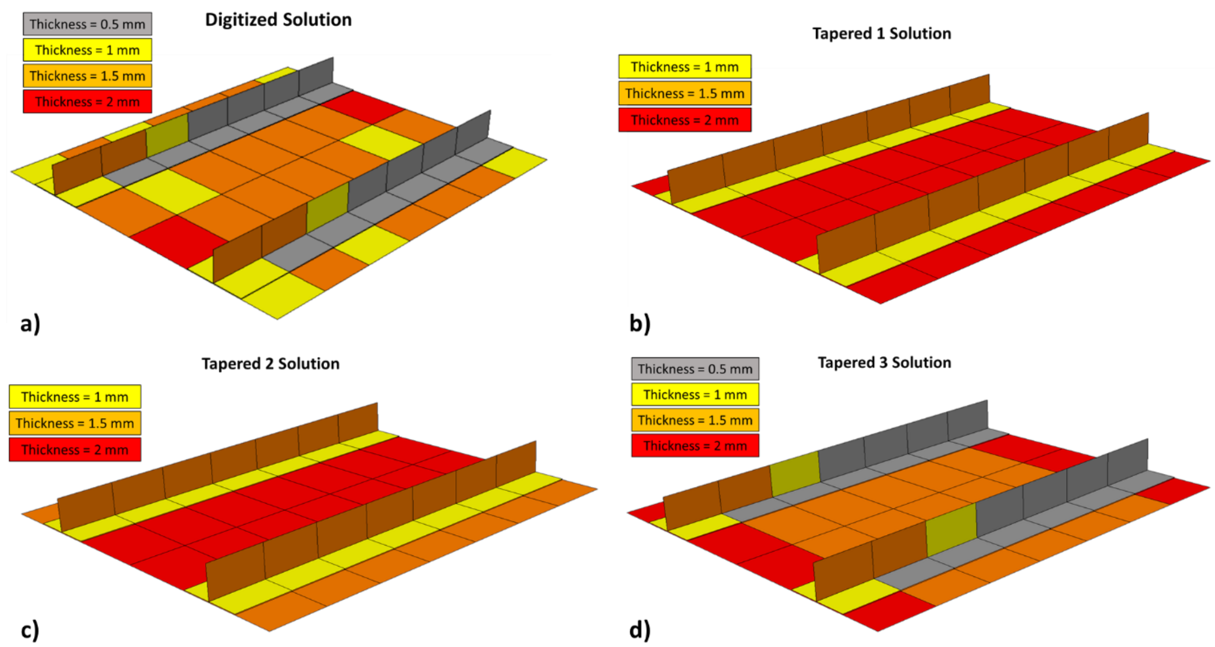


Figure 13 – Discrete thickness distributions solutions: a) Digitized Solution; b) Tapered 1 Solution; c) Tapered 2 Solution; d) Digitized Solution

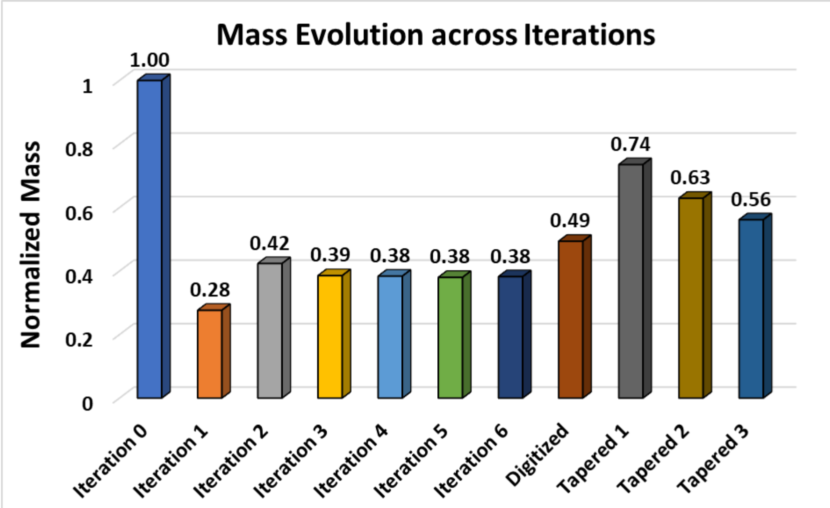
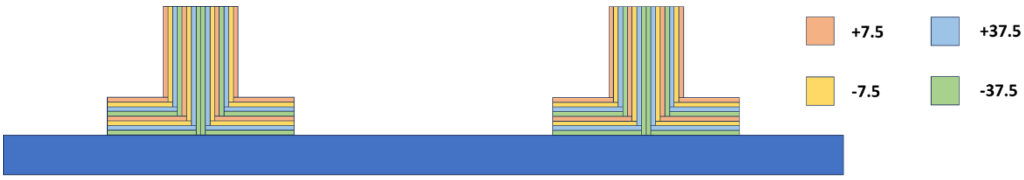


Figure 14 – Normalized component mass evolution across Iterations

The initial mass of the panel resulted as 1.284 kg while the mass of the design proposed at the end of Iteration 6 resulted 0.491 kg. Despite the considerable mass reduction and the compliance with the strength requirements, the proposed best Double-Double design is unfeasible by considering a manufacturing point of view. Being such a consideration, and without accounting for additional requirements on the mechanical behaviour of the component such as stiffness or buckling, the best allowable Double-Double design from strength and manufacturability points of view is the one offered by the Tapered 1 solution. Such design has a mass equal to 0.944 kg, achieving a mass reduction of 26.48% with respect to the starting QUAD configuration.

The main aim of proposing an effective and feasible redesign of a composite panel stiffened with T-shaped stringers according to the strength optimization process offered by Double-Doubles requires a further consideration to be introduced regarding the manufacturing of such components. Specifically, in the performed redesign process two zones have been considered for the stringers: one for the feet and one for the webs. Consequently, two different tapered thicknesses and two different DD lay-ups characterizes such parts. The manufacturing point of view points out that such a configuration for a T-shaped stringer is certainly not straightforward to be produced. Therefore, the potential to extend the lay-up and tapered thickness of one of the two zones to the other has been considered. Specifically, the solution suggested to maximize ease of manufacturing and minimize the mass increase is to extend the lay-up and thickness of the stringer foot to the web, as shown in Figure 15. In this way, the foot and web thicknesses result in 1 mm and 2 mm, respectively, while the lay-up in the web is consistent with that achievable in production. A further FE analysis has been carried out to analyse the proposed solution, demonstrating the compliance with the material strength requirements through the Strength Ratio value examination. The change in the design did not adversely affect the mechanical performance of the component and ensured strength ratio values in the web cells greater than unity, as shown in Figure 14. Such design has a mass equal to 0.976 kg, achieving a mass reduction of 23.98% with respect to the starting QUAD configuration.



ZONE 2 R VALUES		
	A	B
1	1.11	1.12
2	1.55	1.56
3	2.58	2.60
4	3.21	3.23
5	3.10	3.02
6	3.23	3.25
7	3.58	3.61

Figure 15 – Modified best Double-Double design for manufacturing ease

5. Conclusions

The concept of Double-Double laminates presents a significant advancement in the optimization of composite laminate structures within the aerospace industry. This innovative approach offers an alternative method for designing laminated components, focusing on maximizing efficiency in terms of laminate thickness and ply orientation. By strategically allocating plies, the goal is to minimize material usage while still ensuring structural integrity, ultimately resulting in a reduction in the total mass of the component. Benefits lie ahead in the manufacturing processes of such components since the design offered by Double-Double laminates is free of all the production-related issues that typically characterize the manufacturing process of conventional design and lead to unnecessary thickening of structures.

In the present paper, the best Double-Double design for the stiffened panel has been identified through the automated procedure based on the DD-Design tool, determining the optimal lay-ups and thicknesses distribution for the skin and stringers. The optimized design achieved a mass reduction of up to 26.48% compared to the initial design configuration while the final mass of the component, in the most easily manufactured design, achieved a reduction of nearly 24% as compared to the starting QUAD design, while simultaneously complying the material strength requirements.

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7. Copyright Statement

References

[1] Falkowicz K, Dębski H, Wysmulski P, and Różyło P. The behaviour of compressed plate with a central cut-out, made of composite in an asymmetrical arrangement of layers. *Composite Structures*, *214*, 406-413, 2019.

[2] Liu D, Bai R, Wang R, Lei Z, and Yan C. Experimental study on compressive buckling behavior of J-stiffened composite panels. *Optics and Lasers in Engineering*, *120*, 31-39, 2019.

[3] Russo A, Sellitto A, Saputo S, Acanfora V, and Riccio A. Cross-influence between intra-laminar damages and fibre bridging at the skin–stringer interface in stiffened composite panels under compression. *Materials*, *12*(11), 1856, 2019.

[4] Psarras S, Loutas T, Galanopoulos G, Karamadoukis G, Sotiriadis G, and Kostopoulos V. Evaluating experimentally and numerically different scarf-repair methodologies of composite structures. *International Journal of Adhesion and Adhesives*, *97*, 102495, 2020.

[5] Soutis C. Fibre reinforced composites in aircraft construction. *Progress in aerospace sciences*, 41.2, 143-151, 2005.

[6] Toozandehjani M, Kamarudin N, Dashtizadeh Z, Lim E Y, Gomes A, and Gomes C. Conventional and advanced composites in aerospace industry: Technologies revisited. *Am. J. Aerosp. Eng*, 5(9), 9-15, 2018.

[7] Zhao K, Kennedy D, Miravete A, Tsai S W, Featherston C A, and Liu, X. Defining the Design Space for Double–Double Laminates by Considering Homogenization Criterion. *AIAA Journal*, 61(7), 3190-3203, 2023.

[8] Albazzan M A, Harik R, Tatting B F, and Gürdal Z. Efficient design optimization of nonconventional laminated composites using lamination parameters: A state of the art. *Composite Structures*, *209*, 362-374, 2019.

[9] Kogiso N, Watson L T, Gürdal Z, Haftka R T, and Nagendra S. Design of composite laminates by a genetic algorithm with memory. MECHANICS OF COMPOSITE MATERIALS AND STRUCTURES An International Journal, 1(1), 95-117, 1994.

[10] Irisarri F X, Bassir D H, Carrere N, and Maire J F. Multiobjective stacking sequence optimization for laminated composite structures. Composites Science and Technology, 69(7-8), 983-990, 2009.

[11] Suwarta P, Fotouhi M, Czél G, Longana M, and Wisnom M R. Fatigue behaviour of pseudo-ductile unidirectional thin-ply carbon/epoxy-glass/epoxy hybrid composites. *Composite Structures*, 224, 110996, 2019.

[12] Barnes R H, and Morozov E V. Structural optimisation of composite wind turbine blade structures with variations of internal geometry configuration. *Composite Structures*, 152, 158-167, 2016.

[13] Fuller J D, and Wisnom M R. Exploration of the potential for pseudo-ductility in thin ply CFRP angle-ply laminates via an analytical method. *Composites Science and Technology*, 112, 8-15, 2015.

[14] Tsai S W. Double–double: New family of composite laminates. *AIAA Journal*, 59 (11), pp. 4293-4305, 2021.

[15] Vermes B, Tsai S W, Massard T, Springer G S, and Czigany T. Design of laminates by a novel "double–double" layup. *Thin-Walled Structures*, 165, 107954, 2021.

[16] Arteiro A, Sharma N, Melo J D D, Ha S K, Miravete A, Miyano Y, Massard T, Shah P D, Roy S, Rainsberger R, Rother K, Cimini Jr C, Seng J M, Arakaki F K, Tay T E, Lee W I, Sihn S, Springer G S, Roy A, Riccio A, Di Caprio F, Shrivastava S, Nettles A T, Catalanotti G, Camanho P P, Seneviratne W, Marques A T, Yang H T, Hahn H T. A

case for Tsai's Modulus, an invariant-based approach to stiffness. *Composite Structures*, Volume 252, 112683, 2020.

[17] Asakawa K, Hirano Y, Tan K T, and Ogasawara T. Bio-inspired study of stiffener arrangement in composite stiffened panels using a Voronoi diagram as an indicator. *Composite Structures*, 327, 117640, 2024.

[18] Zhang J, Jia W, Peng X, Lu X, Li J, and Jiang S. Buckling analysis and structural optimization of multiple-material omega stiffened composite panel. *Mechanics of Advanced Materials and Structures*, 1-17, 2024.

[19] Asakawa K, Hirano Y, and Ogasawara T. Simultaneous optimization of fiber paths and geometric dimensions for fiber composite laminates using double neural network-surrogate model and genetic algorithm. *Advanced Composite Materials*, 1-23, 2024.

[20] Ye Y, Zhu W, Jiang J, Xu Q, and Ke Y. Design and optimization of composite sub-stiffened panels. *Composite Structures*, 240, 112084, 2020.

[21] Han H, and Dong C. Buckling Analysis for Carbon and Glass Fibre Reinforced Hybrid Composite Stiffened Panels. *Journal of Composites Science*, 8(1), 34, 2024.

[22] Lian C, Wang P, Chen X, Liu F, Yuan K, Zheng J, and Yue Z. Experimental and numerical research on the analysis methods for buckling and post-buckling of inclined stiffened panel under shear load. *Thin-Walled Structures*, 195, 111374, 2024.

[23] Hu C, Xu Z, Huang M, Cai C, Wang R, and He X. An insight into the mechanical behavior and failure mechanisms of T-stiffened composite structures with through-interface debonding defects. *Ocean Engineering*, 300, 117342, 2024.

[24] Russo A, Palumbo C, and Riccio A. A numerical investigation of the interaction between interlaminar and intralaminar damages in a fatigued composite panel. *Fatigue & Fracture of Engineering Materials & Structures*, 46(5), 1750-1762, 2023.

[25] Vermes B, Tsai S W, Riccio A, Di Caprio F, Roy S. Application of the Tsai's modulus and double-double concepts to the definition of a new affordable design approach for composite laminates, *Composite Structures*, 259, art. no. 113246, 2021.

[26] Shrivastava S, Sharma N, Tsai S W, and Mohite P M. D and DD-drop layup optimization of aircraft wing panels under multi-load case design environment. *Composite Structures*, *248*, 112518, 2020.

[27] Tsai S W, Melo J D D. An invariant-based theory of composites. *Composite Science and Technology*, 100:237–43, 2014.

[28] Tsai S W, Sihn S, and Melo J D D. Trace-based stiffness for a universal design of carbon-fiber reinforced composite structures. *Composites Science and Technology*, 118, 23-30, 2015.

[29] Melo J D D, Bi J, and Tsai S W. A novel invariant-based design approach to carbon fiber reinforced laminates. *Composite Structures*, 159, 44-52, 2017.

[30] Garofano A, Sellitto A, Di Caprio F, and Riccio A. On the use of double-double design philosophy in the redesign of composite fuselage barrel frame components. *Polymer Composites*, 2023.