# On the use of double-double design philosophy in the redesign of composite fuselage barrel components

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**Abstract.** Mass minimization and mechanical performance maximization constitute the basic aspects of the structural optimization processes. In particular, the laminate redesign in terms of thickness and lay-up grants the main approach for the optimization of composite components. The innovative Double-Double laminate concept provides an effective approach to design composite components for weight and strength requirements, overcoming the use of the conventional 0°, 90° and ±45° ply orientations. In Double-Double designed components, 4-plies building blocks are stacked one upon the other to constitute a laminate. Each building block is made up of four [±Φ, ±Ψ] oriented plies. In the present work, the Double-Double approach has been adopted in the redesign of the composite lay-up and thickness profile of frames in a composite fuselage barrel. The DD optimized frames achieved a total mass reduction by up to 35% while ensuring mechanical performances comparable to the starting configuration.

## Introduction

Laminate lay-up optimization represents the most feasible field in which structural engineers can work as compared to material changing and components redesign to design more efficient, lightweight and performing composite load-bearing structures in the aviation field. Lay-ups typically used in composite aviation components only involve 0°, 90° and ±45° plies orientations. Moreover, symmetry and balancing requirements must be accounted for manufacturing and performance needs, limiting the optimization processes for mass and mechanical performance requirements to sub-optimal solutions. One step forward is proposed by the newly Double-Double approach introduced by Professor S.W. Tsai [1]. Double-Double laminates are made up by stacking 4-plies building blocks without symmetry and balancing requirements. Each building block, or sub-laminate, consists of four plies based on double bi-axial angles [±Φ, ±Ψ]. Φ and Ψ angles can be tuned assuming each value between 0° and 90° to manage mechanical performances of laminates. DD angles and number of the required building blocks are directly optimized for the application and its load conditions. A new composite lay-up scheme able to optimize the components for weight and strength requirements is given, enabling to overcome the conventional 0°, 90° and ±45° plies orientations [2]. The Excel-based Lam-Search optimizer tool automatically determines the best [±Φ, ±Ψ] angles among all allowed combinations of DD angles to minimize the safety margin by computing the strength ratio R with respect to a selected failure criterion. Laminate thickness is updated according to the computed strength ratio value [3]. In this framework, the present paper is aimed to perform an optimization process on the frames of a composite fuselage barrel subjected to static loads through the Double-Double design approach for mass reduction purposes.

## FE model description

The FE model of a regional aircraft's fuselage barrel has been developed in the Abaqus environment, as showed in Fig. 1. Main structural sub-components have been modelled as solid extruded parts while frames as 3D shell parts allowing to run sequential analyses with variable thickness during the optimization process. The optimized [±37.5, ±45] Double-Double lay-up has been employed for the skin [4]. A uniform $[90,45,0,45,-45,90,45,-45,0,-45,45,-45]_s$ stacking sequence characterized the frames in the starting configuration. The IMS/977-2 CFRP [4], a Woven Fabric [4] and the T700 CPLY64 [4] have been adopted for the composite components while Aluminum 2024-T42 for the metal parts. The FE model has been discretized by means of 8-node continuum shell elements (SC8R) and 8-node linear brick elements (C3D8R) for composite and aluminum components, respectively, while 4-node general-purpose shell elements (S4R) have been used for frames.

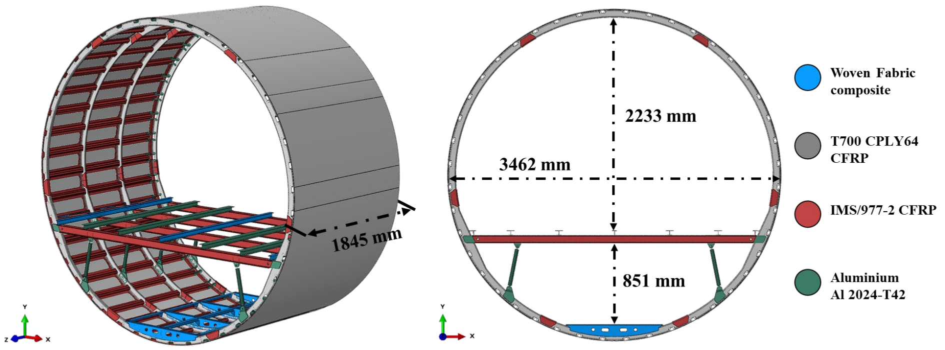


*Figure 1. Fuselage barrel FE model and dimensions: a) isometric view; b) frontal view*

According to the Lam-Search optimizer tool needs to perform the optimization process, frames have been subdivided in zones and cells. A zone has been defined for each frame, enabling one best [±Φ; ±Ψ] DD lay-up for each frame. Seven cells have been defined in each zone by considering only the half of each frame being the structure symmetry, as showed in Fig. 2a. Thereafter, results have been extended to the other half. The thickness profile in cells is computed according to the strength ratio R value with respect to the controlling cell.

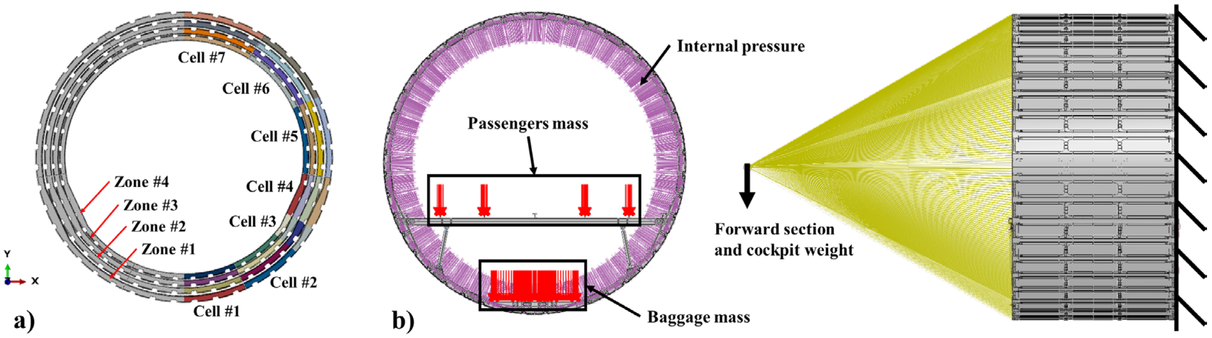


*Figure 2. a) Zone and cells subdivision of the frames; b) applied loading and boundary conditions*

An iterative process has been carried out to reach the strength optimized laminate design for frames through thickness and layup variation in cells of each zone. Linear static analyses considering the operating loads presented in Fig. 2b have been performed in each iteration. In detail, a pressure has been applied to the internal surfaces to simulate pressurization while a force representing the cockpit and forward section weight has been applied to a reference point and transferred to the structure. Mass loads of passengers and baggage have been considered.

## Optimization process

A preliminary linear static FE analysis has been performed on the fuselage barrel in the starting configuration with quad laminates frames and assumed as Iteration 0. The average stress components in all cells of each zone have been used as input data to the Lam-Search optimizer tool, resulting in the best DD angles and cells thickness profiles for each zone as output. The same process has been individually applied to each zone. Results in Iteration 0 suggested the best DD angles and thickness profiles for cells in zones 1 to 4, respectively, leading to a total mass reduction of frames up to 85%. However, R values went above the unity. Consequently, the starting FE model has been updated according to Iteration 0 results and a new FE analysis has been carried out to update the stress components in the cells, generating new input data for the Lam-Search optimizer tool. This process has been repeated until identical DD angles in each zone between two iterations were achieved and any cell exhibited a strength ratio below unity.

At the end of Iteration 3, all cells in all zones achieved a strength ratio R greater than unity. Furthermore, the optimal DD angles in each zone resulted [±37.5; ±60], [±30; ±52.5], [±30; ±60], and [±45; ±45] for zones 1 to 4, respectively, and identical to those obtained in the previous iteration. The thickness optimization led to a total mass reduction of frames up to 71%. The time-history variation of the average value of strength ratio R for each zone across iterations is shown in Fig. 3. In Iteration 3, the thickness optimization led the R-values above and close the unity, offering an effective design solution in terms of mass saving.

ITERATION 0

Tsai-Wu profile of strength ratio R

| Cells | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
|---|---|---|---|---|
| 1 | 3.22 | 3.35 | 3.37 | 3.35 |
| 2 | 5.11 | 3.36 | 4.05 | 5.36 |
| 3 | 3.65 | 3.53 | 3.55 | 4.83 |
| 4 | 4.17 | 3.49 | 3.70 | 5.64 |
| 5 | 6.79 | 4.61 | 5.01 | 7.11 |
| 6 | 6.68 | 4.06 | 4.47 | 7.35 |
| 7 | 7.55 | 4.15 | 4.61 | 7.92 |

ITERATION 1

Tsai-Wu profile of strength ratio R

| Cells | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
|---|---|---|---|---|
| 1 | 0.73 | 0.63 | 0.67 | 0.93 |
| 2 | 0.76 | 0.61 | 0.64 | 0.90 |
| 3 | 0.80 | 0.61 | 0.68 | 0.91 |
| 4 | 0.81 | 0.63 | 0.68 | 0.87 |
| 5 | 0.75 | 0.71 | 0.69 | 0.84 |
| 6 | 0.79 | 0.69 | 0.70 | 0.86 |
| 7 | 0.74 | 0.65 | 0.69 | 0.89 |

ITERATION 2

Tsai-Wu profile of strength ratio R

| Cells | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
|---|---|---|---|---|
| 1 | 1.04 | 1.06 | 1.01 | 0.93 |
| 2 | 1.09 | 1.00 | 1.03 | 0.98 |
| 3 | 1.03 | 1.05 | 1.10 | 0.89 |
| 4 | 0.94 | 1.09 | 1.03 | 0.88 |
| 5 | 1.01 | 1.10 | 1.07 | 0.89 |
| 6 | 0.94 | 1.11 | 1.08 | 0.97 |
| 7 | 0.90 | 1.12 | 1.09 | 0.94 |

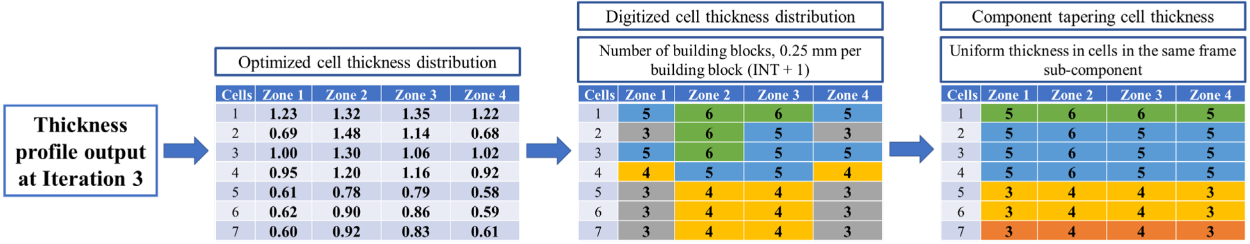
ITERATION 3

Tsai-Wu profile of strength ratio R

| Cells | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
|---|---|---|---|---|
| 1 | 1.03 | 1.05 | 1.00 | 1.04 |
| 2 | 1.07 | 1.01 | 1.02 | 1.08 |
| 3 | 1.02 | 1.04 | 1.09 | 1.01 |
| 4 | 1.02 | 1.08 | 1.02 | 1.06 |
| 5 | 1.00 | 1.09 | 1.06 | 1.05 |
| 6 | 1.01 | 1.10 | 1.07 | 1.06 |
| 7 | 1.02 | 1.11 | 1.08 | 1.01 |

*Figure 3. Time-history variation of the strength Ratio R in cells in all zones across iterations (Note: R-values below the unity in red, R-values above the unity in green)*

The optimized design for frames provided by the optimization process is characterized by a continuously scaled thickness across cells, not applicable to composite materials, as laminates have a discrete thickness. Hence, digitization is required to conservatively convert the cells thickness to discrete values according to the building block thickness. In addition, cells thickness within the same frame sub-components have been equalized to the thickest one to promote an easy manufacturing and uniformity of the sub-component, performing a tapering operation. Digitizing and tapering operations, showed in Fig. 4, reduced the mass saving given by Double-Double designed frames to 65% while providing an increase in the easy of manufacturing.



**Thickness profile output at Iteration 3**

Optimized cell thickness distribution

| Cells | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
|---|---|---|---|---|
| 1 | 1.23 | 1.32 | 1.35 | 1.22 |
| 2 | 0.69 | 1.48 | 1.14 | 0.68 |
| 3 | 1.00 | 1.30 | 1.06 | 1.02 |
| 4 | 0.95 | 1.20 | 1.16 | 0.92 |
| 5 | 0.61 | 0.78 | 0.79 | 0.58 |
| 6 | 0.62 | 0.90 | 0.86 | 0.59 |
| 7 | 0.60 | 0.92 | 0.83 | 0.61 |

Digitized cell thickness distribution

Number of building blocks, 0.25 mm per building block (INT + 1)

| Cells | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
|---|---|---|---|---|
| 1 | 5 | 6 | 6 | 5 |
| 2 | 3 | 6 | 5 | 3 |
| 3 | 5 | 6 | 5 | 5 |
| 4 | 4 | 5 | 5 | 4 |
| 5 | 3 | 4 | 4 | 3 |
| 6 | 3 | 4 | 4 | 3 |
| 7 | 3 | 4 | 4 | 3 |

Component tapering cell thickness

Uniform thickness in cells in the same frame sub-component

| Cells | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
|---|---|---|---|---|
| 1 | 5 | 6 | 6 | 5 |
| 2 | 5 | 6 | 5 | 5 |
| 3 | 5 | 6 | 5 | 5 |
| 4 | 5 | 6 | 5 | 5 |
| 5 | 3 | 4 | 4 | 3 |
| 6 | 3 | 4 | 4 | 3 |
| 7 | 3 | 4 | 4 | 3 |

*Figure 4. Thickness evolution in digitizing and tapering operations starting from the optimized design*

Thickness variation led to a change in the frames total mass and consequently in the fuselage barrel total mass. The time history of the mass variation and mass saving in the frames and in the whole fuselage barrel, compared to the initial configuration is shown in Fig. 5. The frames optimization performed through the Lam-Search optimizer tool resulted in a frames design that reduced their total mass to 35% of the initial mass after tapering. Consequently, the mass variation in frames resulted in the mass reduction of the overall fuselage barrel by up to 12%.

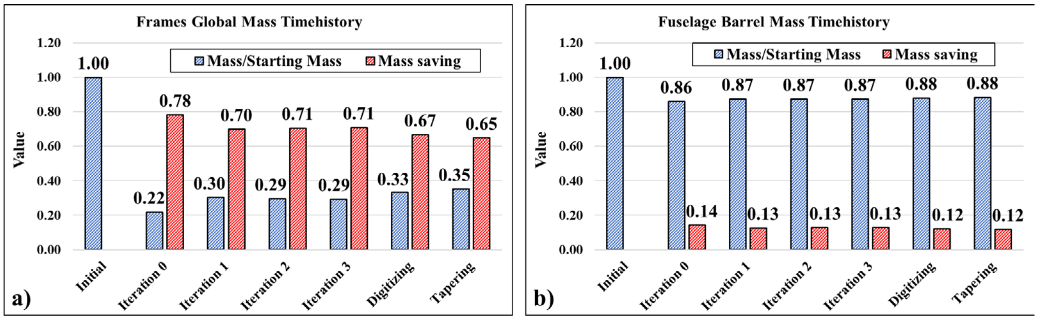


*Figure 5. Mass and mass saving variation in frames and in the whole fuselage barrel through optimization*

## Conclusions

In the present work, the Double-Double lay-up concept has been applied to the frames of a composite fuselage barrel, considering the operating loads. Throughout iterations, the procedure identified the best DD composite lay-up and thickness profiles, providing mechanical performances comparable to the initial configuration while significantly reducing the components total mass. At the end of the optimization process, the initial configuration of frames with quad laminates has been replaced by an optimized configuration with the best DD lay-up for each of the frames, corresponding to [±37.5; ±60], [±30; ±52.5], [±30; ±60] and [±45; ±45] for zones 1 to 4, respectively. The thickness profile has been tailored to the acting loading condition ensuring a total mass reduction of frames by up to 35%. Thus, the use of the Double-Double laminates concept and the Lam-Search optimizer tool proved to be an effective method for optimizing the design of composite components for mass reduction purposes while ensuring a mechanical behavior comparable to the starting configuration.

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