AIRCRAFT WING STRUCTURAL SIZING COMPUTATIONAL TOOL TAILORED FOR A COLLABORATIVE MULTIDISCIPLINARY DESIGN FRAMEWORK

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Abstract

This article presents two innovative tools, **WinG3N** and **WingSizer**, designed to streamline the traditional process of hand-made model development for aircraft wings. **WinG3N** enables the automatic generation of a wing finite element model within seconds, facilitating additional trade-off and sensitivity studies that would be impractical with manual methods. Complementarily, **WingSizer** automates the sizing process for static and buckling analyses, significantly reducing the time required compared to standard procedures, making it a valuable tool for efficient design. The **WingSizer**'s capability to compare metallic and composite structures allows for comprehensive trade-off studies, offering a quantitative assessment of the advantages and disadvantages of using composites. This feature enables a thorough evaluation of the potential benefits of altering the material composition of the entire wing assembly or specific components. While these tools are tailored for aircraft wing analysis, their applicability extends to the initial sizing of horizontal and vertical stabilizers, provided they feature no more than two longitudinal spars. The **WingSizer** versatility by seamlessly integrating into a multidisciplinary optimization framework has been showcased in the 2023 International Forum for Aviation Research (IFAR) Young Engineers Challenge. Two case studies are shown in the current article, one featuring the impact of buckling on a fully metallic wing and another comparing the structural mass of a fully metallic wing against a composite skin with metallic skeleton and a fully composite wing. The results corroborate prior research on the topic.

Keywords: Aircraft Wing, Composite Aircraft, Structural Sizing and Optimization, Collaborative Design, Multidisciplinary Design

1. Introduction

Decisions taken early in the aircraft design process have great impact on the aircraft's performance and total project development cost with, as per Zhao et al [1], around 85% of the total Life Cycle Cost (LCC) being determined by design choices made at the end of the preliminary design stage. Furthermore, James et al [2] carried a study at an aerospace company on two programs covering 7 years of development and determined that early design decisions account for 86% of the cost impact of all design decisions.

It is therefore a differentiating factor to have state-of-the art methods and tools ready to facilitate and foster as many sensitivity analyses, trade-offs, and optimisation studies as possible during the conceptual and preliminary design phases. The more comprehensive these tools become, the more informed designers are from the earliest stages of the project development, thus enhancing the decision-making process.

Finite element models are a fundamental instrument in aircraft design by providing a high-fidelity prediction of the aircraft structural behaviour. Nonetheless, their development with a reasonable degree of detail can take, typically, several days to create and some more to be post-processed using conventional structural analysis methods. Consequently, this design approach is usually replaced with lower-fidelity equivalent models at early design stages.

However, the improvement of computational performance has created an opportunity for the employment of higher-fidelity models throughout the entire aircraft development process. Recent works have focused on the development of automated structural design and optimization frameworks using both low and high-fidelity analysis methods.

Chintapalli et al [3] have presented a methodology for the preliminary design optimization of a skin-stringer panel of an aircraft wing-box. The ability to resist the compressive load is assessed through a stability study to compute the critical buckling load of the stiffened panel while the ability to resist the tensile load is assessed through damage tolerance analysis of the lower wing panels. Nasoulis et al [4] have used an in-house Python-based tool and OpenVSP to generate the aircraft initial geometry, taking into consideration user defined Top-Level Aircraft Requirements, and the BETA CAE suite to generate, solve and post-process a wing box finite element model, all parts of an automated sizing procedure executed using a Python script. The design framework is applied to the optimization of a hybrid-electric aircraft wing considering both component position and thickness variables and resulting in an estimated mass reduction of 29%.

Additionally, aircraft structural design is coupled with other disciplines, such as aerodynamics and loads. A design optimization should consider the impact of structural changes in the remaining aircraft disciplines to avoid discrepancies and changes to the project in latter design stages. Incorporating multidisciplinary variables into structural optimization falls within the scope of Multidisciplinary Design Optimization (MDO). Benaouali and Kachel [5] have presented a fully automated framework dedicated to the high-fidelity multidisciplinary design optimization of an aircraft wing. Aiming at maximizing the aircraft range, given by the Breguet equation, while maintaining the lift coefficient and the structural performance. The case study resulted in a 8.9% increase in the aircraft range by considering shape and structural design variables. Kilimtzidis and Kostopoulos [6] presented a multidisciplinary optimization framework of high-aspect ratio composite aircraft wings combining variable fidelity computational tools. The input aerodynamic loads are calculated using a low-fidelity tool in the initial iteration and a high-fidelity tool in subsequent loops, followed by flutter and static analysis. Throughout the iterations, a significant mass reduction is obtained by employing high-fidelity CFD solutions.

To enhance aircraft performance and efficiency the aerospace industry interest in incorporating composite materials into aircraft design and in improving manufacturing costs and consistency of composite parts has grown during the last decades. Several recent works have targeted structural optimization of aircraft wings considering composite materials.

Kennedy and Martins [7] have devised a wing aerostructural optimization framework and compared metallic to composite structures. They have shown that the composite wing designs are between 34% and 40% lighter than the equivalent metallic wings. Ebadi et al [8] have benchmarked a typical aluminum structure against CFR carbon composite to evaluate the potential mass savings and the environmental effects associated with the move from metallic to composite structures. They have come up to a 37% reduction in the mass of the composite structure compared to that of aluminum.

The current research aimed to develop a wing sizing tool using finite element models, **WingSizer**, to expedite the conceptual design and preliminary sizing of an aircraft wing and provide an early insight on the advantage of using composite materials for selected structural components. **WingSizer** includes another standalone development, the **WinG3N** tool [9], which automatically generates a wing finite element model from its geometric parameters, thus reducing the model development time to a few seconds.

The developed sizing framework was designed to allow for an easy and simple integration within a multidisciplinary design optimization schema. This integration was tested during the 2023 International Forum for Aviation Research (IFAR) Young Engineers Challenge, in which 18 international institutions contributed with design tools addressing different design disciplines, including aerodynamics, propulsion, loads, structure, performance, mass, cost and air traffic management.

The developed framework was further reduced in the number of involved partners (DLR [1], CEiiA [2], ONERA [3], JAXA [4] and TUWien [5]), but considering a wider scope of optimization cases in another ICAS 2024 publication [10].

2. WinG3N - WinG GFEM GENerator

WinG3N [9] was developed to speed-up the generation of a wing finite element model by allowing the user to define its most relevant design parameters, including its span, aspect ratio, sweep and dihedral angles, front and rear spar location, stringers and ribs spacings, among others. Once these inputs are defined, the routine creates a Nastran coded bulk data file with the finite element model of the wing, ready to run a linear static analysis. If the user intends to conduct a parametric study evaluating the impact of changing some of these variables, it is possible to decide to generate as many wing skeletons as required for a given wing loft. This way, **WinG3N** enables the creation of different wing geometries, as shown in Figure 1, in a few minutes.

Although this tool has been tailored to the development of aircraft fixed wing structures, it is easily adaptable to other lifting surfaces, namely the horizontal and vertical stabilisers, with the single limitation of not allowing the existence of more than two longitudinal spars.

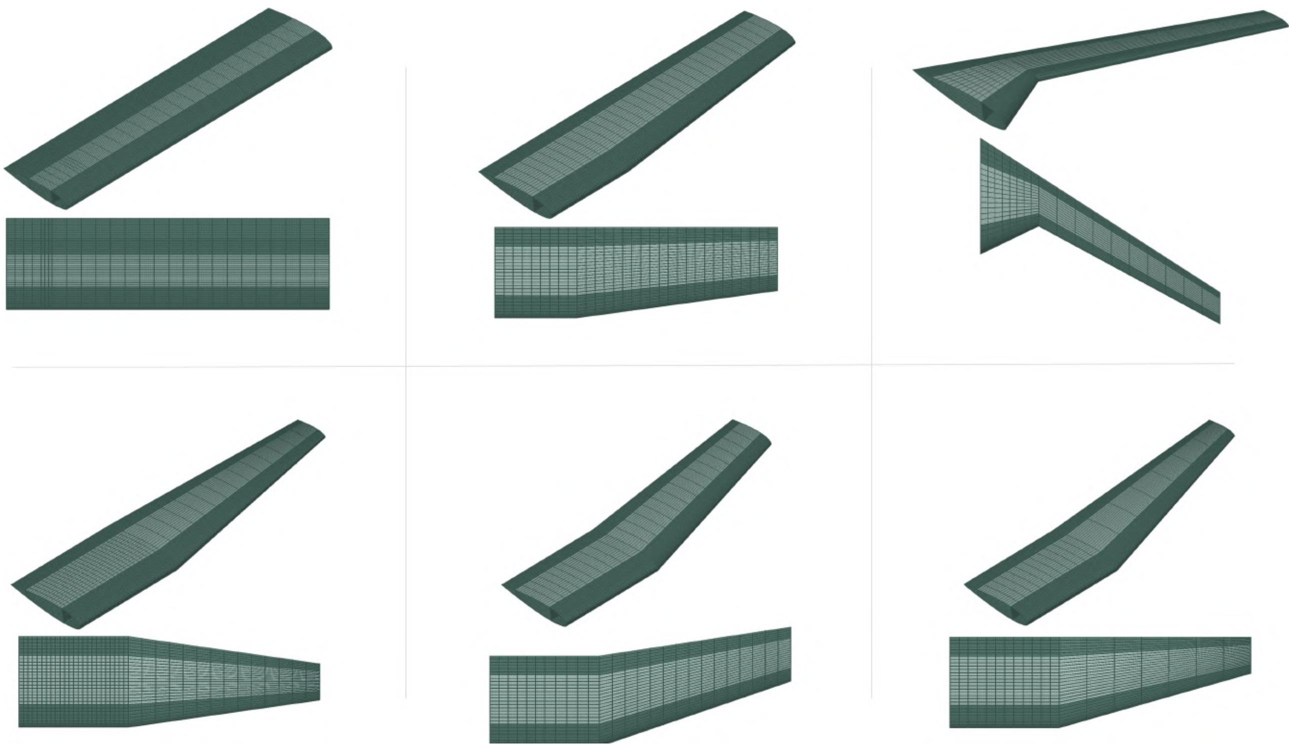

Figure 1 – Different wing layouts, all of which have been generated using **WinG3N**.

3. WingSizer - Wing Sizing Tool

The wing sizing tool, **WingSizer**, uses **WinG3N** to create a baseline wing model which is run using Nastran and post-processed using Altair Hyperview. After running the baseline model, **WingSizer** will initiate a sizing loop using the Fully Stressed Design (FSD) method where, for each component, the maximum stresses are compared with their respective allowable and each component thickness or ply lay-up is updated until a positive margin of safety is obtained for all considered failure modes. In each loop, the updated model is run using a Nastran linear static solution and post-processed

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using Altair Hyperview. The tool mainframe, presented in Figure 2, is developed in Python and uses an auxiliary TCL script to interact with Altair software and collect the maximum structural stresses for each component under analysis. The TCL script creates an Hyperview session, imports the model and the respective results file, creates an extreme envelope with the results of all load cases and loops through all model components to extract the maximum von mises stress, the minimum longitudinal compression stress, the maximum shear stress or the failure index, depending on whether the component is metallic or composite.

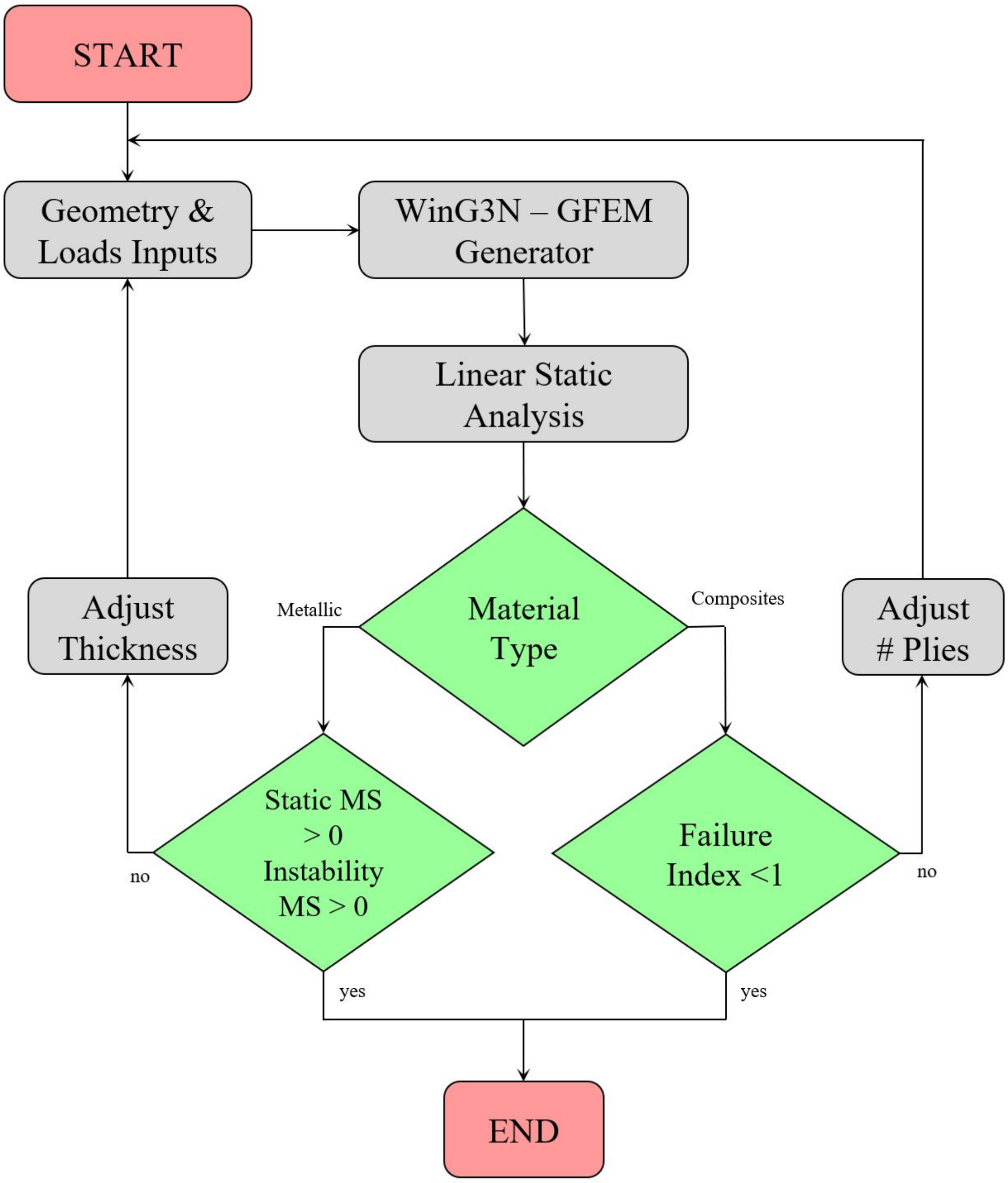

Figure 2 – **WingSizer** framework schematic.

WingSizer evaluates the structural behaviour of wing skins, ribs, spars, leading and trailing edges. For metallic components, the tool is focused on two of the main concerns regarding wing structural analysis: static failure and instability, which tends to size a significant portion of the structural components exposed to the highest compressive loads. Instability analysis is based on NACA experiments from the 1940s [11], [12], aimed at evaluating the behaviour of flat and curved panels when subjected to pure shear, pure compression and a combination of these two types of loads. Some of these studies made it possible to draw curves for several buckling coefficients for metallic panels with different boundary conditions and understand how the buckling coefficients varied with the panels' geometry. For now, the instability assessment is applied to the wing central box skin panels only by evaluating compressive buckling, shear buckling and combined (shear and panel longitudinal stress) buckling.

To evaluate static failure the resulting von-mises stress (f_{vms}) is compared against the material ultimate tensile allowable (F_{tu}), as per Equation (1).

$$\text{MS} = \frac{F_{tu}}{f_{\text{vms}}} - 1 \tag{1}$$

The compressive buckling stress allowable ($F_{c_{cr}}$) is computed using Equation (2).

$$F_{c_{cr}} = \frac{\pi^2 k_c E}{12(1-\nu_e^2)} \left(\frac{t}{b}\right)^2 \tag{2}$$

, where:

- b is the panel width
- E is the skin material Young's modulus
- k_c is the axial compressive buckling coefficient (considering simply-supported edges)
- t is the panel thickness
- ν_e is elastic Poisson's coefficient

The respective MS is computed using Equation (3).

$$\text{MS}_{\text{comp}} = \frac{F_{c_{cr}}}{\sigma} - 1 \tag{3}$$

, where:

- σ is the acting compressive stress

Likewise, the shear stress can also cause a panel to buckle. The shear stress buckling allowable is computed from Equation (4).

$$F_{s_{cr}} = \frac{\pi^2 k_s E}{12(1-\nu_e^2)} \left(\frac{t}{b}\right)^2 \tag{4}$$

, where:

- k_s is the axial shear buckling coefficient, considering hinged edges

The respective MS is computed using Equation (5).

$$\text{MS}_{\text{shear}} = \frac{F_{s_{cr}}}{\tau} - 1 \tag{5}$$

, where:

- τ is the acting shear stress

The combined action of shear and compression can decrease the resultant component buckling allowable, whereas the action of shear and tension can increase it. The combined shear and compression/tension buckling margin of safety (MS_{comb}) is computed using Equation (6).

$$\text{MS}_{\text{comb}} = \frac{2}{R_L + \sqrt{R_L^2 + 4R_S^2}} - 1 \tag{6}$$

$$R_S = \frac{\tau}{F_{s_{cr}}} \tag{7}$$

$$R_L = \frac{\sigma}{F_{c_{cr}}} \tag{8}$$

For metallic components, **WingSizer** increases the component thickness until all applicable margins of safety, calculated using Equations (1), (3), (5) and (6), are positive.

As for composite components, only a static analysis is devised in the current study, where the structural integrity of the component is assessed using the laminate failure index. As it is common for composite materials, the Tsai-Wu failure criteria has been adopted, as per Equation (9).

$$FI = \left(\frac{1}{X_t} - \frac{1}{X_c}\right)\sigma_1 + \left(\frac{1}{Y_t} - \frac{1}{Y_c}\right)\sigma_2 + \frac{\sigma_1^2}{X_tX_c} + \frac{\sigma_2^2}{Y_tY_c} + \frac{\sigma_{12}^2}{S^2} + 2F_{12}\sigma_1\sigma_2 = 1 \tag{9}$$

, where:

- σ_1 is the ply longitudinal stress
- σ_2 is the ply transverse stress
- σ_{12} is the ply shear stress
- X_t is the tensile stress allowable in the principal x (or 1) direction of the material
- X_c is the compressive stress allowable in the principal x (or 1) direction of the material
- Y_t is the tensile stress allowable in the principal y (or 2) direction of the material
- Y_c is the compressive stress allowable in the principal y (or 2) direction of the material
- S is the shear stress allowable in the principal material system
- F_{12} is the interaction strength constant, experimentally determined

The respective MS is computed using Equation (10).

$$\text{MS} = \frac{1}{F.I.} - 1 \tag{10}$$

If the failure index $(F.I.)$ is higher than unity, the number of composite plies is increased until the MS becomes positive.

Further than sizing a structural component composite laminate, the **WingSizer** aims at benchmarking metallic with composite structures with the same geometry by providing a first-hand assessment of the mass difference between the two material categories. That can be done for individual components (e.g. wing spars, wing ribs) or for the wing as whole.

3.1 Assumptions

The forthcoming sections present results derived from an engineering modeling approach, underpinned by several key assumptions outlined in the current section:

- The hence referenced stringer pitch is the distance between stringers at the wing root, which is progressively reduced proportionally to the wing taper ratio as one moves towards the wing tip.
- The wing sizing procedure presented below relies solely on Nastran linear static analysis. Nevertheless, it should be noted that for metallic materials, an empirically based instability assessment facility has been devised.
- In order to guarantee, as much as possible, a fair comparison between the structural performance of composite versus metallic wings, the instability analysis of the metallic wing components was disabled, since there wasn't an analogous feature for the composite components.
- The stringers section and material (metallic) remain unchanged regardless of the wing components material choice.

- The model is clamped at the wing root using NASTRAN single point constraints (SPC) with all degrees of freedom restrained. Therefore, the first bay (wing root) components have been disregarded from the analysis due to the existence of unrealistic stress concentration points. Their thickness was set to 3mm for the metallic wing and the number of plies was set to 4 plies for the composite wing.

It should be noted, regardless of the assumptions listed above, the conclusions drawn from the results presented below come without loss of generality.

3.2 Material Properties

For benchmarking purposes, Aluminum 2024-T3 has been chosen as the reference metallic material. Its properties are presented in Table 1.

Table 1 – Metallic material properties (Al2024-T3, QQ-A-250/4)) [13].

Symbol	Value	Units	Description
E	72395	MPa	Young's modulus
ν	0.33	$-$	Poisson coefficient
ρ	2.768×10^{-6}	kg/mm^3	Density

The physical and mechanical properties considered for the composite material [14] are presented in Table 2. The values with asterisk on Table 2 were not available in Hexcel properties datasheet and have been assumed by the authors based on their experience.

Table 2 – Composite material and mechanical properties, Hexply 8552 AGP 280-5H [14]

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Symbol	Units	Value	Description
E_{12}, E_{21}	MPa	67000, 66000	Elasticity modulus
G^*	MPa	5280	Shear modulus
ν^*	-	0.07	Poisson coefficient
ρ	kg/mm^3	1.57×10^{-6}	Density
X_t	MPa	876	Tensile stress allowable X-direction
X_c	MPa	924	Compression stress allowable X-direction
Y_t	MPa	800	Tensile stress allowable Y-direction
Y_c^*	MPa	844	Compressive stress allowable Y-direction

3.3 Case Studies

The case studies presented hereinafter have considered the Airbus A320 wing loft/geometry. Given the absence of data regarding the wing skeleton or the wing airfoil, typical values have been assumed. The front and rear spars have been assumed to seat at 25% and 79% of the mean aerodynamic chord, respectively. Likewise, the spacing between ribs ranges between 500mm and 800mm. One-dimensional elements have been used to represent the stringers, spar caps and rib caps, which have not been analysed for the current report. In the results that follow, these cross-sections are assumed to remain unchanged, being the same regardless of having metallic or composite structures.

Two design variables are particularly relevant in what concerns to wing structural sizing or optimization: the wing material (either metallic, composite or a combination of the two) and the spacing between stringers (skin panels longitudinal reinforcements).

In order to grasp the relevance of each of these variables on the wing under study, three pitches between stringers (180, 210 and 240mm) have been considered. These stringer pitches were combined with three different material arrangements, namely:

- Fully metallic wing structure
- Composite skins with a metallic skeleton
- Fully composite wing structure

Three fully metallic finite element models have been created, with the only difference between them being the stringer pitch: 180mm, 210mm and 240mm, respectively.

A baseline thickness of 1.0mm has been considered for all metallic components. The **WingSizer** tool evaluates the static failure modes for all components. The metallic skins are further evaluated in compressive, shear and combined (shear + compressive) buckling modes. In all components featuring positive margins of safety the thickness will remain unchanged while the remaining components' thicknesses will be progressively increased until positive margins of safety are attained.

Conversely, a baseline stack of 4 plies is used for the composite components, being that, whenever the failure index of a given component is greater than unity, the number of plies is incremented so that the stacking remains symmetrical and as close to balanced as possible. Figure 3 shows the stacking sequence as the number of plies is increased, with the baseline stacking shown in gray and the added plies shown in white.

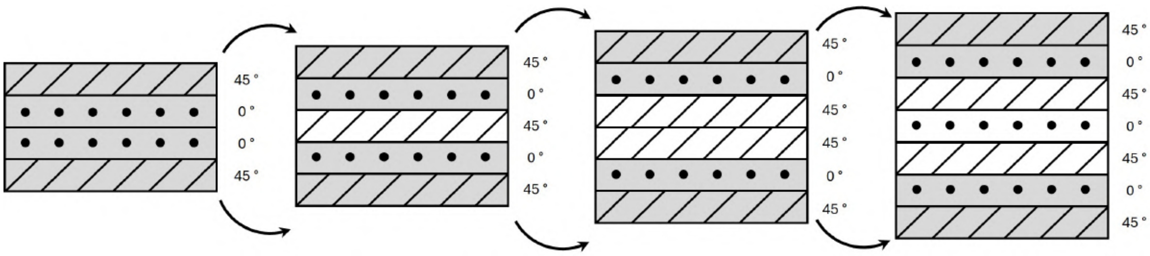


Figure 3 – Composite Stacking sequence.

The aerodynamic loads for a 2g's positive load factor of the Airbus A320 in its maximum take-off mass (78,000 kg) configuration have been considered in all case studies.

4. Results & Discussion

4.1 Fully Metallic Wing Structure

In order to understand how the evaluation of skin instability affects the overall wing structural mass a comparative study with the skin instability evaluation activated and deactivated has been devised.

As expected, there is a slight mass penalty associated with the consideration of skin buckling. Moreover, while the most efficient wing, without buckling consideration, is the one with the greatest pitch between stringers, considering buckling, the most efficient wing becomes the one with the lowest pitch between stringers. The results are presented in Figure 4 and Table 3.

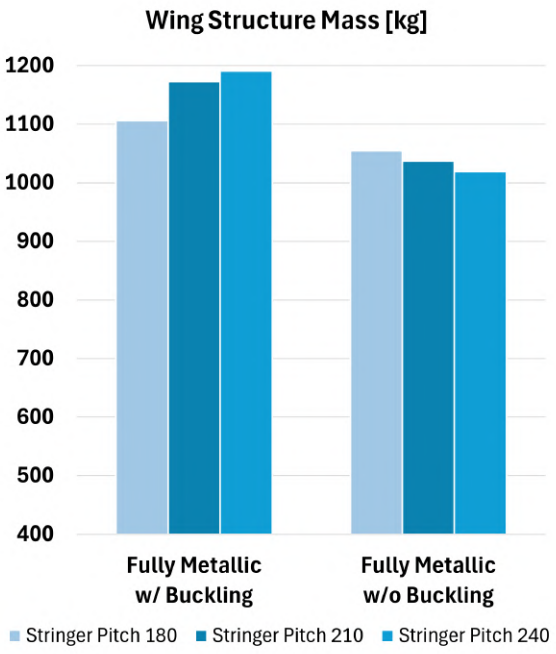


Figure 4 – Metallic Wing Structure Mass [kg] as a function of the pitch between stringers, considering buckling and not considering buckling.

Table 3 – Wing Structure Mass [kg].

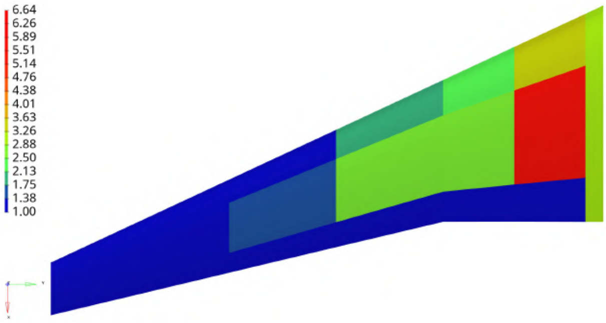
Pitch Between Stringers [mm]	Fully Metallic considering Buckling Mass [kg]	Fully Metallic without considering Buckling Mass [kg]
180	1106.3	1054.9
210	1172.6	1037.2
240	1191.1	1019.3

It is thus apparent that it is crucial to consider the evaluation of skin buckling while conducting trade-off studies during conceptual and preliminary design stages, given that skin buckling may significantly affect the optimum wing configuration.

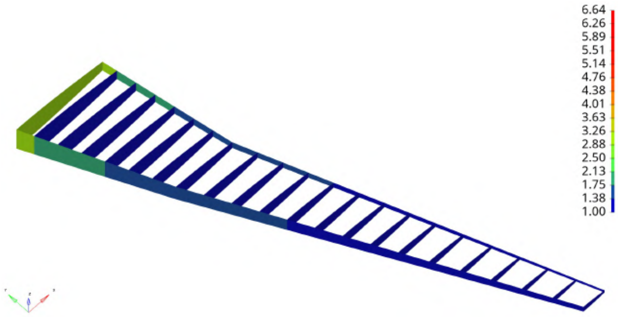
Furthermore, it is noticeable that the wing's structural mass depends on the stringer spacings under consideration. The results suggest that stringer pitch can have meaningful impact and should be carefully evaluated. In order to fully profit from the **WingSizer** potential, a broader study should be carried out, considering a broader range of stringer pitches.

4.1.1 Static Analysis + Buckling

The components' thicknesses for the fully metallic wing, considering buckling, are shown in Figure 5 for spacing between stringers of $180mm$, $210mm$ and $240mm$, respectively. The legend of each plot has been patterned so that the reader can relate the colors between plots. It is noticeable that the thicknesses change depending on the pitch between stringers.

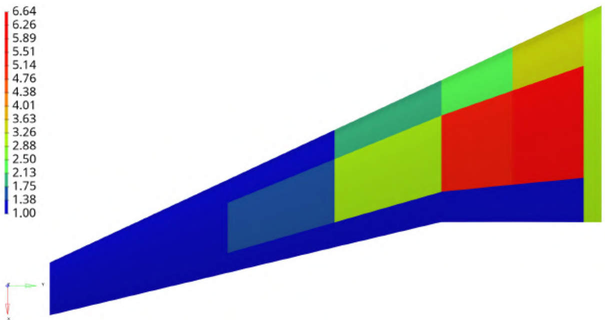


(a) Skins.

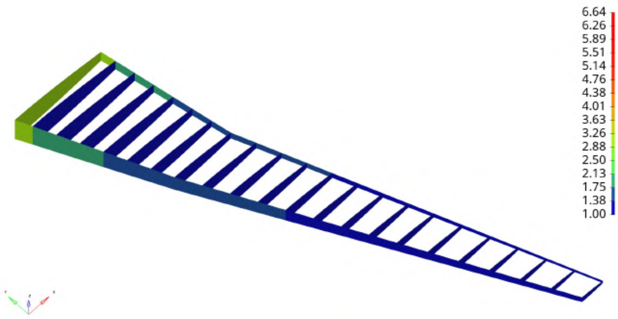


(b) Skeleton (ribs and spars).

Stringer pitch: 180mm.

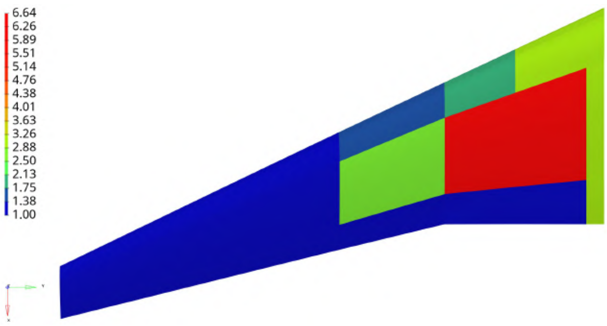


(c) Skins.

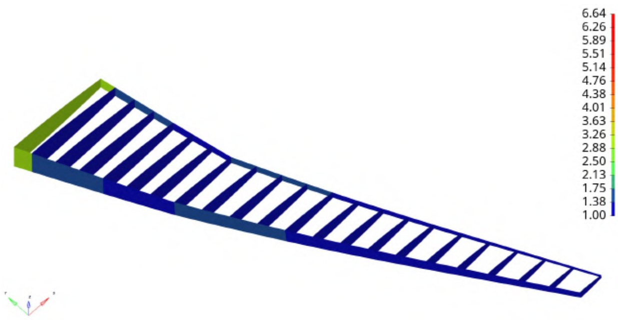


(d) Skeleton (ribs and spars).

Stringer pitch: 210mm.



(e) Skins.



(f) Skeleton (ribs and spars).

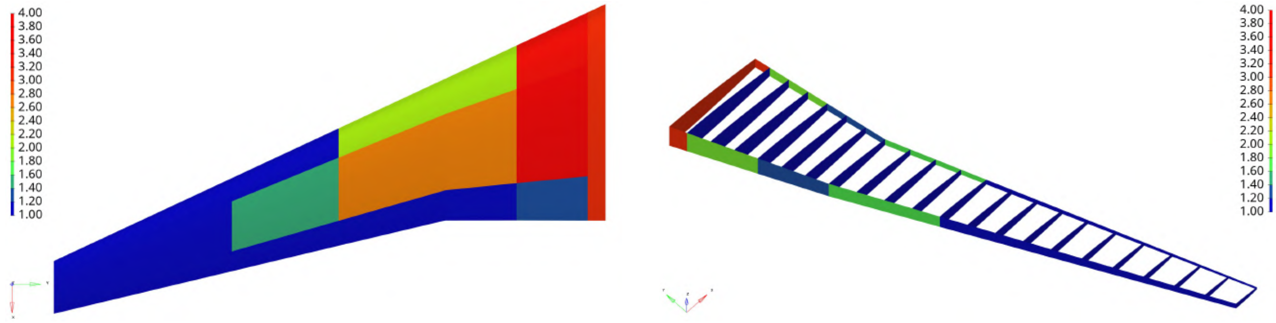
Stringer pitch: 240mm.

Figure 5 – Fully metallic wing, considering buckling.

4.1.2 Only Static Analysis

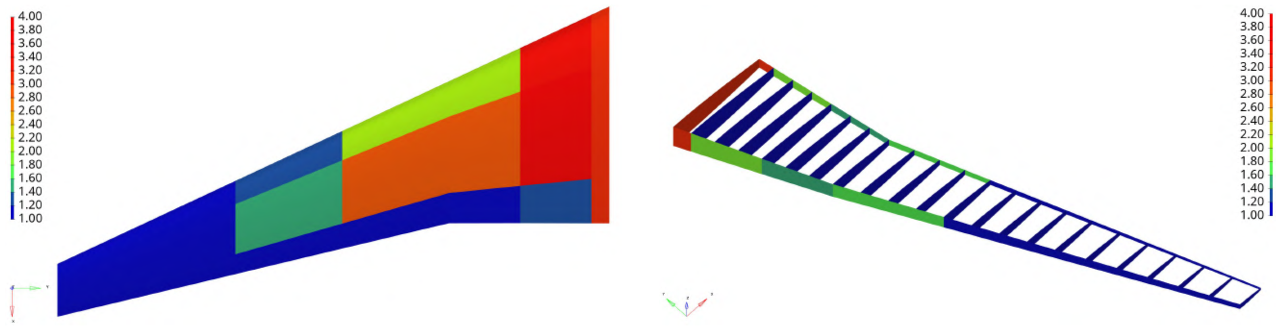
The components' thicknesses for the fully metallic wing, without considering buckling, are shown in Figure 6 for spacing between stringers of $180mm$, $210mm$ and $240mm$, respectively.

The legend of each plot has been likewise patterned so that the reader can relate the colors between plots. It is noticeable that the thicknesses change depending on the pitch between stringers.



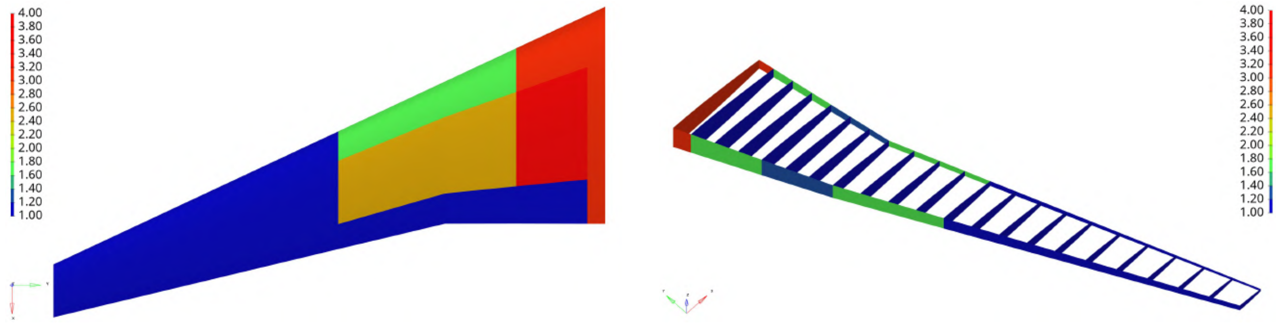
(a) Skins. (b) Skeleton (ribs and spars).

Stringer pitch: 180mm.



(c) Skins. (d) Skeleton (ribs and spars).

Stringer pitch: 210mm.



(e) Skins. (f) Skeleton (ribs and spars).

Stringer pitch: 240mm.

Figure 6 – Fully metallic wing, without considering buckling.

4.2 Metallic versus Composite Wing Structure Benchmark

While the **WingSizer** tool allows for an instability evaluation of metallic skins, it wouldn't be equitable to compare composite solutions without also considering skin instability. Therefore, in the current section, the wings encompassing composite materials will be assessed against a fully metallic wing without considering buckling.

The results presented in Table 4 and Figure 7 show that from a structural mass standpoint, the more composite materials are used, the more efficient the wing will be. That is in line with what would be expected.

As for the 9 simulations which have disregarded the skin buckling, the larger the pitch between stringers, the lower the wing structural mass.

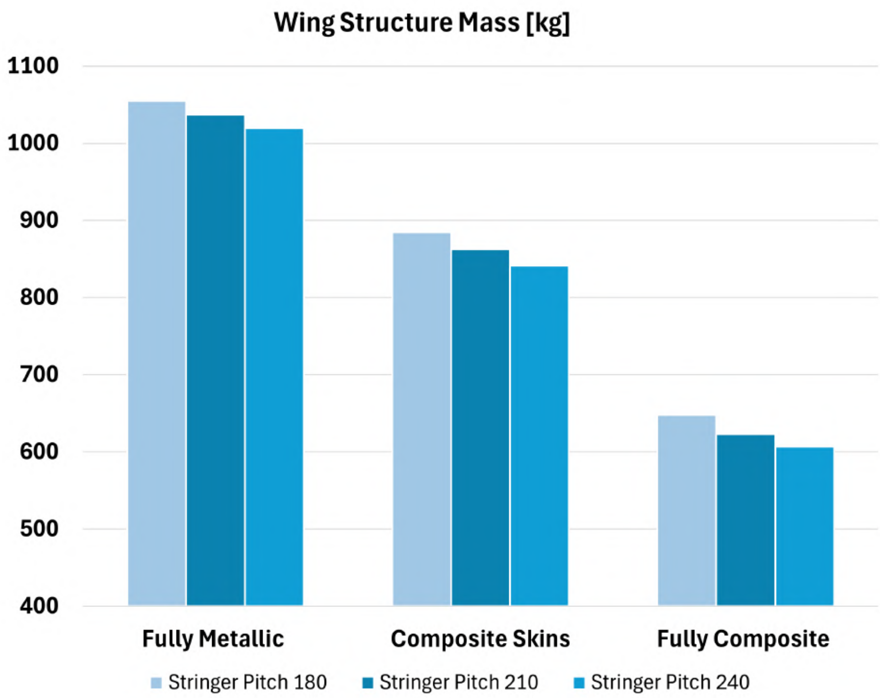


Figure 7 – Metallic, Composite and Hybrid Wings Structure Mass [kg] as a function of the pitch between stringers.

The results presented in Figures 7 have been summarized in Table 4.

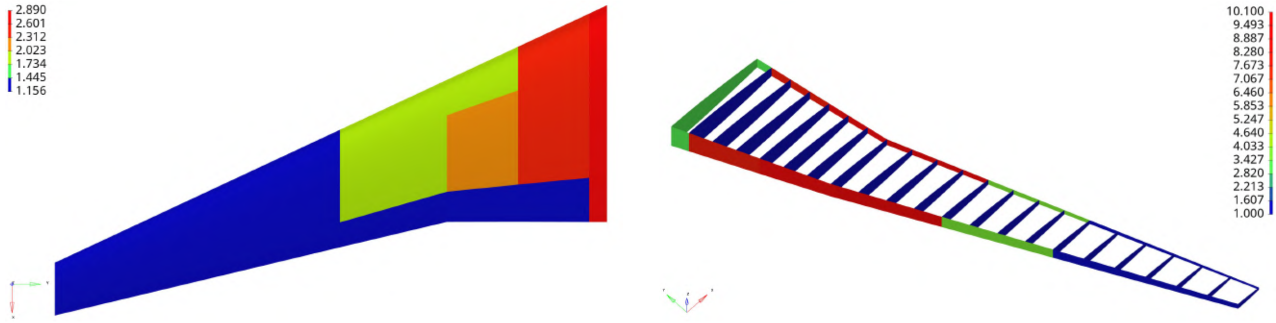
Table 4 – Wing Structure Mass [kg] without considering skin buckling.

Pitch Between Stringers [mm]	Fully Metallic Mass [kg]	Composite Skins Mass [kg]	Fully Composite Mass [kg]	Mass Saving (F. Composite vs. F. Metallic)
180	1054.9	884.9	648.0	39%
210	1037.2	862.8	623.0	40%
240	1019.3	841.5	607.1	40%

A mass saving between 39% and 40% was achieved by changing all wing components material from metallic to composite material. Despite the underlying assumptions in the WingSizer, which aims to be a preliminary sizing tool, these results are in line with the mass savings obtained by Kennedy and Martins [7].

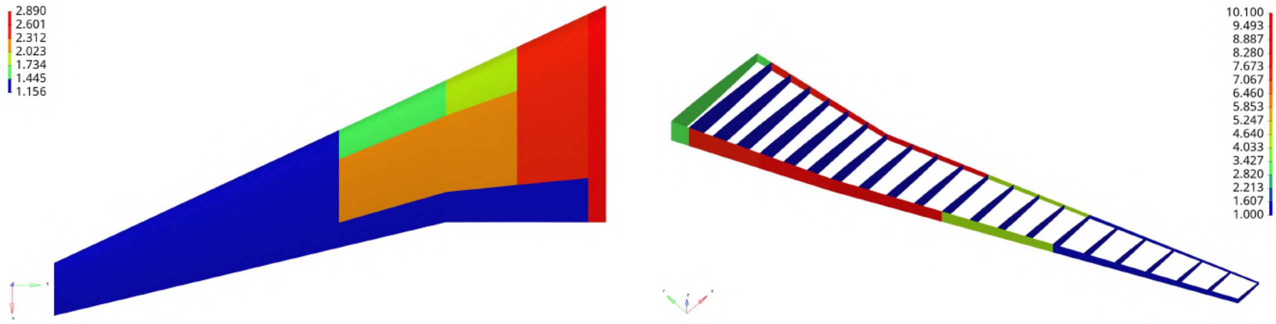
4.2.1 Composite Wing Skin with Metallic Skeleton

The components' thicknesses for a wing featuring composite wing skins and a metallic skeleton, without considering buckling, are shown in Figure 8 for spacing between stringers of $180mm$, $210mm$ and $240mm$, respectively. The legend of each plot has been likewise patterned so that the reader can relate the colors between plots. Each 1.156mm refers to 4 plies (for the composite skins). It is noticeable that the thicknesses change depending on the pitch between stringers.



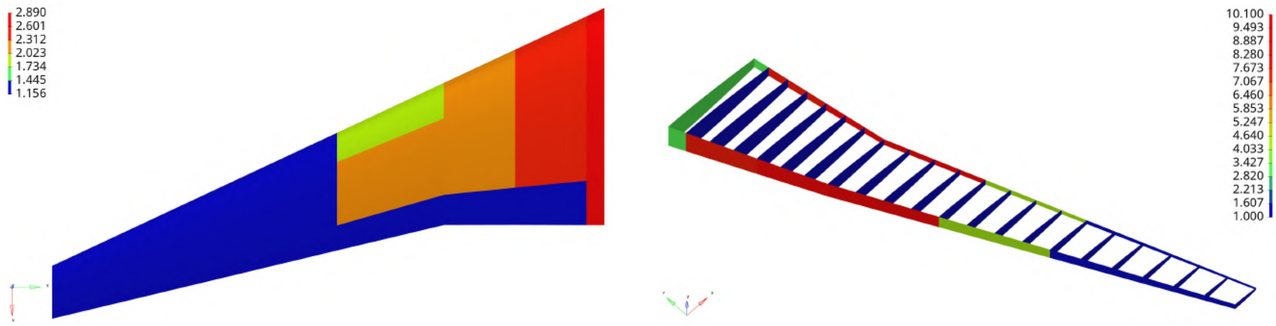
(a) Composite Skins. (b) Metallic skeleton (ribs and spars).

Stringer Pitch: 180mm.



(c) Composite Skins. (d) Metallic skeleton (ribs and spars).

Stringer Pitch: 210mm.



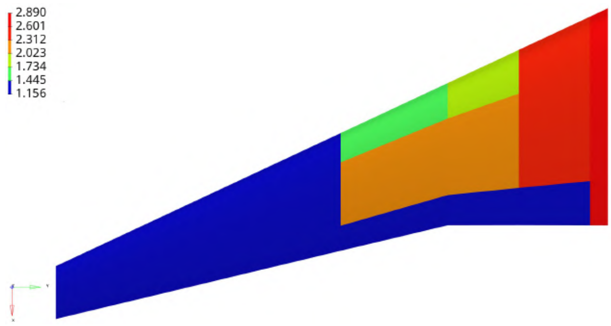
(e) Composite Skins. (f) Metallic skeleton (ribs and spars).

Stringer Pitch: 240mm.

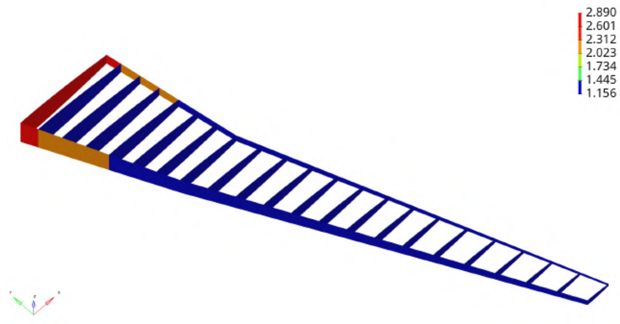
Figure 8 – Composite wing skin, disregarding buckling, wing components thickness [mm].

4.2.2 Fully Composite Wing Structure

The components' thicknesses for a fully composite wing, without considering buckling, are shown in Figure 9 for spacing between stringers of $180mm$, $210mm$ and $240mm$, respectively. The legend of each plot has been likewise patterned so that the reader can relate the colors between plots. Each 1.156mm refers to 4 plies. It is noticeable that the thicknesses change depending on the pitch between stringers.

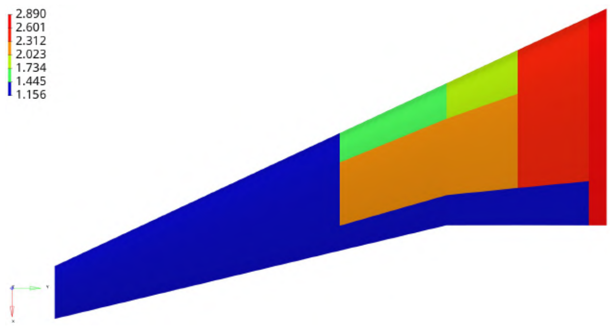


(a) Skins.

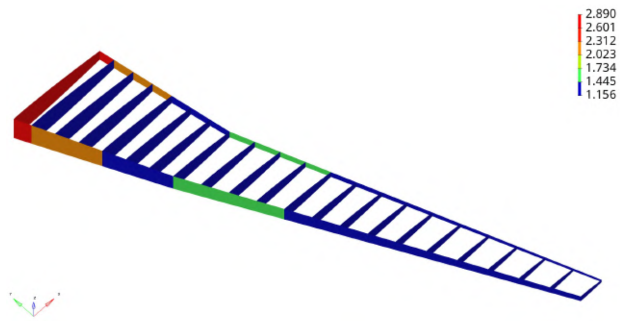


(b) Skeleton (ribs and spars).

Stringer Pitch: 180mm

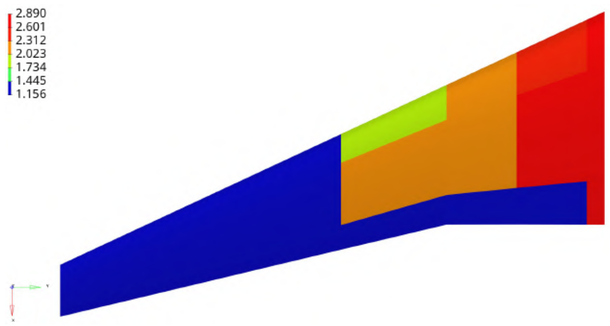


(c) Skins.

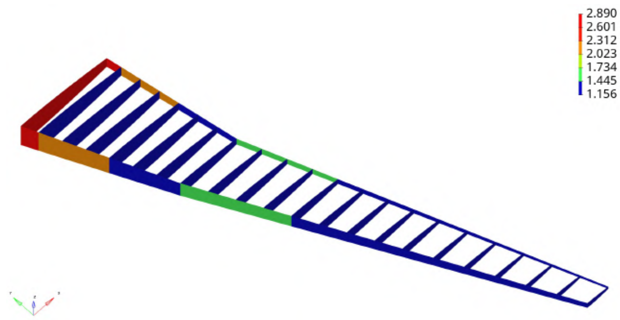


(d) Skeleton (ribs and spars).

Stringer Pitch: 210mm



(e) Skins.



(f) Skeleton (ribs and spars).

Stringer Pitch: 240mm

Figure 9 – Composite wing, disregarding buckling, wing components thickness [mm].

5. Wing Configurations Displacements

Lastly from the case studies presented in the previous sections, Figure 10 shows the wing deformation for a stringer pitch of 180mm.

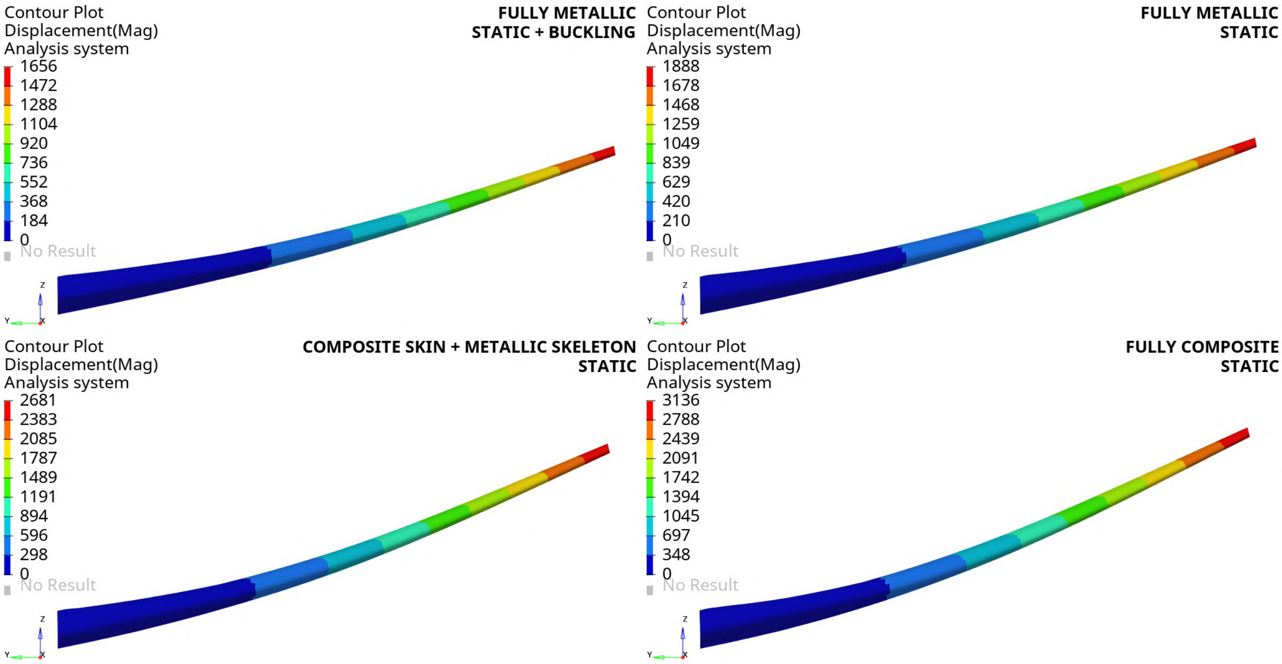


Figure 10 – Wing displacements, depending on the wing structure material and sizing considerations, for a stringer pitch of 180mm.

It is clear that the fully composite wing yields a much larger deformation than the fully metallic wing. As expected, the composite skin with a metallic skeleton seats somewhere in between the fully metallic and fully composite solutions. It is noticeable that, when buckling was considered (fully metallic wing), the wing became structurally stiffer, which resulted in a smaller deformation with respect to the homologue metallic wing where only static failure was considered.

6. WingSizer Tool Performance

As a preliminary design tool, the **WingSizer** should swiftly deliver low-fidelity analysis results in order to drive the designer's choice concerning key design variables throughout the early stages of aircraft design. The WingSizer can be an invaluable tool to evaluate the worthiness of using composite materials, or the extent to which they should be used, optimizing the wing skeleton (spars, ribs and stringers spacings) and even evaluating how changing the stringers inertia may modify these conclusions.

Figures 11 and 12 show the simulation running time and convergence loops for each of the simulations run for the current article, respectively.

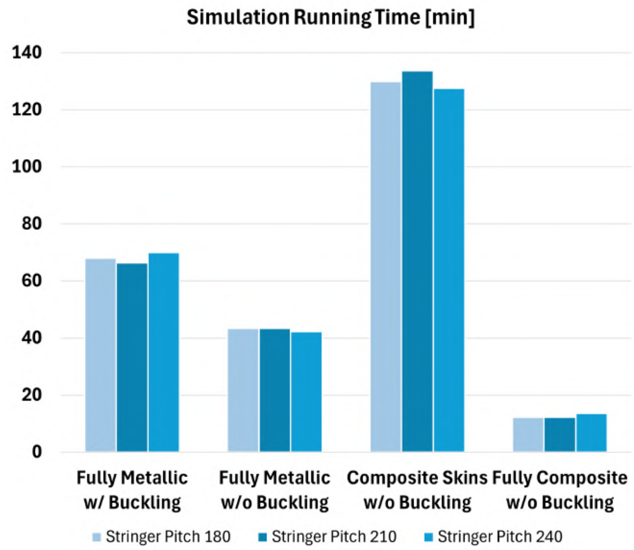


Figure 11 – WingSizer running time until convergence [min].

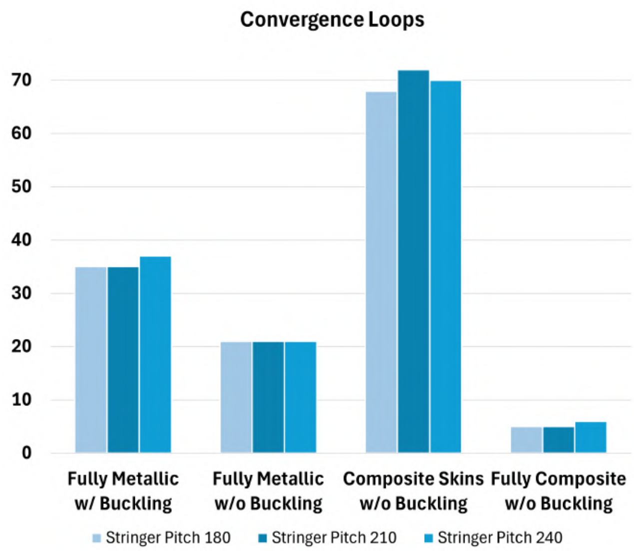


Figure 12 – WingSizer simulations number of loops until convergence.

Although there is margin for greater computational performance, namely by revising the components thickness gain function, the simulations have taken anywhere from 12min up to 2h15min, which is quite acceptable to perform a large number of trade-off and preliminary sizing studies in a rather efficient way. It should also be considered that several simulations can be run in parallel thus enhancing the tool's output performance.

Despite its advantages, the WingSizer tool results should not be regarded as a full wing sizing, even when buckling is activated, because most failure modes are not grasped by the underlying methodology. Nevertheless, both the tool results and performance figures indicate that it can be extremely helpful to drive better design decisions from the earliest stages of wing design.

7. Integration within a MDAO workflow

The **WingSizer** integration within a multidisciplinary design optimization schema was tested during the 2023 International Forum for Aviation Research (IFAR) Young Engineers Challenge.

All contributing tools were integrated within a collaborative Multidisciplinary Design Analysis and Optimization (MDAO) Workflow Design Accelerator (MDAx) developed by the DLR [6]. The exchange of data between the different disciplines/partners was done using a common xml based parametric scheme known as Common Parametric Aircraft Configuration Schema (CPACS) [10]. CPACS is therefore a driver for multidisciplinary and multi-fidelity design in distributed environments and widens the chances of collaboration by eliminating the need to share proprietary tool information.

The **WingSizer** tool received as inputs the wing loft (from ONERA) and the wing aerodynamic loads distribution (from ILOT [7] – Polish Institute of Aviation) and provided as outputs the thickness per component and the wing structural mass (to A*STAR [8], Singapore Institute for High Performance Computing).

The developed framework was further reduced in the number of involved partners (DLR, CEiiA, ONERA, JAXA and TUWien), but considering a wider scope of optimization cases in another ICAS 2024 publication [10].

8. Conclusions

The standard hand-made wing finite element model can take from a few days to some weeks to develop, the **WinG3N** tool makes it possible to automatically generate a wing finite element model within a few seconds, thus unfolding a number of additional trade-off and sensitivity studies which would be unfeasible otherwise.

Likewise, a first sizing of a wing finite element model (for static and buckling) analysis may take several days as well. With the sizing framework implemented in **WingSizer**, not only does that process become automatic but also much faster than the traditional standard procedure, once more saving from a few hours to up to several days, depending on the model dimension and complexity.

The results have shown the worthiness of this tool in the automation of the preliminary sizing of an aircraft wing main structural components. It contributes to make the conceptual and preliminary design stage more efficient and effective due to the swiftness inherent to the automation process and the consequent much larger number of trade-off studies and parametric optimisation analysis that can be made that would otherwise be limited due to their cost.

Further to the preliminary sizing of the structure, **WingSizer** makes it possible to benchmark the performance of metallic against composite materials in selected components of the wing assembly. This ability can be used to perform trade-off studies which can provide a quantitative assessment of the advantages or disadvantages of using composites instead of metallic structures enabling the assessment of changing the whole wing assembly material or only some of its components.

The case study results presented have shown that considering skin instability (for metallic materials) can have a great impact on the wing's structural mass and the best stringer pitch is not the same whether wing sizing is made considering buckling or only considering static failure.

An additional comparative study was undertaken in order to compare a fully metallic wing against a composite skin with a metallic skeleton and a fully composite wing. The results indicate a potential wing mass saving ranging between 39% and 40%, which is in line with literature. These results were achieved with the buckling option being deactivated for all three wing material arrangements, for the sake of fairness, due to the methodology not supporting buckling on the composite components.

[6] German Aerospace Centre, Germany
[7] Institute of Aviation, Poland
[8] Agency for Science, Technology and Research, Singapore

Although the two tools developed (**WinG3N** and **WingSizer**) have been tailored to the development and analysis of aircraft wings, they may be likewise used for the initial sizing of aircraft horizontal and vertical stabilizers, provided they feature no more than two longitudinal spars.

In addition to its standalone features, **WingSizer** was designed to allow for an easy and simple integration within a multidisciplinary design optimization framework, as it has been shown in the context of the IFAR-X 2023 Young Engineers challenge, where it interacted with other partner tools and design disciplines using a standard common xml based parametric scheme to exchange inputs and outputs, further enhancing its scope.

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10. Acknowledgements

The authors would like to thank Witold Klimczyk from ILOT [9] for contributing with the aerodynamic load distribution used in Section 4.

11. Copyright Statement

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