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EXECUTIVE SUMMARY OF THE THESIS

# Strut-Braced Wing Aircraft Configuration: An Aeroelastic Assessment

LAUREA MAGISTRALE IN AERONAUTICAL ENGINEERING - INGEGNERIA AERONAUTICA

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## 1. Introduction

Climate changes should happen because of nature. Unfortunately, starting from the last century, human activities have become the main reason for these phenomena to occur. In particular, carbon-based fuels released $CO_2$ is one of the principal concerns. Being these fuels employed practically in every sector (e.g. industry, agriculture, energy, transport), it's easy to understand the need for everyone to actively participate in the attempt to reduce the emissions. Of course, also the aviation world is involved. Indeed, as reported by the International Energy Agency in [1], in 2021 air transports were responsible for over 2% of global $CO_2$ emissions. Being well aware of the situation, in the last decades several work has been done to produce and employ advanced technologies such as composite materials, modern aerodynamic profiles, efficient propellers, but it must be admitted that a sort of plateau has been reached and following this path does no longer allow for the required gains. A change of perspective is needed. This justifies the late interest in unconventional configurations such as Blended Wing Body (BWB), Box-Wing (BW), Strut-Braced Wing (SBW) and Truss-Braced Wing (TBW), which can represent a gamechanger. An overview of these concepts can be found in [2].

In this context, a EU funded Clean Sky 2 project leaded by POLIMI was started in May 2020, as a response to the call JTI-CS2-2019-CFP10-THT-07, whose name is U-HARWARD, acronym of Ultra-High Aspect Ratio Wing Advanced Research and Designs [3]. The aim of the project is to investigate the use of innovative aerodynamic and aeroelastic designs exploiting a multi-fidelity multi-disciplinary optimal design approach in order to develop (Ultra-)High Aspect Ratio Wings ((U)HARW) for medium and large transport aircrafts. One of U-HARWARD tasks was to study the SBW configuration, which appears to be particularly promising. An aeroelastic assessment of this unconventional configuration is given in the present work, along with some considerations regarding its design.

## 2. SBW working principle

Recalling Breguet range formula

$$R = \frac{V_{TAS}}{g}\left(\frac{L}{D}\right)\frac{1}{SFC}ln\left(\frac{W_{MTOW}}{W_{MTOW}-W_{fuel}}\right)$$

which shows how aircraft efficiency is influenced by aerodynamics (L-to-D), propulsion (SFC) and structure (logaritmic term), an effective way to reduce aircraft emissions is to increase aerodynamic efficiency. Drag is subdivided in several contributions, e.g. wave, friction, induced drag. The latter is the most relevant component. As shown in (1),

$$C_{D_i} = \frac{C_L^2}{\pi ARe}, \tag{1}$$

induced drag coefficient depends proportionally on the square of lift coefficient ($C_L$) and inversely on Oswald coefficient ($e$) and wing AR, hence: augmenting the AR lowers the induced drag. However, high ARs lead to an increase in wing bending moment, and, consequently, in wing weight, possibly withdrawing the benefits of having such a high AR. The introduction of a strut between fuselage and a certain wing span, allows to keep wing weight limited, by alleviating its bending moment, as qualitatively shown in Figure 1.

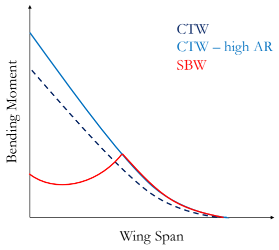


Figure 1: Qualitative behavior of wing bending moment for different aircraft configurations

Moreover, if bending moment is reduced, wing-box thickness can be lowered too, along with thickness-to-chord ratio (t-to-c). Since transonic wave drag depends proportionally on t-to-c, it decreases too. Smaller sweep angles can then be employed, leading to an increased area of natural laminar flow. The efficiency gain allows for smaller consumptions, which possibly turns into smaller engines and smaller noise. All these interactions, which include structure, aerodynamics and propulsion, suggest that a multi-disciplinary approach is the best suited for the problem, potentially bringing to important gains. Some additional considerations that justify the interest in studying aeroelasticity of SBW reagrds the fact that introducing the strut leads to an overconstrained system, which is intrinsically complex, and the wing flexibility, which is particularly relevant for high ARs. Both these aspects can play a role on aeroelasticity outcomes.

# 3. Aeroelastic model

The starting point is the model produced by ONERA and ISAE-SUPAERO inside U-HARWARD project, presented in [4]. The Airbus A321-LR was chosen as the reference aircraft. Being its configuration a Classical Tube and Wing (CTW), it was modified into its SBW version. Some geometrical data are reported in Table 1.

| | A321-LR | SBW | Unit |
|---|---|---|---|
| **Wing Span** | 34.1 | 55.13 | m |
| **Wing Surface** | 126 | 161.8 | $m^2$ |
| **Wing AR** | 9.23 | 19 | - |
| **Wing Sweep** | - | 19 | deg |
| **HTP Span** | 12.45 | 12.44 | m |
| **HTP Surface** | 30.75 | 35.83 | $m^2$ |
| **HTP AR** | 5.04 | 4.31 | - |
| **VTP Span** | 5.87 | 6.88 | m |
| **VTP Surface** | 22.3 | 33.93 | $m^2$ |
| **VTP AR** | 1.55 | 1.4 | - |

Table 1: Geometrical values of baseline configuration A321-LR and its SBW version

Moreover, the wing was translated from the bottom to the top part of the fuselage, becoming a high wing in order to accomodate the strut. To avoid potential interferences, fuselage-mounted engines were selected, along with a T-Tail configuration. Finally, the strut was chosen to be lifting.

## 3.1. Modeling choices

Up to this point, this thesis followed the same path proposed by ONERA. However, it will become clear later that discrepant results have been obtained. This outcome is due to the different adopted modeling choices, here listed.

1. Wing-strut attachment: in [4] it was modeled through a sleeve aligned with the wing Elastic Axis (EA) that allows the strut to be inactive in compression, in order to avoid buckling problems. Indeed, if the strut could experience buckling, this condition would become the driver of its sizing, leading to an increase in weight that could cancel the benefits of reduced induced drag. Since no dedicated studies were conducted on this connecting mechanism, which was firstly proposed by NASA in the 1990s, it has been here considered a non-realistic so-

lution, at least for the moment. Therefore, the attachment has been modeled by a double hinge: one along fuselage and one along vertical direction, meaning that neither out-of-plane not in-plane bending moment can be transfered from strut to wing. This choice leads to a significant conceptual difference with respect to [4]. Of course, an increase in weight is here expected.

2. Loads sustained by the strut: in [4] the strut has been sized considering only axial tensile loads. However, being the strut lifting, all the loads should be present in the sizing process. In particular, shear and bending due to lift play an important role. For this reason, in the present work, the strut has been modeled following the same path of the wing. Semi-monocoque structural concept has been adopted for both components and a fully-stressed design approach has been applied.
3. Load cases for sizing: in [4] the wing was sized thorugh a 2.5g and a $-1$g manouvre, while the strut, basing on the aforementioned considerations, was sized only thorugh the 2.5g. In the present work, no distiction was made for wing and strut sizing, i.e. the same set of manoeuvres sized both components. As already stated, this reasonably leads to a difference in the estimated weights.

## 3.2. Model generation and verification

### 3.2.1 Software

The SBW model has been generated through NeoCASS [5], an open-source code developed at POLIMI, whose principal aim is to consider aeroelasticity yet at the conceptual design phase of an aircraft. This is particularly useful for unconventional configurations such as SBW, whose high flexibility could generate non-expected behaviors that if discovered earlier allow for a more effective design. Structure is represented by a stick model, while aerodynamics is introduced through VLM/DLM. It is subdivided in modules, where the most relevant ones are: AcBuilder, which is a graphical editor that receives as input mainly geometry and payload, and GUESS, which is dedicated to sizing and requires as input AcBuilder file along with some additional informations such as the manoeuvres (prescribed by EASA CS-25), and the mass configurations (MTOW, MZFW and OEW). SMARTCAD is the module dedicated to analyses, e.g. modal analysis, static aeroelasticity (i.e. trim, divergence) and flutter. An optimizer is included, called NeOPT, which corrects the symmetrical wingbox generated in GUESS by exploiting a section Finite Element solver and producing a more complete description of the wingbox accounting also for couplings.

### 3.2.2 Verification method

In order to check if sizing produced reasonable results, it has been chosen to evaluate both linear and nonlinear trim in dive, reported in Table 2. The importance associated to nonlinear analyses will be explained later on.

| | **M [-]** | **h [m]** | **$N_z$ [g]** |
|---|---|---|---|
| **Dive condition** | 0.89 | 6760 | 1 |

Table 2: Definition of dive condition

### 3.2.3 Procedure

A schematic representation of the followed procedure can be found in Algorithm 1 and in Figure 2. Since some underestimation of torsional stiffness has been found from GUESS sizing, NeOPT has been exploited. In particular, in order to increase the property, a constraint of aileron efficiency $\geq 30\%$ has been introduced, along with structural requirements (i.e. no buckling and no failure). A Safety Factor (SF) of 1.5 has been chosen.

Algorithm 1 Procedure for model generation and verification

```
1: Establish geometry.
2: Give geometry as input to AcBuilder.
3: Give AcBuilder file as input to GUESS, which sizes the model.
4: Compute the trim analyses in dive with SMARTCAD, for verification purpose.
5: if Verification is satisfied then
6:     Exit.
7: else if Issues have been found then
8:     Go to the next step.
9: end if
10: Correct the sized model with NeOPT.
11: Go back to step 4.
```

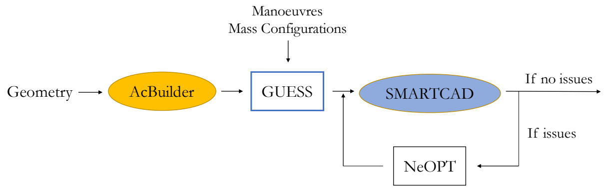


Figure 2: Procedure for model generation and verification

### 3.2.4 Verification results

After having optimized the model, trim in dive has been studied. Figure 3 shows the obtained results for linear trim only. Nonlinear trim was even worse.

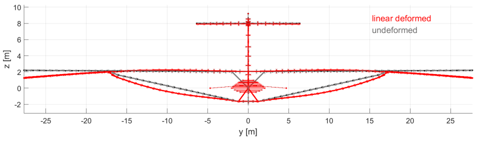


Figure 3: Linear trim in dive (front view)

The wing bends downward. This was explained by considering that ONERA strut is very slender, and therefore very flexible, but it is also lifting. The aerodynamics due to lift, jointly with the presence of the wing, at this high pressure flight point, loads a strut with very low stiffness, leading to high deformations. Being the wing attached to the strut, it is dragged down.

## 3.3. Model update

A way to solve the aforementioned problem is to re-design the strut. Figure 4 shows a comparison between ONERA geometry and the updated one. Strut data are reported in Table 3. Strut-fuselage attachment has been translated toward the tail, leading to a change in strut sweep. This could help to partially increase wing torsional stiffness. Moreover, the inboard portion of the strut is horizontal, in order to reduce strut oblique length, for buckling considerations. To produce the updated model, the same path presented in Figure 2 was followed. Also the optimization was computed because GUESS torsional stiffness was again underestimated. The results of the verification analysis are reported in Figure 5.

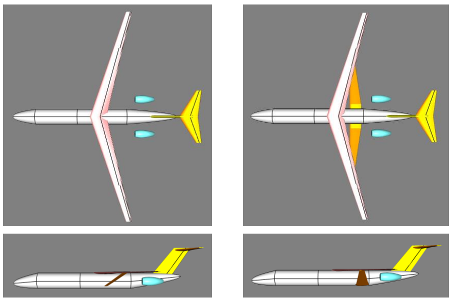


Figure 4: Comparison between ONERA and updated models

| | ONERA | Updated | Unit |
|---|---|---|---|
| **Strut Span** | 34.5 | 34.5 | m |
| **Strut Surface** | 32.4 | 80 | $m^2$ |
| **Strut AR** | 36.73 | 14.9 | - |
| **Strut Taper Kink** | 1.15 | 1 | - |
| **Strut Taper Tip** | 1.15 | 0.3 | - |
| **Strut Sweep Inboard** | 12.5 | 0 | deg |
| **Strut Sweep Outboard** | 12.5 | $-1$ | deg |
| **Strut Attachment to Wing** | 65% | 65% | - |

Table 3: Comparison between ONERA and updated models strut

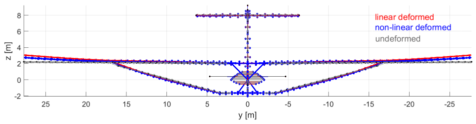


Figure 5: Trim in dive for updated model (front view)

Updated SBW model weights are reported in Table 4, where they are compared to the original ONERA ones, where original ONERA is the model with the sleeve mechanism presented in [4]. An increase in weight is encountered, due both to model choices discussed in Subsection 3.1 and strut re-design.

| | Updated SBW [kg] | original ONERA SBW [kg] | Δ% |
|---|---|---|---|
| **MTOW** | 101685 | 85014 | 16.4 |
| **MZFW** | 83084 | 68719 | 17.3 |
| **OEW** | 63284 | 45719 | 27.8 |

Table 4: Comparison of weights between original ONERA and updated models

## 3.4. Comparison of SBW and CTW

It is possible to quantify wing bending moment reduction, along with its mass, by comparing the results of the updated SBW model with the ones of a correspondent CTW, obtained sizing the very same geometry, without the strut. Figure 6 shows bending moments, while Table 5 reports structural masses.

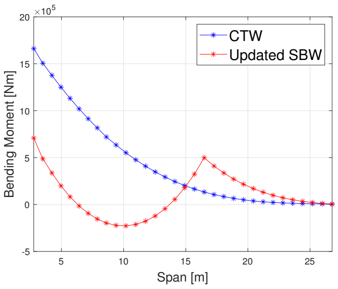


Figure 6: Bending moment comparison between CTW and updated SBW models

| | CTW [kg] | SBW [kg] | Δ% |
|---|---|---|---|
| **Half Wing** | 7982 | 5976.4 | 25 |
| **Half Strut** | - | 1796.9 | - |
| **Total Half** | 7982 | 7773.3 | 2.6 |

Table 5: Structural mass comparison between CTW and updated SBW models

# 4. Aeroelastic analyses and results

## 4.1. Analyses

NeoCASS allows to study several aeroelastic linear analyses: static such as trim and divergence, and dynamic such as gust response and flutter. Recently, the possibility to compute also nonlinear trim and flutter has been introduced. The only limitation is that the aircraft must be grounded. Therefore, to keep consistency, when nonlinear analyses have been evaluated, first of all a linear trim in the required flight point has been produced, then the resulting attitude has been imposed to the grounded model. Having the studied SBW an AR=19, high flexibility is involved, and large displacements can be reached. It is then important to study also nonlinear analyses, when possible, because the presence of the geometrical stiffness could lead to results that are not captured when only the material stiffness matrix is involved. Geometrical stiffness is also important for model reduction when nonlinear flutter is considered. For this type of analyses, in every chosen flight point a nonlinear trim is firstly evaluated, aerodynamics is then updated for the deformed configuration, tangent stiffness is used to both reduce the model and update structural stiffness. Finally, flutter analysis is computed.

## 4.2. Results

First of all, linear and nonlinear trim in cruise, linear gust, linear divergence and linear and nonlinear flutter have been studied for the updated model defined in Subsection 3.3, here named *reference* model. Then, it has been evaluated how changing wing and strut material, mass configuration, strut geometry and wing-strut attachment chordwise position affect the results. Only the most relevant results will be reported in this Subsection.

### 4.2.1 Impact of wing and strut material

The models compared in this Subsection are summarized in Table 6.

| | Reference | Composite |
|---|---|---|
| **Material** | AL7075-T6 | CFUD<br>$[0/45/-45/90]_s$ |
| **Mass configuration** | OEW | OEW |
| **Strut geometry** | straight | straight |
| **Wing-strut attachment** | on EA | on EA |

Table 6: Compared models: change of wing and strut material

**Sizing** Table 7 shows the obtained structural masses obtained. Some interesting savings are gained, thanks to composite high performances.

| | Reference [kg] | Composite [kg] | Δ% |
|---|---|---|---|
| **Half Wing** | 5976.4 | 3946.7 | 34 |
| **Half Strut** | 1796.9 | 1349.9 | 25 |
| **Total Half** | 7773.3 | 5296.6 | 32 |

Table 7: Structural mass comparison between reference and composite models

**Divergence and flutter** Divergence and flutter have been studied in the red diamonds reported in Figure 7, in order to follow as much as possible the regulations, which require to demonstrate the abscence of flutter up to a velocity that is 1.15VD (dive velocity). Since for aerodynamics DLM was used, the black line represents a limit, therefore point 3 has been translated on 1.05VD.

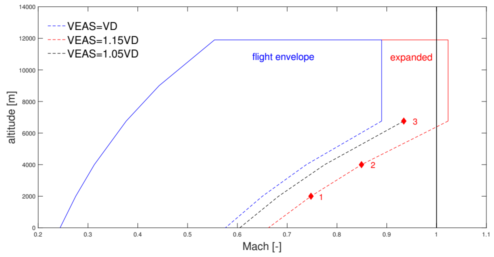


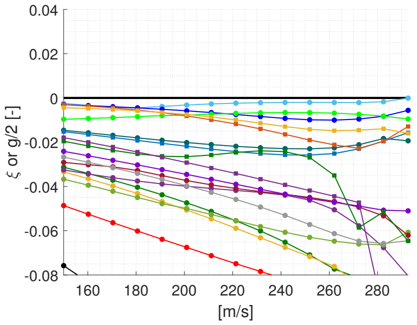
Figure 7: Flight points for divergence and flutter analyses

The results are presented as $V - g$ diagrams, for point 3, in Figure 8. Some irregularity in mode tracking has been obtained for the reference model. This is a numerical issue related to the fact that there are close modes that are difficult to be distinguished. Other than that, in both cases there is a mode with damping close to zero, but if for aluminium alloy it tends to increase eventually also reaching positive values, this does not occur for composite, where the mode tends to become more and more negative as velocity increases. Therefore, it can be concluded that composite materials are beneficial for flutter. Actually, in both cases no flutter was found inside the considered flight envelope, because even if the reference model presents a velocity where a mode reaches $g = 0$, no structural damping was included. Indeed, the regulations require for a 2% of structural damping, meaning that in these analyses flutter would be detected if a mode reaches $g = 0.02$.

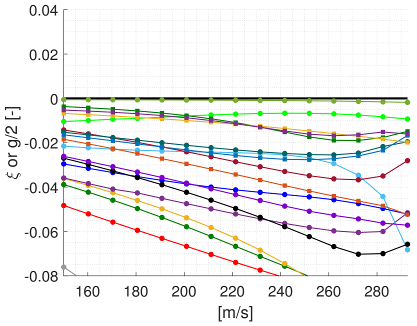
Composites appear to be beneficial for divergence too, as reported in Table 8. In any case, also divergence does not represent an issue for the studied models. It must be however recalled that only linear divergence has been studied. If nonlinearties are considered, the results could be different.

| | $q_{max}$ [Pa] | Ref [Pa] | Comp [Pa] |
|---|---|---|---|
| **Point 1** | 31118 | 72771 | 87401 |
| **Point 2** | 31118 | 66486 | 79925 |
| **Point 3** | 25942 | 51326 | 61927 |

Table 8: Comparison of divergence results between reference (Ref) and composite (Comp) models



(a) $N_z = 1$, reference



(b) $N_z = 1$, composite

Figure 8: Comparison of nonlinear flutter results for point 3 between reference and composite models

### 4.2.2 Impact of mass configuration

Table 9 reports the models analyzed in the present Subsection.

| | MTOW | MZFW | OEW |
|---|---|---|---|
| **Material** | CFUD | CFUD | CFUD |
| **Mass configuration** | MTOW | MZFW | OEW |
| **Strut geometry** | straight | straight | straight |
| **Wing-strut attachment** | on EA | on EA | on EA |

Table 9: Compared models: change of mass configuration

**Sizing** As show in Table 10, the highest structural mass is found for MTOW, which was expected.

| | MTOW [kg] | MZFW [kg] | OEW [kg] |
|---|---|---|---|
| **Half Wing** | 4541.3 | 4306.1 | 3946.7 |
| **Half Strut** | 1879.1 | 1794.7 | 1349.9 |
| **Total Half** | 6420.4 | 6100.8 | 5296.6 |

Table 10: Structural mass comparison between composite MTOW, MZFW and OEW models

**Divergence and flutter** While for flutter no interesting differences have been found between the mass configurations, divergence dynamic pressure turned to be higher for heavier weights, as reported in Table 11. Indeed, MTOW model resulted to be the one with heaviest structural weight, but also with highest stiffness.

| | $q_{max}$ [Pa] | MTOW [Pa] | MZFW [Pa] | OEW [Pa] |
|---|---|---|---|---|
| **Point 1** | 31118 | 109080 | 100145 | 87401 |
| **Point 2** | 31118 | 100261 | 92000 | 79925 |
| **Point 3** | 25942 | 78991 | 72411 | 61927 |

Table 11: Comparison of divergence results between composite MTOW, MZFW and OEW

### 4.2.3 Impact of strut geometry

Even if in the present work the employed methods do not allow for the estimation of interference drag caused by the interaction between wing and strut, some studies can be found in literature, where it is evidenced that a higher distance between the two components have beneficial effects on drag. This change can be introduced by updating strut geometry. It could be interesting to see which is its effect on the results. The model compared are reported both in Table 12 and Figure 9.

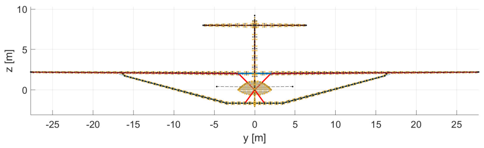
| | Straight | Curved |
|---|---|---|
| **Material** | CFUD | CFUD |
| **Mass configuration** | OEW | OEW |
| **Strut geometry** | straight | curved |
| **Wing-strut attachment** | on EA | on EA |

Table 12: Compared models: change of strut geometry

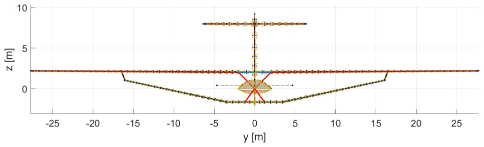
**Sizing** As one can notice in Table 13, strut mass changes significantly between the compared models. On the contrary, wing was kept more or less equal.

| | Straight [kg] | Curved [kg] | Δ% |
|---|---|---|---|
| **Half Wing** | 3946.7 | 4006.9 | 1.5 |
| **Half Strut** | 1349.9 | 2098.8 | 35.7 |
| **Total Half** | 5296.6 | 6105.7 | 13.25 |

Table 13: Structural mass comparison between composite straight and curved models



(a) Straight



(b) Curved

Figure 9: Compared models: change of strut geometry (front view)

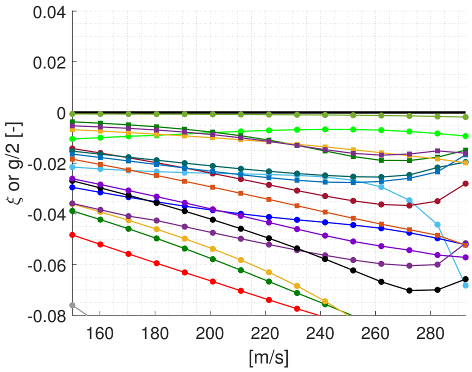
| | M [-] | h [m] | $N_z$ [g] |
|---|---|---|---|
| **Cruise condition** | 0.78 | 11000 | 1 |

Table 14: Definition of cruise condition

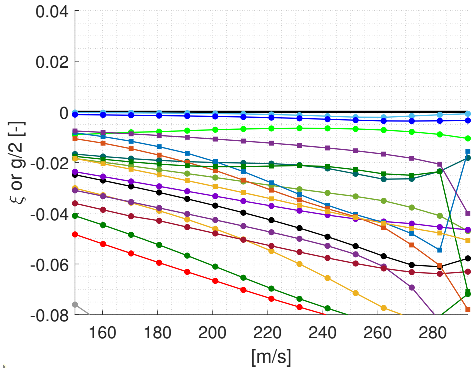
**Trim** Linear and nonlinear trim in cruise (Table 14) have been evaluated and led to a difference of 20% in tip wing vertical displacement, while torsional rotation is more or less unchanged. The curved model bends more than the straight one.

**Divergence and flutter** Figure 10 shows nonlinear flutter results of the compared models for flight point 3.

As one can notice, for the highest velocities, the curved model presents a mode that tends to reach zero damping. This does not occur in the straight case. Even if flutter has not been detected, it can be concluded that the introduced strut geometry change has a negative effect on flutter. On the contrary, it does not affect divergence results, which are very similar for both the models and widely outside the maximum allowed dynamic pressure.



(a) $N_z = 1$, Straight



(b) $N_z = 1$, Curved

Figure 10: Comparison of nonlinear flutter results for point 3 between composite straight and curved models

### 4.2.4 Impact of wing-strut attachment chordwise position

As was anticipated earlier, during sizing, some issues concerning torsional stiffness have been found. This problem was somehow common in literature, due to the reduced wingbox dimensions of SBW. Some studies were computed changing the position of the wing-strut attachment along wing chord, in order to introduce an offset with respect to wing EA, along with a torsional moment that would be accounted for during sizing, possibly helping to increase stiffness. In NeoCASS, being the structure represented as a stick model, the components are automatically connected on EA. However, the offset can be introduced in NeOPT by rigidly translating the strut along fuselage axis. The compared models are summarized in Table 15.

| | Front | EA | Rear |
|---|---|---|---|
| **Material** | CFUD | CFUD | CFUD |
| **Mass configuration** | OEW | OEW | OEW |
| **Strut geometry** | straight | straight | straight |
| **Wing-strut attachment** | on front spar | on EA | on rear spar |

Table 15: Compared models: change of wing-strut attachment chordwise position

**Sizing** Table 16 shows the obtained masses for the different strut chordwise position.

| | Front [kg] | EA [kg] | Rear [kg] |
|---|---|---|---|
| **Half Wing** | 4233.4 | 3946.7 | 3638.2 |
| **Half Strut** | 1307.9 | 1349.9 | 1425.6 |
| **Total Half** | 5541.3 | 5296.6 | 5063.8 |

Table 16: Structural mass comparison between composite front, EA and rear models

The model with strut on front spar is the one with heaviest wing and lightest strut, while the one with strut on rear spar is the opposite.

**Trim** From trim in cruise, for both linear and nonlinear analyses, it resulted that having strut on front spar leads to the smallest wing tip deflection, which is highest for strut on rear spar. However, if trim in dive is computed for model verification purposes, as discussed in Subsection 3.2, an unexpected deformation is obtained for rear spar model: a twisted wing bending downward. This issue could seem to be similar to the one obtained for ONERA model (Figure 3). However, the reason is now different. Indeed, the rear spar model is the one with heaviest strut. If the strut position leads to an attitude that is not sufficient to create enough lift to recover from the jump introduced by strut weight, the tip portion of the wing is loaded with forces that pull it down. Since the verification was not satisfied for this model, it is ignored in the following analyses.

**Divergence and flutter** Strut position does not have any particular effect on flutter, while if strut is on the front spar, it seems to be beneficial for linear divergence, as shown in Table 17.

| | $q_{max}$ [Pa] | Front [Pa] | EA [Pa] |
|---|---|---|---|
| **Point 1** | 31118 | 92721 | 87401 |
| **Point 2** | 31118 | 84617 | 79925 |
| **Point 3** | 25942 | 64539 | 61927 |

Table 17: Comparison of divergence results between composite front and EA models

## 5. Conclusions

An aeroelastic model of SBW has been produced. Some design issues have been found concerning the strut, which, if too flexible, has a negative impact on wing, leading to non-desirable deformations. Since the strut is intended to alleviate wing bending moments, some stiffness is required. Therefore it has been redesigned increasing its geometrical properties. This reasonably led to an increase in weight. Most common aeroelastic analyses have been computed, and, when possible, also accounting for nonlinearities. Some changes have been imposed to the model and their effect on the results have been investigated. Promising outcomes have been reached with composite material for both strut and wing, gaining around 30% of structural mass reduction. Composites also had a positive influence on flutter and divergence. Gust analyses, which were not reported in this document, had not produced any sizing load, meaning that the considered ones are not critical for the studied models. For none of the considered cases flutter was detected. Also divergence was widely outside the flight envelope. However, to have a clearer overview on aeroleasticity of SBW, all the analyses should be extended to nonlinear.

## References

[1] IEA, "Aviation analysis," 2022.

[2] P. D. Bravo-Mosquera, F. M. Catalano, and D. W. Zingg, "Unconventional aircraft for civil aviation: A review of concepts and design methodologies," *Progress in Aerospace Sciences*, vol. 131, p. 100813, 2022.

[3] S. Ricci, N. Paletta, S. Defoort, E. Benard, J. E. Cooper, and P. Barabinot, "U-harward: a cs2 eu funded project aiming at the design of ultra high aspect ratio wings aircraft," in *AIAA Scitech 2022 Forum*, p. 0168, 2022.

[4] G. G. Carrier, G. Arnoult, N. Fabbiane, J.-S. Schotte, C. David, S. Defoort, E. Benard, and M. Delavenne, "Multidisciplinary analysis and design of strut-braced wing concept for medium range aircraft," in *AIAA SCITECH 2022 Forum*, p. 0726, 2022.

[5] L. Cavagna, S. Ricci, and L. Travaglini, "Neocass: an integrated tool for structural sizing, aeroelastic analysis and mdo at conceptual design level," *Progress in Aerospace Sciences*, vol. 47, no. 8, pp. 621–635, 2011.