Multi-fidelity weight analyses for high aspect ratio strut-braced wings preliminary design

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Abstract. In the wake of “flygskam” movement that emerged in Sweden a couple of years ago many voices recently raised denounced the environmental footprint of aviation. Even if the real impact of the sector could appear rather limited the critics reveal the necessity to propose cleaner aircraft to both meet public expectations and environmental goals. Because the classical wing-tube configuration seems to have reached its limits, disruptive designs must be considered. Among the perspectives to reduce emissions, high-aspect ratio wings represent a promising path to be explored within the European CleanSky2 project U-HARWARD. Indeed, substantial diminution of induced drag are expected from those new configurations resulting in fewer fuel consumption. To achieve high-aspect ratio without compromising the structural weight strut can be introduced. They allow for an alleviation of the bending moment at the wing root and therefore lighter structures. However, the consideration of those new wing configuration at early design stages is not straightforward and new methods have to be introduced. In this paper, we present three different fidelity approaches to tackle with (ultra) high-aspect ratio strut-braced wings sizing and weight estimation in preliminary design context. Already existing analytical formulations for the wings are extended, intermediate fidelity aero-structural coupling has been developed and high-fidelity structural representation are considered. Depending on the maturity of the concept these methods could be used to explore the design space, to refine the optimum or to analyse the final concept. Validation with respect to reference configurations is provided. Then the methods are applied to the analysis of strut-braced wings.

1. Introduction

In the wake of protest movements like “flygskam” that emerged in Sweden few years ago, many voices have raised to claim for a greener and more sustainable aviation. Even if the real contribution of aviation to global equivalent CO₂ emissions could appear rather limited and does not exceed 3% of total anthropogenic emissions [1], the critics reveal the necessity to propose cleaner aircraft to meet public expectations and environmental goals. As the classical tube and wing configuration with under-wing engines seems to reach its limits, disruptive designs should be explored. Among those concepts, (ultra) high aspect ratio (UHAR) wings are a promising way toward more efficient aircraft. Because induced drag is inversely proportional to aspect ratio an increase of the latter has substantial impact on the former and on overall aircraft efficiency. But rise of aspect ratio induces an increment in loads, particularly at the wing root. Structural reinforcements are then necessary and the overall weight could be...
detrimentally impacted. Besides, airports regulation imposes span limits. Those two constraints have strongly limited the extension of wing aspect ratio. Gradually weight issue has been pushed back thanks to deeper knowledge in material behaviour and introduction of lighter composite assemblies but the airport regulations remained a hard constraint until very recent years. In 2013 Boeing introduced the 777X equipped with folding wingtips to allow for high aspect ratio wings without violating span limits. As the airport constraint vanishes it is replaced by the one on weight. To avoid prohibitively heavy (ultra) high aspect ratio wings struts can be introduced to alleviate the additional bending moment due to larger spans. This technical solution was successfully used on the Hurel-Dubois HB34 in the 1950s and then fallen into disuse until recently. Indeed, in the last decades academic and industrial research projects have brought up to date strut-braced configurations and highlighted their usefulness to lighten high aspect ratio wings structures [2]. Particularly, NASA and Boeing have been working conjointly on the SUGAR program which focuses on mid-range aircraft and has extended the concept to the Trust-Braced-Wing where juries are introduced to avoid strut buckling [3]. On the European side, the ONERA developed its own strut-braced reference configuration known as Albatros [4]. In this context, the European CleanSky2 project U-HARWARD is aimed at assessing several technological paths for ultra-high aspect ratio wings as strut braced configurations. To assess the influence of strut-brace wing parameters on final design, accurate estimate of the structural weight is necessary from the preliminary design stages to the validation of the concept. Such multi-level methods are already implemented in tools used at ONERA and ISAE-SUPAERO but need to be extended to strut configurations. In this work, analytical models are first derived for wing and strut weight assessment at a very limited cost. An aerostructural process relying on vortex lattice method and beam approximation is implemented into an existing tool for preliminary aircraft design. Finally, higher fidelity finite element models are deployed to calibrate lower fidelity tools and validate the conceptual design.

2. Models for strut-braced wings weight estimation

2.1. Low fidelity analytical models

At the conceptual design phase, many configurations must be explored to gain knowledge on the sensitivity of the problem to the design parameters. That requires fast to evaluate models with sufficient accuracy. For weight estimation of high aspect ratio wings, analytical formulations based on beam and material strength theories have proven to better perform than statistical models with a similar computational cost [5]. These methods have been implemented into the preliminary design tool FAST-OAD [6](jointly developed by ONERA and ISAE-SUPAERO) and tested on a general aviation distributed propulsion concept [7]. Here, the developments are extended to commercial transport aircraft with strut-braced wings. The strut parameters and convention for forces and moment orientation are described in Figure 1.

The wing structure is simplified to an equivalent spar (flange plus web) and skin assembly. Each structural element is supposed to sustain a particular mechanical load and is sized accordingly:

- The spar web supports shear. Its local surface is given by: \( S_{web} = \frac{|F_s(y)|}{\tau_{allow}} \)
- The spar flanges support bending moment and normal force from the strut. Their local surface is given by: \( S_{flange} = \pm \frac{M_s(y)}{h_{box} \sigma_{allow}} - \frac{F_s(y)}{\sigma_{allow}} \cdot h_{box} \cdot c_{box} \).
- The box skins support torsion. Its local surface is given by: \( S_{skin} = \frac{M_s(y) \cdot (c_{box} + h_{box})}{h_{box} \cdot h_{box} \cdot \tau_{allow}} \).
- The strut is assumed to be straight and to sustain only traction (and eventually compression loads, depending on the strut design technological choice). Then its local surface is given by: \( S_{strut} = \frac{F_{strut}}{\sigma_{allow}} \).
The internal wing can also be sized considering buckling due to strut compressive force. An Euler criteria is considered with clamped-free boundary conditions. The box height and chord, $h_{box}$ and $c_{box}$, are defined as in Figure 2 and depend on the local aerodynamic chord and relative thickness. The maximum allowable shear and tensile stress, respectively $\tau_{allow}$ and $\sigma_{allow}$, are material properties.

The spanwise loading is assumed to be elliptical or could be estimated through Vortex Lattice Method (VLM) [9] using AVL [8]. The traction force within the strut in manoeuvre condition is expressed as a portion of the total lift. It is then assumed that the strut can be pre-constrained to meet this traction value. Engine and fuel weights alleviation are not considered so far but could be added for further detailed analyses.

Only static pull-up manoeuvre, with a targeted load factor of 2.5g, is considered in this analysis.

To complete the wing weight computation, empirical formulations are considered for secondary structure and ribs. Particularly, it is assumed that the ribs have a constant thickness of 3 mm and a constant spacing of 0.5 m. Further development to accurately estimate the ribs weight is beyond the scope of this paper but will be considered for future work. For example, to consider local reinforcements due to engine pylons or landing gear bays.

2.2. Intermediate fidelity aerostructural sizing

The methods previously described are very fast to evaluate and well suited for design space exploration. However, they do not take into account the wing deformation due to aerodynamic loading. For low aspect ratio wings this assumption is rather acceptable but as the aspect ratio increases deformations cannot be neglected nor their impact on aerodynamic forces and moments. That is why, to increase the fidelity of the computations for UHAR strut-braced wings, an aerostructural module has been implemented within FAST-OAD.

As for low-fidelity case, VLM is used to assess the aerodynamic forces and moments. The computations are performed for the trimmed aircraft adjusting the angle of attack and tail lift to meet the lift coefficient consistent with the load case under consideration.

The structural model consists in a beam-like representation of the primary structure i.e. wings and struts. The section properties are assessed considering a box like section with stringers on the skin sides. Root, kink and tip wing sections are parametrised according with skins and webs thickness $t_{skin}$ and $t_{web}$, stringers area $A_{stringer}$, and box chord and height $c_{box}$ and $h_{box}$ as illustrated on fig.2.

The wing and strut deformations and internal stresses are computed using Mystran, an opensource version of Nastran Code [10]. The structure is sized so that maximum stress within the structure does not exceed material yield stress.

The same load case as previously exposed is used for aerostructural sizing of (strut-braced) ultra-high aspect ratio wings. Finally, the weight of the structure is evaluated from wing box geometry and material density.
2.3. High-fidelity structural analysis
The models described so far are appealing because of their limited computational cost. However, they may lack precision for more detailed analyses and need to be calibrated. Therefore, an additional level of fidelity has been implemented to complete the tool kit. It relies on more detailed finite element models (FEM) representing the whole primary structure. In this approach, skins, ribs and spars are considered through 2D plate elements while evenly distributed stringers are modelled with 1D bar elements. The model is parametrised so that the thickness of each plate and the area of the stringers can be adjusted.

The fuel weight within the wing can be adjusted. The spanwise distribution ensures consistency with the volume available between two sections (i.e. between two ribs).

An optimisation procedure using Nastran is set up to size the structure. In addition to static load cases considered for low and intermediate fidelity methods, five gust cases are taken into account through equivalent static loading. The structural weight is derived from material volume and density.

A flutter analysis completes the procedure and is performed after the optimisation loop. In case of aeroelastic instability skins and spar thickness is increased to reach stable designs.

3. Models validation
3.1. Validation of analytical approach
The low-fidelity weight estimate approach has been compared to the legacy empirical models and reference data from CeRAS-CRS01 [11]. This aircraft is representative of a short-to-medium range single aisle with a maximum take-off weight (MTOW) of 77 tons.

Figure 3 presents the mass breakdown comparison between legacy and analytical approaches. It reveals that the new model delivers a slightly higher MTOW and operational weight empty (OWE) due to an increase of the airframe weight. However, as per Table 1, both values remain consistent with the reference ones. As expected, the main difference comes from wing weight computation that is almost 5% heavier with the analytical approach. However, it remains an acceptable discrepancy considering the empirical models are calibrated to fit data from CeRAS generation aircraft.

![Figure 3: Mass breakdown comparison between legacy and analytical models.](image)

3.2. Validation of aerostructural coupling
The aerostructural model has been validated considering two different test cases:
Table 1: Aircraft weight estimates.

| Weight (kg) | Legacy | Analytical | Reference |
|-------------|--------|------------|-----------|
| MTOW        | 77006  | 77587      | 77000     |
| OWE         | 42000  | 42485      | 42100     |
| Wing        | 8057   | 8476       | 8097      |

- CeRAS-CSR01 short-to-middle range single aisle reference aircraft [11].
- uCRM long range widebody reference aircraft [12].

For both configurations, the wing has been sized for a positive pull-up manoeuvre at 2.5g and 0ft altitude. For CeRAS the considered flight speed in Mach 0.6 while it is Mach 0.64 for CRM case. Aluminium material is considered with Young’s modulus of 73GPa and allowable stress of 420MPa.

An optimization aimed at minimizing the structural weight is run considering the skin thickness at root, kink and tip as design variables. The maximum stress within the structure is constrained to be less than the material allowable stress.

For CeRAS test case, the computed wing primary structure weight is around 4 tons. If the secondary structure and the ribs weight computed through empirical formulations are added the total weight ends at 8.4 tons. This result is consistent with the 8.0 tons of the reference [11] and with the analytical approach.

For CRM test case, the wing primary structure weight is 23.6 tons that is 1.3% lower than the reference value provided in [12].

Both results demonstrate the reliability of the developed aerostructural approach to approximate wing weight taking into account wing deformations.

4. Strut-braced wings analysis

4.1. Low-fidelity assessment of strut location and force impact on weight

In this section, a high aspect ratio unswept strut-braced wing whose geometric characteristics are summarised in Table 2 is considered. The spanwise location of the junction with the wing is varied from $\eta_{strut} = 0$, that correspond to the cantilever configuration, to $\eta_{strut} = 1.0$. The traction force within the strut ($F_{strut}$) is also changed from 60% of total lift to 160%. The impact of those variations on structural weight is assessed for a 2.5g pull-up manoeuvre at MTOW (77 tons).

| Parameter      | Value |
|----------------|-------|
| Ref. Surface [m²] | 160   |
| Aspect Ratio [-]  | 16    |
| Thickness Ratio [-] | 0.1   |
| Taper Ratio [-]  | 0.3   |
| $h_{strut}$ [m]  | 4     |
| Wing box Ratio [-] | 0.45  |
First, the buckling constraint on the inner wing is not activated. The resulting overall wing weights are presented in Figure 4. It shows a substantial benefits of the strut-braced configurations with junction around 65% of wing span and a traction force within the strut in between 100% and 130% of total lift. For that design, the wing weight can be reduced by almost 50%.

Figure 4: Strut-braced wing overall weight and structural components weights variation with spanwise junction location and traction force without buckling constraint.

It should be remarked that when the strut is attached at the tip and exerts a large traction, the strut-braced configuration becomes unfavourable. For those cases, locally large negative bending moments appear on the outer wing leading to local reinforcements of the flanges and a weight penalty as illustrated in Figure 5 where local flange surfaces are presented for cantilever and an extreme \((F_{strut} = 1.6 \times \text{lift}, \eta_{strut} = 1.0)\) strut-braced configurations.

Adding a buckling constraint on the inner wing, makes the strut-braced wing less favourable. As observed in Figure 6 the wing weight increases rapidly as the strut attachment reaches the most outward locations. As a consequence, the optimal strut location shifts inward between 40% and 45% of wing span and the expected weight saving is reduced to 30%.

4.2. Wing weight optimization
This previous parametric analysis shows potential for wing weight optimization by adjusting strut location and traction force for both buckling constrained and unconstrained situations. The results of the optimisation for the primary structure weight presented in Figure 7a and Figure 7b confirm the points aforementioned:

- The beneficial impact of strut-braced configurations independently on buckling considerations.
- The necessity to move the strut inward to avoid inner wing buckling at the cost of reduced gains.

The optimization also reveals the increasing interest for strut-braced configuration as aspect ratio raises. Particularly, if no buckling is considered the weight reduction varies from around
Figure 6: Strut-braced Wing weight variation with strut location and traction force with buckling constraint.

50% for aspect ratio 10 to more than 75% for aspect ratio 20. When buckling is introduced, the benefit in term of mass remains stable between 40% and 50%. This last aspect raised the question of the relevance of the buckling constraint computation based on Euler’s formulation that seems to introduce a high degree of conservatism. A less conservative criteria has to be formulated based on high-fidelity computations presented above. Particularly, these approaches will allow to refine the design and predict wing and strut buckling behaviours. For example, a preliminary work showed a favourable behaviour of curved strut under -1g manoeuvre condition that avoid collision between wing and buckled strut.

5. Conclusion

This paper describes the multi-level weight estimate strategy implemented at ONERA and ISAE-SUPAERO to assess strut-braced wing weight at preliminary design stage. Analytical approach based on a simplification of the wing structure is shown to provide relevant information and sensitivities while insuring low computational cost. In support, aerostructural sizing is proven to give accurate results while taking into account wing deformation. A low fidelity parametric analysis confirms the interest for strut-braced configurations independently on buckling considerations. Weight savings from 40% to 50% are demonstrated. It also reveals the need to move the strut inward to avoid inner wing box buckling. A weight optimization highlights the increasing benefit of strut-braced wing as aspect ratio increases. Finally, future works will focus on the determination of a less conservative buckling criteria relying on high-fidelity computations completed with considerations about static and dynamic aeroelasticity to refine the design.

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Figure 7: Strut-braced wing weight optimization depending on aspect ratio and buckling consideration.

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