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Overall Preliminary Sizing and Optimization of the Metallic Structures of a PrandtlPlane Civil Transport Aircraft

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Abstract

The paper aims at presenting and summarizing the activities carried out on the structural aspects of a box-wing aircraft, called PrandtlPlane, proposed as a more efficient alternative to present commercial aircraft. The results hereby shown represent the major achievements in preliminary structural design, within the on-going Project PARSIFAL ("Prandtlplane ARchitecture for the Sustainable Improvement of Future AirpLanes"), funded by European Union under the Horizon2020 Program. The paper deals with structural peculiarities of such box-wing aircraft configuration, and presents some methodologies and computational tools, suitable for unconventional aircraft structures, made of metallic materials.

1 Introduction

According to research conducted in the last years by the European Commission (EC) [1] and by industry and academia [2-3], three are the main challenges the Air Transport System will have two deal with in next decades:

(i) the increase of air traffic demand improving flight safety;
(ii) the reduction of noxious emissions and noise (both intended per passenger-kilometres);
(iii) making travellers within Europe able to complete their journey within 4 hours (door-to-door).

Among the possible ways to reach these goals, novel aircraft configurations, conceived to have a higher aerodynamic efficiency, i.e. lift-to-drag ratio, have been proposed. Some of the candidate configurations for future aviation are the ones shown in Figure 1: the Blended Wing Body (BWB), the Truss Braced Wings (TBW) and the Box-Wing (or Joined Wing).

Figure 1: Blended Wing Body (BWB), Truss Braced Wings (TBW) and PrandtlPlane (PrP) concepts

The Box-Wing concept has been studied since early 1990s at University of Pisa, where the attention has been focused on the possible applications in aviation of the so-called *Best Wing System* (BWS) concept, due to L. Prandtl. In [4], he demonstrated the existence, for fixed wingspan and generated lift, of a wing configuration which minimizes the induced drag, with a proper lift distribution. According to Prandtl study, this optimal configuration is a box-wing one. In particular, in [5], a closed-form-solution of the optimal lift distribution has been derived. Starting from that point, studies have been focused on the application, into aeronautical engineering, of the BWS. The aircraft architecture based on the BWS has been then called "PrandtlPlane" (PrP), in Prandtl's honour.

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Although the drag minimization is the main advantage of the PrP concept, other interesting benefits have been found in subsequent studies, for different aircraft categories. In fact, the PrP architecture has a smooth stall behaviour, and the post-stall is characterized by only a partial reduction of manoeuvrability and controllability [6]. Furthermore, from Flight Mechanics point of view, pitch control can be obtained by using counter-rotating elevators (on both front and rear wing), which can introduce a pitching moment without perturbation to the total lift [7]; moreover, the pitch damping is higher than in the case of a wing-tail configuration, with benefits in terms of comfort and safety [8]. In addition, as summarized in [9] and [10], the PrP flexibility makes it a suitable concept for aircraft of very different dimensions and purposes, such as Light Sport Aircraft, ultra large airliners, freighter aircraft [11] or *cryoplanes* [12].

Given such a context, this paper aims at presenting the approach adopted for the structural conceptual design of a PrP civil transport aircraft conceived in the framework of the EU research PARSIFAL Project, funded under the Horizon 2020 program and coordinated by the University of Pisa [13]. Other partners of PARSIFAL Project are TU Delft (Delft, Netherlands), ONERA (Meudon, France), ENSAM (Bordeaux, France), DLR (Hamburg, Germany), and SkyBox Engineering (Pisa, Italy).

PARSIFAL Project aims at demonstrating that the application of the PrP configuration to aircraft with a wingspan limited to 36 m, such as Airbus A320 or Boeing B737, can increase the number of transported passenger of from about 200 to more than 300, keeping the aircraft dimensions compatible with current airport infrastructures typical of point-to-point air traffic. This way, the higher lift-to-drag ratio of the PrP is exploited for the increase of payload capabilities and for the reduction of fuel consumption per passenger. Benefits are addressed to airlines, which can have higher profit margins, to airport management companies, which can increase the number of travellers without changing the airside infrastructures, and to travellers, which can reasonably have access to lower fares a[14].

Concerning the structural design of the PrP object of study in PARSIFAL, the main activities have been devoted to:

(i) the conceptual design of the fuselage, conceived to fulfil the TLARs, with a detailed study concerning the landing gear [16].

(ii) preliminary structural analyses using a lower-fidelity tool based on Finite Element Methods (FEM);

(iii) preliminary optimisation of fuselage structures

(iv) structural sizing and weight estimation.

2 Conceptual design of the fuselage

The solution investigated in PARSIFAL is the application of the PrP configuration to the aircraft category mainly adopted for short-to-medium routes. According to modern data, it consists of single-aisle aircraft with less than 320 passengers, such as competitors Airbus A320 or Boeing B737, with reference to the 2018-2037 global market forecasts of both Airbus [17] and Boeing [18].

Starting from the choice of the fuselage cross-section shape, this section describes the conceptual design of the PrP fuselage which fulfil the Top-Level Aircraft Requirements (TLARs) defined in PARSIFAL ([28]):

- number of passengers between 250 and 320 (high density),
- maximum range covered with maximum number of passengers of 2160 NM (4000 km),
- initial cruise altitude of 36000 ft,
- Mach number in cruise flight greater than or equal to 0.78
- compliance with the ICAO Aerodrome Reference Code “4C”, where:
  - “4” indicates a Take-Off Field Length longer than 1800m;
  - “C” refers to a wingspan limited to 36m and wheel span between 6m and 9m.

In order to carry a higher number of passengers than the short-medium range competitors, maintaining the same overall length, it is not possible to use a single-aisle circular fuselage layout. The fuselage cross-section for this purpose has a resulting shape of a C^1 curve, composed by tangent circular arcs tangent (Figure 2-b). This allows the reduction of the external wetted surface of a two-aisle cabin, with 8 seats abreast in 2-4-2 layout. For the mathematical description

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of the final curve, in [19] is reported a recursive formulation in terms of radius, centre coordinates and arc amplitude for each of the arcs describing the curve.

Considering a high-density scenario, the need to speed up ground operations, i.e. to reduce turnaround times, leads to new solutions for the interior architecture. In particular, the two aisles are wider with respect to the conventional actual economy-class ones. The leading idea of this concept is that a passenger can lay his baggage into the overhead bin without stopping the flow of other passengers (as clearly illustrated in Figure 2 with a comparison with a conventional single-aisle section). The space in the overhead bins is enough to allocate two standard hand-baggage per passenger. The combination of wider aisles and a larger available space for luggage may represent an opportunity for airlines: making passengers to prefer not to embark a cargo baggage can in fact facilitate ground operations, especially if short point-to-point flights are considered.

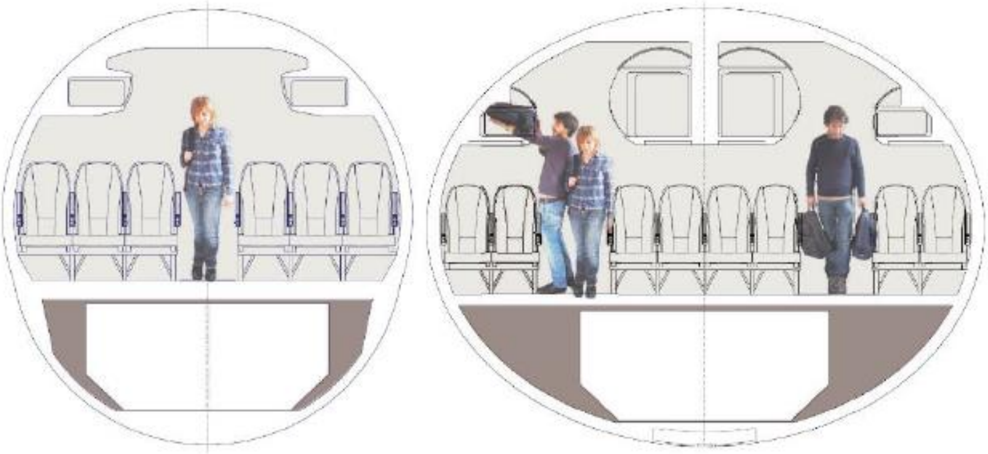

Figure 2: Comparison between conventional single aisle (a) and PARSIFAL layout (b)

The embark/disembark time reduction leads also to the possibility to introduce an extra door in the middle of the fuselage; the increase of the passenger number is supported by three different entrance/exit paths, as highlighted in Figure 3; with this high-density arrangement it is possible to transport 308 passengers. Each door is equipped with autonomous air-stairs, in order to make the aircraft independent of airport infrastructures also in aprons far from the terminal [20]. Technical solutions for air-stairs are currently object of study.

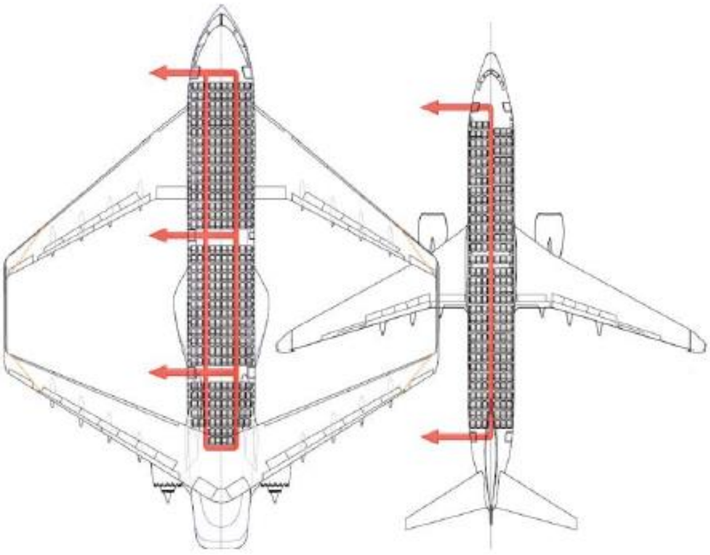

Figure 3: Interior cabin layout and exit paths for conventional and PARSIFAL aircraft

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Nevertheless, such a cross-sectional shape presents many interesting structural challenges, which have been quantified in the preliminary design phase of the project. In particular, two are the main issues due to the pressurization load:

(i) since the shape is no more (quasi-)circular, if compared to conventional aircraft (see Figure 2), the pressurization leads to stress rises, linked to a weight increase, in the correspondence of the shorter axis of the section;

(ii) the effect of the piece-wise continuity of the curvature radius, in the circumferential direction, leads to a weight increase, if compared to a more regular (i.e. perfectly elliptical) solution.

In [19], a general closed form-solution for a circular arc subject to radial and tangential line loads has been derived, considering the infinitesimal beam element depicted in Figure 4-a and the Euler-Bernoulli displacement class.

Starting from the analytic solution, weight increments due to cross-sectional external shape have been estimated by studying the in-plane behaviour of frames under pressurization. In particular, many non-linear constrained optimization problems (NLCPs) have been formulated, in order to catch the main features, trends and possibly leading parameters. Of course, as a general rule, results can be directly compared only if at the same degree of optimum. From a mathematical point of view, the problems can be stated as follows:

$$\begin{gathered}\min_{\boldsymbol{x}} f(\boldsymbol{x};n) \qquad subject\ to \\ g_i \leq 0, \quad i=1,\dots,m \\ \boldsymbol{lb} \leq \boldsymbol{x} \leq \boldsymbol{ub},\end{gathered} \tag{1}$$

where the objective function *f* is defined as the mass of the frame, depending upon the optimization variables, collected in the vector ***x***, and upon the number of arcs *n*; constraints *g* take into account the maximum admissible stress and the maximum admissible displacement. Design variables include the geometry of the frame cross-section, and the centre coordinates and radius for each of the *n* arcs. Components of vector ***x*** are limited from above and below by ***lb*** and ***ub*** vectors. For further details the reader is addressed to ([19], [21]).

With little abuse of definition, let *a* be the minor semi-axis and *b* be the major semi-axis of the resulting cross-section (see Figure 4-b). The (pseudo)-ellipticity ratio is defined as ξ :=*a*/*b*.

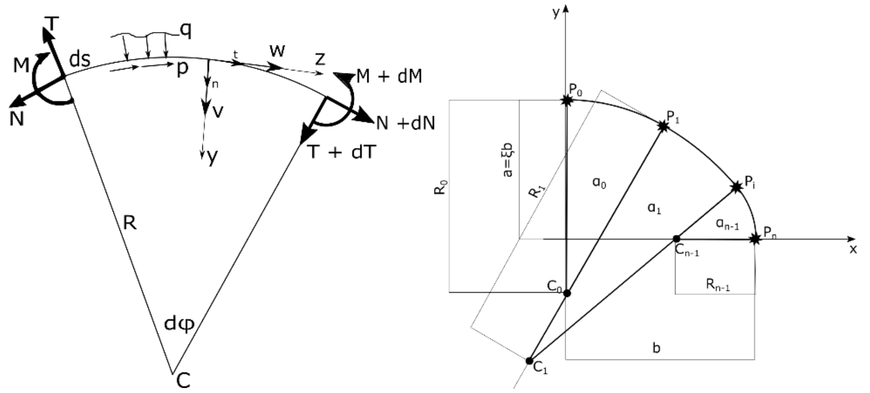

Figure 4: (a) Circular arc subject to radial (*q*) and tangential (*p*) line loads; (b) generic quarter of fuselage frame.

From the preliminary parametrical study of frames composed by *n* arcs (without the presence of floor beams), it has resulted that the leading parameter is the pseudo ellipticity ratio ξ. Optimal points are shown is Figure 5. It can be appreciated that the more the frame is flattened, the more is penalised in terms of mass. Conversely, enlarging the number of arcs of the cross-section, i.e. enlarging the design space, is beneficial, even though there seems to be a saturation of this effect for $n \geq 5$ arcs. Of course, the best solution is represented by the circular frame (independent of *n*), where membrane stress distribution is by far beneficial.

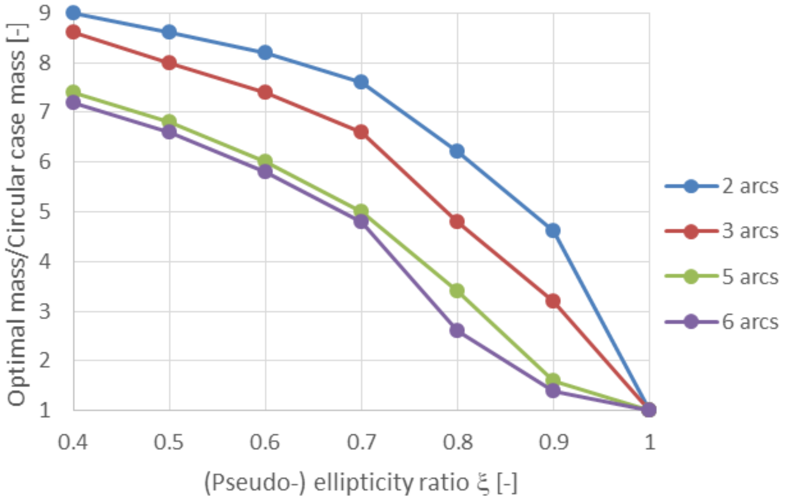

Figure 5: Weight increment for optimal frames with respect to circular case

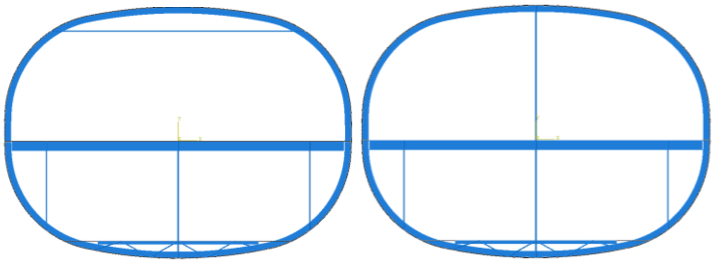

Figure 6: Possible fuselage cross section schemes: solutions with vertical truss (a) and horizontal crossbeam (b)

A new concept for the design of the fuselage cross section also is accomplished by innovative structural solutions; it has been analysed the possibility to connect the upper and lower part of each fuselage frame by means of a vertical truss, made in composite material, which undergoes tension when pressurization loads are applied (Figure 6-a). Another considered solution is to position a stiffening crossbeam in the upper part of the frame (Figure 6-b), or a combination of the two solutions.

The effect of the introduction of vertical and/or horizontal truss has been preliminary studied with a FE in-plane beam model, whose validation is presented in [19], which consider perfectly elliptical frames, in order to isolate the effect of the ellipticity ratio. By modifying the ellipticity parameter of the cross-section ξ, as well as considering the presence or the absence of the truss, FEM optimisations have been performed in order to evaluate the effects of such parameters on the section mass, chosen also in this case as the objective function. It is worth noticing that the fuselage section height has been kept constant: the ellipticity has been varied only modifying fuselage width.

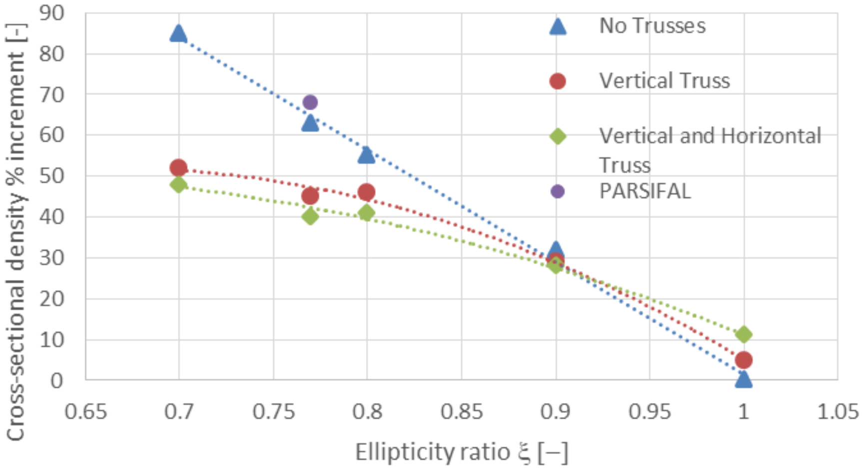

Figure 7: Section ellipticity and truss influence on the variation of section mass/cross-area ratio

Results are reported in Figure 7 where the plotted quantity is a cross-section density, i.e. frame mass over encircled area. In so doing, results are independent from the natural increment in mass simply due to a larger frame perimeter. Considering the circular section without any trusses as the baseline case, it is possible to see that the cross-section density increases significantly with decreasing ellipticity, and that trusses provide an opposite contribution for ellipticity values above 0.9. This fact can be explained by considering that the perturbation trusses introduce in the stress field is greater than the beneficial effects they provide. For the PARSIFAL case, where ξ=0.77, the cross-section density would rise of about 45%, as a result of a 63% increase due to section ellipticity and an 18% reduction introduced by the truss. Further details can be found in [21]. Figure 8 shows the effect of the Von Mises stress due to the presence of trusses. The absence of any disposal gives origin to three zones of stress rise, whilst the introduction of at least one truss flattens almost everywhere the stress distribution, but at the connection upper point. From both Figure 8 and Figure 9 it can be seen the further presence of the horizontal crossbeam is not as efficient as the presence of the vertical truss alone.

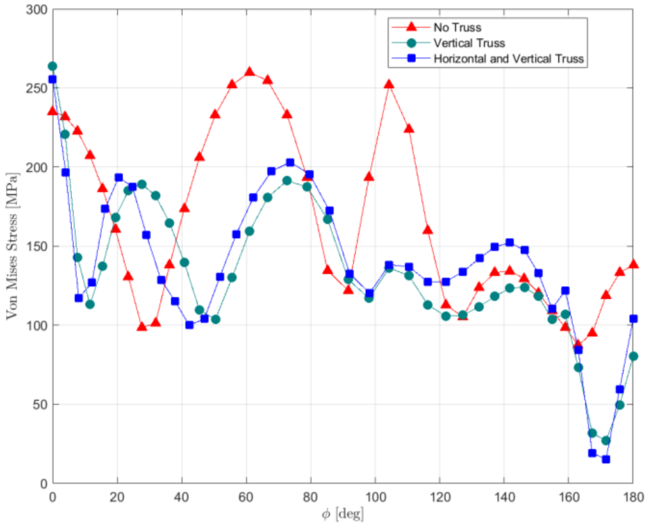

Figure 8: Effect of trusses on Von Mises stress over frame semi-perimeter

Moreover, the effect of considering a piece-wise circular cross-section instead of a perfectly elliptical cross-section, has been quantified with similar models. For the PARSIFAL case, the piece-wise circular solution, as expected, gives a 4% increase in mass for a single frame, as reported in Figure 8. Of course, the adoption of the piece-wise circular shape is due to manufacturability consideration rather than pure structural aspects.

3 Preliminary structural analyses

Preliminary structural analyses have been conducted by means of a software developed at University of Pisa, called WAGNER. Using Python language and Abaqus libraries, WAGNER automatically creates a complete meshed FE model of the aircraft, ready to be submitted for the requested structural analysis.

WAGNER has been deeply developed, debugged and enriched with new features with respect to the previous version already presented in [22]. The generation of the wing system, with ribs and stringers, has been implemented, so that analyses are performed on the complete aircraft model. This feature is quite important, since the PrP configuration presents an over-constrained structure, with regard to the fuselage and lifting system. Therefore, the equilibrium stress and displacement distributions depend on the relative stiffness of the aircraft parts, which must be considered at once. At the same time, the last version of WAGNER can deal with conventional configurations [20], with minor modifications of the input file.

WAGNER input data and parameters are defined in an *.xml* file, having a functional tree structure; by means of Python standard libraries and some in-house routines, the code can read input data and create the model.

The detail level of the FE model includes stringers, frames, ribs, pressurization bulkheads, floor beams and floor struts.

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In 15 minutes, WAGNER creates the meshed model, solves the problem for stresses and displacements fields (linear elastic solution), evaluates quantities of interest, and reports them in an output file.

At the initial stage of the project, the goal is the preliminary sizing of the structure, fulfilling static requirements of strength, under both aerodynamic and pressurization loads. Moreover, WAGNER is useful to predict the total structural weight of the configuration, as well as the coordinates of centre of gravity and the components of inertia tensor. The evaluation of such quantities is in good agreement with the values found by means of the well-known statistical and semi-empirical preliminary aircraft design methodologies available in literature ([23], [24]).

FEM analyses have been carried out under the following reasonable hypotheses:

(i) linear, homogeneous and isotropic elastic materials (light Alloys);

(ii) absence of geometrical non-linearity;

(iii) the non-structural components weights have been estimated using statistical formula from [25]; these additional masses have been included in the structural FE model as fictitious densities assigned properly positioned to zones, so that the resultant mass is conserved and the error on the evaluation of the centre of gravity position is limited;

(iv) engines and landing gears have been considered as points characterized by an equivalent mass and inertia;

(v) inertia relief has been used to simulate the realistic free flight condition;

(vi) aerodynamic load distributions are calculated through the aforementioned Vortex Lattice Method (AVL) and then applied to wings and winglet ribs;

(vii) payload has been modelled as line load, applied to decks floor beams;

(viii) payload contributing to the global configuration inertia has been considered by means of statistical formula about the inertia of the human sit body ([26]);

(ix) doors, windows, rivets and other small components are not modelled by WAGNER; therefore, their contribute is neglected in this preliminary weight evaluations;

(x) only the wing-box of the lifting system is modelled;

(xi) according to [22], geometrical non-linearity tend to reduce stresses and displacements, as the structure results stiffer, therefore FE analyses are performed under linear elastic hypothesis in order to provide conservative results.

The procedure implemented in WAGNER has provided a preliminary sizing of main structural components of fuselage, box-wing system and vertical tail. The structural weight prediction indicate a total weight of about 20% of MTOW, divided as follows:

(i) fuselage structures weight 9.5 %

(ii) box-wing + tail (twin-fin) structures weight 10.5 %

Further interesting results concern the volume of in-wing fuel tanks, which can be calculated by means of WAGNER. Such results show a great availability of space for fuel in both wings. This fact introduces a new feature in the design of an aircraft: the relative repartition of the necessary fuel between the two wings can be used as a design variable in order to control the centre of gravity position in all the flight conditions, and to guarantee a proper margin of stability of the configuration in all the scenarios.

Preliminary runs have shown that, by meaningfully varying the relative fuel repartition in the two wings, while keeping all the other parameters constant, the longitudinal position of CG can move in a range of more than 2 m.

4 Fuselage structures optimisation

Results obtained in the previous section through such in-plane models have been compared to more accurate 3-dimensional FE simulations. From the global FE model of the whole aircraft, generated using WAGNER tool, a six-

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bay barrel fuselage has been considered for preliminary design optimization. The barrel has been extracted from the central zone of the fuselage, in order to avoid the direct effect of wings connections.

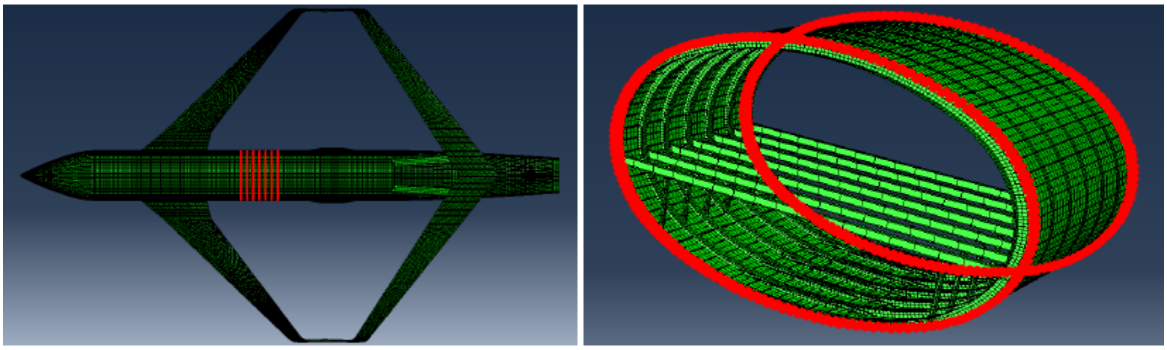

Figure 9: Global model (a) and six-bay fuselage barrel (b)

The mass of the barrel has been set as the objective function to be minimized, whilst constraints include static strength, stiffness and buckling of panels and stringers via classical analytical formula for simply supported plates and beams. Boundary Conditions (BCs) are applied to the first and last frame, as depicted in Figure 10, in terms of displacements from the global model. The considered load condition is ultimate pressurization, equal to 0.0834 MPa.

Since frames cross-section geometry may vary in the optimization loop, the superimposed BCs must take into account for that. If not so, the same displacements may be imposed to very stiff frames (a dramatic stress rise would be expected) or, conversely, to very compliant ones (the stress field would be unrealistically flattened, with enhanced deformations).

Using analytical results, it has turned out that the relative displacement *v* of points lying on the vertical axis of the frame is inversely proportional to the second-order moment of inertia of the frame section. In particular, for six values of the second order moment of inertia *J* normalized with a reference one J_{ref} varying from 10^{-1} to 10, the correlation with the a-dimensional relative displacement v/v_{ref} is depicted in Fig. 11a (*Actual* curve).

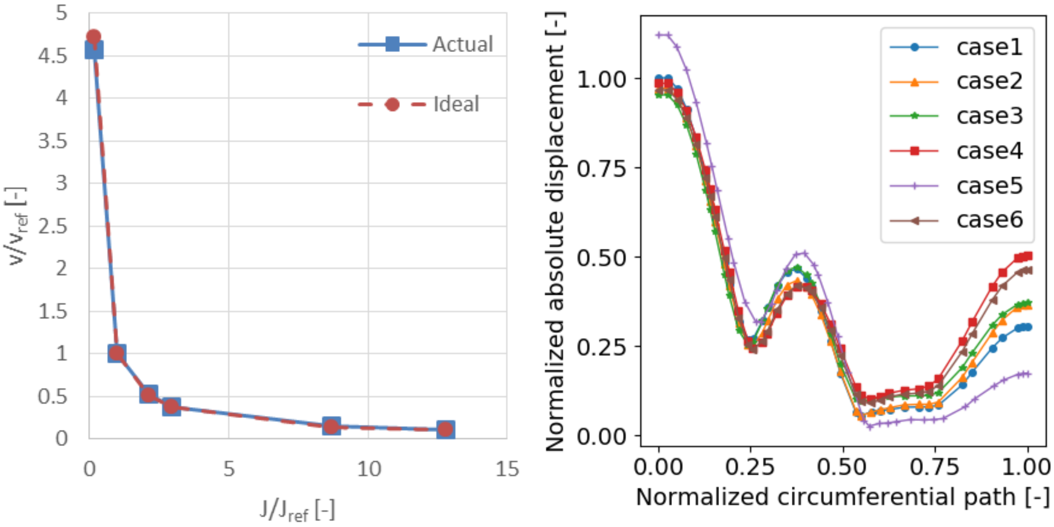

Figure 10: Scaling of displacement over the moment of inertia: relative top and bottom displacement (a), displacement of the frame (circumferential path) (b)

The result can be generalised and extended to the radial displacement of the frame *v*(φ) in circumferential sense. In particular, minimising in the L^2-norm the distance between the six *Actual* and the *Ideal* cases, Eq. (2),

$$\min_x \sum_{i=1}^{6} \left\| 1 - \frac{v_i(\varphi)}{v_{i,ref}(\varphi)} \left(\frac{J}{J_{ref}}\right)^x \right\|^2, \qquad \textbf{(2)}$$

the scaling relationship from *Actual* to *Ideal* has turned out to be

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$$v_i(\varphi) = v_{i,ref}(\varphi)\left(\frac{J_{ref}}{J}\right)^{0.9056}. \tag{3}$$

Hence, as the frame geometry may vary during the optimization loop, the reference BCs are scaled of the factor $\left(\frac{J_{ref}}{J}\right)^{0.9056}$.

The scaled radial displacement of the six considered values of J are reported in Figure 10-b, which shows a good agreement of the proposed scaling, at least for the upper part of the frame.

The optimization campaign investigated frame pitches of 400, 500 and 600 mm; only for the pitch of 600 mm the solution with the vertical truss has been investigated, as well. Results are reported in Figure 11. Apparently, the larger the frame pitch, the lighter the fuselage will be. It is worth noticing that no considerations of durability and fracture mechanics were taken into account for this preliminary investigation. Furthermore, the difference in mass for the trussed case, with respect to the no-truss one, is -15%, in an excellent agreement with data reported in Figure 7 (-18%), for ξ=0.77.

In addition, from Figure 12, it can be observed that the radial displacement of the analytic solution and the radial displacement from WAGNER FE simulations result in a good agreement (the quantity has been measured at the central frame of the barrel).

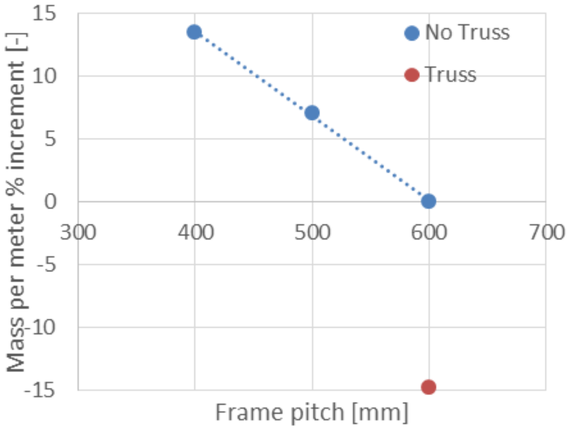

Figure 11: Mass increment of a six-bay fuselage barrel for various frame pitch values

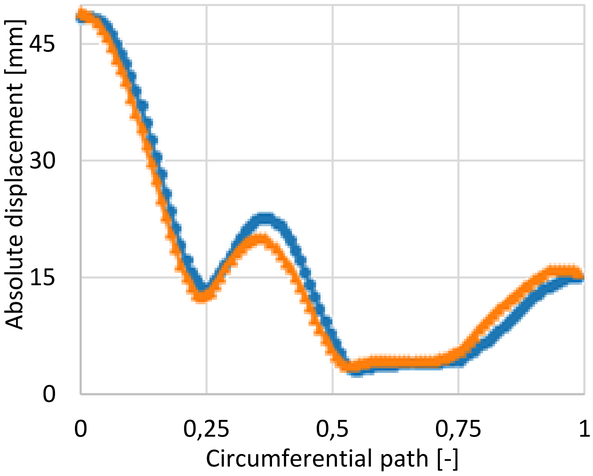

Figure 12: Comparison of radial displacement of frame: analytic 2D solution and WAGNER 3D model

Figure 13 shows an example of FE model and results generated by using WAGNER together with a commercial FEM solver. Remarkable are the stress rises, for the case with no truss, at the central sides of the upper sector, whilst for the vertical trussed case at the connection points (see also Figure 8).

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Even though the central truss may create a lighter fuselage structure, it has been chosen not to include it in the final reference PARSIFAL aircraft design. This decision has been mainly based on the uncertainties due to manufacturability, design of the connections and certification.

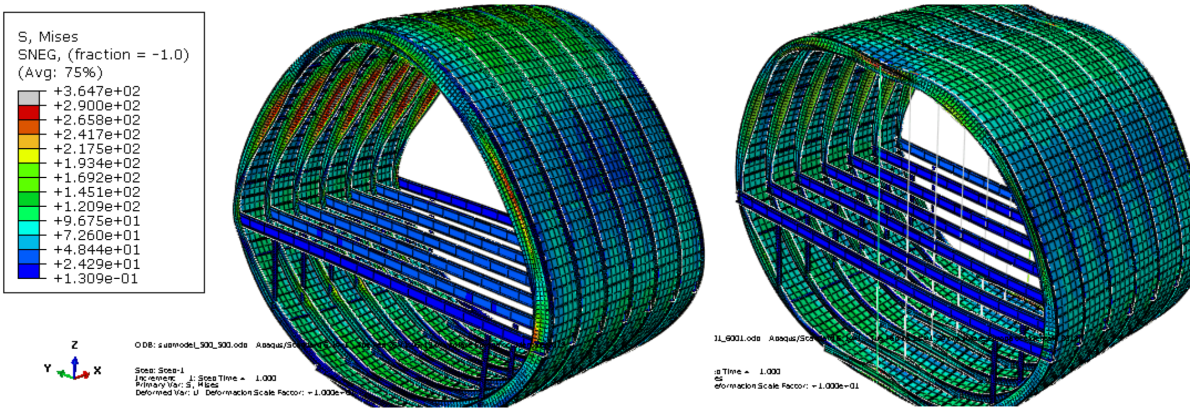

Figure 13: WAGNER particular for six-bay fuselage barrel, with and without vertical truss (magnitude factor x10)

5 Structural sizing and weight estimation

To preliminary size the aircraft, literature data for conventional aircraft, well-known theory results and the cumulated experience at the University of Pisa on the PrP configuration have been used [29]. Starting from this design, knowledge-driven corrections have been introduced, in order to refine the result. In so doing, the final sizing is not an output of rigorous optimisation campaigns, which however remain a mandatory output of the Project. Corrections have been added gradually, as more detailed phenomena had been deepen, as the fuselage barrel optimisation of Section 4, or landing gear-frames connection design [16].

In addition to design hypotheses already outlined in Section 3, the considered loads conditions have been:

(i) Cruise condition with $n_z = 1$ and limit pressurization load = 0.0627 MPa;

(ii) Limit loads condition with $n_z = 2.5$ and limit pressurization load = 0.0627 MPa;

(iii) Ultimate pressurization load = 0.0834 MPa;

while considered design criteria have been:

(i) All components maximum stress must be under the yielding stress of the considered material, in zones which are not affected by connections or other singularities sources;

(ii) Floor beams must carry payload, in all conditions, with a prescribed maximum displacement (i.e. 1/50 of the beam length)

(iii) Floor struts and stringers (fuselage and wing) must not undergo instabilities (Eulerian buckling)

(iv) Wing tip displacement must be less than a prescribed maximum displacement (i.e. 1/15 of the semi-span).

No aero-elastic, durability, nor other instability requirements have been taken into account.

As a result the aforementioned activities, the weight estimation for structural components is reported in Table 1, whilst Figure 14 summarises the MTOW mass breakdown

Table 1 Structural mass breakdown

Component	**Mass [tons]**
Front Wing	7.54
Rear Wing	3.81
Vertical Wing	0.61
Fin	1.07
Fillets	0.25
Total Lifting System	**13.28**
Fuselage Skin + Sponson	4.83
Frames	2.04
Stringers	1.51
Floor Beams and Struts	1.46
Bulk heads	0.66
Total Fuselage	**10.50**
Total Structural Weight	**23.78**

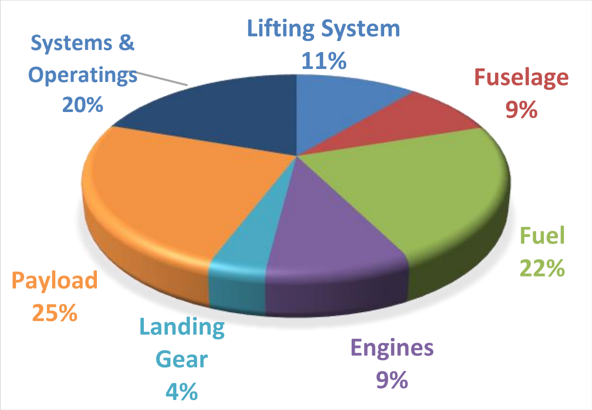

Figure 14: MTOW mass breakdown

Such results have been used to define the PARSIFAL baseline configuration, shown in Figure 15 and object of further optimisation and studies among the project's partners [1].

Design conditions	
N. Passengers (high density)	310
Flight Altitude [m]	11000
Flight Speed [m/s]	233
Cruise Mach	0.79
Aircraft data	
Wing Area (front + rear) [m^2]	267
Wingspan (including winglets) [m]	36
Fuselage Diameter [m]	5.40
Fuselage Length [m]	44
MTOW [tons]	122

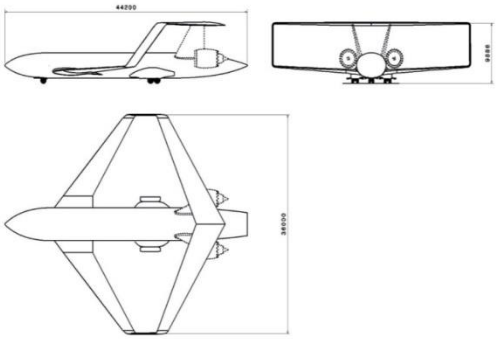

Figure 15: The baseline PrP configuration

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6 Conclusions and perspectives

From structural point of view, efforts have been put on fuselage design, landing gears and the estimation of the overall aircraft mass. The studies on cabin have led to a 8 seats abreast layout, with larger aisles, more room for hand baggage and 3 doors per side, in order to minimize the time required for passenger boarding and debarking.

Preliminary investigation on this innovative fuselage shape have quantified weight penalties due to the piece-wise circular shape and to the ellipticity of the section. In particular, some preliminary tool have been developed, validated via higher fidelity FE simulations. In general, these tools can be adapted to better describe the fuselage behaviour in the preliminary phases of aircraft design, for conventional or non-conventional architectures.

In addition, a code, called WAGNER, has been developed at University of Pisa for the automatic generation of FE models of fuselage and wing structures. FEM analysis have been then used to size structural components and evaluate their weight.

Among the analysed configurations, a reference one has been chosen in order to perform further investigations in next project phase, with more complete and rigorous procedures. Such analyses aim to assess the performance of the PrandtlPlane in terms of fuel consumption, noise emissions, etc. in order to evaluate the expected impact coming from the application of the PrandtlPlane architecture to the selected aircraft category.

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