DEFINITION AND AERO-ELASTIC OPTIMISATION OF THE STRUCTURE OF THE LAPCAT A2 MACH 5 AIRLINER

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Abstract

The high temperatures encountered during flight severely impact the structural design of hypersonic aircraft. They can lead to high thermal stresses and a significant reduction in material strength and stiffness. This reduction in structural rigidity requires innovative structural concepts and a stronger focus on aero-elastic deformations in the design and optimisation of the aircraft structure. A closer coupling of the aerodynamic and structural tools than is currently practiced is therefore needed. The current paper presents how the different sizing, analysis, design, and optimisation tools are coupled in the structural design of the LAPCAT A2 and gives results of the optimisation of a hot structure for the wing. The results indicate that skin buckling is the main driver for the wing structural weight regardless of the number of spars and ribs used. The lightest solution is obtained by a wing structure with 6 spars and 6 ribs with cross-grid stiffeners, weighing in just under 20 tons. Uni-axial stiffened skin concepts result in a much heavier structure.

1 Introduction

Trends in aeronautics clearly show a continuous increase in air traffic across all ranges, including long distance flights such as from Europe to the Asia-Pacific region. Connecting two major cities between those regions results in long-distance flights that easily take up to 16 hours or more [1]. Flights on these routes would become more attractive if the travel time could be reduced drastically. Since the optimum “wing and tube design” is approached with present aircraft and propulsion technology, margins for improvement of the overall vehicle system are getting small. Thus, only drastic changes in aircraft configuration, propulsion concepts and flight velocities can provide a step change. In the "classical" subsonic flight regime new configurations (e.g. blended wing bodies), and new propulsion concepts (e.g. geared turbofans) are explored to improve the aerodynamic and propulsive performance of aircraft. These developments will enable a decrease in fuel consumption of up to 30% but will not lead to reduced travel times. With the exception of Concorde, new aircraft development seems to be stalled with respect to flight speed for the last 4 to 5 decades [1-3]. A step change in flight Mach number is therefore needed to drastically reduce travel times and reach antipodal destinations in 4 hours or. This results in hypersonic speeds.

Hypersonic flights however present several technological challenges that have to be overcome. The LAPCAT (Long-Term Advanced Propulsion Concepts and Technologies) and LAPCAT II programs are set up to design different vehicle concepts and to develop critical technologies and know-how to realise antipodal flights in less than 4 hours [1,4]. At hypersonic speeds, conventional turbojet engines must be replaced by advanced airbreathing propulsion concepts. During the first LAPCAT program, different propulsion cycles and concepts were analysed, comprising both turbine- based and rocket-based combined cycles. Using the developed engine concepts, vehicles were then defined and their aerodynamic performance was optimised for a nominal Brussels to Sydney mission. From the different vehicles studies in LAPCAT I, two were selected for further evaluation in LAPCAT II: one for Mach 5 and one for Mach 8 cruise flights.

The current article presents the initial structural design work for the Mach 5 A2 vehicle as part of LAPCAT II. Structural design of hypersonic aircraft differs significantly from that of classical subsonic aircraft as the structure is subject to very high temperatures in flight. This not only results in severe thermal stresses for the structure, but also reduces both the yield stress and the stiffness of most materials. Due to the reduced material rigidity, particular attention needs to be paid to aero-elastic deformations during the structural design. This demands innovative structural concepts and imposes the need for a closer coupling of the tools used for both the aerodynamic and the structural calculations. The different tools used in the current design phase and their coupling and integration are presented in section 3, after an introduction of the A2 vehicle in section 2. The fourth section of the paper gives the results of the several optimisation analyses that were performed. Results for a varying number of spars and ribs and different wing stiffening concepts are given and the impact of buckling on the wing weight is analysed. Finally conclusions are drawn and future work is outlined.

2 The LAPCAT Mach 5 A2 vehicle

The A2 vehicle was designed by Reaction Engines to fly at Mach 5 using hydrogen-fuelled pre-cooled engines. The proposed configuration is shown in Figure 1. The vehicle consists of a slender fuselage with a low aspect ratio delta wing positioned slightly aft of the mid fuselage section. The vehicle is controlled by an all movable canard in pitch, an all movable fin in yaw, and ailerons in roll. The selected configuration leads to good supersonic and subsonic lift to drag ratios and acceptable low speed handling qualities for takeoff and landing. A leading edge sweep angle of 55 degrees was chosen in order to generate a stable separated vortex at high angle of attack [1]. All aerodynamic surfaces utilise a 3% thickness airfoil. The fuselage diameter was chosen as 7.5 m to trade off a small increase in drag for a saving in fuselage mass [1]. The fuselage is nonetheless much longer than existing aircraft at 139 m. Of that length only 32 m is occupied by the passenger compartment (arranged in two decks). The passenger compartment is located over the wings on the vehicle center of gravity. The liquid hydrogen fuel tanks occupy the remainder of the fuselage volume and are split into two large pressurised tanks on either side of the passenger compartment. Storage of the fuel in the fuselage instead of in the wings allows circular cross section tanks, which minimises insulation and pressure vessel mass.

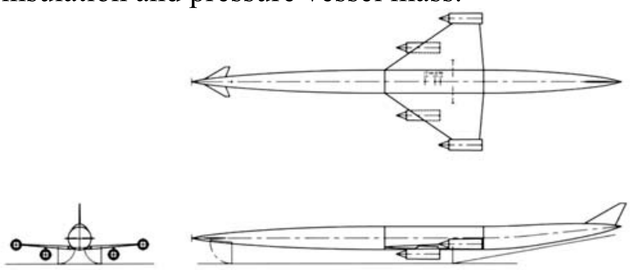

Fig. 1. The LAPCAT A2 Configuration.

The A2 uses 4 precooled turbojet engines, called Scimitar, for its propulsion [5]. The Scimitar engines are mounted in axi-symmetric nacelles on the wing. Two engines are located on the wingtips . The remaining two are installed in inboard nacelles located under and ahead of the wing leading edge. The use of separate nacelles reduces the possibility of a mechanical failure in one engine causing damage to the adjacent engine. It also causes less aerodynamic disturbance when an engine is shut down or unstarts [1]. Carrying the engines on the wing leads to a good matching between the centre of pressure and the centre of gravity and is structurally efficient. Engines of supercruise vehicles are however normally mounted underneath the wing trailing edge to capitalise on shock wave compression. The wing shock wave at Mach 5 is however at an angle of only 8.9 degrees relative to the wing lower surface. To capture the shock wave compression the nacelle would have to be moved so far aft that the intake face would be behind the wing trailing edge, which is structurally impractical [1]. The nacelles are therefore positioned with the intake face ahead of the wing shockwave in relatively free-stream conditions. The inboard nacelles are mounted underneath the wing to reduce wing skin acoustic fatigue damage. The main disadvantage of the inboard nacelle location is that the nacelle cross section is introduced ahead of the wing maximum thickness which is opposite to normal area ruling practice and will increase transonic wave drag [1].

Table 1 summarises the main features of the A2. As shown in the table, he aircraft weighs approximately 400 tons at takeoff of which roughly half is empty weight. The wing area is set at 900 m^2 to ensure subsonic cruise at a reasonable lift coefficient. The Mach 5 phase of the 18700 km design mission takes place between 25 and 28 km.

Table 1. LAPCAT A2 vehicle characteristics.

Characteristic	Value
Maximum Takeoff Weight [ton]	400
Empty Weight [ton]	202
Wing Area [m^2]	900
Wing Span [m]	41
Overall Vehicle Length [m]	139
Design Range [km]	18700
Passengers [--]	300
Cruise Height [km]	25-28

Table 2 shows 3 of the critical load cases used to size the structure. The first 2 load cases represent manoeuvre loads. The third case is a high weight gust load case. Besides those 3 flight cases, additional cases will be considered related to the maximum cabin pressure differential, the maximum hydrogen tank pressure and the 9-g crash loads on the mounting structure of the tanks. The canard structure will be sized for a maximum upload at take-off rotation, whereas the fin will be sized by a twin engine out consideration (at the same side of the fuselage) at Mach 5. The current analysis considers only the Mach 5 load case at 2.5g and -1g.

Table 2. Load Cases.

Altitude [km]	Mach Nr	Weight [ton]	Load Factor
1.2	0.67	396.2	2.5
25.4	5.00	350.8	2.5
5.9	1.11	386.3	2.87

3 Structural Optimisation Set-Up

The aforementioned characteristics of the A2 were determined by Reaction Engines Ltd. during the first LAPCAT project. A verification of the component weight estimates and a detailed sizing and optimization of the structure of the A2 vehicle are performed as part of LAPCAT II. For this structural design and optimisation study several software tools are combined and integrated as shown on Figure 2. In this figure, the green dashed line indicates the preliminary sizing that was performed by Reaction Engines as part of the first LAPCAT project, whereas the red dashed line indicates the current structural analysis, sizing and optimisation. The black arrow represents a possible restart of the design loop with the updated structural weight.

The pressure and temperature loads for the different cases identified in Table 2 are calculated using Argo®, an in-house developed code of Cenaero [6,7]. Argo® is a domain-decomposition-based parallel three-dimensional Navier-Stokes solver on unstructured tetrahedral meshes with implicit time-integrators based on a Newton-Krylow-Schwarz solver. Figure 3 shows a typical pressure load obtained from RANS calculations with Argo® for Mach 5. The temperatures and pressures from the Argo CFD mesh are then translated into the corresponding loads for the FE mesh using MpCCI®, a code-coupling interface. After all, an FE mesh is typically much coarser than the corresponding CFD mesh. Figure 4 shows a zoom on the CFD/FE translation for the nose cone and the canard at Mach 5. The MSC/Nastran® FE mesh is generated in Matlab®. As shown, the skin is

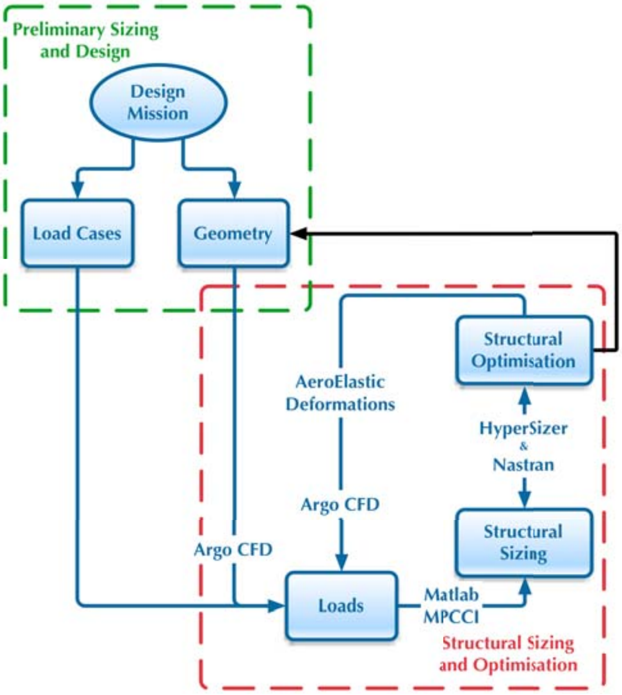

Fig. 2. The Sizing Process Used in the Optimisation of the A2 Structure.

meshed in the FE model to allow for aero-elastic coupling with Argo®. The mesh consists of predominantly quadrangular elements for the fuselage, wing, canard, and fin. The intersections between the meshes for the individual components are however done with triangular elements as this allows more freedom in the definition of the mesh for each individual component while still ensuring that all nodes that are on the intersection between two components are linked to both components.

Once the loads are translated to the FE mesh, the internal structure of each of the components is sized and optimised using MSC/NASTRAN® and HyperSizer®. HyperSizer® is a sizing and optimisation software that can be mathematically coupled with MSC/NASTRAN®. HyperSizer® is able to discretely optimise structures in a manner that guarantees structural integrity of the selected optimum design, using methods to accurately compute margins-of-safety for all potential failure modes (over 100 modes can be analysed for both ultimate and limit load cases [8]). Failure mode analyses vary from traditional closed form methods to modern instability algorithms (such as those used for asymmetric panel buckling). HyperSizer®'s unique panel and beam stiffness formulations using equivalent-plate generalized-stiffness terms achieve accuracy with coarsely meshed finite element models and allow simultaneous optimisation at various levels [8].

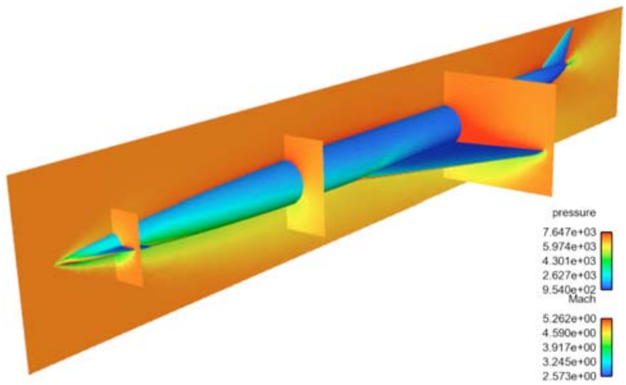

Fig. 3. Mach 5 CFD results from Argo®.

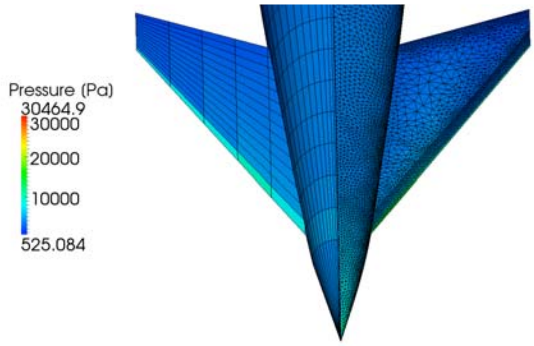

Fig. 4. FE/CFD mesh interpolation.

Because the model does not have to be re-meshed for different panel designs, a rapid optimisation of concept, shape, size, and material selection are possible. Tight coupling with MSC/NASTRAN® allows finite element properties and materials (PSHELL, PBAR, MAT1, and MAT2) to be automatically generated in HyperSizer® and included in the FEA to obtain correct and consistent running loads [8]. Over 40 different panel and beam concepts are provided such as hat and Z stiffened panels, honeycomb sandwiches, and I, Z, T, and C beams. For a hot structure of a hypersonic vehicle, only the spars and ribs of the wing, fin, and canard and the longerons and frames of the fuselage have to be manually changed to analyse different structural concepts. After all they are represented by CBAR elements and can therefore not be smeared out in the skin as is done with stiffeners.

In a final step, the stiffness of the finite element model of the optimised structure is coupled with the Argo® CFD code for aero-elastic calculations. A new methodology is currently implemented in Argo® to deform the CFD mesh while preserving a good quality of the anisotropic cells of the boundary layer near the aero-elastic interface. This will enable Navier-Stokes aero-elastic calculations with a viscous sub-layer instead of Euler aero-elastic calculations as performed in the past [6,7]. The structural optimisation loop using HyperSizer® and Nastran® will then be re-initiated based on the aero-elastic calculations.

4 Structural Design for the A2 Wing

The current section presents the sizing results for the wing of the A2. The first section describes the down-selection of the different structural concepts and materials. After this the numbers of spars and ribs are optimised for titanium, followed by an optimisation of the stiffener concept and spacing. Finally the use of beryllium alloys is assessed.

4.1 Selection of Structural Concepts and Materials

One of the biggest structural challenges of any hypersonic design is the management of the heat load to the structure. For airline-like hypersonic vehicles this is even more crucial than for transatmospheric launch type vehicles as the vehicle structure is subjected to high temperature for a very long period. Whereas the the stagnation temperature at Mach 5 is only around 750 K, the leading edge of the wing, canard, and fin, and the nose of the fuselage will be exposed to that temperatures for up to 4 hours for the A2 design mission. Managing the resulting high heat loads for those long exposure times is critical. Three primary solutions have traditionally been explored for structures of hypersonic vehicles. In a hot structure, the external surface acts as a load-bearing structure and absorbs all the heat. This type of structure has the advantage that it is easy and simple to maintain, but the use of a hot structure leads to high thermal stresses and requires adequate materials to be used [9]. In the so-called cold structures the load bearing and heat absorbing structures are on the other hand decoupled. An external “shield” absorbs the heat, with the internal structure suspended inside it. Insulation is used to protect the load bearing structure from the heat [9]. Cold structures can potentially be lighter than hot structures but the load bearing structure is difficult to access and inspect. Differences in thermal expansion between the hot “shield” and cold structure can furthermore result in integrity issues [9]. Finally, in actively cooled structures, the heat sink potential of the cryogenic liquid hydrogen is exploited to remove the heat by passing the liquid through pipes near the hot areas. Even though this allows the actual load bearing structure to be much lighter [9], this type of structure is not considered for this particular application. The redundancy needed to ensure reliability of the cooling system in case of blockages of the cooling pipes and the additional complexity and manufacturing cost namely make it an unattractive option for airline-like operation. Only hot and cold structures are therefore considered for the A2. The current article presents the initial hot structure solutions.

The high operating temperatures severely limit the material selection for hot structures. The choice of aluminium for the Concorde limited its maximum operational Mach number to 2.2 [10]. Aluminium is therefore not an option as a structural material for the A2. Moreover, with the anticipated long exposure times, the complete structure will end up at elevated temperatures as heat will conduct throughout the entire vehicle. Hence, titanium alloys are considered the primary candidate material at this stage as they can be used effectively for temperatures up to 800K and have, relative to most other metals, a significantly high specific strength. [9]. From a structural perspective beryllium is an interesting alternative candidate. Beryllium has a low density, low elasticity and a high thermal conductivity, which aids in reducing thermal stresses. It also retains both its specific stiffness and specific strength up to elevated temperature, which makes it particularly interesting for the current design. Further to this, beryllium can be machined and worked with relative ease [9]. The toxicity of beryllium oxide however limits its use in practice [9]. It will nonetheless be considered for the A2 to allow a comparison with titanium. The major alternatives to titanium and beryllium alloys are carbon-carbon composites and metal matrix composites. They will be considered in a later stage.

4.2 Optimisation of the Rib and Spar Configuration

Finding the lightest combination of ribs and spars in the wing is pivotal to creating the lightest possible design. For subsonic transport aircraft a two-spar configuration is standard. For supersonic aircraft typically a higher number of spars is used due to the low aspect ratio of the wing. In a first series of analysis the numbers of spars and ribs is therefore varied to find the combination that leads to the lightest solution. Whereas the rib spacing, and to a some extent also the spar spacing, will normally not be uniform, a uniform spacing is maintained for the current analysis to enable a rapid generation of the different concepts. The number of ribs and spars is varied from 3 to 8. Figure 5 shows the resulting wing weights for a varying number of ribs and spars for the 2.5g load case at Mach 5. All analyses were performed with a cross-grid-stiffened skin with Titanium 6242. The results presented here represent a sample of the full matrix of analyses that was executed.

Figure 5 shows the weights for 3 to 7 spars with 6 equally spaced ribs. The figure shows that the lightest solution is obtained for 6 spars. The weight of the beams (spars and ribs) remains fairly constant but the weight of the panels (skin) varies considerably. Figure 6 shows a similar analysis for a varying number of ribs with 6 equally spaced spars. The overall wing weight varies only with around 10% but for an increasing number of ribs, the fraction of the weight from the beams increases considerably. The lightest of all analysed solutions is the 6 spars and 6 ribs combination that weighs in at just under 20 tons. For the majority of the combinations, skin buckling was by far the largest contributor to the skin weight.

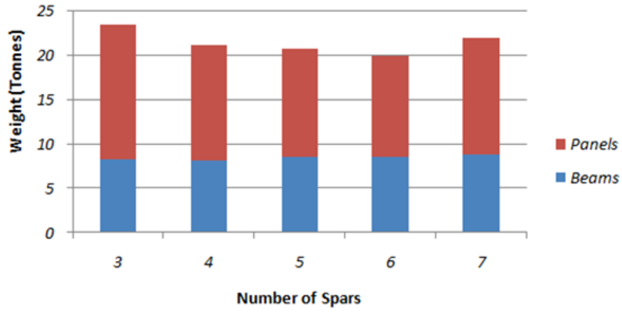

Fig. 5. Wing weight with 6 ribs.

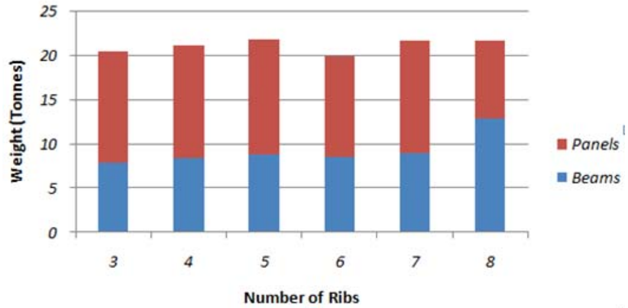

Fig. 6. Wing weight with 6 spars.

When considering both the 2.5 and -1g loads, the trends remain the same but the weight of the lightest solution increased to about 24.5 tons. Figures 7 and 8 show the deflection of the resulting structure for the 2.5g and -1g load case at Mach 5. The figures clearly indicate that for both load cases the rear spars are loaded to higher stress levels due to the torsion of the wing.

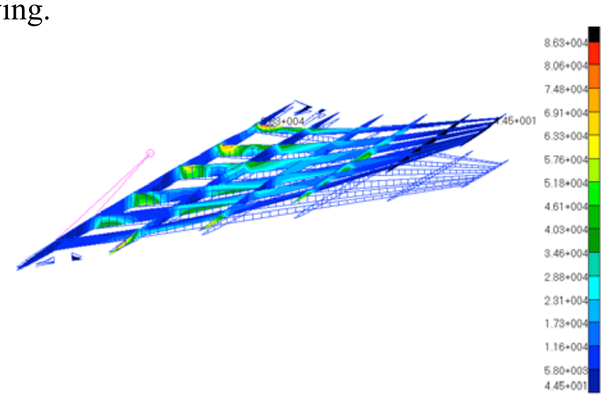

Fig. 6. Wing deflection at 2.5g at Mach 5, colored by stress level.

4.3 Optimisation of the Stiffener Concept and Spacing

As indicated previously, buckling was the primary failure mode for the skin was buckling for all considered combinations of spars and ribs. An in-depth analysis of skin stiffening was

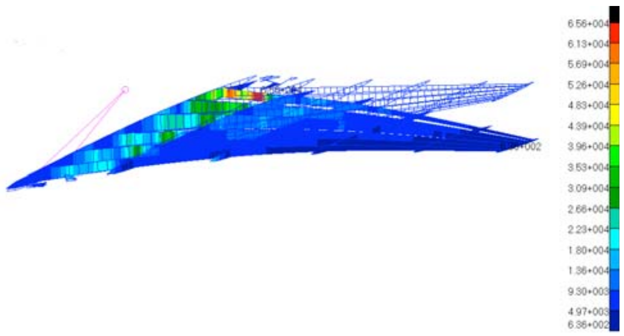

Fig. 6. Wing deflection at -1g at Mach 5, colored by stress level.

therefore performed. As the HyperSizer® approach to define equivalent-plate generalized-stiffness terms allows to analyse several stiffening concepts of the skin, the same model was used for all of these analysis. Several stiffening options are available in HyperSizer®. The skin can either be un-stiffened, stiffened using uniaxial stiffeners, or using a cross-grid of stiffeners. With the cross-grid stiffeners up to 4 directions of stiffeners can be selected. For each of the stiffened concepts, Z, I and T shaped stiffeners were analysed. For each of those analyses the spacing of the stiffeners was optimised initially. The results for the different stiffener concepts at optimum spacing are given in Table 3. In order to check consistency across the range of possible combinations, three different rib/spar combinations were analysed.

Table 3. Weight variation for different stiffening concepts [tons].

	Cross-grid	Uni-axial	Un-stiffened
3 spars & 3 ribs	24.5	106.5	80.3
3 spars & 8 ribs	35.8	137.3	69.3
6 spars & 6 ribs	19.9	92.7	62.4

The results in table 3 clearly show that a significant weight reduction is obtained for cross-grid stiffeners. The un-stiffened and uni-axial stiffened concepts are 100 to 400% heavier than the un-stiffened concept. Across the range of stiffening concepts the combination with 6 spars and 6 ribs is the lightest. The uni-axial stiffener skin is heavier than the un-stiffened skin as the stiffeners run parallel to the fuselage centreline. HyperSizer® increases the stiffener dimensions to the maximum value of the specified range to try to reduce the impact of the buckling constraints which results in a heavier design than the un-stiffened skin where the spars and ribs are beefed up to take care of the extra load.

In a second step, cost considerations were added to the stiffener concepts. First the cross-grid stiffening concept was restricted to only orthogonal stiffeners parallel and perpendicular to the fuselage centerline (instead of 4 different directions for the spacers for the full orthogonal grid). Then a minimum spacing of 150 mm was imposed to limit the total number of stiffeners. Table 4 shows the outcome of this analysis. The table clearly indicates that the sensitivity to the current analysis is an order of magnitude smaller than for the stiffening concept. For the 6 spars and 6 ribs combination weight increases only by 2.6%. When using 3 spars and 3 ribs the orthogonal stiffener concept is however 10% heavier and the 150 mm spacing drives the weight up by 29%.

Table 3. Weight variation for different stiffener spacings [tons].

	Optim.	Ortho	150 mm
3 spars & 3 ribs	24.5	27.0	29.3
6 spars & 6 ribs	19.9	20.4	20.4

4.4 Weight reduction from allowing buckling at limit load

As the previous analysis confirms the importance of buckling on the skin sizing and design, the buckling margin of safety was deactivated for limit load analysis. Allowing the wing skin to buckle lead to a significant reduction of the wing weight as shown in Table 5. In the table, B stands for a case where buckling was allowed at limit load, NB stands for no buckling allowed. For the 6 spars and 6 ribs combination with cross-grid stiffeners the wing weight was reduced by 37%. For the 3 spars and 3 ribs case, a reduction of 10.6% is obtained. Even if the weight reductions for the un-stiffened skin and uni-axial skin are significantly bigger than for the cross-grid

Table 5. Weight reduction when buckling is allowed at limit load [tons].

	3 spars & 3 ribs		6 spars & 6 ribs	
	NB	**B**	**NB**	**B**
Cross-grid	24.5	21.9	19.9	12.6
Uni-axial	106.5	61.3	92.7	57.1
Un-stiffened	80.3	51.1	62.4	53.2

stiffened skin, the latter still remains the lightest concept. For the uni-axial stiffened skin the weight is reduced by approximately 40% for both spar and rib combinations. For the un-stiffened skin, the weight reduces by 36% for the case with 3 ribs and 3 spars. The weight of the 6 ribs and 6 spars combination however only reduces by 15% as the ribs and spars are much closer together. This reduces the buckling length considerably, making the overall structure slightly more buckling resistant. As a consequence, the weight reduction by allowing buckling is a lot smaller for this case.

Whereas the overall wing weight reduces the weight of the spars and ribs actually remains fairly constant for the cross-grid stiffened case as shown in Fig. 7. As the spars and ribs take up loads that are otherwise taken by the stiffeners allowing buckling does not impact their weight considerably. However, the skin (and stiffener) weight is significantly reduced, especially for the configuration with 6 spars and 6 ribs. Indeed, the skin weight for this configuration reduces by 60%.

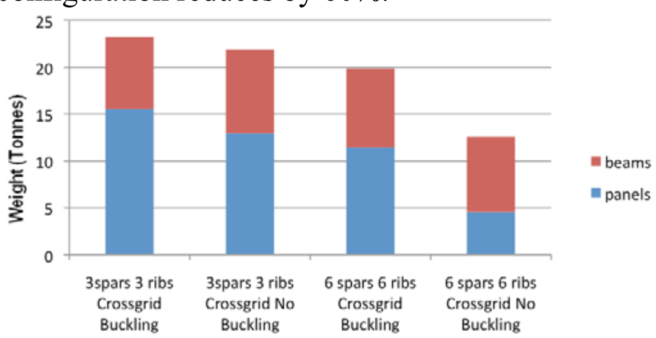

Fig. 7. Influence of buckling on wing weight.

5 Conclusions and Future Work

Hypersonic transport aircraft can potentially reduce flight times of antipodal flight significantly provided several technological challenges can be overcome. Structural design of hypersonic aircraft is severely impacted by the high temperatures encountered during flight as they can lead to high thermal stresses and a significant reduction in material strength and stiffness. This reduction in rigidity of the structure requires innovative structural concepts and a stronger focus on aero-elastic deformations in the design and optimisation of the aircraft structure. This imposes the need for a closer coupling of the aerodynamic and structural tools than is current practice. The current paper presents how the different sizing, analysis, design and optimisation tools are coupled in the design of the structure for the A2 vehicle during LAPCAT II and gives results of the optimisation of a hot structure for the wing. The results indicate that skin buckling is the main driver for the wing structural weight regardless of the number of spars and ribs used. A wing structure with 6 spars and 6 ribs with cross-grid stiffeners leads to the lightest solution, weighing in just under 20 tons for the 2.5 g manoeuvre load at Mach 5. Uni-axially stiffened and un-stiffened skin concepts are considerably heavier. As shown allowing buckling could lead to considerable weight savings, and so does the use of beryllium alloys instead of titanium alloys. In a next step a non-uniform spacing of the ribs and spars will be analysed and extra materials will be considered for all of the identified critical load cases. The full aero-elastic cycle will be closed by coupling the CFD and FE codes through a traveling boundary layer CFD mesh.

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