

Air Cargo Challenge 2019

Stuttgart

REPORT

Team 01



The Beauty...



**UNIVERSITY
OF UDINE**



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List of Symbols:

A	Brake pads area [m ²]	L	Lift [N]
A_R	Aspect ratio [-]	L_{tt}	Tip-tube distance [m]
A_T	Horizontal stabilizer surface [m ²]	L_c	Control surface average length [m]
a_T, b_T	Experimentally derived constants [-]	M	Bending moment [Nm]
A_W	Wing surface [m ²]	M_{brake}	Braking moment [Nm]
b	Distance, along the y-axis, between the aerodynamic centres of wing and horizontal stabilizer [m]	SM	Static margin [-]
C	Battery capacity [mAh]	m	Airplane weight [kg]
c_c	Control surface average chord [m]	P	Braking power [W]
$C_{D,0}$	Fuselage drag coefficient of resistance [-]	P_p	Payload prediction [kg]
$C_{D,2D}$	2D profile drag coefficient [-]	R_e	External brake disc radius [m]
C_D^{tot}	3D airplane drag coefficient [-]	R_i	Internal brake disc radius [m]
$C_{L,2D}$	2D profile lift coefficient [-]	R_{wheel}	Wheel radius [m]
C_L^{tot}	3D airplane lift coefficient [-]	S	Distance required to stop the aircraft [m]
$C_{L,\alpha}^T$	First derivative for the lift coefficient of the tail [-]	S_W	Wingspan [m]
$C_{L,\alpha}^W$	First derivative of the lift coefficient for the wing [-]	T	Traction [N]
c_w	Mean chord value [m]	t_s	Time to stop the airplane [s]
D	Drag [N]	v	Airplane speed [m/s]
E	Energy required to brake [J]	V_f	fibre volume/total volume [-]
e	Oswald's factor, assumed equal to 0.8 [-]	V_m	matrix volume/total volume [-]
E_1	Young's modulus in the direction of the fibers [MPa]	x_{cg}	Distance of the centre of gravity from the leading edge [m]
E_2	Young's modulus in the direction orthogonal to the fibers [MPa]	x_{pn}	Distance of the neutral point from the leading edge [m]
E_f	Young's modulus of the fibers [MPa]	y_{pn}	Distance, along the y-axis, of the neutral point from the wing aerodynamic centre [m]
E_m	Young's modulus of the matrix [MPa]	α	Max control surface deflection [deg]
F	Force [N]	α_w	Wing angle of attack [deg]
F_{brake}	Braking force [N]	δ_y	Angle between two different reference system [deg]
I	Current absorbed by the engine [A]	Δt	Total flight time [s]
k_ε	Derivative coefficient of wing downwash deflection [-]	ε	Wing downwash deflection [deg]
		ρ	Air density [kg/m ³]
		μ	Friction factor between wheels and asphalt [-]



1. INTRODUCTION

At the University of Udine, the participation at competitions like Air cargo Challenge (ACC) is a well established opportunity for the students of engineering courses. Despite the original handicap of not having an aeronautical engineering course (all AeroUD team members are and have been mechanical engineering or electronics students) AeroUD teams always succeeded in the past competitions, ranking in high positions, missing the podium for a few points in the last two editions.

In October 2017 a new team was founded, composed largely by new people that joined the group and, thanks to the economic support given by our University, it was decided to take part in the 2019 edition of ACC. The work that led to the actual model that will be flying in Stuttgart, which has been named “Gabriele”, is the result of a development and optimization process of the previous airplane used in ACC2017, the “DCA”.

The improvements cover mostly aerodynamic and structural design, in an attempt to increase the performances of the plane and lighten its structure. In particular, the team has focused his efforts on the design of its own airfoil, optimizing the FX 60-100 airfoil to have better performances in terms of maximum flight speed. Concerning the aerodynamic design, the wing plant was also optimized to reduce the induced drag effects. On the other hand, CAE tools have been largely used to model and test new structures for the wing.

Moreover, since bonus points are granted for landing in a 60 meters span, in the last months a mechanical brake system has also been developed.

The following sections provide an overview about the most relevant issues of the project.

2. PROJECT MENAGEMENT

2.1 Financial budget

At the start of the project the budget made available by the University of Udine was 15.000 euros. Based on the experience of the team that took part in the 2017 edition of Air Cargo Challenge, and after having decided with them that the way forward was to use composite materials, a rough assessment of the development expenses was made. Since “Gabriele” was born after the knowledge gained in ACC2017, a first slice of the budget was allocated for the construction of a prototype, called DP8, which inherited most of its components from the DCA except for the wing that had a different airfoil. Another consistent amount of budget was used to create a new prototype for Gabriele which included the use of new materials, to fit the different internal structure of the wing. An even bigger sum of money went into the construction of the plane that will take part in the race. In addition to this, a considerable amount of resources was used to cover all sorts of “general expenses” like the wooden moulds made to fabricate the wings, the electronic components, the payment for the registration fees and the trip to Stuttgart.

A detailed report of the expenses is given in Tab. 1.

DP8 construction materials	€	400
DP8 electronics	€	200
Tensil tests on composite materials	€	300
Mold manufacture	€	1.800
Prototype construction materials (carbon/glass fabric, PVC foam sheets, Epoxy resin, plywood, ...)	€	700
Prototype electronics and propulsion system (servos, cables e plugs, battery, ...)	€	600
Gabriele construction materials (new carbon fabric, glass fabric, PVC foam sheets, Epoxy resin, plywood, ...)	€	1.500
Gabriele electronics and propulsion system (servos, cables e plugs, battery, motor, propellers, ...)	€	600
Carbon tubes	€	2.000
Application fee	€	2.450
Uniforms	€	1.000
Travel costs	€	2.000
TOTAL	€	13.550

Table 1: Financial budget.

2.2 Time schedule

The first months of AeroUD – The Beauty project were dedicated to the development of the DCA plane. First of all the team worked on the construction of the DP8 prototype, with the same features of DCA, except for the airfoil, which was the one used by one of the teams from the University of Munich that took part in ACC2017 and that made available its airfoil geometry. After several flight tests this project was abandoned, because of its performances both in terms of lift and maximum speed and also for the complexity associated with the accurate manufacturing of a multi body wing. However this months were useful to improve the knowledge of the new team members in terms of aerodynamics, composite materials, structural design and construction techniques.

After the construction of DP8 plane, the team has been divided into three working groups:

- Aerodynamic design: that worked on the optimization of a new airfoil and on the design of the wing;
- Structural design: that developed and tested a new internal structure of the wing;
- Electronics and propulsion system: that tested the performance of the new propeller.

A detailed view of project timing is provided in Fig. 1.

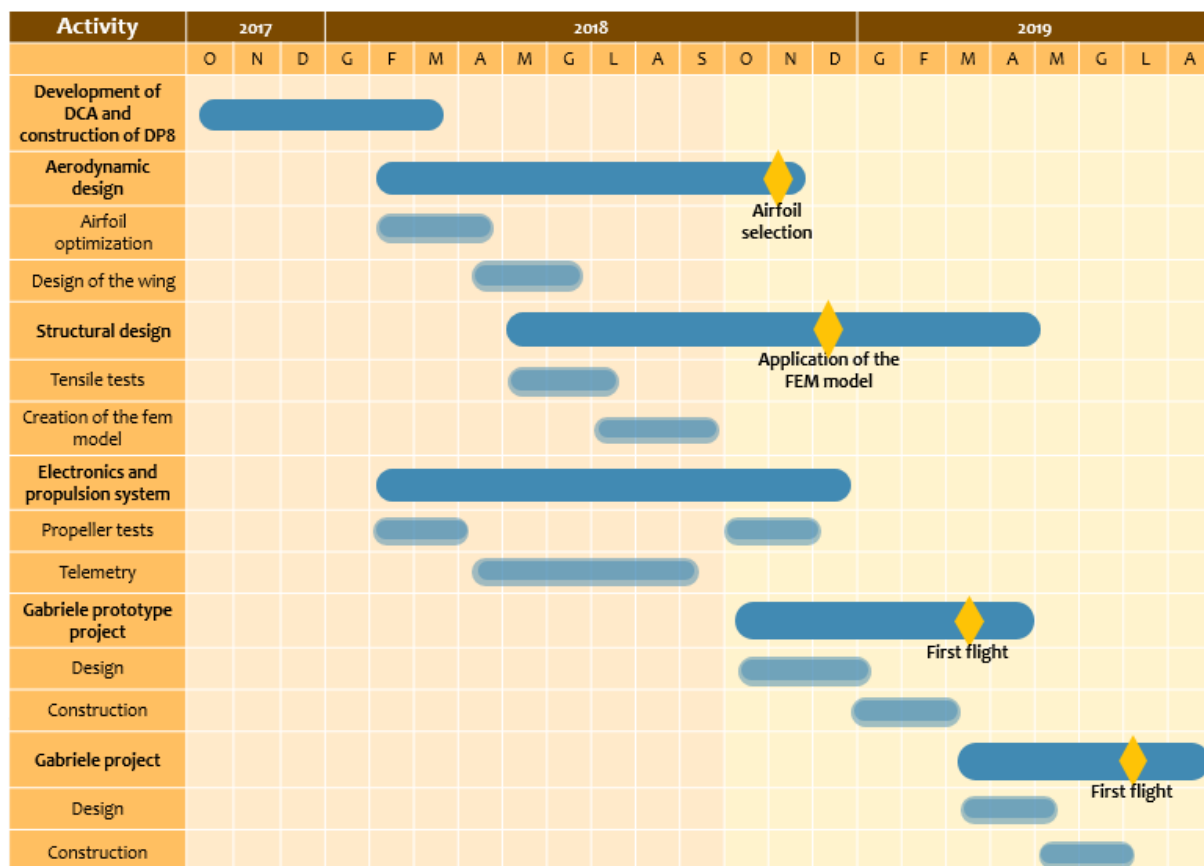


Figure 1: Time schedule.



3. AERODYNAMIC DESIGN

As a starting point for the Gabriele project, a critical analysis was carried out on the previous AeroUD design, the DCA. The goal was to understand why the model didn't perform sufficiently well to gain the podium, in particular by comparing our old design with those of the other three better performing teams.

Going into details, the DCA plane showed an inherent limit concerning maximum speed, although the chosen airfoil gave good lift performances. Similarly, we found out that the rectangular wing plant of the DCA plane, alongside its too low aspect ratio were not a good choice. Because of this design, the induced drag effects caused bad performances in terms of maximum speed.

The new Gabriele Project 2019 aimed to improve the aerodynamic performances of DCA, both with a more conscious choice of the airfoil, to optimize the 2D polars, and with a better wing design. The Selig S1223 airfoil chosen for the DCA project turned out not to be the best for the competition goals because of its too high drag values.

Further elements guiding our aerodynamic development were the results of the propeller traction tests (see section 3.1). The available traction of the new propeller is about the same as the old one, at least about the flight speed we would like to reach with the new design.

The idea was therefore to proceed with the development of the new plane with about the same wing area of the DCA, but with much lower drag, so that the airplane should be able to fly faster, overcoming the unavoidable loss of lift coefficient associated with the choice of a less loaded profile.

In terms of architecture and general lay-out, the new airplane will have:

- monoplane architecture;
- high wing;
- trapezoidal planform with elliptical transition towards the wingtips;
- tractor propeller configuration;
- tricycle landing gear;
- T-tail configuration with rectangular and trapezoidal plant for the vertical and horizontal stabilizer, respectively.

A monoplane architecture was chosen because is the simplest possible configuration, that can guarantee better efficiency than other ones, also to simplify the design and construction processes.

High wing and tractor propeller configurations were selected because of their intrinsic higher stability. The landing gear layout allows great manoeuvrability.

Thanks to the T-tail configuration the horizontal stabilizer is kept well out of the wing and fuselage wakes, resulting in improved pitch control and aerodynamic performances.

Another fundamental issue concerns the position of the payload with respect to the wing. Stability considerations would probably suggest putting the payload in a lower position (detached from the wing) but on the contrary, a higher payload position (i.e. closer to the wing pressure surface) allows for a better overall manoeuvrability especially when the airplane rolls. Furthermore, by implementing this solution we were able to reduce the frontal area.

The ESC and the batteries are placed in a pod located closer to the electric motor in order to reduce the length of the power cables as much as possible.

3.1 Propeller test

Some early traction measurements had already been carried out in the previous edition of ACC with the APC 13x7 propeller. The traction measurements were repeated with the Aeronaut Cam Carbon light prop 12x7 propeller set by the new ACC 2019 regulations.

All these tests have been performed through an appropriate testbench already available at the University's Laboratory, see Fig. 2.

On the test bench, the propeller traction is measured by mounting the engine at the free end of a cantilever beam. The small bending of the beam due to the action of the propeller is measured by means of strain gauges fixed on the clamped side of the beam. The deformation is associated to the applied force (i.e. propeller traction) by means of calibration. The data have been acquired simulating different flight speeds by placing the system in front of the exit of and open loop wind tunnel. Data have been acquired by powering the engine controller at the fixed voltage of 12V. The results are shown in Fig. 3.

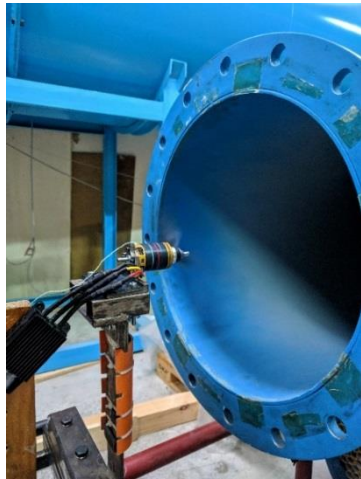


Figure 2: Propeller test bench.

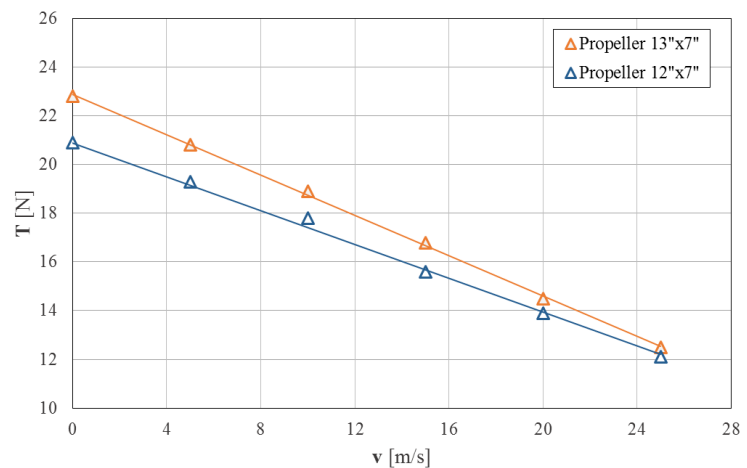


Figure 3: Propeller test results.

3.2 Airfoil optimization

The first aspect of the aerodynamic optimization has been the study and the development of a better airfoil, with higher performances for the competition goals. The first choice has been a less loaded airfoil (with respect to the Selig S1223), the Wortmann FX 60-100. However from a bidimensional analysis, it was found that its lift performances were lower than the ones required to reach the desired target score. So, using the XFLR5 software and its airfoil design tool, the airfoil's geometry has been modified in order to obtain higher lift, with good performances also in terms of low drag.

The procedure followed to determine the best airfoil has been:

- definition of the 3D correlations for drag and lift coefficient;
- determination of a simplified score function to optimize;
- identification of the geometrical parameters to increase the score, the rate of variations and range;
- generation of a population of new airfoils;
- identification of the best airfoil.

This procedure was carried out on the wing planform of the DCA, which would have been later optimized with the new airfoil.

The drag and lift coefficients used in this study take into account 3D effects:

$$C_D^{tot} = C_{D,0} + C_{D,2D} + \frac{C_L^{tot}}{\pi A_R e} \quad (3.1)$$

$$C_L^{tot} = \frac{C_{L,2D}}{1 + \frac{C_{L,2D}}{\pi A_R e}} \quad (3.2)$$

where

$$A_R = \frac{S_W^2}{A_W} \quad (3.3)$$

The area value used is the DCA one, as it is for the aspect ratio. To choose the best airfoil, a comparison of the obtained polars has been performed for an angle of attack of 0 deg. The airflow speed has been calculated from the equation obtained for the thrust of the propeller at a voltage of 12 V by linearizing the propeller performance of Fig. 3:

$$T = a_T v + b_T \quad (3.4)$$

In horizontal flight, the relationship between traction and drag is:

$$T = D = \frac{1}{2} \rho C_D^{tot} v^2 A_W \quad (3.5)$$

it can be used to compute the flight velocity and, successively, the lift value given by the airfoil:

$$L = \frac{1}{2} \rho C_L^{tot} v^2 A_W \quad (3.6)$$

To calculate the score not the entire formula has been studied, but all the considerations that have been made are related to the function:

$$Score = L v \quad (3.7)$$

which has the same trend of the score function.

Because of the team members' lack of knowledge about aerodynamic design, a thorough literature review has been necessary to understand how to modify the airfoil to obtain the desired performances (S. Hoerner, Fluid Dynamic Lift, 1992). In particular, it was necessary to understand how and how much airfoil thickness should be varied, along with camber

curvature and positioning of the camber maximum displacement. The effects of these three parameters in function of the score were independently analysed.

As an example, Figs. 4 and 5 report the variation of the profile geometry and of the polar curves with the airfoil camber curvature. The polar data, as said, have been computed for the 2D airfoil by means of XFLR5 and the 3D effects are successively added with the simplified correlations of above.

The score function can be then computed and compared for the different geometries. Fig. 6 provides an insight how the score varies with the only variation of the camber curvature.

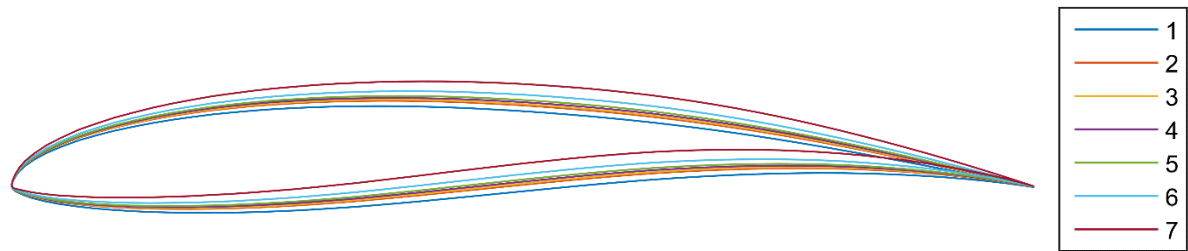


Figure 4: Variation of the airfoil's geometry with the camber curvature.

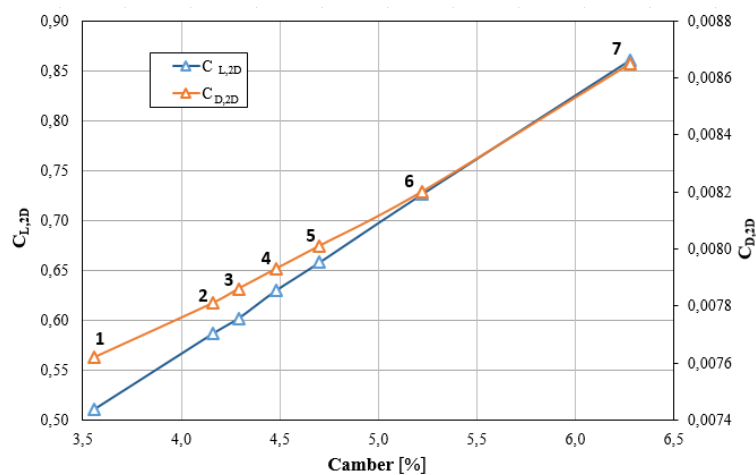


Figure 5: Variation of the lift and drag coefficients as a function of camber for the seven airfoils of Fig. 4. Data at Reynolds=300000.

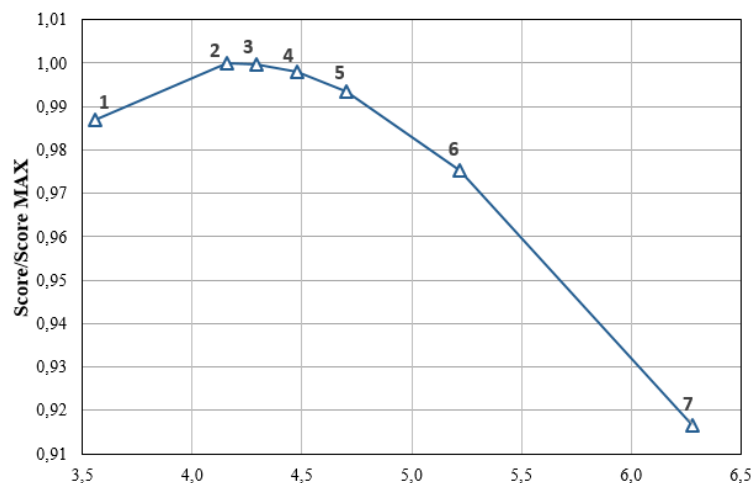


Figure 6: Variation of the dimensionless score as a function of camber for the seven airfoils of Fig. 4.

Thanks to this simplified investigation, it was possible to define the ranges of variation for the three geometrical parameters in question. In particular the range chosen for the thickness is 9,99 – 15,5, about the value of thickness for maximum lift ($\approx 12\%$) proposed by Hoerner.

The camber curvature varies within the range 3,5% - 4,5% of the chord, while the position of the maximum camber displacement varies between 50% and 70% of the chord.

An automatic drawing tool was used to generate the full population of airfoils that have been successively simulated by XFLR5 at a fixed Reynolds number value. The top ten geometries were identified (see Fig. 7 and Tab. 2) and a next step of simulations was carried out taking into account 3D effects and actual variations of the Reynolds number. About this latter point, an iterative procedure is needed to define the flight speed, i.e. the Reynolds number at which the airfoil simulation has to be performed. The score has been finally computed as a function of the ten configurations, and its trend is provided in Fig. 8. Therefore, the configuration we chose is the fifth one.

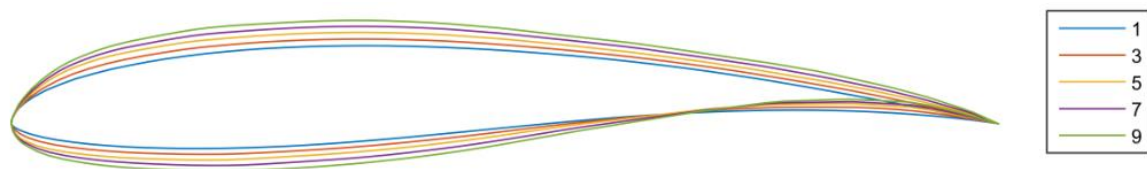


Figure 7: Five of ten configurations generated to optimize the airfoil.

Configuration	1	2	3	4	5	6	7	8	9	10
Thickness [mm]	9,99	10,60	11,20	11,80	12,40	13,00	13,60	14,20	14,80	15,40
Camber [%]	3,56	3,64	3,72	3,80	3,88	3,96	4,04	4,12	4,20	4,28
Position of camber maximum [%]	56,56	58,58	58,59	60,61	62,63	63,64	65,06	66,48	67,90	69,32

Table 2: Configurations generated to optimize the airfoil.

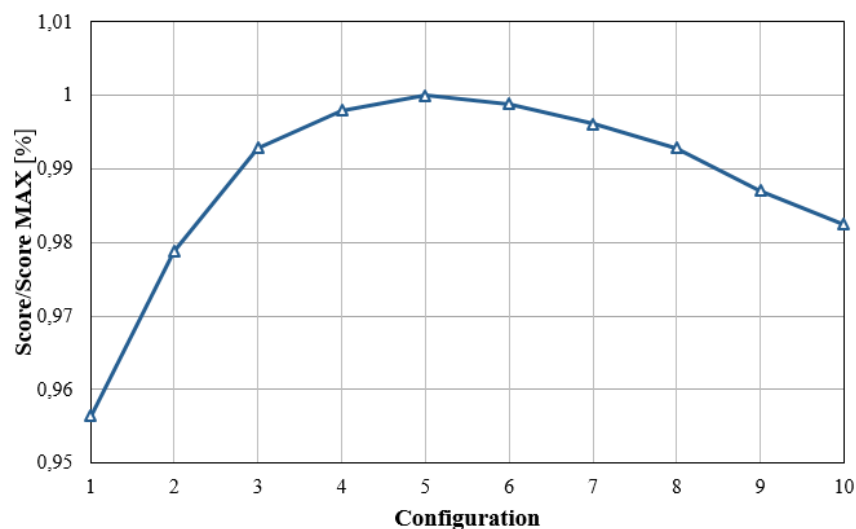


Figure 8: Dimensionless score as a function of the configurations of Tab. 2.

3.3 Design of the wing

The design of the wing follows the results obtained for the new airfoil, and aims to improve the performances of the DCA wing, carrying the same payload but reaching a higher speed. Starting from the value of root chord that is kept the same as the DCA one, the aerodynamic design aims to reduce the induced drag effects decreasing the chord value in the central sections, while choosing for the tips an elliptical variation for the leading edge and a linear one for the trailing edge, allowing an easier installation of the flaps. The purpose was the optimization of the lift distribution, since an elliptical shape allows to enhance the performances of the entire wing.

The new span has been chosen after the maximum dimensions set by the rules for the transportation box, and considering the structural problems created by a bigger spanwise during the static test before the race. At the same time, the aspect ratio has been increased and optimized. Fig. 9 shows the final planform of the Gabriele wing, divided into the five sections.

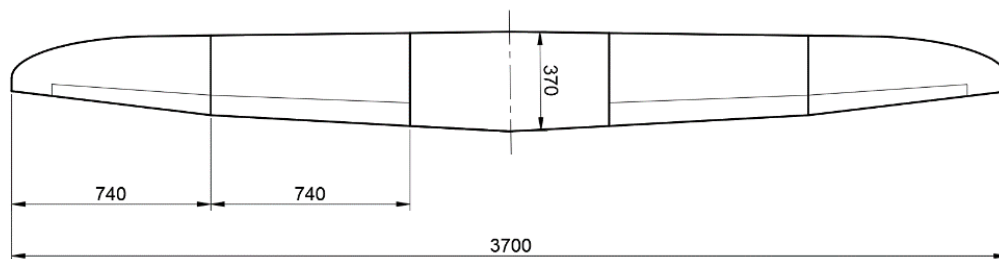


Figure 9: Wing planform in [mm].

3.4 Tail design

The new tail represents the development of the DCA's tail, and its design comes from the experience gained by the team in the previous tests with the old aircraft. On the DCA plane, thanks to the many flights and to the stability studies done with XFLR5, it was found that the area of the tail was oversized, creating excessive drag which reduced the maximum speed. To improve this feature, the tail of the new plane is smaller. The main characteristics of the tail are:

- T-shaped tail;
- rectangular planform of the vertical stabilizer (0.07 m^2);
- trapezoidal planform of the horizontal stabilizer (0.14 m^2);
- symmetric NACA0009 airfoil for both horizontal and vertical stabilizers.

In order to facilitate the tail's construction, the vertical stabilizer chord was chosen to be equal to the horizontal stabilizer root chord. Based on the DCA experience, the resulting rudder area was judged sufficient to ensure yaw control.

The tail boom has been designed with an angle of 5° , to reach the maximum pitch angle during take-off, without touching the ground.

Once the geometries of both wing and tail had been defined, the last parameters that had to be determined were the angle of incidence, the location of the horizontal stabilizer, and the location of the centre of gravity of the payload. The evaluation of these parameters was based on static stability considerations and two approaches were used to perform the stability analysis of the model: the first exploited the results given by XFLR5 and the second one was based on

the results of a previously in-house developed Matlab® routine. The development of an algorithm to perform the stability analysis was useful to reduce the computational time during the design process, where several configurations had to be evaluated. In this way a rough model was used in order to limit the number of configurations that in a second phase would be computed with the XFLR5 software.

The main assumptions at the bases of the developed model are:

- 2D model;
- airplane centre of gravity located on the y-axis (see Fig. 10);
- turbulence and transition are not considered;
- linear evolution of the lift and momentum pitching coefficients;
- 3D effects evaluated with corrections already explained;
- negligible momentum generated by the tail drag.

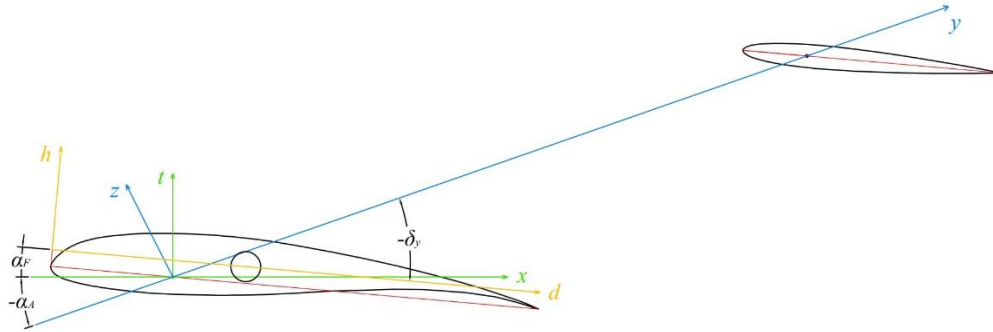


Figure 10: Reference systems used for stability analysis.

Once the aerodynamic centres had been determined, the following reference systems were defined:

- airplane reference system: the y-axis, with its origin in the aerodynamic centre of the wing, is defined by the line which connects that point to the aerodynamic centre of the horizontal stabilizer, while the z-axis is orthogonal to it and points upwards;
- wind reference system: the x-axis has its origin in the aerodynamic centre of the wing and direction parallel to the flow, while the t-axis is orthogonal to it;
- body reference system: the axis d is the line that passes through the centre of the boom tail, while the h-axis is orthogonal to it and passes through the leading edge of the airfoil.

The T-tail configuration requested an improvement of the previous Matlab® routine, since that version assumed that α_A was small and therefore many simplifications could be made. By making the appropriate corrections to the previously developed theory, it was possible to obtain the following formula:

$$y_{pn} = \frac{(1 - k_\varepsilon) C_{L,\alpha}^T A_T}{C_{L,\alpha}^W A_W + (1 - k_\varepsilon) C_{L,\alpha}^T A_T} b \quad (3.8)$$

where k_ε is defined as

$$k_\varepsilon = \frac{d\varepsilon}{d\alpha_w} \quad (3.9)$$

The main difficulty using this formula is to correctly determine the coefficient k_ε which required an experimentally derived formula to be defined. The simulated results in straight flying conditions have been later compared with the ones from flight tests: these data were collected by measuring the air speed with a Pitot tube and by looking at the angle of incidence of the horizontal stabilizer during actual flight.

The common parameter that is used for the evaluation of static stability is static margin defined below:

$$SM = \frac{x_{pn} - x_{cg}}{c_w} \quad (3.10)$$

where

$$x_{pn} = y_{pn} \cos \delta_y \quad (3.11)$$

In order to have as little downforce as possible on the horizontal stabilizer and, therefore to maximize payload, the centre of gravity should be near the centre of pressure of the wing. On the other hand, as the centre of gravity is closer to the wing's pressure centre the static margin decreases. To regain static margin, the tail boom could be extended, but this would require a heavier structure, making it difficult to get an acceptable rotating angle during take-off, which however should be less severe in this design thanks to the 5 deg. inclination of the tail boom. It is clear that the parameters we are looking for are related. Matlab[®] and XFLR5 were used to find the best trade-off among the following parameters:

- center of gravity position;
- distance between the leading edge of the wing and the leading edge of the horizontal stabilizer;
- horizontal stabilizer angle of incidence;
- static margin.

Finally, the configuration selected (Fig. 11) is characterised by a distance of 1270 mm between the two leading edges (wing and horizontal stabilizer), a horizontal stabilizer at zero incidence, and with the possibility to vary the payload position in order to guarantee a minimum value of the static margin of about 10% (control and manoeuvrability considerations).

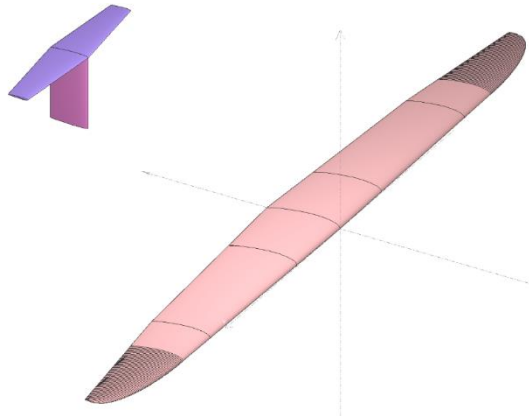


Figure 11: Final configuration of the aerodynamic bodies of the new Gabriele model.

4. STRUCTURAL DESIGN

4.1 Wing structure

The DCA was designed with a variable section carbon tube that runs internally through the entire wing plan to ensure the necessary structural support for the airplane in flight and during the static test.

For the ACC2019 we decided to improve our project by investing our effort in the development of a new solution that moves the structural support from the tubes to the wing skin. The new structural solution ensures easier wing stiffness management and a significant overall weight reduction.

The expected load from the dynamics of flight include two main moments applied to the wing, a bending moment and a torque. The torque is supported exclusively by the skin of the wing, by a bi-directional carbon layer placed with its fibres at an angle of ± 45 deg. with respect to the longitudinal direction of the wing. The bending moment, the most critical, is supported by unidirectional 35 mm carbon strips placed along the entire length of the wing at 25% of the chord from the leading edge on both suction and pressure sides. Coupling between the facing strips on the two wing surfaces is made by means of a vertical slab of composite sandwich. In the following paragraphs, the design and verification of this structure is described.

4.2 FEM modelling

The design of the new structure was tested and modelled through an assisted design program. We created a simplified model that allows the simulation of the entire wing, subject to a static bending and torsion. The study developed in three different steps described in the following.

Step 1: Mechanical properties of composite materials

The design is completely based on the mechanical behaviour of composite materials, so tensile tests were performed on glass fibre and carbon fibre samples, Fig. 12. Tests have been performed according to the standard ASTM 3039/D-3039/M-00 and on a number of samples large enough to ensure a statistical significance of the results.

In addition to the experimental data, the elasticity modulus in the longitudinal and transverse directions with respect to the fibres can be estimated through the Rule Of Mixtures (ROM), which represents a weighted average of the characteristics of the composite:

$$E_1 = E_f \cdot V_f + E_m \cdot V_m \quad (4.1)$$

$$\frac{1}{E_2} = \frac{V_m}{E_m} + \frac{V_f}{E_f} \quad (4.2)$$

- E_1 : Young's modulus in the direction of the fibres
- E_2 : Young's modulus in the direction orthogonal to the fibers
- V_f : fibre volume/total volume
- V_m : matrix volume/total volume

Table 3 shows the average values for measurements and estimates for longitudinal modulus and ultimate tensile strength.



Figure 12: Carbon fibre specimen subjected to a tensile test.

Material	Glass fibre		Carbon fibre	
	Experimental	Estimate	Experimental	Estimate
E_1 [MPa]	12115,36	18793	81165,16	85173
σ_{max} [MPa]	261,82	-	918,49	-

Table 3: Properties of composite materials.

The data obtained experimentally are in line with the classical values provided by the producers of fibre composites regarding elasticity and tensile strenght. The use of Rule of Mixture can be considered useful for a rough estimate of the properties of the unidirectional ones. Conversely for fiberglass fabric, the stiffness values have an error of 50% which makes them unreliable. The experimental data were obviously taken as reference for the structural design.

Step 2: verification of the FEM model

For validation purposes, the FEM model has been applied to a reduced wing section, for which a prototype has also been manufactured and tested. We made use of the moulds of the DCA plane that were available from the former team, so it was possible to build a wing section one meter long and with the following structure:

- 1) Glass fabric biaxial, weight 49 g/m²
- 2) PVC foam (Airex)
- 3) Unidirectional carbon fabric, weight 125 g/m², width 35 mm
- 4) Glass fabric biaxial, weight 49 g/m²

A lamination process is shown in Fig. 13, where the carbon strips are clearly visible. The prototype was tested for both bending and torque moment to verify the quality of the prediction of the finite element model. For the bending test, Fig.14-left, the specimen was supported at both ends and a concentrated load was applied at the centre. For torque tests, Fig. 14-right, the

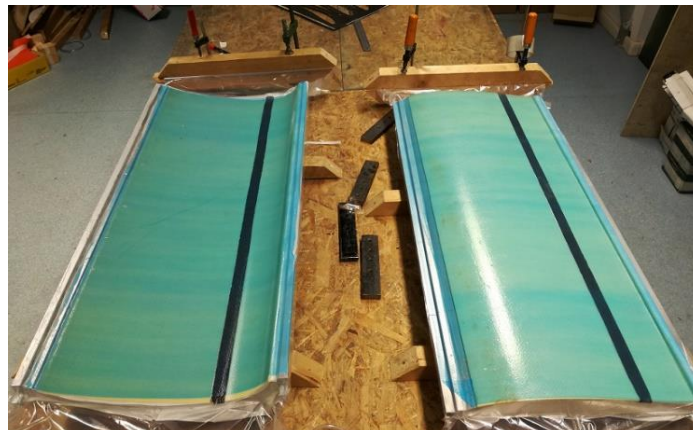


Figure 13: Vacuum lamination of the wing section for validation.



Figure 14: Test bench for deflection (left) and torsion (right) measurements of the wing structure.

wing section was clamped at one end, while a torque was applied to the free end by means of a cantilever.

In both cases, wing displacement was measured by means of a centesimal dial gauge.

The same geometry has been modelled with the same FEM approach that would be used for the new wing. Shell elements were used to generate a mapped mesh, the number of elements were determined through a sensitivity analysis. Bending tests were simulated exploiting the condition of symmetry for both geometry and loads. Therefore, interlocking constraints were placed in the central section of the wing, while a vertical force, equal to half the supported load, acted on the apex of the tip. Torsional tests were carried out on the entire geometry with interlocking constraints only at one end.

The results of the finite element model are absolutely in line with the experimental measurements. Fig. 15-left shows the stiffness values obtained from the FEM model and from experimental measurements. The average measured value is 773 Nm^2 while the value obtained from simulations is 769 Nm^2 : confirming the quality of the model given the error of 0.5%. In the same figure, on the right, the comparison is also made in terms of applied torque and angular displacement, the accuracy of the numerical data can be appreciated.

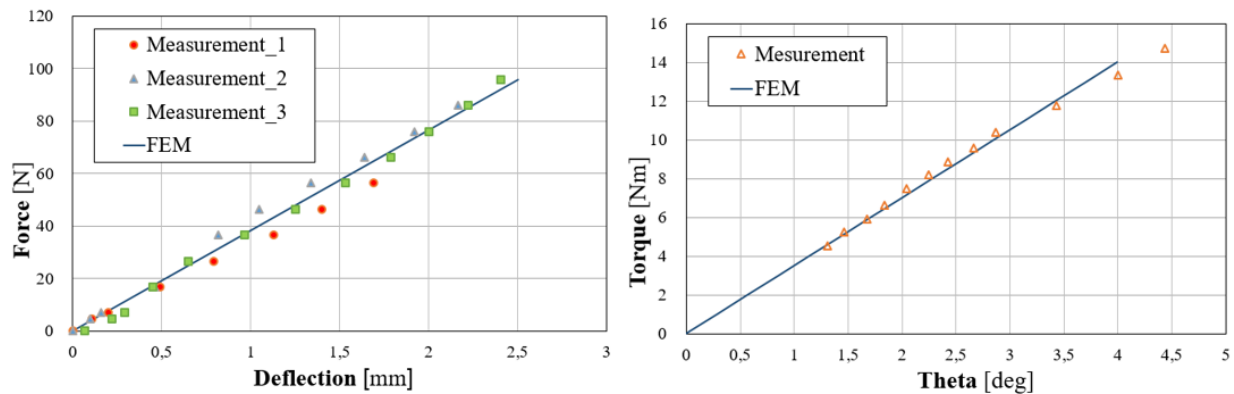


Figure 15: Comparison of experimental results against FEM predictions: for applied bending (left) and for applied torque (right).

Step 3: Application of the FEM model to the new wing

The simplifications present in the model mainly concern the geometry of the wing: the real geometry is characterized by tapering that runs along the entire profile. The simplified model is characterized by a wing planform with a constant medium chord, calculated as a weighted average between the different sections. The model is therefore an extruded profile along the entire length of the wing. As previously said, given the condition of symmetry at the centre of the wing, interlocking constraints were placed there, while a vertical force was placed at the apex of the tip equal to half the load supported by the aircraft. This loading condition does not reflect the one that occurs in flight but is more severe. Indeed, it simulates the pre-flight static test where a bending moment is applied to the entire wing by means of a concentrated load (i.e. the weight of the airframe and payload). The nodes belonging to the last section of the wing have been made integral to simulate a rib of ends to avoid a local deformation due to forcing.

The design was made with the idea of keeping maximum constant tension between the various sections of the wing, Fig. 16. This objective was achieved with a decreasing number of carbon strips starting from the centre of the wing towards the outside. It was not possible to obtain a constant maximum tension on all three sections of the wing because the number of carbon strips must obviously be an integer. With the use of a decreasing number of carbon strips we optimized the used material.

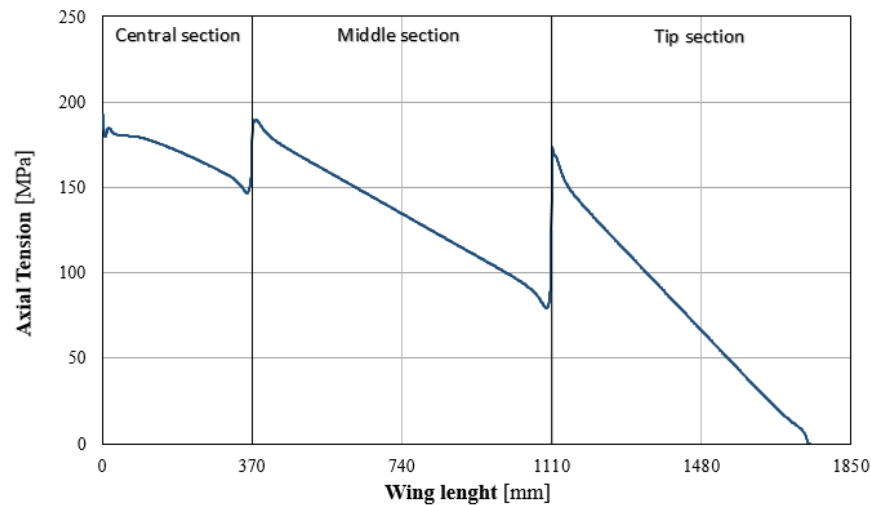


Figure 16: Tension distribution on carbon strips from the centre of the wing with 16 kg.

From the first data on the maximum tension on the wing skin we observed that the criticality of the structure was not the yielding or breaking of the fibres, but the rigidity of the structure. Therefore, the number and distribution of carbon strips were redefined by imposing a maximum acceptable deformation, Fig. 17. This goal was achieved by using a variable number of strips: 4, 8, and 10 for the tip, intermediate and root sections, respectively. The resulting structure doesn't only respect a maximum displacement criterion but also a condition of tension distribution as uniform as possible along the wing span. The results obtained from the simulations on stiffness are comparable to the old aircraft supported by carbon tubes. The safety coefficients that distinguish the unidirectional carbon reach at least a value of 2. Reaching lower safety coefficients would have been risky given that the production process of the composite sandwich is handmade and, consequently, some parameters can be out of our control.

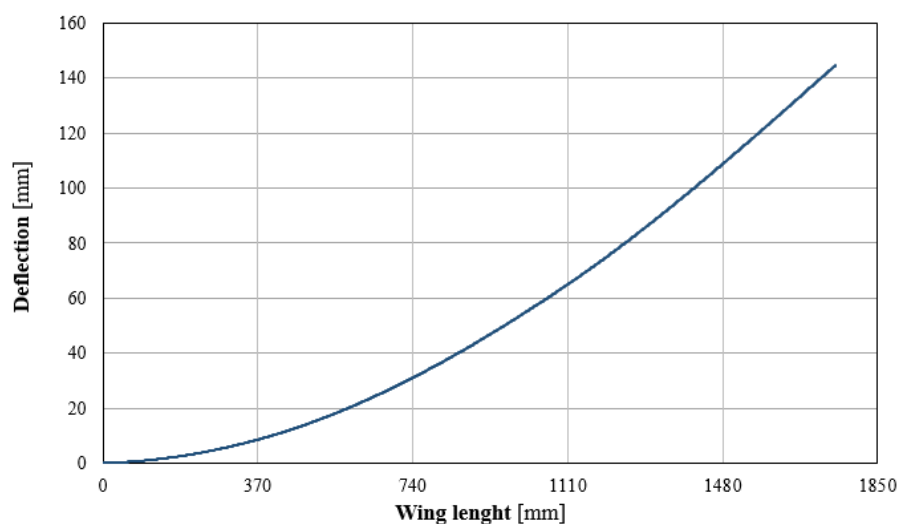


Figure 17: Strain trend on half wing with 16 kg.

4.3 Wing junction sizing

In the wing sections female carbon tubes 90 mm long are embedded and grafted with other carbon tubes to create the connection. The size of the tubes is a function of the distance of the connection from the centre of the wing. The analytical model is formed by a beam resting on two hinges and a downward directed force is applied to the centre, Fig. 18. The bending moment developed on the wing has a linear trend inversely proportional to its distance from the centre of the wing. The tubes have been sized to withstand the bending moment only. They are supplied by an external company and manufactured according to our specification in terms of external diameter and ultimate tensile strength. The safety factor in the most severe loading configuration of the wing is at least 2.

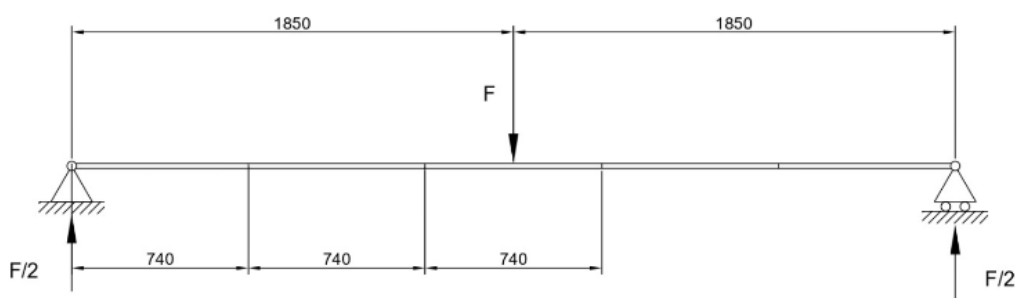


Figure 18: Wing spar static load test.

4.4 Prototype realization

The wing was made with composite materials through a lamination process:

- 1) Carbowave biaxial Carbon NCF, fibre orientation ± 45 deg, weight 55 g/m^2 ;
- 2) PVC foam (Airex);
- 3) Unidirectional carbon fibres, 125 g/m^2 , 35 mm in width;
- 4) PVC foam placed over the carbon strip (only for the central section of the wing);
- 5) Glass fabric biaxial, weight 25 g/m^2 .

The unidirectional carbon strips are laminated together with the wing skin, both on the pressure side and on the suction side. The union of the two skins, suction side and pressure side, takes place with epoxy resin with the addition of hollow glass spheres to make the resin denser. In the internal structure, ribs have been added to support and position the carbon tubes needed to couple the wing sections. Coupling between the two wing surfaces is made by means of a vertical slab glued on top of the facing carbon strips. This feature is placed on site when the two skins are joined together and is made of a sandwich of glass fibres and PVC foam.

The lamination was carried out on top of the MDF moulds which were painted to increase their impermeability.

Lamination is divided into five main phases:

1. cutting of carbon fabrics, glass fabrics and PVC foam, preparation of the suction system and bags to generate the vacuum;
2. the moulds were treated with one coat of clean and glaze, three coats of wax, one coat of PVA primer and one coat of PVA. This treatment is necessary to obtain a detaching surface above the mould which allows to detach the laminate without consequences for the mould;

3. the fabrics were spread on the mould in order and one at a time were impregnated with epoxy resin;
4. a micro-perforated sheet, useful for removing excess resin, is placed on the laminate and the mould is closed inside a bag and attached to a vacuum pump. The mould is attached to clamps to preserve its shape and prevent its deformation caused by heat released by the resin polymerisation process;
5. after 10 hours of vacuum, the bag is opened and the laminate is left to rest for another 24 hours to be sure that the resin has finished reacting and has hardened.
6. the leading edge, the trailing edge and the side sections are trimmed. The complete open wingspan is visible in Fig. 19;
7. the ribs and connection elements are glued on all the intrados layers, paying particular attention to the alignments between one section and the other;
8. the closing of the two moulds, suction side and pressure side, is the last phase, and requires 24 hours for the final yield.



Figure 19: Complete laminated wing.

Experimental tests were carried out on the wing as a final check on the prototype. The wing was bound to the tips on a support and was loaded with weights inside the cargo bay to recreate the same distribution of forces used in the numerical model, Fig. 20. The test was performed up to the total load that we would like to lift during the race. Measurements of deformations were taken at the wing centre and compared with the numerical prediction, see Fig. 21.



Figure 20: Loading the wing to determine the overall stiffness of the structure.

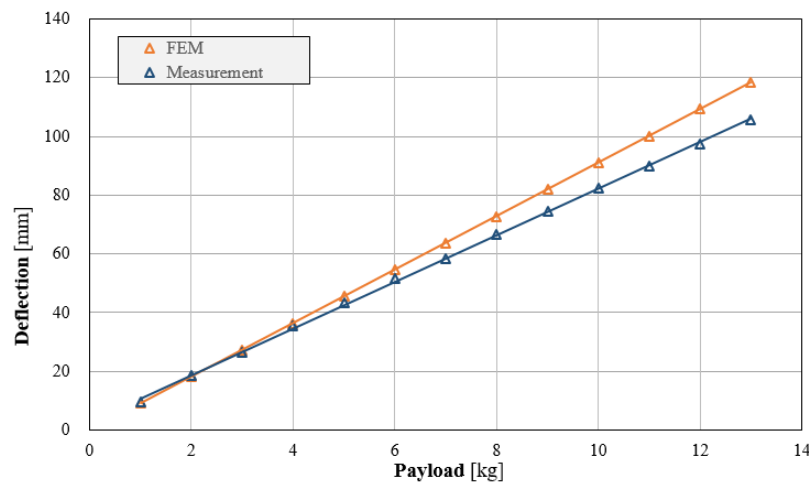


Figure 21: Comparison of measured and computed deflection.

The tests confirmed that the structure is able to withstand the desired load and the FEM model had predicted correctly the deformation, despite the geometrical simplification adopted. Having the model proved to be accurate for the bending load, its predictions for torque deformation were judged also reliable and therefore were not experimentally verified.

The validation of the wing structure must also take into account possible flutter phenomena. The analytical evaluation of this issues is rather complicated, also in view of the complexity of the composite structure that makes up the wing. For this reason, the team decided to proceed as soon as possible with the construction of a first prototype to be tested in flight to rule out flutter phenomena. The first prototype with the new wing flew in March 2019 and no wing flutter was observed, even for flight velocities higher than that the model could reach in horizontal flight.

4.5 Tail boom

The empennage is connected to the wing by means of a tail boom made of carbon tubes. This solution was adopted for the DCA plane and proved to be very efficient in terms of rigidity, weight and easiness of construction. Considering that the aerodynamic loads insisting on the empennages of Gabriele are lower than those acting on the DCA and that the final length of the tail boom is practically identical, the most obvious solution was to adopt the same configuration. The tubes are custom made and composed by three sections that can be grafted one in the other for reasons associated with the dimensions of the transportation box. The resulting structure was verified by the former AeroUD team for both static load (assuming a cantilever model) and flutter (with test in a wind tunnel).

4.6 Fuselage

The cargo-bay structural design and consequent construction must fulfill many requirements:

- minimal dimensions required by the ACC rules;
- allow an easy and fast payload loading;
- it must be able to withstand the acceleration forces on the payload during flight;
- in the present configuration, it must be able to house the landing gear and therefore withstand the landing loads;
- minimal cross section and aerodynamic shape in order to limit drag.

With these requirements in mind, the final design of the cargo-bay is essentially made of two flat walls emerging from the wing pressure side and a horizontal bottom plate glued together, Fig. 22. The whole structure is made by an aero carbon fabric 160 g/m^2 - PVC foam sheet 1.2 mm - aero carbon fabric 160 g/m^2 sandwich. Only a few components that are critical from a structural point of view (e.g. main landing gear supports, connection to the fuselage) are additionally reinforced by 4 mm thick birch plywood.

The outer portions of the cargo-bay (frontal, rear and bottom fairing) have only an aerodynamic function and for this reason they are made of a very thin vacuum moulded layer of glass fibres and epoxy resin.

The payload loading will be done from the rear of the cargo-bay, where the fairing is fixed with four magnets for easy and fast loading operations. The bolts that keep in position the payload grip on a slide which is then fixed on the bottom wall of the cargo bay in variable positions along the airplane's longitudinal axis, thus allowing to set the payload position as requested by stability requirements. On the bottom of the fuselage, the landing gears are attached, frontal and rear wings are connected to commercial carbon fibre tubes that proved (by numerous landings in flight tests) to be able to withstand the impulsive load due to landing. On the axis of the main carriage wheels, a mechanical disk brake is installed (see section 6).

The engine boom is composed by a pod and a carbon fibre tube used for coupling with the wing central section. To avoid the occurrence of resonance phenomena, the boom dimensions and structure were selected in such a way to ensure that its natural frequency is much lower than the frequency induced by propeller and motor spinning.

The engine pod must ensure the accessibility to a load bay where engine regulator, engine and RX system batteries have to be located. The only significant load that the engine pod must be able to sustain is the propeller torque. It was therefore decided to manufacture this component again with the vacuum moulding technique applied on a layer of aero carbon fabric 160 g/m^2 and epoxy resin. A 3 mm thickness sandwich of aero carbon fabric 160 g/m^2 - PVC foam sheet 1.2 mm - aero carbon fabric 160 g/m^2 is used for internal bulkheads that are adopted to improve torsional stiffness, to support the engine and to connect the engine pod to its tube.

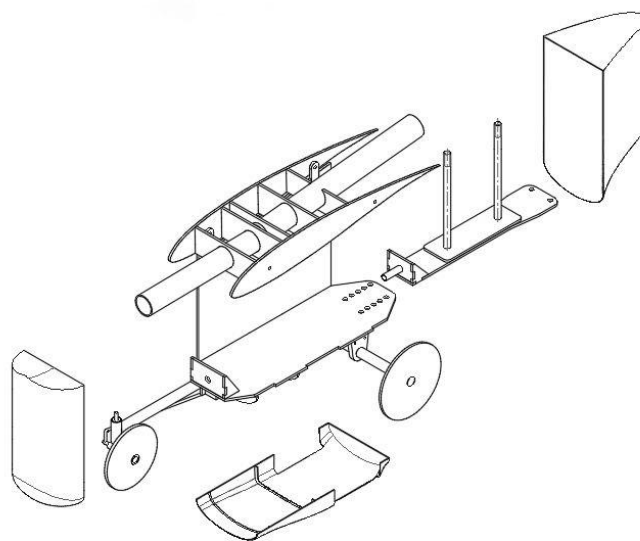


Figure 22: Cargo bay.

5. ELECTRIC AND ELECTRONIC COMPONENTS

5.1 Battery sizing

As imposed by regulations, a three-cells Lithium based battery (LiPo type) is used to supply the airplane's engine. To choose the most suitable battery, the minimum capacity required for a flight in the worst case scenario was calculated. The overall time has been estimated at 4 minutes, or 240 seconds, calculated as follows:

- 80 seconds to the take-off, considering more than one attempt;
- 30 seconds to gain some altitude and fly into the circuit, as imposed by the regulations;
- 80 seconds to complete the race circuit;
- 50 seconds to land.

Assuming as a precaution to operate the motor at full throttle for all the flight time and considering an average overrated current of about 50 A, the minimum battery capacity must be at least 3330 mAh, according to the following equation:

$$C = 1000I \frac{\Delta t}{3600} \quad (5.1)$$

where:

- C : (wanted) battery capacity [mAh];
- I : current absorbed by engine [A];
- Δt : total flight time [s].

The engine will be supplied by a battery with a capacity even greater than specified above, in accordance with commercial availability and reliability. In particular, we chose a Lipo 3S 4200 mAh with a continuous discharge current of 50C. However, battery quality and capability to discharge high continuous currents are mandatory requirements to avoid excessive voltage drop of the LiPo cells, which would turn in less propeller traction. The search for the best possible battery will therefore continue in the next months before the competition.

Concerning the battery that supplies the on-board RC system, the regulations require a battery capacity of (at least) 600 mAh. This imposed lower bound is largely sufficient to cover the estimated flight time.

5.2 Servomotor sizing

To choose the servomotors we began from the estimation of the aerodynamic force applied on the control surfaces, under these assumptions:

- airflow as non-compressible flow;
- negligible friction;
- profiles' incidence equal to zero

In order to do that, the surfaces were approximated into rectangular plates with the same width of the profile (L_c) and height equal to its average chord (C_c). We then assumed that the angle α of the plate relative to wind direction, for each configuration of the mobile surface, is equal to the inclination of the profiles' part, between pressure side and suction side, with the highest exposure to wind. The aerodynamic force acting on the surface is considered normal to it and overestimated by:

$$F = \frac{1}{2} \rho v^2 c_c L_c \sin \alpha \quad (5.2)$$

where $\rho = 1,225 \text{ kg/m}^3$ and, as a cautionary assumption, $v = 30 \text{ m/s}$. We also assume that the force is zero if no surface (pressure side or suction side) is directly exposed to wind. Particular care has been put in the installation of the servomotors and linkages to the control surfaces with the aim to minimize as much as possible the aerodynamic drag. A solution was found in the system depicted in Fig.24. It is a commercial support for servomotor that allows the installation of all the mechanism inside the aerodynamic body. From a kinematic point of view, the system can be modelled as a four-linkage mechanism, as represented again in Fig. 23, where joint A is the servomotor and joint B is the hinge of the control surface.

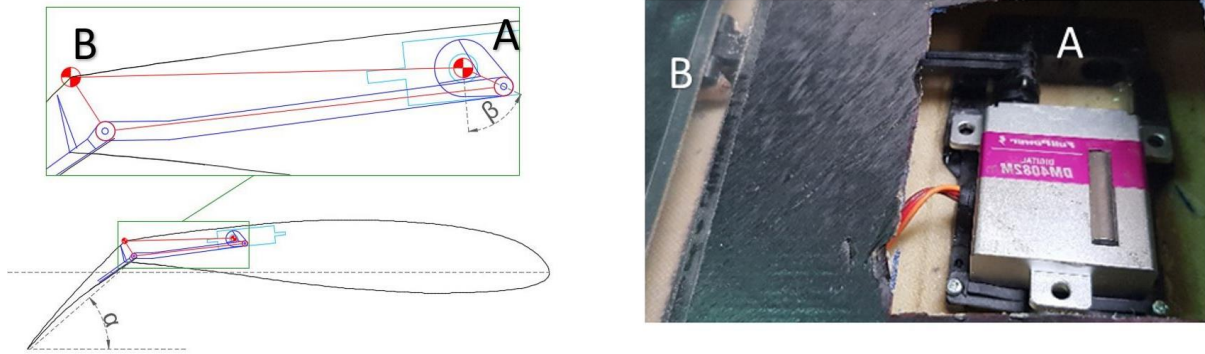


Figure 23: Linkages to control surface's flap to optimize the aerodynamic drag.

From Fig. 23 it can be understood that the force insisting on the profile generates a torque about B, (assuming half of the medium chord as its arm):

$$Torque = \frac{1}{2} \rho v^2 c_c L_c \sin \alpha \frac{c_c}{2} \quad (5.3)$$

that must be compensated by servo-motor torque provided at point A. However, because of mechanism's geometry (articulated quadrilateral) there is a variable transmission ratio between A and B and so the maximum torque needed is not necessarily at maximum force. Because of this, we developed a tool to solve kinematic analysis of the mechanism in order to find the various transmission ratios for many positions of the servo (and of the profile). Figs. 24 and 25 showing previous calculations on the wing's flap follow as an example.

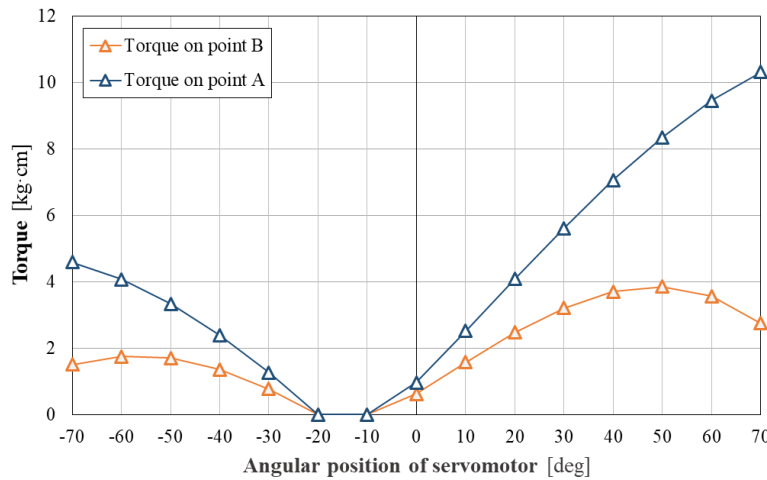


Figure 24: Torque on joint A and B function of angular position of servomotor.

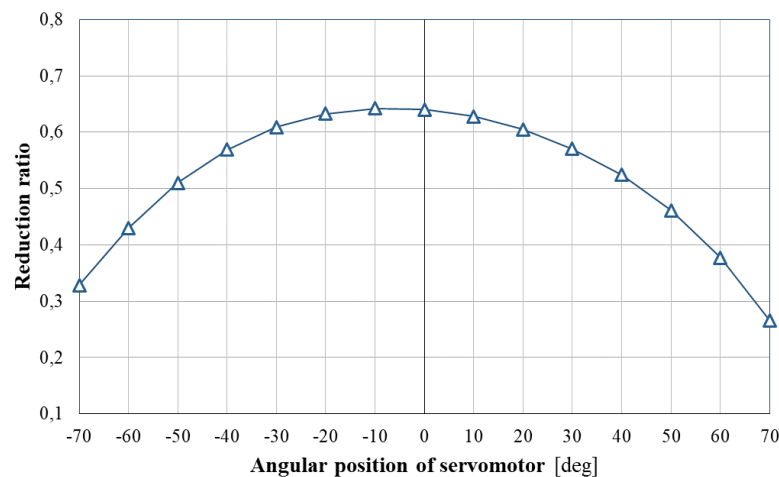


Figure 25: Transmission ratios for different position of articulated quadrilateral.

Surface	Length [m]	Average chord C_c [m]	Torque [kg cm]
Aileron	0,591	0,0588	1,23
Flap	0,740	0,08	3,85
Rudder	0,322	0,0636	2,2
Elevator	0,894	0,0486	2,64

Table 4: Minimum required torques from the servos.

Maximum required torques are reported in Tab. 4. The chosen motors can provide a maximum torque of 7,5 kg·cm, so they are adequate to sustain the load.

6. BRAKE SYSTEM

As the ACC 2019 edition regulations granted bonus points for performing a 60m arrested landing, a brake mechanism was taken into consideration. Different solutions were put under test: the first consisted in turning the propeller backwards and the second was a disc brake.

The first idea was potentially very interesting since it essentially demanded to enable the motor ESC to control the engine in both directions and therefore ensured a brake system with no addition of weight to the aircraft. Some test were done on a commercial ESC with this possibility but the solution was discarded mainly for two reasons. The controller needs to stop completely the propeller rotation before switching the rotation's direction. Therefore, an additional mechanical brake was necessary. Moreover, the ESC mode that enables to switch between both directions had no soft start. This turned into very high peak current at engine start up (as high as 200A) which caused the damaging of the engine under test.

Consequently, this solution was not feasible, and the team focused on the development of a disc brake. As this scheme is already widely used on rc-cars, the team decided to buy one rather than fully develop it, believing that the hypothetical weight advantage of a custom solution would prove not enough to justify the designing efforts. The brake system is mounted on the axe of the main carriage.

6.1 Disk brake sizing

A preliminary calculation of the deceleration was necessary to evaluate if brakes could stop the aircraft. We assumed an aircraft weight of 16 kg and a velocity of 20 m/s before touching the field, finally it must stop in 50 meters (assumed that 10 meters are enough to touch the field). Assuming that deceleration is constant during landing, the energy to dissipate is:

$$E = \frac{1}{2}mv^2 = 3.2 \text{ kJ} \quad (6.1)$$

We adapted a kit for RC-cars, so dimension of pads and disc brake are fixed. In particular, the dimension of the pads are about 130 mm² (1/4 annulus pads $R_e = 15\text{mm}$, $R_i = 8\text{mm}$). We chose not to take in account the wearing effect of the pads, since we expect to change the pads after 3 or 4 flights in order to maximize the braking performance. The brake moment is:

$$M_{brake} = \frac{\mu F_{brake}}{A} \oint r dA = \mu F_{brake} \frac{2 R_e^3 - R_i^3}{3 R_e^2 - R_i^2} \quad (6.2)$$

and the brake power:

$$P = M_{brake} 2\pi v / R_{wheel} \quad (6.3)$$

Finally for energy balance:

$$E = \int_0^{t_s} P dt \quad (6.5)$$

where t_s is the time to stop the plane, assuming uniform deceleration.

Brake force and moment can be considered independent by the velocity of the airplane on ground (velocity of the wheels), since they depend only upon the friction between disc and pads. Therefore, the equation of above can be re-arranged to extract the braking force.

Analysing the mechanism (which is a parallel 4-bar mechanism, Fig. 26) in the braking position, we can estimate the servo torque.

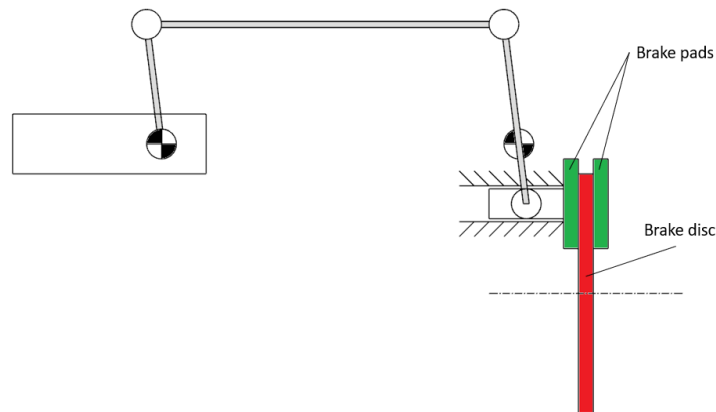


Figure 26: Schematic of the braking mechanism.

7. PAYLOAD PREDICTION

Gabriele's Payload prediction was developed through a numerical analysis. Starting from the three-dimensional polars, we obtained the value of Lift and Drag as a function of density through the formulas:

$$C_D^{tot} \frac{1}{2} \rho v^2 A_W = D(v) \quad (7.1)$$

$$C_L^{tot} \frac{1}{2} \rho v^2 A_W = L(v) \quad (7.2)$$

From this information, we have the possibility to derive the speed by equalizing the Drag force to the propeller pull, then also to obtain the value of Lift developed by the aircraft. By removing the weight of the airplane, we determine the value of Payload that the aircraft is able to carry.

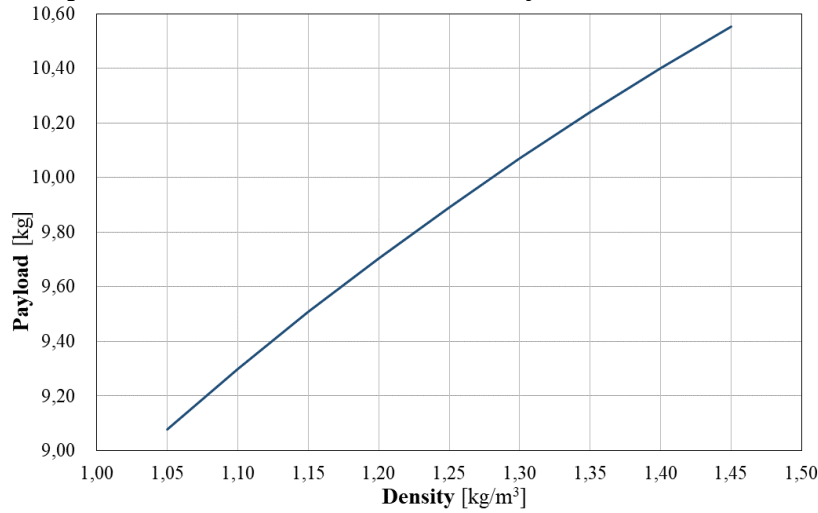


Figure 27: Payload prediction.

To do this, we have created a model to understand how the propeller traction varies with density, using data from the numerous propeller tests performed at different ambient conditions.

The regulation requires that payload prediction must be calculated as a linear function of the air density:

$$P_p = 3.68\rho + 5.26 \quad (7.3)$$

where ρ is the density altitude in Fig. 27.

The prediction was also verified in occurrence of flight tests with different density altitudes.

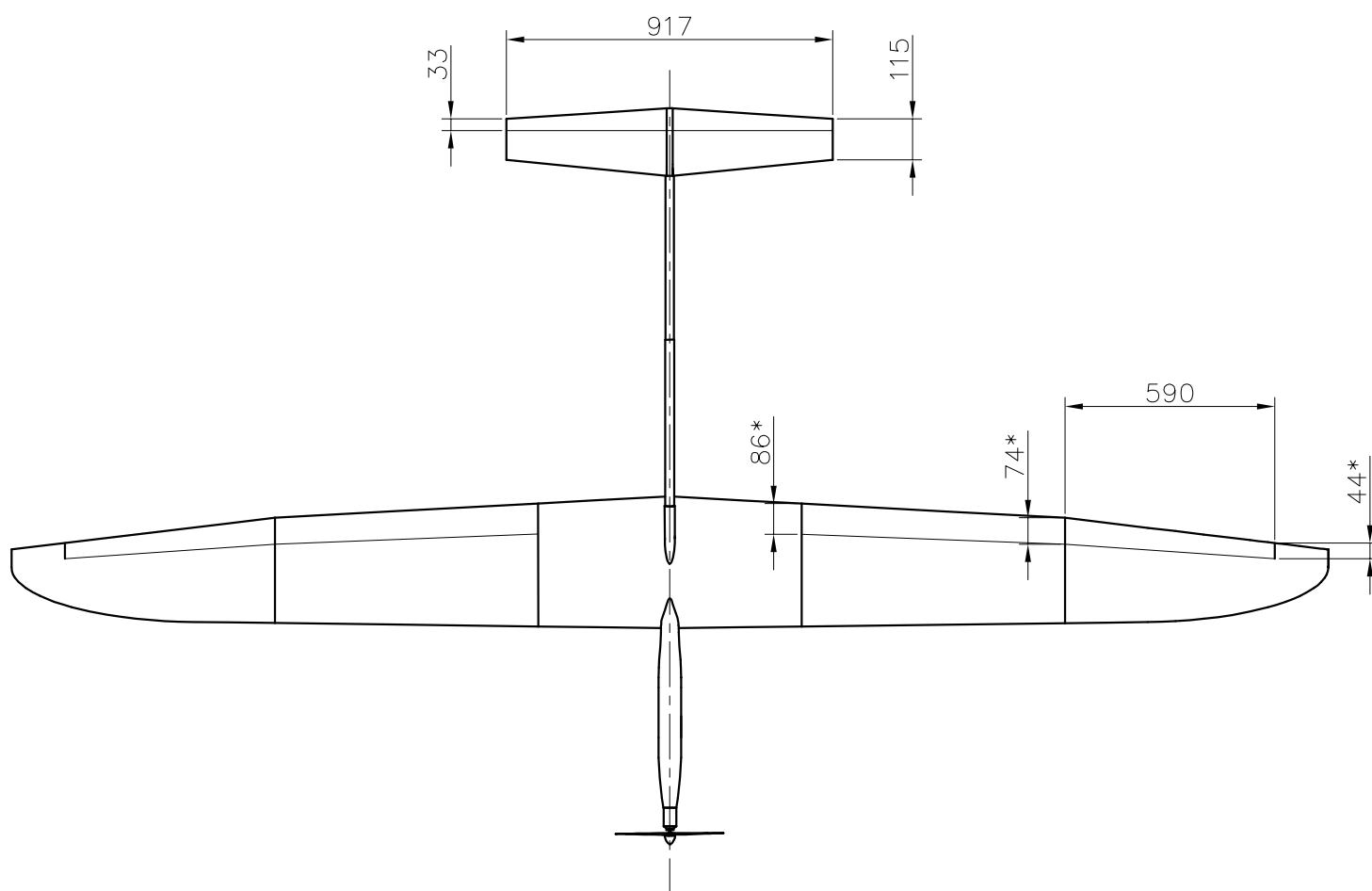
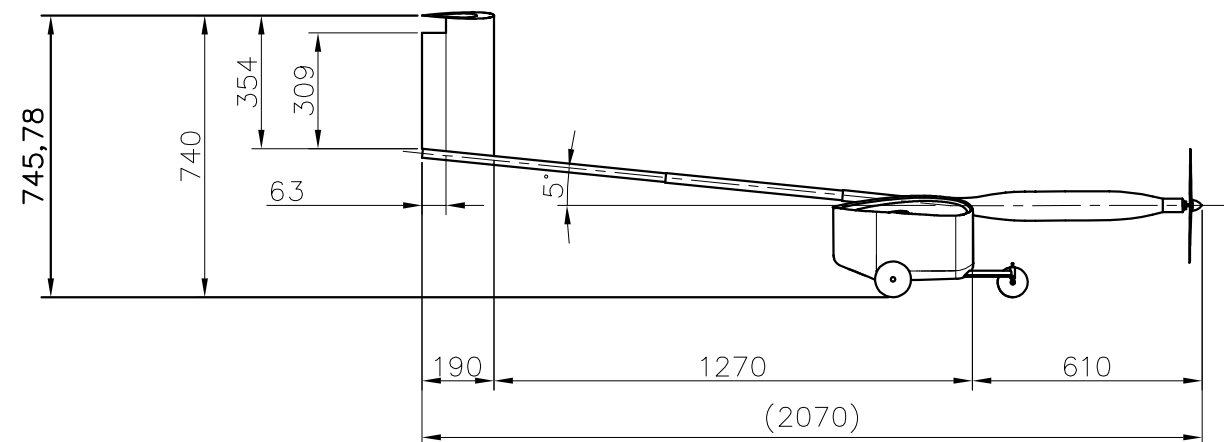
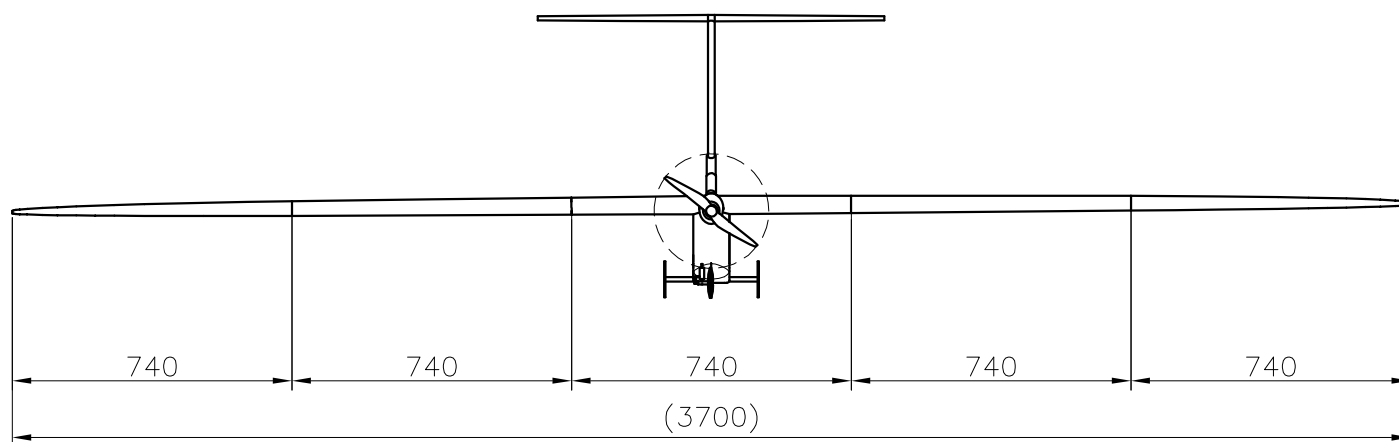


9. OUTLOOK

An early version of “Gabriele” was built in the months of February and March 2019 with the goal to solve the structural problems described in the preliminary report. This prototype was used by the team for a variety of tests, both in laboratory and in flight. In this later period, while some team members dedicated themselves to writing the report others focused on putting the final touches to the project. At this point we will continue building the plane for the race, with the firm goal to build a lighter plane than its predecessor. Meanwhile we shall continue to use the existing prototype to train all team members for the specific jobs that they will perform during the race (such as finding the best possible trajectories, calling the start of the turn...etc)

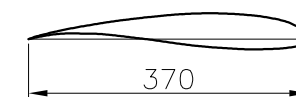
Attachments:

DRAWINGS and APPLICATION FORM

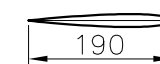


Airfoil – SCALE 1:10

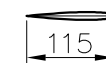
Wing airfoil at the root
(Optimized Fx 60-100)

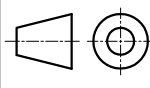


Vertical and Horizontal stabilizer
airfoil at the root
(NACA 0009)

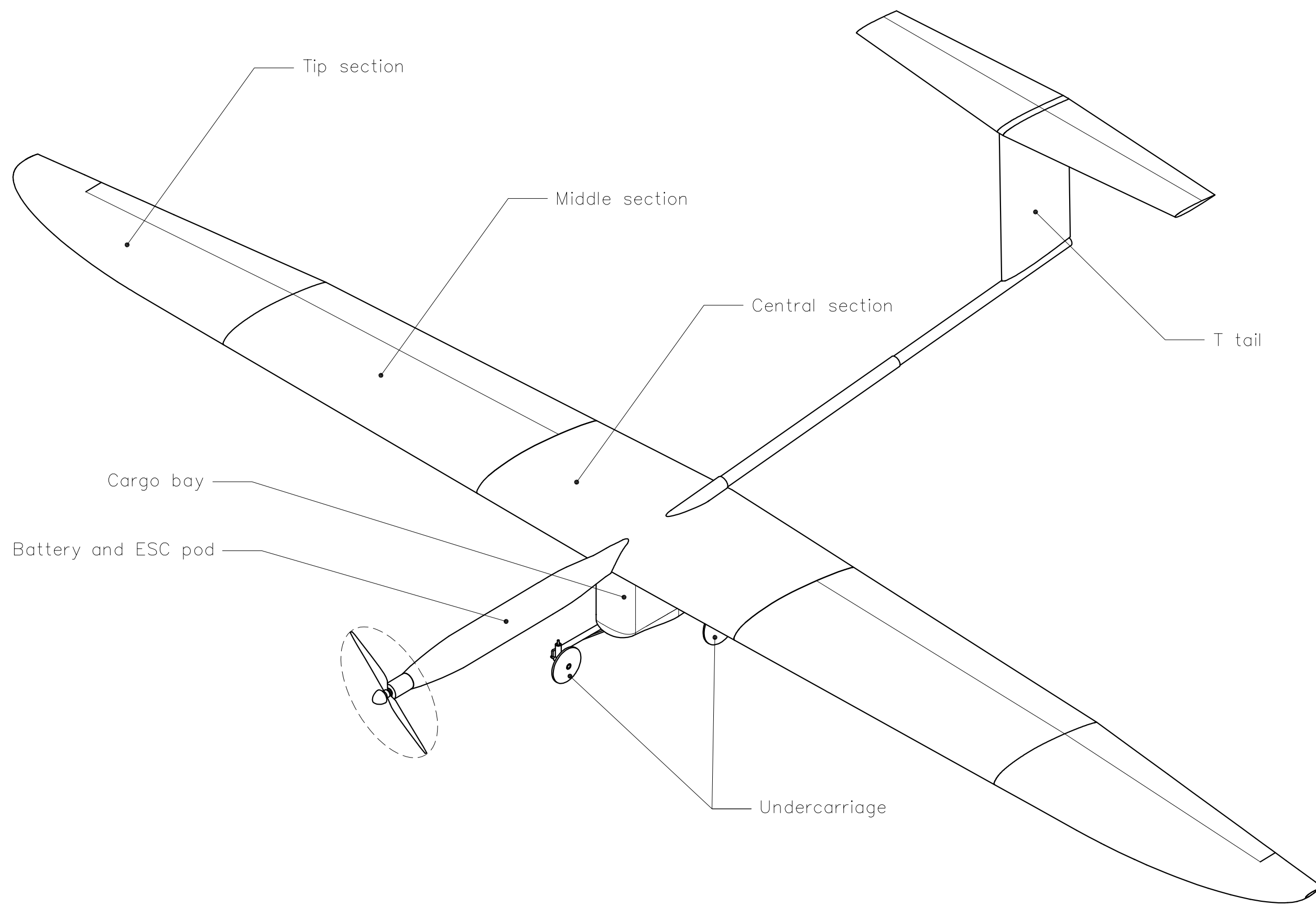


Horizontal stabilizer airfoil at the tip
(NACA 0009)

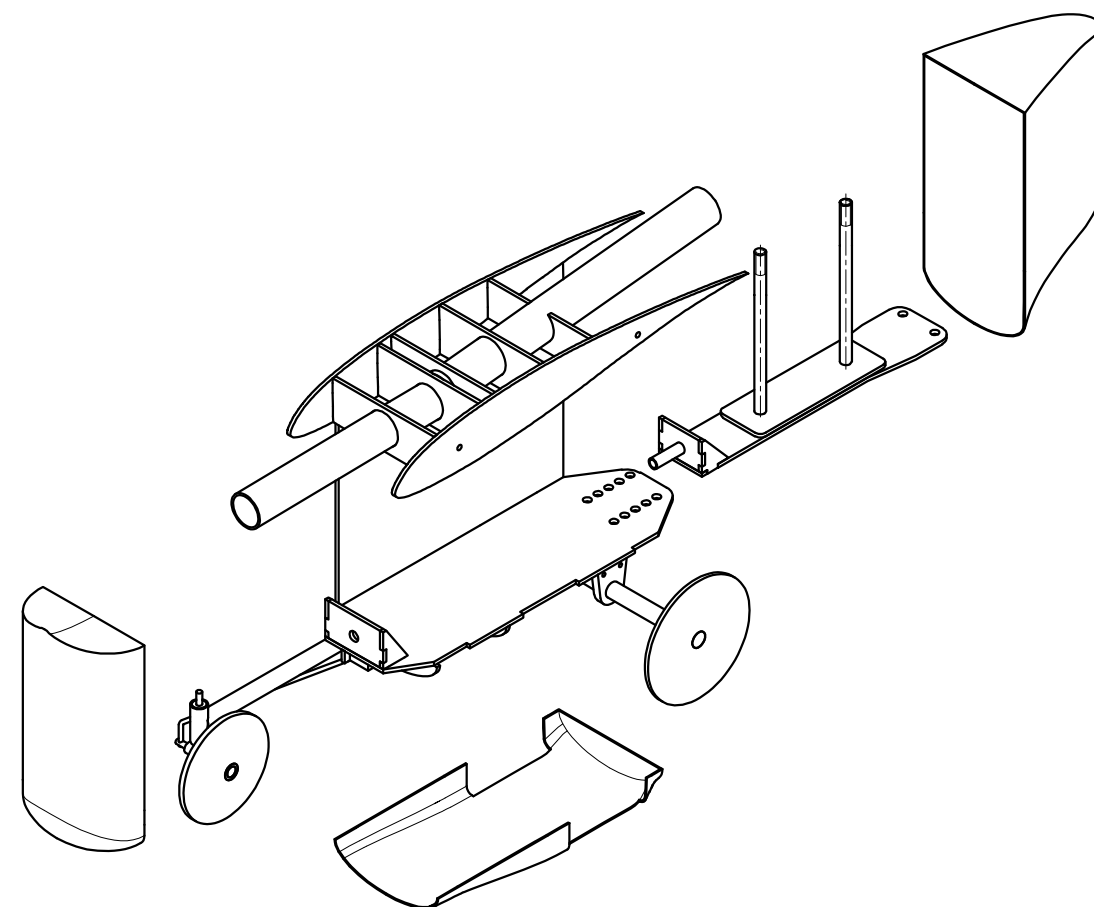
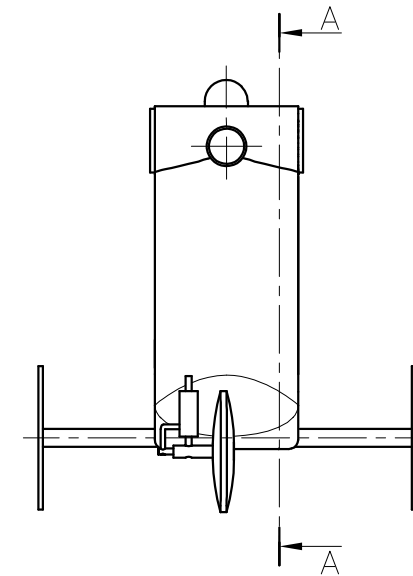
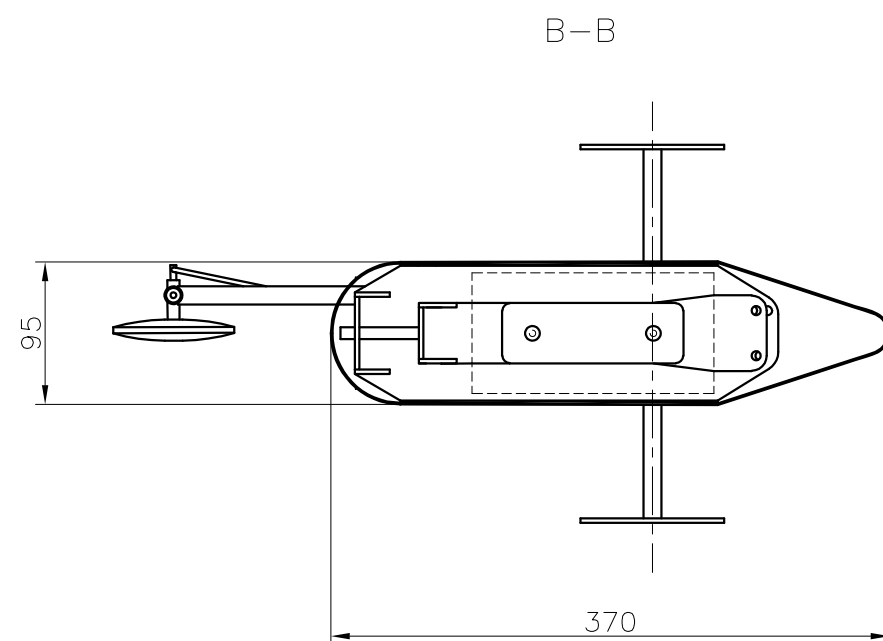
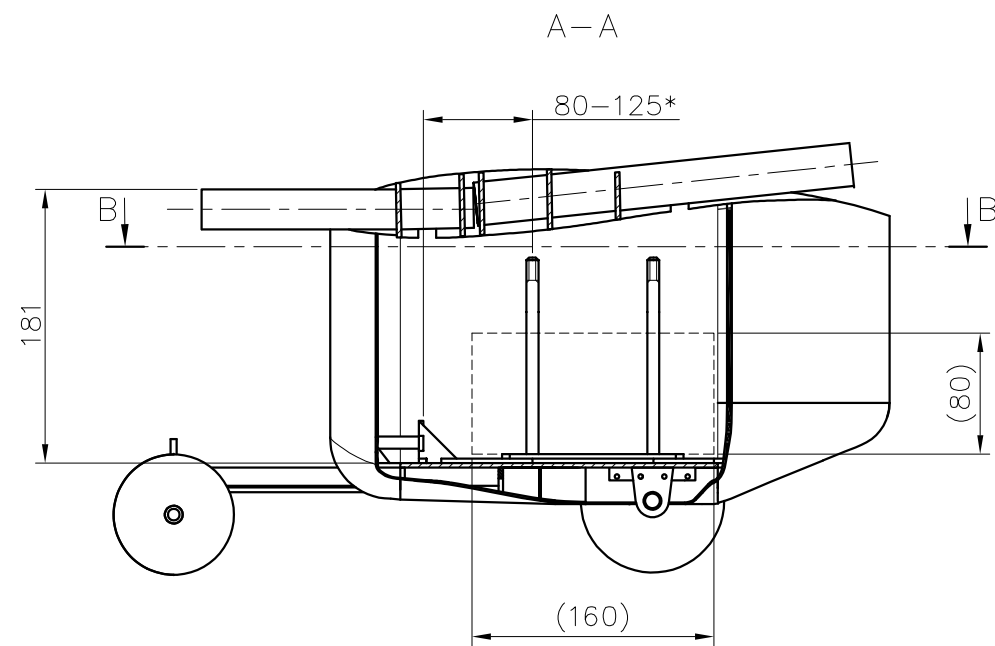


Surface	Area	Surface	Area
Horizontal stabilizer	0.140 m ²	Elevator	0.0440 m ²
Vertical stabilizer	0.0672 m ²	Rudder	0.0195 m ²
Wing	1.07 m ²	Ailerons and flaps	0.188 m ²
TEAM'S UNIVERSITY University of Udine		GENERAL TOLLERANCES UNI EN-ISO 22768-1-v	
		TEAM'S NAME / NUMBER AeroUD-The Beauty.../N.01	
		DATE 06/05/2019	
TITLE 3-VIEW DRAWING		SCALE 1:20	
DESCRIPTION - front view at the top left corner - top view below - starboard view on the right			

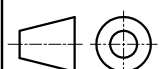
(*) length measured on the wing airfoil chord

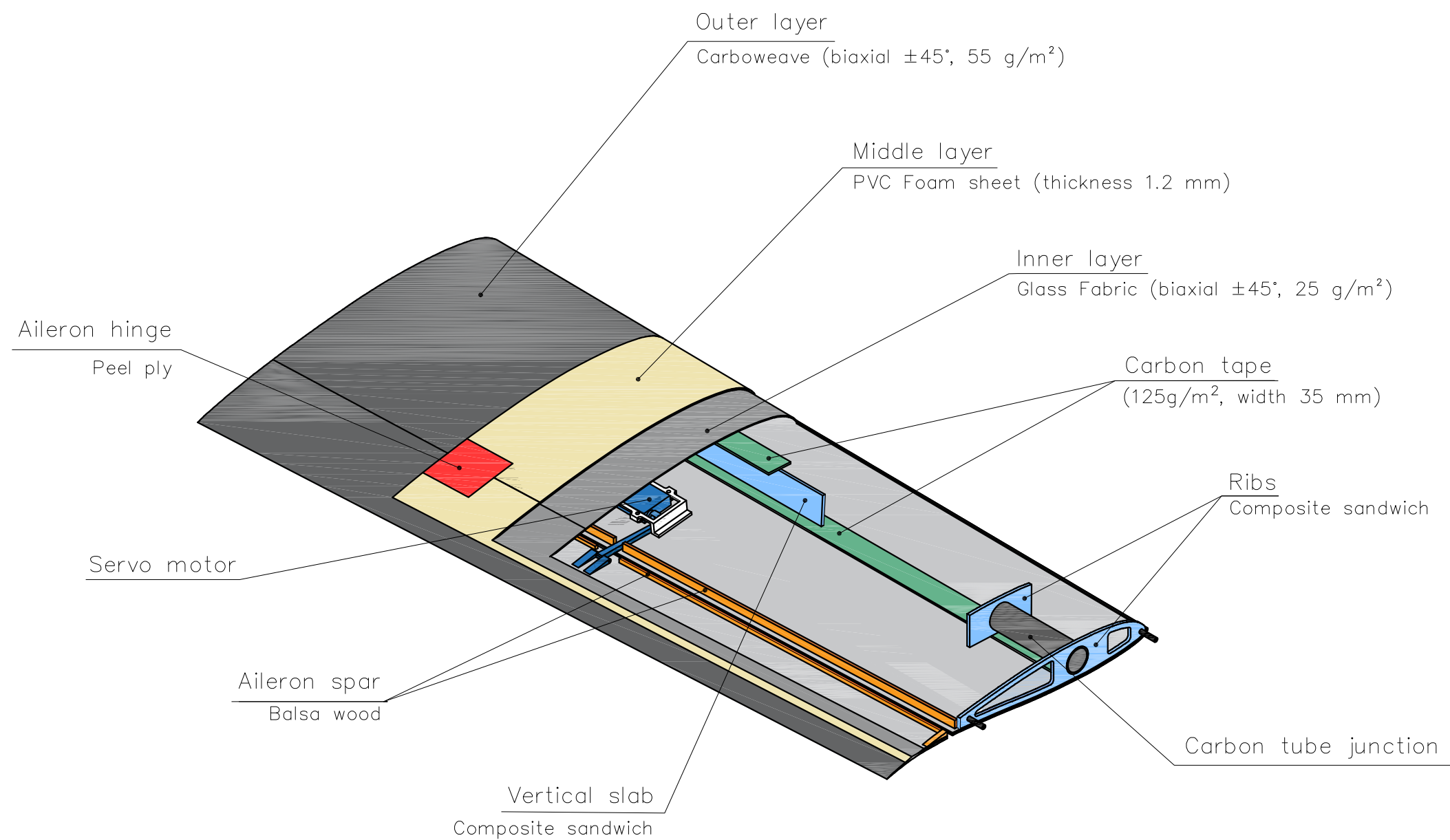


TEAM'S UNIVERSITY University of Udine		GENERAL TOLLERANCES ---	TEAM'S NAME / NUMBER AeroUD-The Beauty.../N.01	
	TITLE ISOMETRIC PERSPECTIVE VIEW		DATE 06/05/2019	
	DESCRIPTION Isometric perspective view with indication of the main airplane elements		SCALE 1:10	



(*) Slide excursion for correct setting of the center of gravity

TEAM'S UNIVERSITY University of Udine		GENERAL TOLLERANCES UNI EN-ISO 22768-1-v	TEAM'S NAME / NUMBER AeroUD-The Beauty.../N.01	
	TITLE CARGO BAY		DATE 06/05/2019	
	DESCRIPTION Cargo bay location and principal dimensions On dashed line: orthogonal volume of 160x80x80 mm for technical inspection		SCALE 1:5	
				



TEAM'S UNIVERSITY University of Udine		GENERAL TOLLERANCES ---	TEAM'S NAME / NUMBER AeroUD—The Beauty.../N.01	
	TITLE WING'S LAMINATE LAYERS		DATE 06/05/2019	
	DESCRIPTION Wing laminate layers and some glimpses of the internal structure		SCALE 1:5	



**UNIVERSITY
OF UDINE**



The Beauty...

TEAM 01: Participants

NAME	SURNAME	GENDERS	DATE OF BIRTH	T-SHIRT SIZE	TEAM ROLE	SIGNATURE
Luca	Casarsa	male	18/12/1974	M	pilot	<i>Luca Casarsa</i>
Cecilia	Venturini	female	07/11/1996	L	leader	<i>Cecilia Venturini</i>
Gabriele	Toffoletti	male	25/05/1996	M	member	<i>Gabriele Toffoletti</i>
Filippo	Madinelli	male	30/07/1996	L	member	<i>Filippo Madinelli</i>
Marco	Tognasca	male	10/09/1994	M	member	<i>Marco Tognasca</i>
Tommaso	Vescovo	male	12/03/1996	M	member	<i>Tommaso Vescovo</i>
Francesco	Basso	male	14/12/1994	S	member	<i>Francesco Basso</i>
Davide	Nespolo	male	25/07/1994	XL	guest	<i>Davide Nespolo</i>
Andrea	Lorenzon	male	09/11/1991	S	guest	<i>Andrea Lorenzon</i>
Fabio	Pagnacco	male	06/12/1989	M	guest	<i>Fabio Pagnacco</i>

Team leader

Cecilia Venturini

Cecilia Venturini

Professor in charge

Luca Casarsa

Luca Casarsa