BMFA Payload Challenge 2026 - Challenge 5 Weight

Technical Report

Team: AIRBORNE ARCHBISHOPS

Institution: Archbishop Holgates Sixth Form
Reference Number: W05

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Design Philosophy

Project Requirements

The objective of the 2026 BMFA Payload Challenge 5 (Weight) is to operate a fixed-wing radio-controlled aircraft maximising the payload-to-empty-weight ratio. The aircraft must be capable of carrying a liquid payload and completing all competition rounds safely and reliably.

The primary scoring objective of the challenge is to maximise the ratio of payload carried to empty aircraft weight, where empty aircraft weight is defined as the aircraft mass including flight batteries, but excluding the payload and payload receptacle.

The aircraft must also show sufficient strength to withstand the maximum payload loading throughout the competition and the design must prioritise lightweight construction while maintaining adequate strength, stiffness and repairability.

The overall project requirement is not just to build an aircraft capable of lifting 4 kg, but to produce a design that achieves a good balance between low structural mass, aerodynamic efficiency and payload carrying capability while also proving our design is economically viable.

Project Objectives

Our Aircraft was, naturally, designed with the main focus of achieving the highest possible payload-to-empty-weight ratio, but economic efficiency was a major design consideration too, due to the project's funding coming from team member contributions. This meant material selection and manufacturing methods had to remain cost-effective as well as technically suitable. For this reason, relatively low-cost materials were selected for the majority of the airframe, with more expensive high-performance materials reserved only for critical structural components where the performance benefit justified the higher cost.

One way we achieved this was through extensive use of 3D printing which allowed us to rapidly prototype complex parts, enabling iterative development without significant financial risk. This proved particularly valuable during the design process, allowing multiple design revisions to be tested and improved quickly which was a core project methodology throughout the challenge.

We recognised that some teams may pursue more advanced lightweight structures or better aerodynamic concepts in an attempt to maximise performance. However, our

design philosophy focused on producing a robust and competition-ready aircraft rather than unnecessary technical risk.

Concept Developments

We initially began our design by reviewing the challenge criteria and researched first the flying wing which at the time we believed would give us very good strength using the least material possible and would offer better lifting capabilities for the weight of the aircraft. Shown below is what we thought would have been a good attempt at the flying wing type of plane. However due to the nature of the project this methodology was soon ruled out.



Unfortunately even with the flying wing's superior payload lifting capability with a large water payload such as the one being used for the project we thought we would seriously struggle to balance the aircraft when different payloads were being used in the rounds of the competition. Furthermore, due to the limited separation of the wings, fuselage and tail this design would be very difficult to iterate upon as each time we wanted to improve a section of the aircraft lots of time and money would have to be spent to redevelop an entire plane.

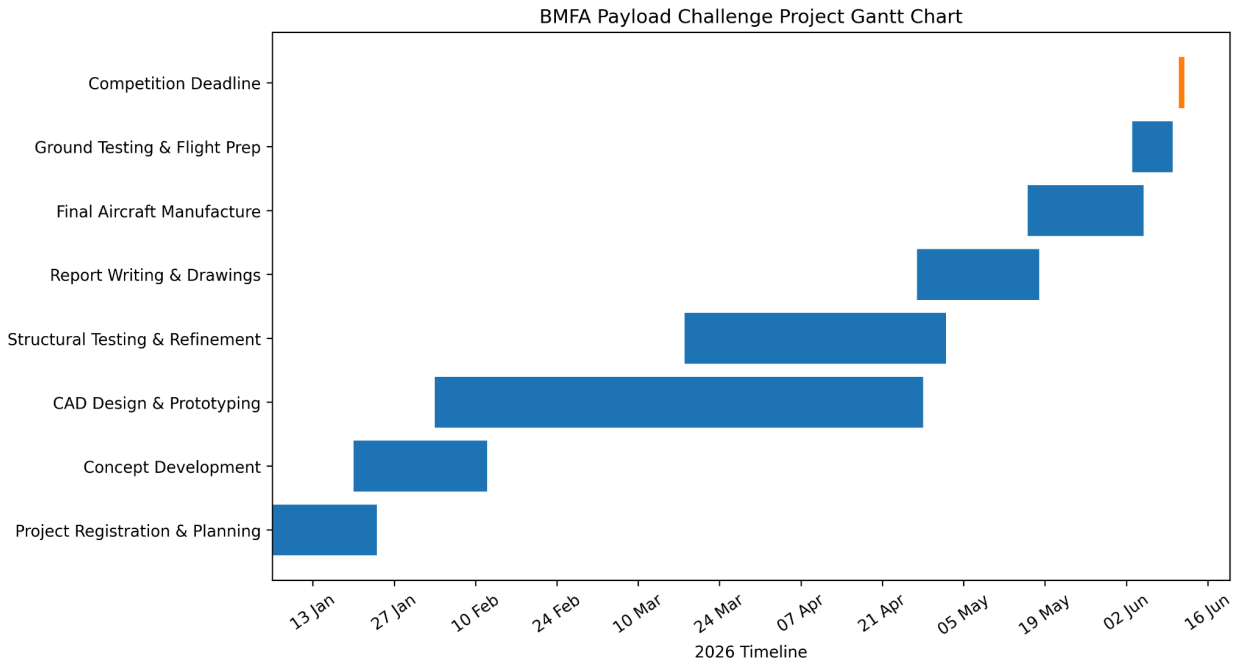
We now had decided to go for a more traditional fixed wing aircraft as it offered reliable and repeatable performance, which for a student lead team was exactly what we would need to succeed. However within this category there were many parameters to configure, and although low-wing and pusher configurations offered possible aerodynamic advantages, both introduced greater complexity. A mid-wing tractor configuration was selected due to its low speed stability characteristics, simplified landing gear arrangement, and improved payload access and positioning allowing us to put the payload very close to the centre of gravity. Using a simpler design approach to the challenge would allow us to hopefully develop an aircraft which is sufficiently capable for all rounds of competition.

Further concept development came through material choice which for an aircraft with weight being the most important factor to the competition success. The initial design

utilised 3D printing as a way to fabricate the majority of the components for testing and sizing. This included spars, ribs and the fuselage which were all printed initially but eventually will be made using either balsa wood or carbon fibre where seen fit. Following the trend of previous competitors we used an iron-on covering which will be attached to all control surfaces, wings and tail for an ultra-light solution to maintain a smooth and effective airfoil profile.

As most of our concept development such as wing sizing and tail design was a result of simple calculations verifying our design a more detailed justification of wing sizing, control surface design, spar selection and material usage is provided in following sections of the report.

Project Timeline



Shown above is the Gantt chart we created at the beginning of the project which we referenced throughout. This was made to hopefully ensure we could reach the deadlines of final assembly and report and drawing submission on time

Throughout we tried to follow this as best as we could, however often met delays as testing wouldn't go to plan and the design would have to be rethought. However we had left enough time such that these delays wouldn't affect the outcome of the project. The majority of time spent on the project was designated for testing sections of wings and components as this quickly ruled out many methodologies of plane assembly which we otherwise would have spent lots of money developing at a full scale. This allowed us to test lots of different methods while keeping initial investment low.

As shown we have not yet finished the final aircraft assembly but as we have over a month as of writing to finish the final construction of the plane we are not concerned with time constraint and can ensure proper construction such that we can survive three rounds of the competition. Throughout our testing of components we have preconstructed components which will help with the final assembly.

Resource Management

The competition has been entirely student funded with each one of the members of the team contributing ⅕ of the overall project cost. Initially almost all material used was 3D printing filament and it was only once a design was finalised and in theory would work before money was spent on expensive components such as carbon tubes. Below is a table containing the current costs of the competition. However it should be noted that final assembly may increase the total due to more material than we have anticipated and some essential components are not on the sheet yet such as covering film, etc.

ITEM	COST	# QUANTITY	TOTAL	Weight
PO-3541-1070 brushless motor	£33.49	1	£33.49	127
4M-HESC50AV2, Electronic Speed controller + prog box	£57.94	1	£57.94	41
PPL-60C3S-2200, 3s battery	£24.00	1	£24.00	170
ER6 2.4GHz ELRS PWM Receiver	£22.01	1	£22.01	14.5
XT-60 type connector, XT-60 type connector	£5.99	1	£5.99	10
competition entrance	£80.00	1	£80.00	NA
Radiomaster Pocket	£65.00	1	£0.00	NA
BMFA - 4M-175AMG-030 Servo 1pcs	£8.73	4	£34.92	68
14mmOD 20000mm carbon tube	£38.94	1	£38.94	131.4
BMFA - APCE 12 x 6 Prop	£5.50	1	£5.50	26
BMFA - XT60-Wall Connector	£2.99	1	£2.99	10
Esun PLA+ 1kg	£17.85	2	£35.70	NA
balsa wood sheets 3mm,5mm	£10.50	2	£21.00	NA

So far this totals to £360 or £72 per member which we believe is a brilliant achievement for us as a team as one of the main objectives of the project was to create a relatively budget friendly attempt (under £100 per person), as funding was completely out of pocket.

Throughout development all decisions often did lead back to the cost but this was not an issue as many materials are cheap compared to the worth that they provide to make a light and working attempt.

Due to the limited budget and lack of specific engineering studies more advanced materials and design practices could not be used but realistically this did not affect the outcome of the project.

Aerodynamic Design

Wing Sizing

The wing of the aircraft was designed such that with a 4kg payload we would be able to fly the plane with sufficient handling to ensure the round completion. However due to the nature of the competition lower weight of the wing was prioritized which may negatively impact flight performance, but we believe this was a suitable risk to take as we didn't want a plane which was far too large and therefore heavy in return for floaty forgiving flight characteristics.

A relatively high aspect ratio wing was chosen which provided good aerodynamic efficiency by reducing the drag at wing tips. The final geometry is a wingspan of 1.83m, a root chord of 230mm and a tip chord of 147mm. This gives the wing a taper ratio of 0.64 and an aspect ratio of 9.7. This was purposely kept lower than theoretically optimal due to the structural strain a much wider wing would put onto the carbon tube spar system causing a net increase in weight if we were to use a much wider wing. It can also be noted that alternative designs for the wing could have been used such as dihedral characteristics which could have aided to a more stable wing platform but we wanted to keep the main spar (2000mm, 14mmOD woven carbon) in one piece as any cutting that we did to the spar would result in a weak point due to the connection that we would use.

Wing loading was used as a sizing guide to ensure acceptable handling across different competition payload rounds. The plane weighs approximately 1200g with no payload or payload container. Wing loading is given by the formula:

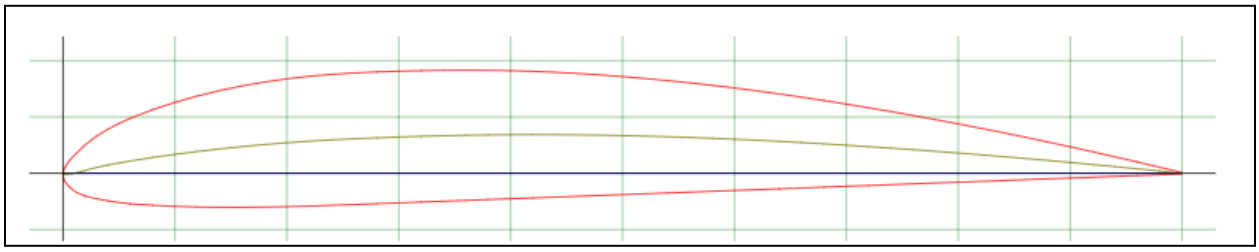
$$\text{Wing Loading} = \frac{\text{Total Aircraft Weight (W)}}{\text{Wing Surface Area (S)}}$$

Assuming the maximum payload required of 4kg and our main wing area is 0.35m² our maximum take-off mass will be 5.2kg during the competition. This gives three wing loading values for each round of the competition. 3.47 kg/m² with no payload ,9.27 kg/m² with 2kg and 15.06 kg/m² with 4kg.

Rather than designing for a single operating condition, the aircraft was considered across multiple mass cases: empty aircraft configuration, 2 kg round and maximum 4 kg round. This approach ensures that the aircraft remains efficient across all competition phases rather than being optimised for a single extreme case. Our resulting maximum take-off wing loading was selected as a deliberate compromise as moderate stall speeds are acceptable in exchange for a smaller wing which is lighter, hopefully giving us an edge over competitors but we do understand that this could negatively impact the flight performance of the aircraft as we will have a higher stall speed requiring more speed on takeoff and landing.

Aerofoil Selection

The airfoil selected for the main wing was the Clark Y airfoil as pictured below:



Significant consideration was given to the aerodynamic performance and assembly due to the demanding payload requirements of the BMFA Challenge. The aircraft was designed for high lift generation at relatively low flight speeds, whilst maintaining handling characteristics and straightforward construction.

Several alternative aerofoils were initially considered during the design phase, including the NACA 2412 and NACA 4412 aerofoils. The NACA 2412 offered acceptable aerodynamic efficiency, however its lower camber produced reduced lift capability at low Reynolds numbers, making it less suitable for high payload take-off conditions. The NACA 4412 provided improved lift characteristics due to its increased camber, but introduced greater drag and a more curved lower surface, increasing manufacturing complexity for the balsa rib and carbon spar wing structure.

The final selection of the Clark Y airfoil was made due to its strong balance between lift generation, stability and ease of manufacture. The airfoil features a relatively high maximum lift coefficient, enabling lower stall speeds and improved payload carrying capability during take-off and climb. The aircraft has an estimated cruise speed of 21 m/s and a maximum payload stall speed of approximately 13.6 m/s, therefore strong low-speed aerodynamic performance was considered essential.

The Clark Y also possesses a largely flat lower surface, simplifying rib production and spar alignment during manufacturing. This was particularly advantageous for the chosen construction method utilising balsa ribs with carbon fibre spars, as the flat lower geometry improves assembly accuracy and reduces manufacturing time. In addition, the airfoil thickness provides sufficient internal structural depth for spar installation and improves overall wing stiffness under payload loading.

The use of this airfoil is further verified in the performance calculations which shown using the CLmax for this airfoil our performance metrics are suitable for flight and metrics such as takeoff speed and distance is achievable.

Stability and CG analysis

Our aircraft is designed such that it will remain controllable and predictable throughout all stages of the competition. The design philosophy prioritised low-speed flight characteristics while carrying a large payload, as stable handling became increasingly important with the significant variation in aircraft mass between rounds. Maintaining an acceptable centre of gravity range and predictable stability characteristics was therefore a major consideration throughout the design process.

The table below details the location of all major aircraft components and their respective distances from the nose of the fuselage. These values were then used to calculate the aircraft centre of gravity for each payload configuration.

Component	Mass(kg)	Weight(N)	Distance from Nose (mm)	Moment(Nmm)
Motor	0.127	1.25	-22 mm	-27.4
ESC	0.012	0.12	82 mm	9.7
Battery	0.17	1.67	82 mm	136.7
Wing	0.48	4.71	290 mm	645
Tail Boom	0.065	0.64	640 mm	395.9
Tail Surfaces	0.15	1.47	971mm	1501.4
Payload	4	39.24	180 mm	7063.2

Although the aircraft incorporates a long tail moment arm, this allows the tail surfaces to generate sufficient stabilising moments with relatively small surface areas due to the increased leverage available. This reduces unnecessary structural mass at the rear of the aircraft while still providing adequate static stability.

The fuselage has also been designed such that the electronics and payload position can be adjusted during flight testing for a more optimal CG position.

During the qualification round, where no payload is carried, the calculated centre of gravity is approximately 270 mm from the nose. This represents the most rearward CG position experienced during the competition due to the absence of the large forward payload mass. Although this reduces longitudinal stability slightly, the aircraft is still expected to remain controllable within an acceptable stability margin.

For the 2 kg payload round, the calculated centre of gravity moves forward to approximately 210 mm from the nose. The payload produces a significant forward balancing moment while remaining positioned close to the wing root, minimising additional structural loading within the fuselage. This forward shift improves pitch stability while maintaining predictable handling characteristics.

For the final 4 kg payload round, the calculated centre of gravity moves further forward to approximately 198 mm from the nose. Despite the substantial increase in aircraft mass, the more forward CG position improves static pitch stability during lower speed phases of flight such as take-off and landing. Positioning the payload close to the aircraft centreline also helps minimise rotational inertia effects and reduces bending loads within the fuselage structure.

Overall, the aircraft has been designed such that the centre of gravity remains within a controllable range throughout all competition rounds while still prioritising efficient payload carrying capability and stable low-speed flight performance.

Payload Container

The requirements of the payload container are simple but very important to the success of the plane. The main objective is to carry 4kg of a liquid payload which equates to 4L of water. The simplest solution to the payload container was using a 3D printed module connected to the underside of the aircraft fuselage which is holding two 2L standard water bottles. These bottles can be detached using the simple 3D printed bracket for easy filling. This method of payload containment was not ideal for the best possible flying efficiency but offered an easy solution to a big design challenge.

Although this is the design that we have chosen we do acknowledge more advanced payload containment would be more suitable for the competition. For example if we were to integrate an airfoil into the payload container we could reduce the size of the wings and also include the weight of stronger landing gear into the payload container having it included in the 400g payload container buffer. This would reduce the weight of the plane as we could use light weaker suspension for the first round of the flight competition.

However as previously stated simplicity was key for us to make a working design and an integrated method would be too complex and would likely cause failure during rounds causing us not to be able to have a valid run with the 4kg payload.

Aircraft Control Surfaces

The aircraft uses a conventional tail arrangement using a horizontal and vertical stabiliser, elevator and rudder mounted on the end of a 14mmOD carbon tube 610mm from the end of the fuselage.

During the initial development a V-tail was considered and designed due to its increased aerodynamic efficiency and potential to be lighter than other configurations. However further research showed that the V-tail suffered with low speed flight and lacked in pitch and yaw authority. Furthermore the increased structural complexity would have led to more weight than a conventional design and the complicated control mixing wasn't something that we thought was worth a slight reduction in drag.

The main component of the wing is the horizontal stabiliser which is designed to provide longitudinal stability during flight and strong elevator authority during flight. The stabilizer is a symmetrical flat plate of 10mm thickness, a span of 696mm, root chord of 172mm and a tip chord of 112.50mm which gives us a moderate aspect ratio but one which balances structural stiffness and aerodynamic efficiency. The nature of the large flat plate profile gives us superior elevator effectiveness,

The secondary component is the vertical stabiliser design providing yaw control and further directional stability. With a height of 250mm, root chord of 172.5mm and tip chord of 91mm this will hopefully maximise the control but due to the reduced height of the stabiliser we will reduce bending loads through the airframe thus keeping the centre of gravity forward and ensuring a safe and controlled flight throughout all stages of competition.

Our aircraft has three types of control surface: ailerons, elevators and a rudder controlling roll, pitch and yaw respectively the tailfin ailerons are made of foam board as this was thought to be the best path to take to take for a very rigid control surface and ease of attachment to the servos.
The Ailerons are positioned on the outer section of the wing to maximize the roll due to the increased distance from the center of gravity. Each aileron spans 405mm of the 915mm half wingspan which is well within the typical region for low speed aircraft. A relatively large control surface was selected to maintain effective roll response even with the slower speeds we expect for the payload challenge

The elevator was sized to provide good pitch ability during takeoff which requires a large control surface. The elevator occupies 30% of the tails chord and stretches 100% of the span. This surface can also deflect 12 degrees up and down which will be more than sufficient for takeoff and mid-flight adjustments. This is in addition to the tail being 730mm from the CG position which will give us large bending moments to further amplify the controllability of the aircraft.

The final control surface is the rudder which is positioned above the elevator with sufficient clearance such that the elevator can fully deflect with no interference from the rudder. The rudder occupies 26% of the rudder chord and like the elevators stretch the full length of the vertical stabilizer.

All control surfaces are attached using nylon hinges as this was seen to be the simplest path for us to take instead of wasting time developing a new hinge. All surfaces are controlled using 4-Max 4M-175AMG-030 Servos which give fast response and are light whilst still being strong enough for faster speeds of the aircraft. For tail control servo pushrods were considered but as this would increase complexity of the aircraft this was avoided and the servos were instead mounted on the tail itself. Although this would move the CG towards the rear harming flight performance it was a sacrifice we are willing to take as the increased complexity was not worth the marginally better performance.

Flight Performance Calculations

Stall speed:

Stall speed is a metric we can use to predict in flight ability to stay airborne as during turns and landing speed will reduce and if this decrease is too drastic this is very bad for aircraft performance. Stall speed can be calculated with the following equation,

$$V_s = \sqrt{\frac{2W}{\rho S C_{L_{max}}}}$$

where W is the weight of the aircraft, ρ is the density of air, S is the wing area and C_{Lmax} is the maximum lift coefficient. The mass of the aircraft can be approximated as 1.2 kg from known component masses, giving a weight of 11.8 N. The wings can be approximated as trapezia, so the total wing area is a value of 0.345 m^2. Since the altitude of flight will be very low, the air density will be very close to that at sea level, which is 1.225 kg m^{-3}. Finally, C_{Lmax} is given as 1.3 for the Clark Y airfoil used in the design.

Putting these numbers into the equation, a stall speed of 6.55 m s^{-1} is obtained for the unladen aircraft. For a payload of 2 kg, this number reaches 10.7 m s^{-1}, and for the full 4 kg, the value is 13.6 m s^{-1}. These speeds show that with the payload we are required to fly, the aircraft will have good flight performance and with a maximum payload we will be able to execute safe turning and landing. However it should be noted that when a 4kg payload is used with stall speeds higher more conservative flight may have to be performed by the pilot as during a tight banking turn or sudden elevation changes risk of a stall greatly increase which would probably be the worst case scenario for flying.

Takeoff distance:

Takeoff distance is used to simply find the distance that the aircraft will take to become airborne. A lower takeoff distance for the aircraft suggests lots of lift is being generated at a low speed which allows the aircraft to take flight in a distance which the runway at BMFA Buckminster will allow for. Using the following formula,

$$s = \frac{V_t^2}{2a_1}$$

where V_t is takeoff speed and a_1 is the acceleration when the velocity is equal to the square root of two times V_t. The first step is to calculate the takeoff speed, which follows the same formula as the stall speed, but with the maximum lift coefficient replaced with the takeoff lift coefficient. For the Clark Y airfoil, this is approximately 1.0, which gives speeds of 7.47, 12.2 and 15.5 m s^{-1} for payloads of 0, 2 and 4 kg respectively. Multiplying these by one over root two, the acceleration of the aircraft must be calculated for ground speeds of 5.28, 8.62 and 11.0 m s^{-1}.
Assuming an approximate drag coefficient of 0.05, the drag forces at those speeds will be 0.29, 0.79 and 1.3 N, according to the drag coefficient formula:

$$F_d = \frac{1}{2}\rho u^2 C_d A$$

As for the friction, the lift at these speeds should be half of the weight of the aircraft, so the friction force should simply be the coefficient of friction multiplied by half the aircraft weight. Using an approximate coefficient of friction of 0.05, given the grassy nature of the runway, the rolling resistances should be 0.29, 0.79 and 1.3 N, notably the exact same as the drag forces (as the coefficients are equal). Having reached these values

through two different routes of calculation, it is possible to be confident that no errors have been made.

With the static thrust being 2040 g = 20.0 N, a linear falloff in efficiency is assumed, down to 5.0 N of force at 20 m s^{-1}. Therefore, the resultant forces forwards on the aircraft are calculated as 15, 12 and 9.2 N. Dividing by mass to give acceleration, the final accelerations for the speeds are 12, 3.7 and 1.8 m s^{-2}. Finally, applying these to the formula, the takeoff distances should be 2.3 m, 20 m and 67 m. These takeoff distances are within the acceptable range for BMFA buckminster main runway whilst also giving sufficient clearance for any underestimates we have made in our flight calculations. These errors will most likely stem from our real value of CLmax not being what we predicted due to the finish of the wings and errors in producing the shape to the accuracy we need. Errors in these calculations could also appear from our drag approximations as these will change drastically depending on surface condition of the grass such as moisture or lack of. Even with these errors taken into account our takeoff distance and other performance estimations fall within a very safe region as the aircraft was not designed not to be on the absolute limit of performance.

Cruise speed:

The cruise speed of the aircraft gives a good estimate to see if the aircraft will generate enough lift and have good stability, handling, structural loading and the drag which will be induced on the wings and tail. Making the same assumption about thrust as previously, whereby static thrust is 20.0 N and reduces linearly according to the linear relationship

$$F = 20 - 0.75 \times V$$

Since drag is equal to V^2 multiplied by a constant (0.011), equating these two expressions gives a quadratic for V, with positive solution 21 m s^{-1}. This represents the maximum speed of the aircraft before it reaches terminal velocity. The cruise speed will be strictly less than or equal to this, following the speed of equal lift and weight. Again, the same equation as for stall speed can be used, with a new lift coefficient of 0.4, to represent efficient cruising.
This gives values of 12, 19 and 25 m s^{-1} for 0, 2 and 4 kg payloads respectively. As the first two are below 21 m s^{-1}, the aircraft should be able to cruise efficiently with the up to a 2 kg payload, whereas with the 4 kg payload, a greater angle of attack will have to be used, in order to achieve a lift coefficient of greater than 0.55. This value is within the reasonable range for relatively efficient cruising, however, and should not pose a

problem for sustained flight in any way. In this way, expected flying speed with the 4 kg payload is expected to be approximately 21 m s^{-1}.

Maximum payload:

As calculated above, the aircraft should be able to maintain a maximum horizontal speed of 21 m s^{-1}. Rearranging the takeoff speed equation, we obtain:

$$W = \frac{1}{2} V_s^2 \rho S C_{L_{takeoff}}$$

This gives a weight of 121 N. Subtracting the unladen weight of the plane and dividing by g, a value of 8 kg is obtained. This is the critical payload mass for which the aircraft should barely be able to take off. Of course, the calculated takeoff distance for this mass is 250 m, which is unreasonable. To maintain a takeoff distance of under 100 m, the payload cannot exceed 5 kg. Furthermore the airframe is designed for a payload of 4kg and much more than this could pose serious risk to catastrophic failure during flight. This would most likely occur in the balsa wood wing spars as the carbon fibre rod would bend under the much increased loads causing the balsa to buckle and crush. The main carbon spar is rated for far more structural strain than we could achieve while being able to take off with the increased payload mass.

Turn radius:

The turn radius of the aircraft shows how maneuverable the aircraft will be during flight and the responsiveness to the pilots intentions to change directions.
Assuming a maximum banking angle of 40°, and using the formula

$$R = \frac{V^2}{g \tan(\theta)}$$

where V is the velocity and theta is the banking angle. Using the cruise speeds above, this would give the calculated turning radii of 17m, 44m, and 54m showing a clear progression as payload increases. This indicates that the aircraft remains capable of controlled manoeuvring at higher weights, but with reduced agility. However during the turn energy will be lost due to the change of direction this will reduce speed and increase risk of a stall. If we use a more conservative baking angle of 20° where stability and low structural loading is prioritised over manoeuvrability for the 4kg payload round a turn radius of 124m is achieved which is still reasonable and an estimate which if achieved in flight wouldn't cause any concern or dangerous flight.

Structural Design

Structural Philosophy

The initial attempt for the structure of the aircraft was a fully 3D printed design with no composite materials. Although this would have been simple it was virtually impossible to execute as printed components can't replicate the strength to weight ratio that a composite material can or even simple materials such as balsa wood.

Throughout the development of the aircraft multiple filaments were used during 3D printing and below is a table consisting of some of the most important physical properties of each material which enabled us to make the best decision for the final filament that we would use for the assembly of the aircraft.

Property	Standard PLA	PLA+	Bambu Lab Aero PLA
Typical Printed Density	1.24–1.27 g/cm³	1.20–1.25 g/cm³	0.54–0.70 g/cm³
Density Reduction vs PLA	Baseline	~0–3% lower	~45–55% lower
Ultimate Tensile Strength (XY)	50–65 MPa	55–70 MPa	18–35 MPa
Tensile Modulus (Young's Modulus)	3.0–3.8 GPa	2.2–3.2 GPa	1.0–1.8 GPa
Flexural Strength	85–110 MPa	75–100 MPa	30–55 MPa
Flexural Modulus	3.0–4.0 GPa	2.0–3.0 GPa	0.8–1.5 GPa
Elongation at Break	3–6%	8–20%	6–12%
Charpy Impact Strength	15–25 kJ/m²	25–45 kJ/m²	10–20 kJ/m²
Interlayer Adhesion Strength	Moderate (~55–70% bulk)	High (~70–85% bulk)	Moderate (~50–70% bulk)
Specific Stiffness (Modulus/Density)	High	High	Moderate
Failure Mode	Brittle fracture	Ductile/toughened fracture	Cellular crushing + tensile fracture

As shown in almost all data points the PLA+ is a much stronger material than the regular PLA with negligible density difference between the filaments. This would enable us to use less of the material as it offers great layer adhesion and far better impact strength but would be primarily used for structural reinforcement rather than volumetric structures due to Aero PLA being 50% lighter. However the use of Aero PLA is greatly flawed by balsa wood which offers far greater stiffness at an even lower density of approximately 0.11 - 0.17g/cm³ depending on the grade of wood. This meant that for almost all volumetric structures balsa wood was used as it has a very high specific stiffness and a failure mode which was not as sudden as brittle PLA and for complex joints 3D printing with PLA+ was used. It should be noted that variable infill for 3D prints has been used which maximises strength in component sections that matter

Wing Design

The main wing is designed using a 14mmOD 12mmID woven carbon tube which acts as the main structural member to resist bending moments which will be experienced during flight. This is the main structural component of the wing and offers a very strong but light solution. Every 150mm across the wing there is a wing rib which acts to distribute the lifting forces on the skin to the spar. These ribs were initially designed to be 3D printed using Aero PLA however 3mm Balsa offers much better stiffness which is essential for maintaining the chosen airfoil throughout flight hence this material was chosen for all the ribs of the aircraft.

The wing also incorporates two 5mm balsa spars which run the full length of the wing, the largest of the two is placed at ¼ of the root chord and the smaller is placed at ¾ of the root chord. These two secondary spars give the wing far better torsional strength as without these the wing would most likely oscillate and twist during flight.

Another major component of the wing's construction is the D-box which is a fully 3D printed component offering further enhanced torsional strength of the wing and also is used to connect the ribs together and to minimize flex between all components of the wing while also being the lightest possible solution. We have experimented with balsa wood for this component but the 3D printed material was lighter and stronger and was much more impact resistant which is key for the frontal structure of the wing in case of collision during testing.

Tail Design

The horizontal and vertical stabiliser are assembled similarly to the main wing but at a much smaller and simpler scale. As we had already tested the construction methods for the main wing we knew a similar assembly would work for the tail. However, ensuring a light tail was under even more emphasis as we wanted to reduce the tail bending moments as much as possible not just so we could use a smaller diameter tail boom but to ensure we maintain a positive static margin.

The main strength of the tail is given by a series of 5mmOD carbon rods which run the full length of the horizontal stabiliser with the whole rod system weighing under 22g. This was a very easy design choice as carbon fibre offers superior specific stiffness and tensile strength. The alternative would have been a complex balsa wood rib structure which would likely be heavier and weaker which are properties we did not want to have in the tail as significant flexing would result in unpredictable flight characteristics.

Landing Gear

The landing gear uses a taildragger approach such that during takeoff with payloads attached the landing gear will provide sufficient clearance so that we do not collide with anything on takeoff. The undercarriage must also have enough stiffness to withstand the landing as with 4kg of payload this will be a large force exerted onto this component. This need for additional strength not only causes the landing gear to be designed with strength in mind but also greatly affects the method of attaching to the wings. This is done by a 3D printed joint in PLA+ which will distribute all of the load into the carbon wing spar which is more than strong enough to withstand the sudden deceleration and is glued to the balsa wood wing ribs and spars for extra torsional stiffness.

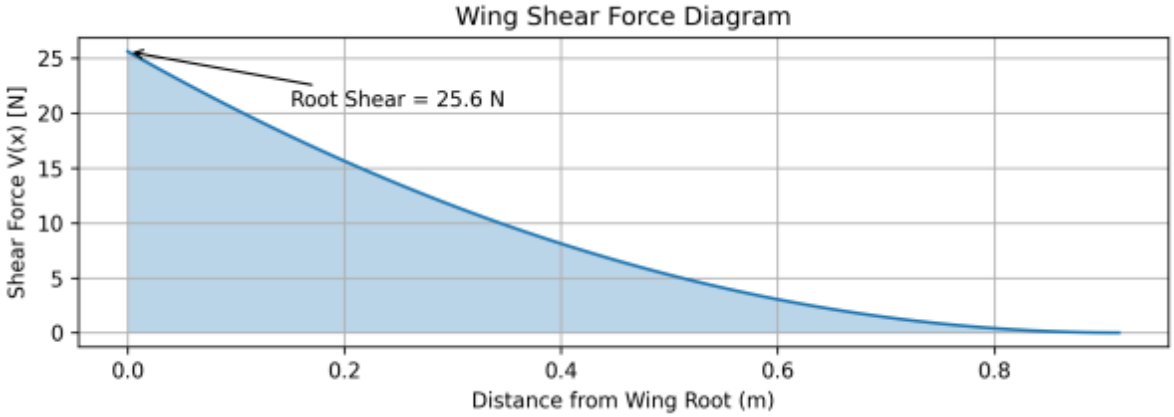
When designing this component, weight saving has been a big priority as usual but is especially relevant with this design as with an exposed part the frontal surface area will negatively affect the flight characteristics due to increased drag. For this reason we have chosen to use a simple single carbon fibre tube which extends from a joint location on the wing spar. This ensures that the smallest and lightest structure can be used while also maintaining sufficient strength for a fast landing which will occur with the 4kg payload as shown in the flight performance section of the report.

Short carbon fibre tubes have also been used for the main landing gear struts as they give superior strength to weight ratio compared to 3D printed parts. They also offer slight felixing which will reduce the rate of change of momentum hopefully making the design more reliable and increase rigidity. Besides the obvious structural gains of the carbon due to their small profile they will also reduce drag of the undercarriage. Rubber wheels for the landing gear have also been chosen as this will further reduce the impact force on the airframe and absorb some shock during landing.

Shear Force

To minimize the likelihood of a shear force structural failure the wing is created using a continuous carbon fibre tube which will not under the loads expected in normal flight shear. Horizontal and vertical stabilizers also are constructed in this way and are very unlikely to shear.

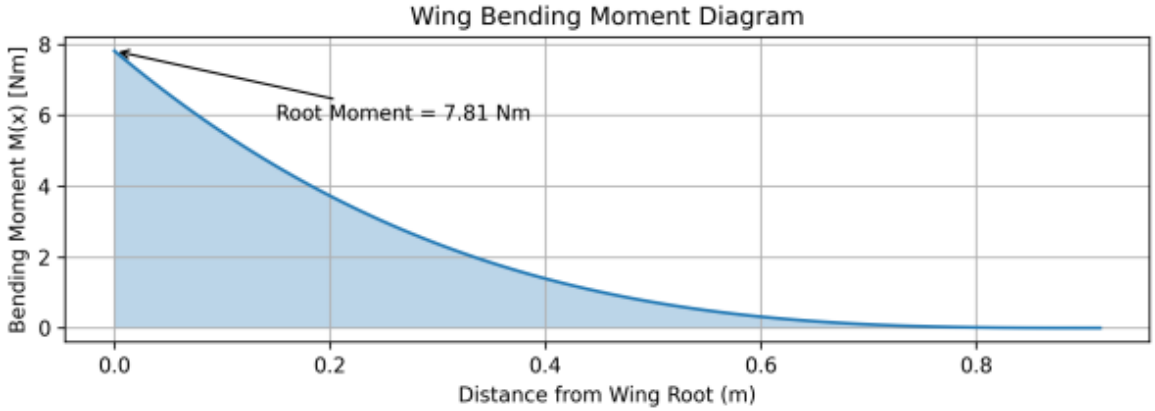
Below is a diagram showing how the shear force will change as lift loads decrease linearly from the wing tip.



However, although the majority of wing loading will be experienced though the carbon spars there will still be significant forces exerted on the 3D printed components such as the torsional force exerted onto the D-box front section. Due to the layers of 3D prints if not carefully designed these parts will almost instantly shear and crack at the layer lines. This was avoided by orienting the 3D print layers so they are parallel to the direction of force. This means that the force is experienced perpendicular to the 3D printed layers. This will increase the strength and resistance to shear force.

Stress Analysis

When stress is considered through the wing section the load path for a vertical force at the wing tip which can simulate the lifting force of the wing. Due to the nature of the wing's construction the forces will be transferred into the carbon wing spar via the balsa wood ribs which will transfer the lifting loads from the covering film into the solid structure of the aircraft. This force will result in flex from the wing structure due to the moments experienced in the diagram below.



This is expected and an extension can be found. Approximating the load on the wings as linearly decreasing towards zero towards the wingtip, the following formula is used to calculate wingtip displacement.

$$D_{max} = \frac{WL^4}{30EI}$$

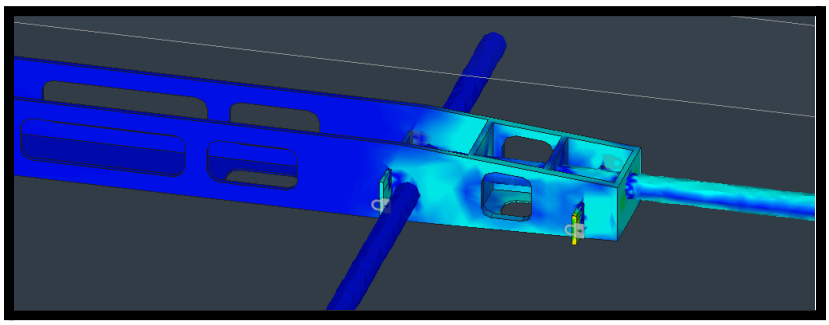
Since the carbon spar is a hollow tube, the moment of inertia is as follows:

$$I = \frac{\pi}{2}(r_1^4 - r_2^4)$$

This gives a result of 1.74 x 10^{-9} m^4.
Here, W is the maximum load intensity, which is equal here to twice the total force over the length. The total force for each wing should be approximately half the weight of the aircraft, that being 5.9, 16 and 26 N for 0, 2 and 4 kg payloads respectively. Given the length of each wing is 0.915 m, the values of W are 13, 34 and 56 N m^{-1}. The carbon fibre has a young modulus of 1 x 10^{11} Pa, so the formula gives wingtip displacements of 2, 5 and 8 mm.

From these calculated values for the wing flexing this shows that we are well within an acceptable region for wing movement even with a 4 kg payload. This also means there will be a reduced buckling force acting on the balsa spars and as a result the wing will be able to withstand much more than expected forces experienced during the 4kg payload round.

Significant stress will also be exerted onto the fuselage which is constructed using 5mm balsa sheets. The Fuselage has sections removed for weight saving and servo cable routing. This causes concentrated stress through the balsa wood sections which are remaining. To ensure that we had sufficient material remaining for the fuselage we used the fusion static force simulations shown below which allowed us to identify the areas of the fuselage which did not require as much reinforcement.

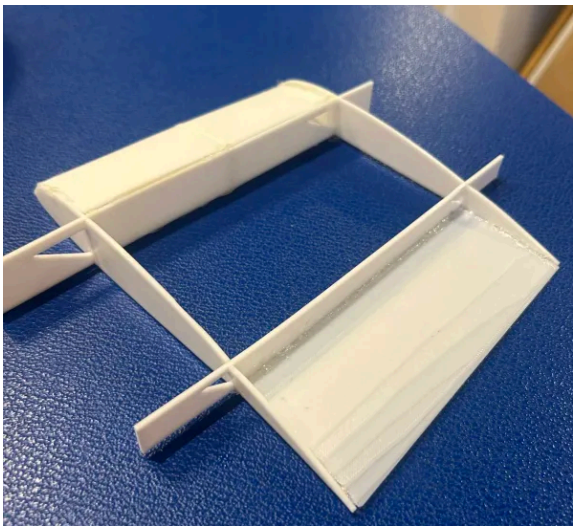


As the simulation showed significant strain in the rear of the fuselage. This is due to the tail boom and wing spars joining in this area. We then removed the frontal sections as they did not require as significant reinforcement. As seen in the drawings the fuselage has sufficient reinforcement such that the bending moment exerted by the tail boom and mass of the tail will be handled easily. Even when a larger moment is produced due to wind or control surface deflection due to this reinforcement of the boom we do not expect any structural failure as we are well within the safe region.

Empirical Testing and Assembly

Wing design assembly

Throughout the design of our aircraft we performed limited computational methods of testing and design validation and opted for quick prototyping and maths approximations to validate our design decisions as we believed we wouldn't be able to replicate the material composition of 3D prints or the variable density of balsa wood easily on a computer. Also trying to refine a CFD model or use static analysis to the maximum potential would most likely return data completely unrelated and unhelpfully due to our inexperience and lack of understanding of the software so we tried to stay away from this for the majority of development.



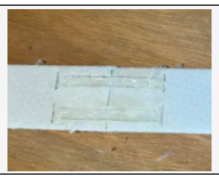
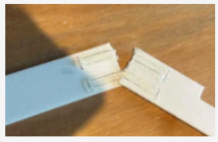
Shown on the left was the first physical prototype of a main wing section with no weight saving at this point but it showed to us that our rib and spar connections are sufficiently strong for the use. The torsional stiffness and tensile strength of the spars was also enough for basic sizing estimates of a larger wing section which we would later develop in full scale. However this design was fabricated before we had decided to use a woven carbon tube as the main source of strength of the wing as later testing showed that the 3D printed spar connections would not be sufficient for the wings to withstand forces experienced during flight.

What we were able to gather from this initial test though was that a fully 3D printed wing could work and was strong. However with no weight saving yet at 60g for only a 15cm wide section we knew we could do better as if the whole wing were to be fully 3D

printed it could weigh almost 800g. Also this was assuming a continuous spar but during real assembly spar joints would have to be made not only creating weak points in the structure but also increasing weight.

Wing Spar Testing

The max printable size using the 3 printers that we had available was 235x235 which for a 1830mm wing span poses an issue. This resulted in the development of spar joints needing to be designed. Shown below are 3 different approaches to solve this issue.

Joint	force max	mass of joint	Nature of break	Joint before test	Joint after test
1	75.3N	12g	At 5kg began to denature but the instant mass was removed it returned to oringial shape. Plastic deformation began at 6kg and then there was a shear		
2	82.1N	12g	at 6kg began to denature. Plastic deformation bgan at 7kg and the joint sheared at 7.6kg		
3	65.5N	14g	Denature began at 5kg then the joint sheared at 6kg of added mass. Unlike other tested joints this sheared not at the joint but before suggesting the joint transferred the force badly into the spar		

Testing control variables

- all spar testing was performed with lateral support such that buckling and bending perpendicular to the force's applied plane was significantly reduced.
- testing included each mass being loaded for 60 seconds before increase in mass to simulate longer term use such as an extended heavy payload flight
- All joints followed the exact same profile, the only difference was the joint
- The spar samples were each 235.00 mm long and had force applied 85mm perpendicular from the joint ensuring that force moments on each spar was the same throughout all tests.

The results gathered show how each joint performed against a bending moment but in reality would only be able to support a much reduced force as the spar would buckle sideways due to the testing rig being removed and the wing would collapse catastrophically failing due to the buckle.

This showed us that 3D printed parts would be possible if they were thicker to reduce buckling but this wouldn't allow us to reach our weight goals and due to the nature of 3D printed components they would be too heavy to provide the strength we would need for a 2m wingspan relative to other materials. This called for a change in design philosophy and we opted to use a 2m woven carbon tube of a 14mm outer diameter to reinforce the wing. This would be placed at 75% of the chord and would stretch the full length of the wing providing the majority of the strength and resistance to bending moments.

As we knew the 3D printed spars would no longer be the main source of strength we focussed on weight saving which led to a big shift in material usage. As the spars now would be only there for torsional bending resistance this requirement doesn't suit the 3D printed parts and balsa wood became the standard for the wing construction where all spars, ribs and cross bracing would be made from 5mm and 3mm balsa sheets providing superior stiffness to 3D printing.

Assembly

For the final assembly of the plane we have started and are building outwards from the fuselage. As the carbon tube is continuous all parts for the wing will slide onto this tube allowing for perfect fitment between parts. The purchased tube is 2000mm in length and the actual wingspan is 1830mm giving us a large tolerance region in case our wing assembly is significantly longer than we expect. For almost all parts we are first printing the component to ensure that our dimensions are correct before using our limited supply of balsa wood to test fit the components.
For easy transport the aircraft is designed to be separated via removal of the tail boom from the fuselage. This means that we will have to reattach the front and rear section causing a potential weak spot in the design if not performed correctly however this is the best solution to solve the transportation of a large model.