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MECH 4860 ENGINEERING DESIGN

FINAL DESIGN REPORT

Rapid Prototype Manufacturing for an Advanced Composite Wing Structure

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Dr. Paul Labossiere,

The following report details the final design of Team Kinect12's Engineering Design Project, titled *Rapid Prototype Manufacturing for an Advanced Composite Wing Structure.*

The team has developed a manufacturing process for a small airplane wing which utilizes rapid prototyping and carbon fibre materials to produce a wing structure that is strong, lightweight, and can be assembled very quickly.

This report has been submitted to our advisor, Dr. Vijay Chatoorgoon as well as our client, the Composites Innovation Centre. It marks the completion of Phase III of the Engineering Design course. The next and final instalment in this course will be the Poster and Oral Defense on December 6th, 2011.

Sincerely,

Cameron Mazurek
Project Manager

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GLOSSARY OF TERMS

Airfoil – the shape of an airplane wing's cross-section

Build-up material – a dissolvable material used in rapid prototyping that supports the primary material against gravity while the primary material solidifies

Canard – a horizontal stabilizing surface on an airplane that is in front of the main wing [1]

Chord length – the distance on an airfoil measured from leading edge to trailing edge (root chord length: at the fuselage; tip chord length: at the wing tips) [2]

Dihedral – the upward angle of the wing of an aircraft measured from the horizontal

Integrated fixturing – items used as fixtures during the assembly of a structure and that become part of the final structure

Leading edge – the forward edge of a wing; the first point of contact with the air

Module – one section of an entire frame

Nodal frame – a frame that locates important features of a structure at various locations (nodes)

Quarter-chord – ¼ of the chord length measured from the leading edge; the centre of pressure on a symmetric airfoil (where the plane's load is absorbed by the wing)

Rapid prototyping – automatic construction of 3-dimensional objects by joining material layer upon layer based on computer-based 3D model data [3]

Span – the length of an airplane wing, measured tip to tip (perpendicular to the chord length)

Spar – the main structural member of an airplane wing

Specific strength – the strength of a material divided by its density

Trailing edge – the aft edge of a wing; the last point of contact with the air

Veneer – a thin and flexible sheet of laminated carbon-fibre

ABSTRACT

The Composites Innovation Centre (CIC) requested Team Kinect12 to design a **nodal frame** manufacturing process for a small airplane wing using **rapid prototyping (RP)**. The final design consists of nine lightweight shell-like **modules** which are fabricated by an RP machine. The size of the modules was optimized to the capabilities of the RP machine available to the CIC. These modules define the wing surface profile and locate carbon fibre materials within the structure to provide strength against bending and torsion. A carbon fibre rod is held in place by the modules from tip to tip at the **quarter-chord** for bending strength. Carbon fibre **veneers** are applied over the frame to resist torsion and make up the wing surface. Internal carbon fibre braces are contoured to the wing surfaces and connect these surfaces to the spar to ensure the flight load is not transferred through the weak RP material. Each module requires twenty hours of manufacturing time in an RP machine [4], and the total build time for the wing is estimated at 20 minutes. Recommendations are for further weight reduction by removing material from a bulky **leading edge** section and for geometry changes to crevices in the modules that will assist with the removal of undesirable **build-up material** after the RP fabrication process. The designed manufacturing process very appropriately utilizes the capabilities of RP, and when compared to traditional methods, provides a structure that can be assembled quickly and easily.

1. INTRODUCTION AND BACKGROUND

The CIC required Kinect12 to use RP in a manufacturing technique for a composite structure. The structure particular to this design project is a wing for a small unmanned aerial vehicle (UAV).

The CIC is a not-for-profit corporation that supports manufacturing industries by assisting in the development and commercialization of current and new composite applications. They hope to expand the use of RP technology in the industry by using RP parts as **integrated fixturing** together with adhesives and high specific strength materials (such as carbon fibre) to form stiff, lightweight structures [5].

RP can produce complex and lightweight parts rapidly, precisely, and at very low cost when compared to traditional tooling methods such as milling and casting. RP initially involves transforming a three dimensional computer aided design (CAD) model into thin, virtual, horizontal cross-sections. The physical piece is then created by depositing many successive layers of material characterized by the thin cross-sections until the model is complete.

The CIC has provided the characteristics of the UAV wing that this manufacturing process is to be designed for, which is shown in Figure 1. The UAV is a pusher style aircraft, which means the engin is rear mounted to allow for a front-mountable camera. The expected weight of the entire UAV and its cargo is 5 *lbs* [5].

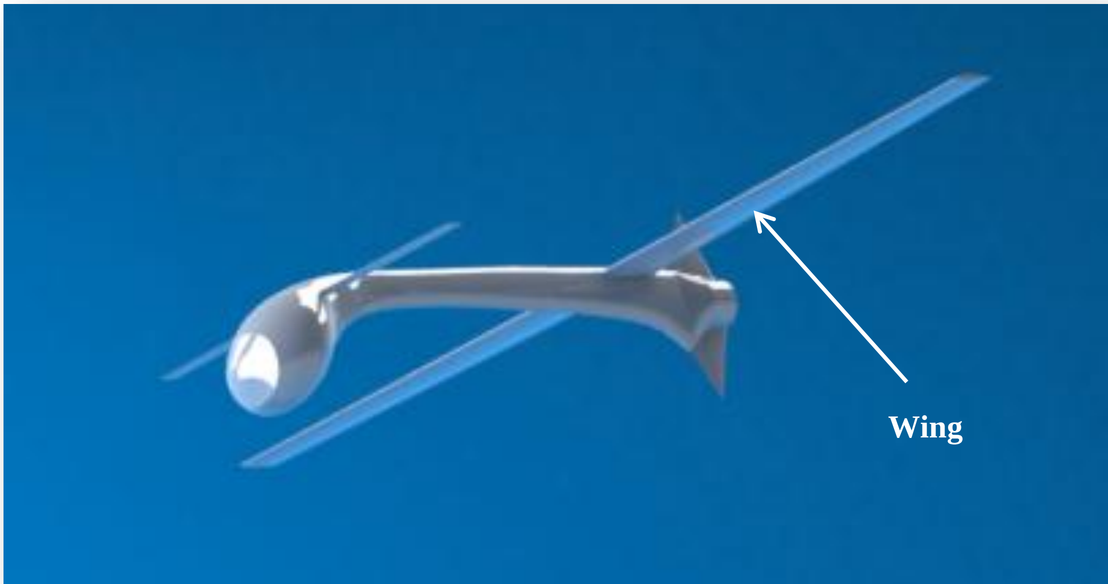


Figure 1. UAV concept with rear-mounting engine and a port for a front-mounting camera (facing forward) [5]

This UAV uses a **canard** wing system, however only the aft wing shown in the above figure is relevant to this project. Additional characteristics were provided by the CIC and are as follows:

- MH 200 **airfoil**
- Root **chord length**: 8 in
- Tip chord length: 5 in
- **Span**: 60 in
- 2° **dihedral**
- Aspect ratio: 9.23
- Area: 388.8 in^2

1.1 OBJECTIVES

At the beginning of the project, a meeting was held with the CIC to establish the following deliverables [5]:

- Nodal wing design utilizing RP
- CAD model of the modularized wing or fixturing
- Description of the advanced composite elements specific to the design
- Assembly process steps
- Estimated weight
- Estimated cost

The team then established the following target specifications for the project that are based on the discussions with the client:

- Manufacturing and assembly must be easy and repeatable
- The wing should weigh as little as possible and no more than 1 lb
- The wing must structurally capable of lifting and supporting a 5 lb UAV
- The process should highlight the complex geometry and lightweight capabilities of RP
- The process should avoid the traditional methods (rib & spar, foam cut) of small UAV wing construction
- The process should be applicable to other structures

1.2 TRADITIONAL WING CONSTRUCTION METHODS

Traditional small UAV wing structures are made from foam. This foam is cut using a hot wire cutter and gives the shape of the wing. Foam is a desirable material since it is lightweight and can be easily reinforced for bending with wood, as shown in Figure 2.

Figure 2. Foam wing shaped with hot wire cutter reinforced with wood [7]

The end product is acceptable; however complex geometries such as taper and dihedral become very difficult to implement using this method. Since taper and dihedral are desirable characteristics in the design of a wing, the lack of these directly decreases the wing's effectiveness.

Further disadvantages to this method are that the foam cutting step is done by hand and will often require numerous attempts before successfully obtaining a piece of foam without any defects in the airfoil shape. This results in the process taking a significantly long time to complete. Some other time consuming steps in this process are manufacturing the die for the hot-wire cutter, sheeting the foam with a smooth plastic, and cutting the channel for the spar. The UMSAE Aero Design Team reported that this method can take over three hours to complete [8].

Further communication with the UMSAE Aero Design Team was regarding another common method for manufacturing small airplane wings. The team uses a rib and spar method for their yearly competition which is shown in Figure 3.

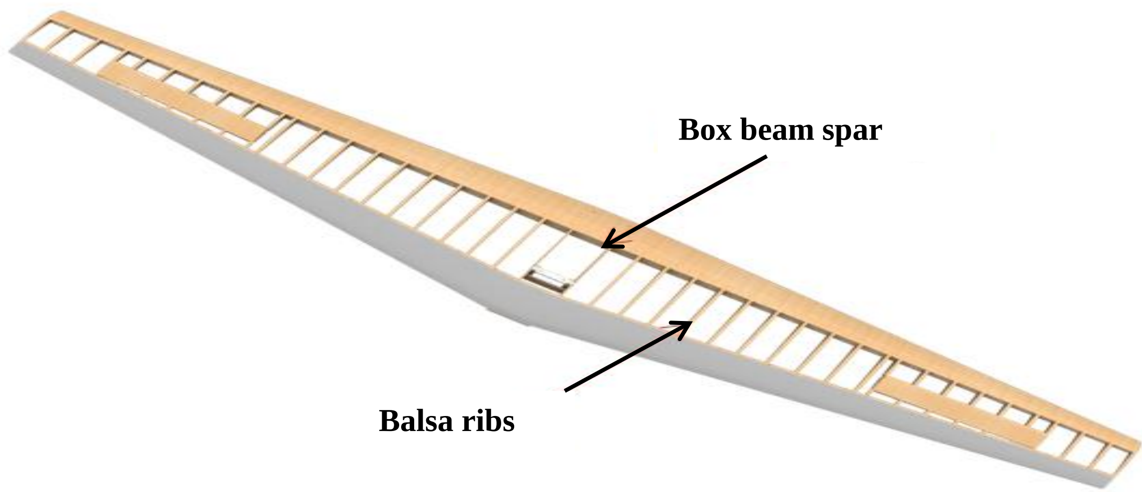


Figure 3. UMSAE Aero Design Team rib and spar wing construction method

This method consists of a box beam that is equal in length to the wing span. The beam is constructed of a hard wood and is supported by balsa shear webs. Balsa ribs are used to provide the airfoil shape at approximately 4 in intervals along the box beam spar. This combination of woods provides a strong structure, however it takes approximately 48 hours to assemble [8].

2. DETAILED DESIGN

This section presents the final design of the RP nodal frame manufacturing method. The composition of the wing structure is given with justifications included for each component. A manufacturing overview provides some additional information on RP and the cost analysis compares the prototype wing cost against potential production systems that will reduce the cost of each structure. Recommendations are given based on a prototype component that was manufactured with RP.

2.1 FEATURES

The wing design consists of RP frame modules, carbon fibre veneers, webs, and a spar. The frame modules connect to each other to form an entire frame of the wing and also locate the structural carbon fibre spar and braces. The veneers are adhered to the exterior shell to provide torsional strength for the wing and additionally provide the airfoil surface. The spar is a rod that was selected to provide high specific strength and covers the entire span of the wing at the quarter-chord. The final items are called braces, which connect the top and bottom airfoil surfaces to the spar. The braces prevent the distributed load on the airfoil from being transferred through the weaker RP material.

Almost any geometry imaginable can be fabricated in an RP machine as long as it can be modeled in CAD. Proper application of carbon fibre rods and veneers over and inside this type of frame will provide a strong, lightweight structure of any shape. For this reason, the process detailed in the following sections can be implemented in other structures.

Each of the four items in the wing design is now described in detail, including the relevant engineering analyses for the spar and veneers.

2.1.1 Frame

The frame is produced in nine different modules. The modules can be printed any time in advance of the actual assembly of the wing. The modules are sized to the maximum sized part that can be produced in the available RP machine, which has maximum dimensions of $10''$ x $10''$ x $11''$ [5].

The RP material is a thermoplastic called acrylonitrile butadiene styrene (ABS), which has a density of 0.0375 lb/in^3 [9]. The largest module is 8 in wide, with a weight of 0.061 lb. All of the frame modules together add up to the total span of 60 in and a total weight of 0.5 lb. This structure is extremely lightweight because of a 0.03 in thick cross-linked shell design, which is shown in Figure 4.

In addition to locating the airfoil surface and structural elements, the RP modules have the **leading** and **trailing edges** of the wing built in. This is because the veneers are unable to bend around the very small radii of the leading and trailing edges. There is minimal torsional load on leading and trailing edges of an aircraft wing, therefore strength from the carbon fibre materials was not required [10]. The physical features of one frame module are labelled in Figure 4.

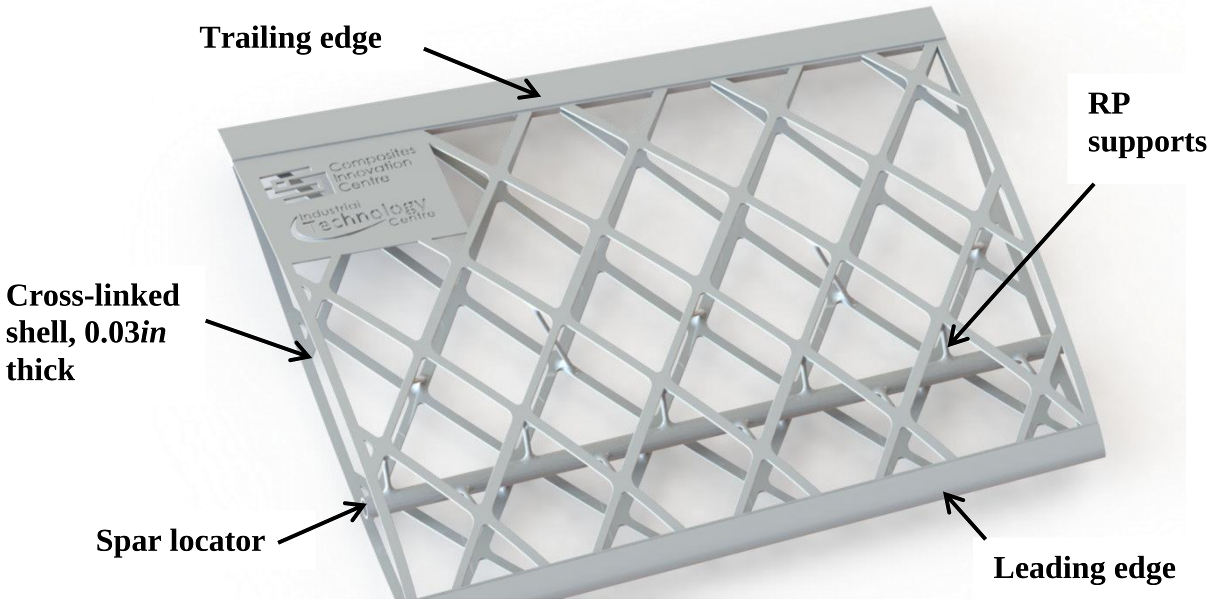


Figure 4. Modularized wing section

The spar locator is along the quarter-chord of the airfoil. There are numerous RP supports within the modules to provide support when physically applying the veneers onto the frame and, in addition to the carbon fibre braces described in Section 2.1.4, to allow transfer of the load from the wing surfaces to the spar.

2.1.2 Carbon Fibre Veneers

The carbon fibre veneers have an adhesive backing and are placed overtop the RP modules to create the wing surface. The veneers selected are from DragonPlate™, an online retailer for carbon fibre composites that the CIC specified as their preferred source [5]. They are 0.018 in thick, have a shear strength of 86 MPa, and a bending diameter as low as 1 in which is demonstrated in Figure 5 [11].

Figure 5. DragonPlate™ carbon fibre veneer with adhesive backing [11]

There are torsional loads on an airplane wing due to the uneven lift distribution along the length of the chord. A worst-case torsion analysis was conducted assuming that the veneers form a rigid shell which can absorb the torsional load on the wing. This shell is considered as a thin-walled member and therefore the torsion analysis is relatively simple.

For this analysis the full weight of the aircraft is assumed to act on the trailing edge of the airfoil and the point of rotation is about the leading edge to give the largest moment arm length. The load actually acting on a cross-section will be a distributed load much less than the 5 *lb* magnitude we have assumed, and the couple will be around the quarter-chord rather than the leading edge, resulting in a shorter moment arm being in the actual case. We can conclude that the wing design is sufficient with respect to torsional loading if the applied torsional load from this worst-case scenario is calculated and determined to be less than the calculated allowable torsional load that follows.

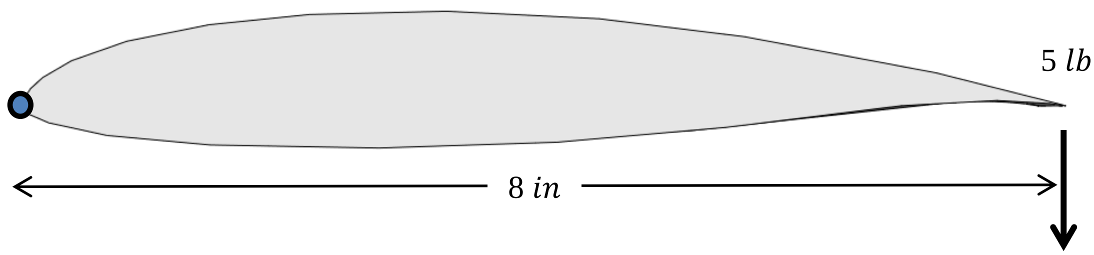


Figure 6. Torsional load free-body diagram showing force and moment arm

The total load on the aircraft is 5 lbs and the length of the airfoil is 8 in. Therefore, the maximum applied torsional load on the wing cross-section is

$$T = 5.0\ lb \times 32.17 \frac{ft}{s^2} \times 8.0\ in = 45.3\ lb \cdot in$$

As noted previously, the allowable torsion is calculated by assuming the wing is a thin, hollow shaft made up of the veneers. The smallest cross-section along the span is located at the wing tips and used for this calculation as it represents the weakest cross-section. SolidWorks, the CAD software used by Kinect12, reports that this area is 2.18 in^2. The shear strength of the veneer is 12.47 ksi [11]. The allowable torsion is calculated as

$$T = 2\tau t\alpha$$

Where τ is the shear strength, t is the wall thickness, and α is the mean area which is the airfoil area bounded by the centreline of the veneer surface.

$$T_{allow} = 2 \times (12.47 \times 10^3) \times 0.018\ in \times 2.18\ in^2 = 978.9\ lb \cdot in$$

The allowable torsional load of 978.9 $lb \cdot in$ is much greater than the worst-case scenario load of 45.3 $lb \cdot in$, therefore the design is suitable to withstand the inflight torsional loading.

2.1.3 Carbon-fibre Spar

The spar spans the length of the wing and provides the wing its bending strength. By symmetry, the analysis was focused on half of the span, from the centreline of the fuselage to one wing tip. Realistically, the load distribution over the wing is an elliptical distribution, however, for the purpose of the analysis the load distribution is approximated as an evenly distributed load as shown in Figure 7.

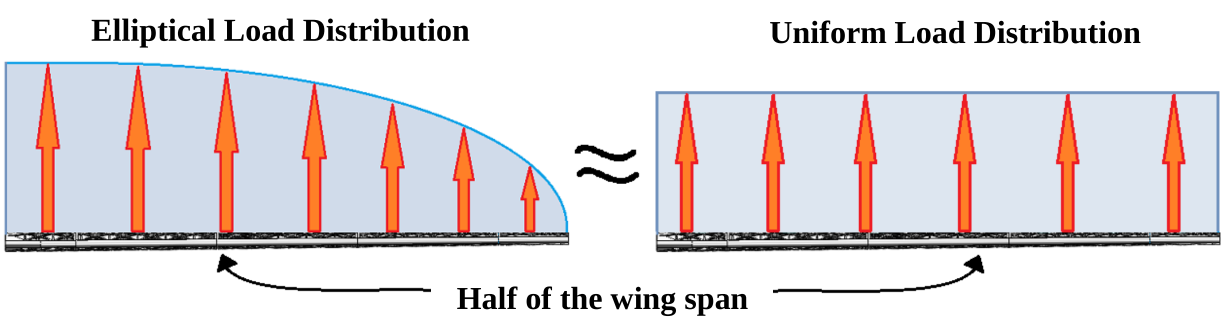


Figure 7. Schematic of elliptical load distribution and evenly distributed load approximation

Utilizing an evenly distributed approximation for a beam in bending is a conservative analysis.

Two main factors were considered when selecting the appropriate spar: its mass, and its maximum deflection due to the load. Minimizing deflection of the wing ensures that lift is not decreased due to warpage of the airfoil and it ensures that the weaker ABS material is not significantly stressed when the structure bends.

The maximum deflection, δ_{max}, for a cantilever beam in bending can be calculated as follows:

$$\delta_{max} = \frac{wl^4}{8EI}$$

Where w = 0.25 lb/in and l = 30 in over half the wing span.

The stress in the spar can be calculated with the following:

$$\sigma = \frac{My}{I}$$

Where the moment for an evenly distributed load is given by:

$$M = \frac{wL^2}{2}$$

The bending moment of inertia will depend on the cross-sectional of the spar being analysed. DragonPlate™ offers a variety of products that were considered viable spar options for the wing. These options are shown in Figure 8 on the following page, clockwise starting from the top left: pultruded tubes, strips, braided tubes, and solid rods.

Figure 8. DragonPlate™ carbon fibre tubes, strips, and rods [11]

The DragonPlate™ website specifies that the modulus of elasticity for carbon fibre is 20,000 *ksi*, the ultimate tensile strength is 500 *ksi*, and the density is 0.057 lb/in^3 [11]. An exception is found with the braided tubes, where the modulus is given as 34,000 *ksi* and the weight is specified in pounds per foot and varies with the size of the respective tube.

The options from DragonPlate™ were screened to those with a maximum diameter of ½ *in*, which is the maximum thickness of the wing's cross-section at the wing tip. Also, the wing deflection was calculated for each of the spar options and no option was considered if the deflection was above 4 *in*. Table I summarizes the carbon fibre spar candidates, ordered by mass to make it easier to view the lightest viable options.

TABLE I
CARBON FIBRE SPAR SELECTION CONSIDERING DIAMETERS LESS THAN 1/2″ AND DEFLECTION LESS THAN 4″

ORDERED BY MASS	Outer Diameter or Hieght (inch)	δ_{max} (inch)	mass of 5ft length (lb)
Solid Carbon Rod	0.5	0.0258	0.6715
Solid Carbon Rod	0.375	0.0815	0.3777
Solid Carbon Rod	0.315	0.164	0.2665
Pultruded Carbon Tube	0.472	0.768	0.258
Braided Carbon Fibre Tube	0.53	0.2845	0.25
Pultruded Carbon Tube	0.5	0.699	0.2417
Carbon Strip	0.5/0.125	0.972	0.21375
Carbon Strip	0.325/0.187	2.366	0.20785
Braided Carbon Fibre Tube	0.415	0.6714	0.2
Pultruded Carbon Tube	0.394	1.497	0.1942
Solid Carbon Rod	0.25	0.4125	0.1679
Pultruded Carbon Tube	0.375	2.03	0.1518
Carbon Strip	0.325/0.125	3.539	0.1389
Pultruded Carbon Tube	0.315	3.917	0.1131
Carbon Strip	0.437/0.07	2.6	0.1046
Solid Carbon Rod	0.187	1.318	0.0939

A solid carbon rod with 0.187 in diameter was selected which will keep the wing as light as possible. With a maximum deflection of 1.318 in due to the given load, the respective stress in the spar is 175.24 ksi, which is 35% of the ultimate strength noted above.

2.1.4 Carbon-fibre Braces

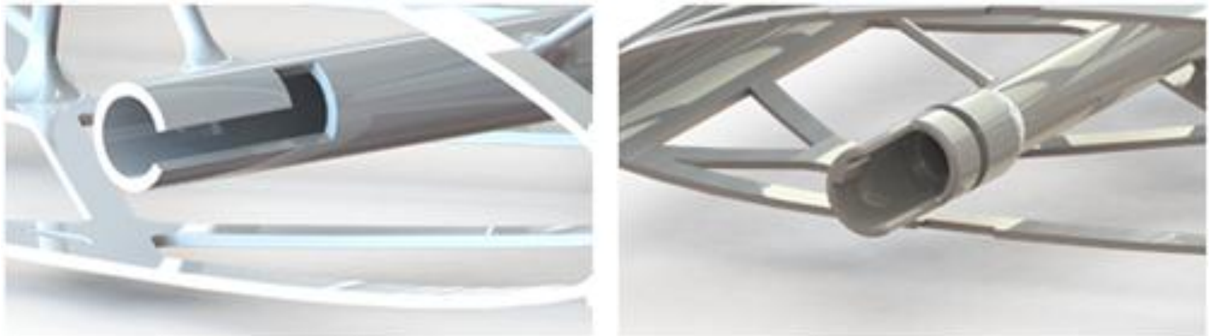
The braces are cut out of the stock carbon fibre veneer material. They connect the airfoil surfaces to the spar at the interfaces between each of the frame modules, as shown in Figure 9.

Figure 9. Load transferring carbon-fibre brace

After fabricating the frame modules and cutting all of the carbon fibre veneers, installing the braces is the first step during assembly. The following section details the entire assembly procedure.

2.2 WING ASSEMBLY

After installing the braces at the male end of each module the frame can be assembled by locking each of the nine modules together using a twist-lock interface on the spar locators (refer to Figure 4 for the spar locator). The twist-lock interface is shown in Figure 10, where one of the joining modules will possess a female connector and the corresponding module will possess the male connector.



Female Connector **Male Connector**

Figure 10. Twist-lock RP module connectors on either side of each wing section

The spar is inserted down the hollow spar locator running through all of the RP modules. An epoxy can then be inserted at the carbon fibre brace and spar interface to ensure the braces are connected directly to the spar (Figure 9). The veneers with adhesive backing are then placed over the surface of the wing shell (Figure 11) where the sides of the veneer sheets butt against a lip of equal thickness at the leading and trailing edges of the wing structure (Figure 12).

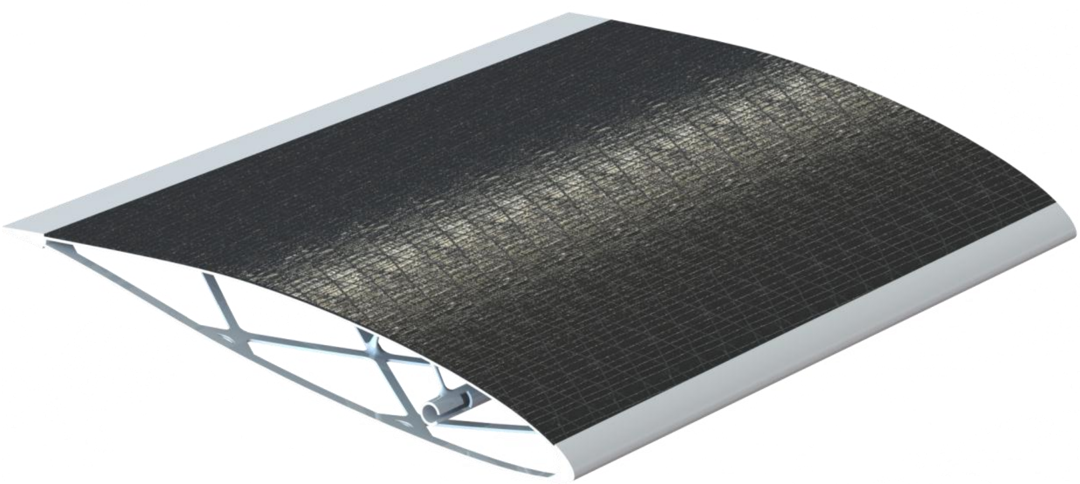


Figure 11. Carbon-fibre veneer adhered to frame module to make up the wing surface

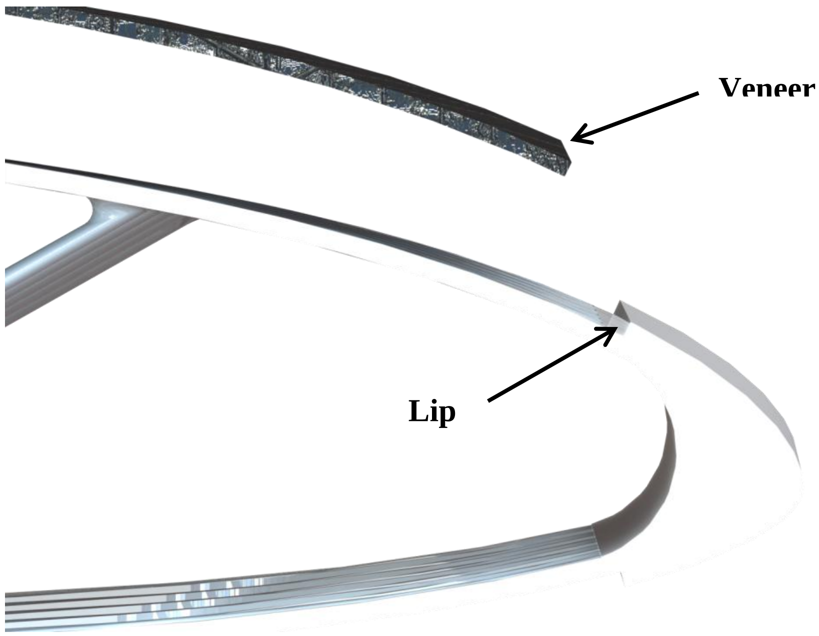


Figure 12. Lip in frame module leading edge for a flush fit with the veneer (side view)

One of the nine modules is as wide as the fuselage and serves as the interface between the wing and fuselage. The remaining eight modules are four mirror-image pairs since the wing is symmetric about the fuselage. Figure 13 demonstrates the fuselage module with half of the wing.

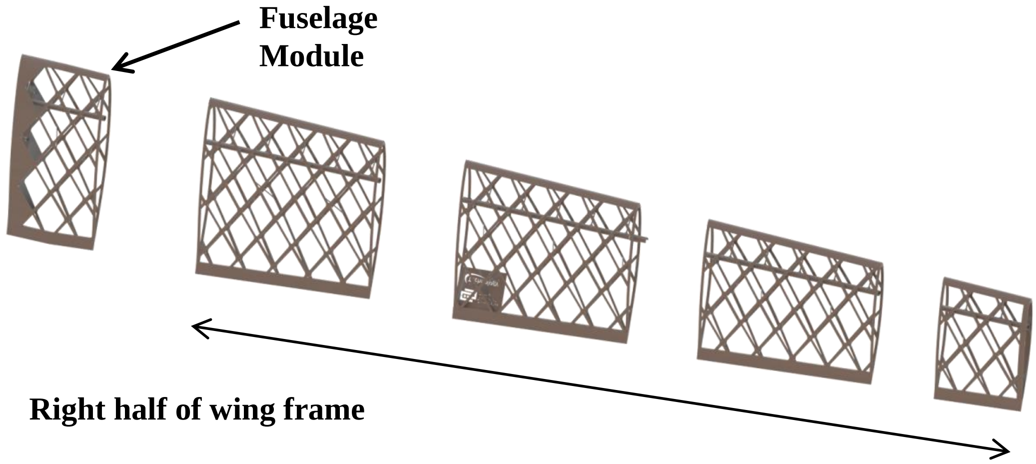


Figure 13. One half of the wing modules shown in exploded view

The veneers are cut into 2 sections and each covers one side of the wing. The veneers do not overlap and they provide additional rigidity to the structure by covering the interfaces between frame modules. Finally, more veneer material will be placed on the ends of the wing tips to finish enclosing the structure. The right half of the wing is shown below in Figure 14 labeling the veneers, braces, modules, and spar.

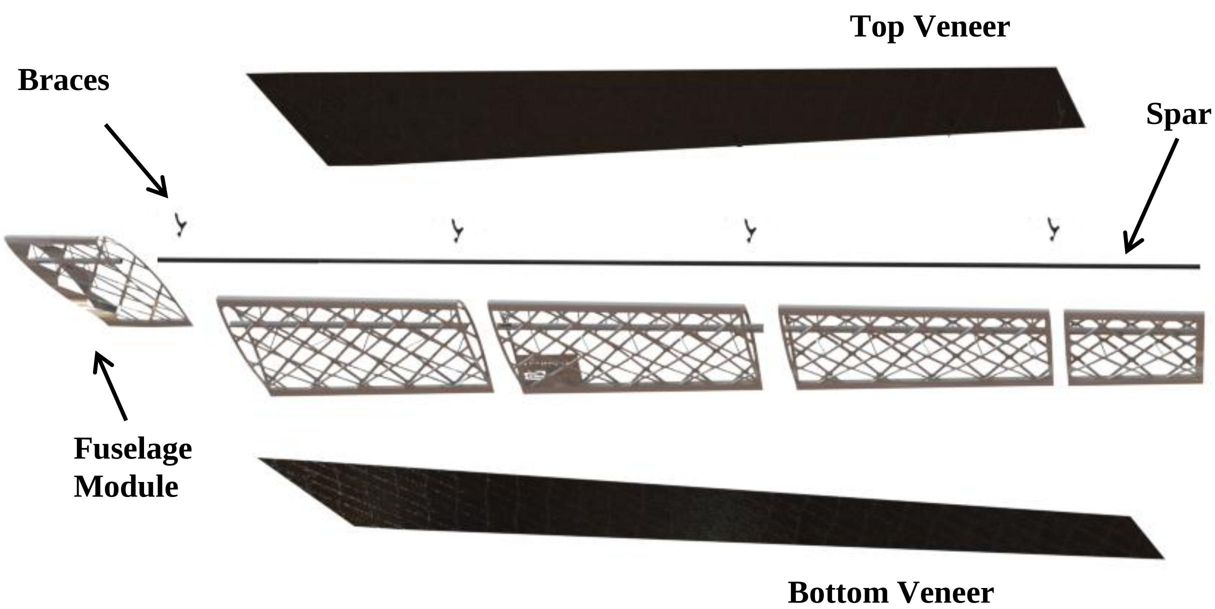


Figure 14. Exploded view of one half of the wing assembly

The estimated assembly time for the whole wing is approximately 20 minutes with the modules being pre- fabricated, and the veneer sheets already cut to size. The fabrication of these modules will be discussed in the following section. The very short assembly time for this process provides a desirable advantage over traditional wing manufacturing methods as previously discussed in Section 1.2.

2.3 MANUFACTURING

The process of manufacturing the frame modules with RP is detailed in this section. The carbon fibre materials are readily available and thus there is no requirement for internal manufacturing.

2.3.1 Rapid Prototyping

Rapid prototyping is an automated process which uses additive manufacturing technology to create solid objects. Additive manufacturing is a type of process where material is deposited to build up a solid object. This is opposed to traditional subtractive manufacturing where you begin with a block of material and then remove (via cutting, drilling, grinding ect.) material to obtain the final desired product. Additive manufacturing for rapid prototyping takes designs from CAD models, processes them into thin, horizontal cross-sections and then creates successive layers of cross-sections until the model is complete. The particular system used for this project deposits thin layers of heated material to create the part. Two types of material are used; ABS for the model structure and build-up material which supports the ABS during the manufacturing process. Figure 15 shows a section of the wing being rapid prototyped. The white coloured material is the ABS and the dark brownish material is the build-up material. Once the part is completed, it is placed in a bath of sodium hydroxide at 70°C where the build-up material is dissolved leaving only the ABS material intact. Note the build-up material is not described as it is proprietary to the RP machine company.

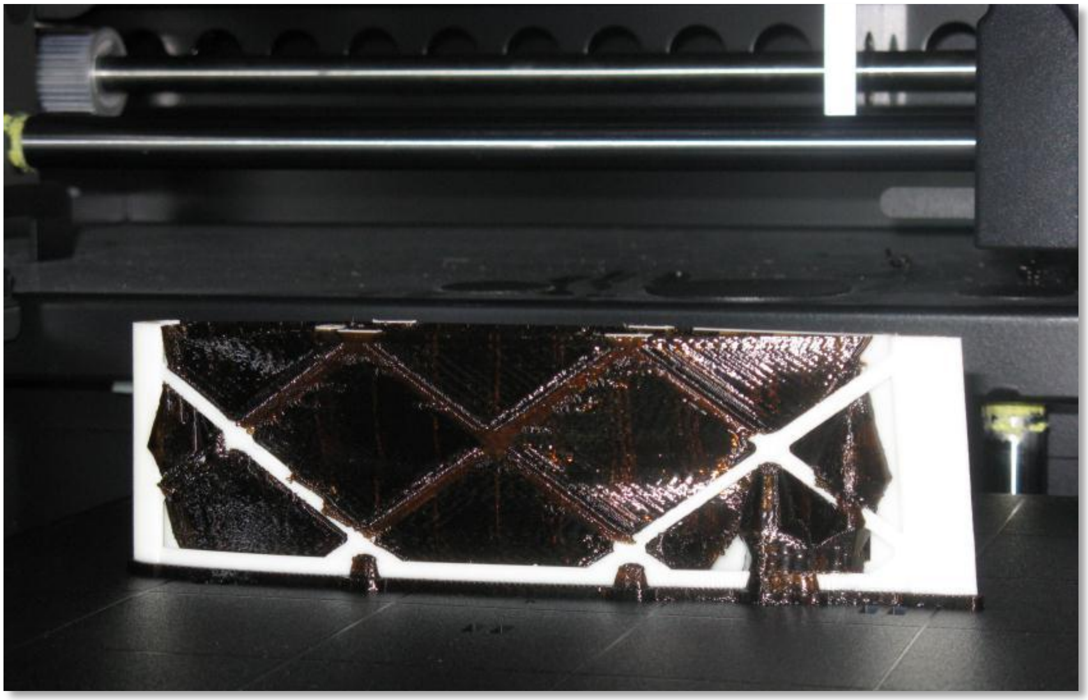


Figure 15. Rapid prototyping of wing design concept

Manufacturing the frame modules is limited by the speed at which the RP machine can operate, as well as the number of machines available to simultaneously produce parts. the machine takes approximately 20 hours to produce one module This time is based on the production of a prototype frame module with the Industrial Technology Centre in Winnipeg, Manitoba.

2.4 DETAILED COST ANALYSIS

Four veneers will be required so that each half of the wing adjacent to the fuselage can be covered in two pieces (one for the top and one for the bottom). DragonPlate™ provides 12 x 36 in veneers at a cost of $98.64 (USD) [11]. After these veneers have been cut to the appropriate shape with a template, the extra material can be cut to shape for the wing tips and the braces.

An epoxy is also required as a fastener between each module. The epoxy is obtained from DragonPlate™ at a cost of $38.99 (USD).

The solid carbon fibre spar of 60 in length and a diameter of 0.187 in can be purchased at the best price from ACP Composites at a cost of $19.75 (USD) [12].

The remainder of the cost is from producing the RP frame modules. This cost is proportional to the volume of the structure being printed as well as the time used on the RP machine. One prototype module has been produced by Industrial Technology Center (ITC) at a cost of $500 (CAD) [4]. Nine such pieces are required for a complete wing structure which would cost $4500 (CAD) total for material cost, machine time, and labour.

Table II is a summary of the costs for manufacturing one full wing structure.

TABLE II
COST SUMMARY OF PROTOTYPE UAV WING USING RP MANUFACTURING METHOD

Section	Item	Cost (USD)	Quantity	Subtotal
SPAR	0.187"x96"	$19.75	1	$19.75
VENEERS	12" x 36"	$98.64	4	$394.56
RP		$500.00	9	$4,500.00
ADHESIVES	Epoxy 3.3 fl. Oz.	$38.99	1	$38.99
Total				**$4,953.31**

The total cost to produce the prototype wing is $4,953.31 before taxes. It is important to note that this price would not be the cost of one unit if the design were to be produced in large quantities.

The carbon fibre components and adhesives are available at discounted prices when ordered in large quantities. The suppliers sourced provide discounts of up to 20% in orders over 100 units. More importantly, the cost of RP decreases as batch size increases, meaning that if large quantities of the wing are produced, the cost per unit of each wing may be reduced.

It is worthy to note that the cost of the RP components contributes to 90% of the total cost of the wing. As RP technologies improve and become more widespread, it is likely that the costs associated with printing a three dimensional part will decrease, which in turn will increases the feasibility of this design..

It is also feasible to consider that RP machines could be purchased to produce these parts internally. ITC has stated a cost of $50 for material and $10 of electricity to manufacture the prototyped wing section The external charge is $500 per part and the machine they use to manufacture the parts has a cost of $32,000 [4]. If the CIC was to purchase a machine, each part would cost approximately $60 which is a savings of $440 over what ITC charges to manufacture one part. The result is that they would need to manufacture 73 individual sections to break even on the total manufacturing cost. 73 pieces is equivalent to 8 full wing structures plus one extra section, therefore if it was desired to manufacture at least 9 full wing structures it would be economical to purchase an RP machine.

2.5 PROTOTYPE FRAME MODULE

As previously mentioned, the CIC and the ITC have produced a prototype frame module for the design team to review. This provided the team with the fabrication time of a frame module, and highlighted some noteworthy areas for improvement on the current design. Shown in Figure 16 and Figure 17 is the actual frame module made of ABS after the sodium hydroxide bath which removes the brown, translucent build-up material that was seen previously in Figure 15.

Figure 16. Top view of prototype RP frame module with CIC and ITC logos

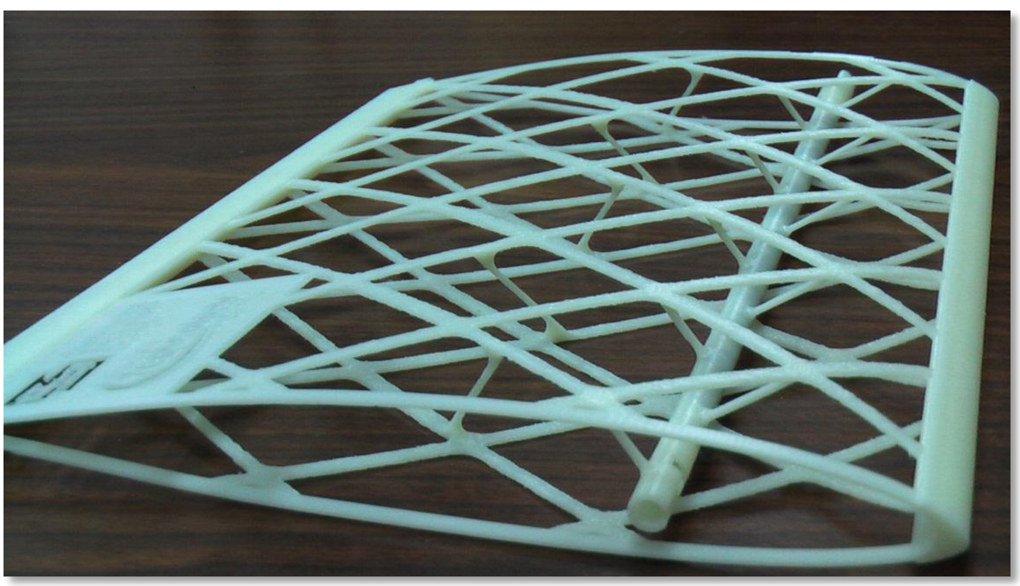


Figure 17. Isometric view of prototype RP frame module

2.5.1 Recommendations

By reviewing the prototype frame module, the following recommendations have been made for the next revision of this manufacturing process:

1. Lots of build-up material remains in the spar locator after over 12 hours in the sodium hydroxide bath. Add holes along the tube section which will allow NaOH to flow inside to wash away this build-up material.

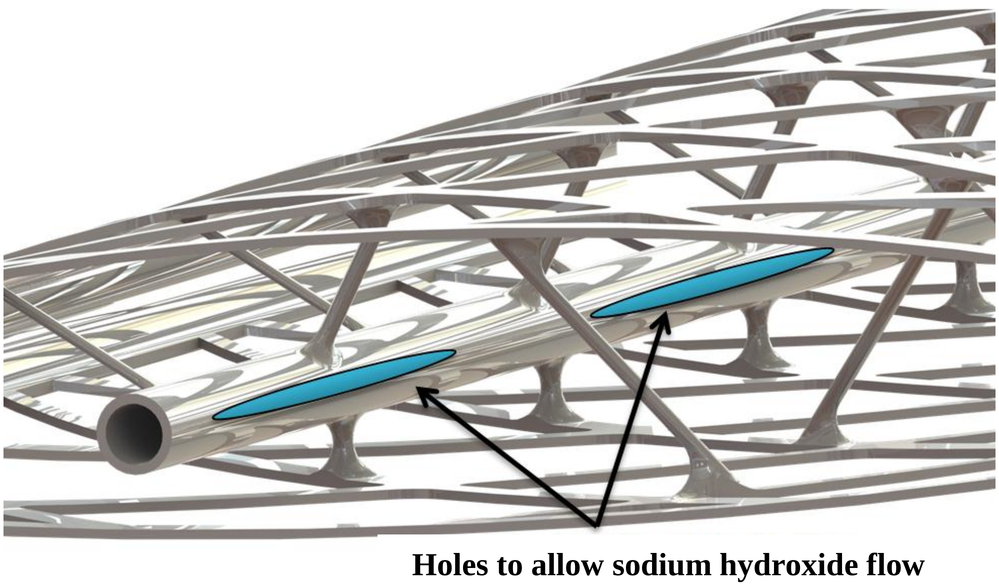


Figure 18. Remove material from spar locator to allow the NaOH bath to remove all build-up material

2. Extrude a hole through the thick leading edge section to reduce weight and fill with another carbon spar for greater strength. It was found that this section was unnecessarily heavy and could be replaced with the stronger, lighter carbon fibre material.

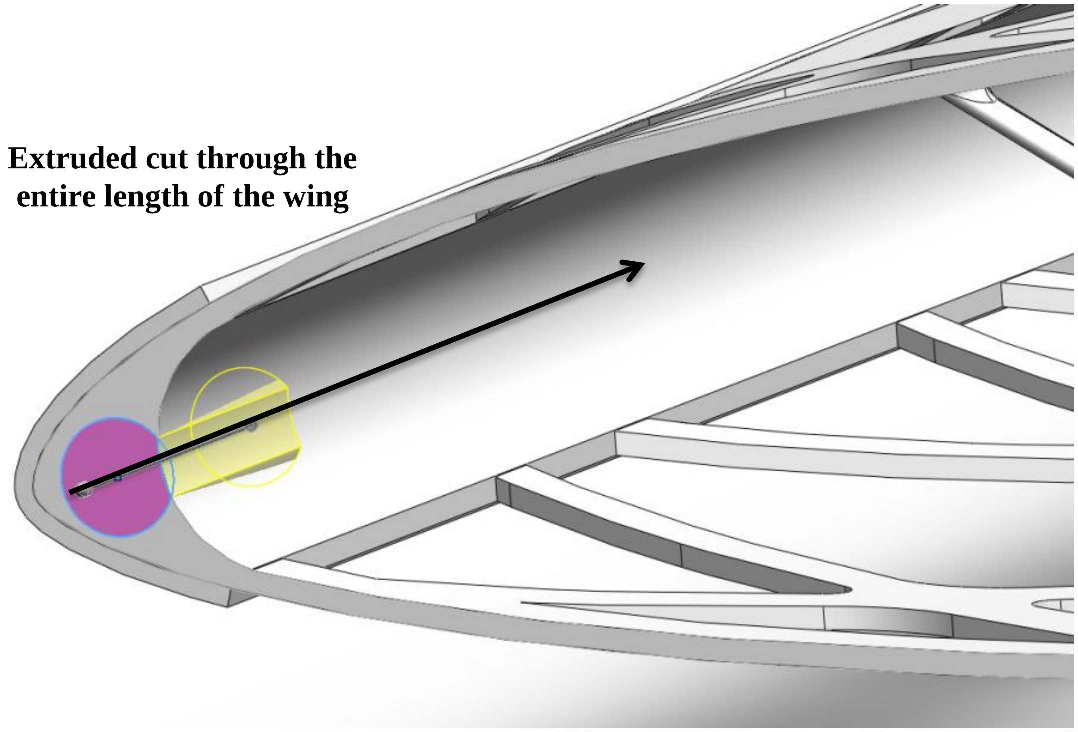


Figure 19. Reduce weight and increase strength by adding another spar in the thick leading edge

3. The adhesive backing on the veneers is thick and therefore weight could be reduced by only using adhesive at the point of contact between the veneer and the frame (shown in blue in Figure 20). The team would like to find a double-sided adhesive sheet that can be laser cut to the appropriate pattern and applied to the frame. Following that, a veneer without adhesive backing can be placed overtop the frame.

4. The RP machine has a much lower resolution than some of the detail provided in the CAD models. These details (such as the fillets shown in Figure 21) that can't be printed need not be included. None of these fillets appeared on the prototype because the resolution is not fine enough, so the time spent modeling these features is unnecessary.

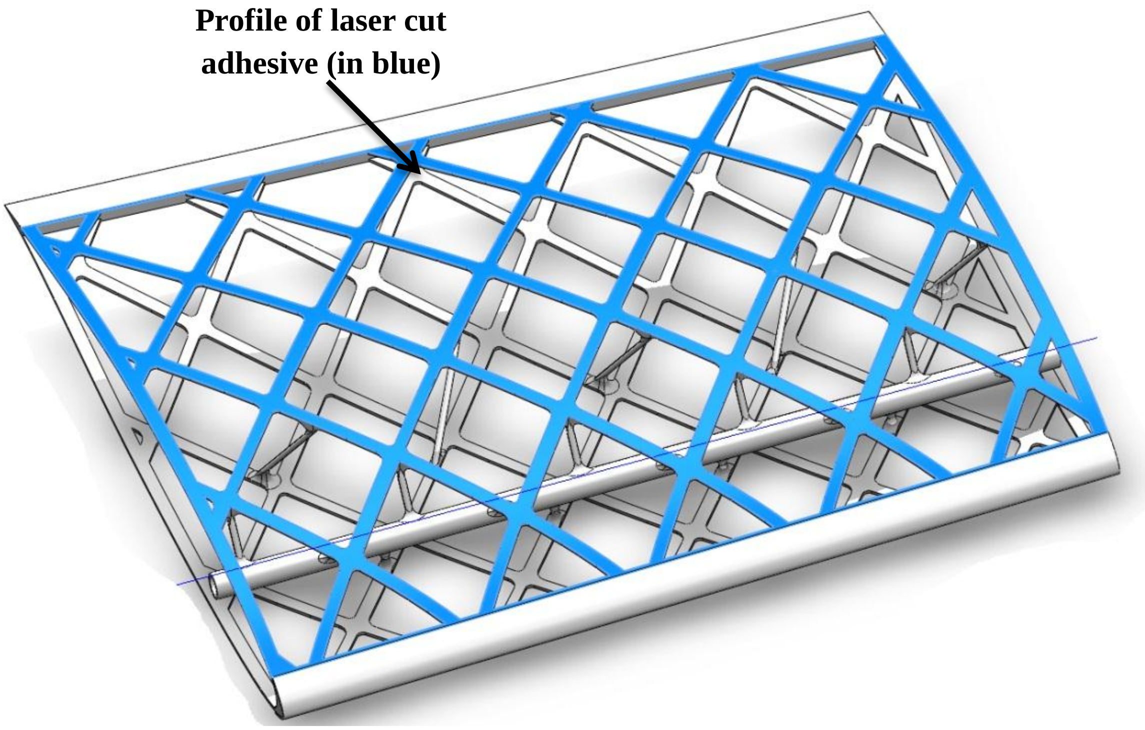


Figure 20. Reduce weight by only using adhesive at the point of contact between the frame and veneer

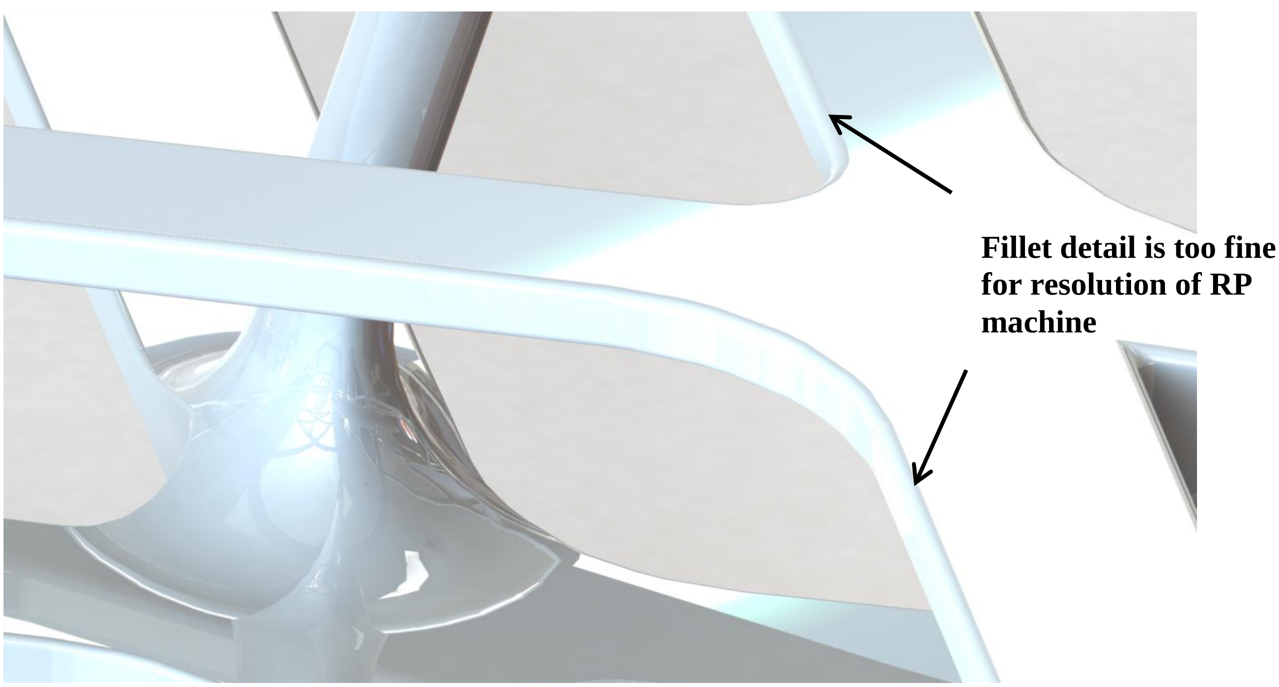


Figure 21. Remove extraneous model detail that cannot be reproduced by the RP machine

3. CONCLUSION

The final design has met the team's target specifications as well as the client-established project objectives. Kinect12 expects that the wing should assemble quickly and be very easy to do. A simple structural analysis has demonstrated that the carbon fibre spar is capable of withstanding the maximum bending load (5 lb) applied by the aircraft's weight and payload. Also, the veneers provide exceptional torsional strength to the wing as has been proven by the very conservative analysis conducted in Section 2.1.2. The carbon fibre materials provide very high specific strength to a wing structure that is already extremely lightweight by design. This shell-like, lightweight structure is only possible with the use of a rapid prototyping machine which can print the very intricate and complicated geometries of the frame modules.

Figure 22 demonstrates the prototype module with the carbon fibre spar and veneer installed.

Figure 22. Prototype RP frame module with carbon fibre spar and veneer installed

The assembly time of this wing structure is significantly less than in the traditional methods detailed in Section 1.2. The rib and spar method reportedly takes 48 hours and the foam-cutting method takes at least three hours. The RP manufacturing method detailed in this report will allow for the wing assembly in an estimated 20 minutes.

Together all nine of the RP modules can be considered a nodal-frame because of the way they locate all important features of the wing. The frame locates the spar at the quarter-chord and defines the airfoil shape for the veneers. The frame is essentially an integrated fixture by locating these structural components and remains after assembly as a functioning as part of the wing (considering the leading and trailing edges are built into the modules).

Modeling a similar frame in the shape of another structure would demonstrate how this manufacturing process applies to more than just a UAV wing. As long as the frame can locate the necessary structural elements (in this case, carbon fibre material) and provide the correct surface profile, Kinect12 believes a variety of other geometries can be produced with this type of nodal frame.

One major shortfall with this design is the long fabrication duration of each module within the RP machine. With nine modules taking up approximately 20 hours each in the machine, it will take nearly an entire week to fabricate the components for one structure. However, this is not so much a fault in the design as much as the technology and availability of RP machines, and these machines were required to be used in the design of this manufacturing process. Therefore to be realistic, if this process were to be used in a production plant many more RP machines would be simultaneously producing frame modules.

The prototype frame module was very valuable to the design team in that it provided light on several refinements that can be made to further reduce weight and increase strength. It also identified that the current geometry of the spar locator does not allow the build-up material to be removed in the sodium hydroxide bath, which prevents the spar from inserting into the modules. Incorporating these minor adjustments to the frame module design will result in a manufacturing method for producing a wing structure that very appropriately utilizes the capabilities of RP, and when compared to traditional methods, provides a structure that can be assembled simply and a in a short time.

REFERENCES

[1] Merriam-Webster [Online]. (2011, December). Available: http://www.merriam-webster.com [December 2, 2011].

[2] L.J. Clancy, *Aerodynamics*. London, UK: Pitman Publishing Ltd., 1975.

[3] Paul K. Wright, *21st Century Manufacturing*. New Jersey, United States: Prentice-Hall Inc., 2001.

[4] Myron Semegen (private communication), Nov. 21, 2011.

[5] Composites Innovation Centre (private communication) , September 22, 2011.

[6] Dan Winship. (2003, August) *Foam Wing Cutting And Coring* [Online]. Available: http://winshipmodels.tripod.com/myfav3.htm [Nov. 13, 2011].

[7] UMSAE Aero Design Team (private communication), Oct. 25, 2011.

[8] Statasys, Inc. (2011, Nov. 8). "Density of P430 ABSplus", Personal e-mail.

[9] T. H. G. Megson, *Aircraft Structures for Engineering Students*, 4th ed. Oxford, UK: Elsevier Ltd., 2007.

[10] DragonPlate [Online]. (2011, November). Available: http://dragonplate.com/default.asp [Oct. 13, 2011].

[11] ACP Composites [Online]. (2011, December). Available: http://www.acpsales.com/index.htm [Nov. 17, 2011].

APPENDIX

This appendix provides information on the other concepts considered by Kinect12 and the selection process used to determine the best approach to solving CIC's design problem.

A.1 CONCEPTS OVERVIEW

The team held brainstorming sessions to bring forward a number of ideas to consider for the final design. This section will provide brief descriptions of each of the main concepts, as well as the selection criteria used to determine which ideas were carried forward.

Seven initial concepts were submitted to the screening process. These concepts were evaluated against the traditional rib and spar assembly method for comparison. The initial concepts are:

- Geodesic Wireframe
- Geodesic-Rib
- Small Piece
- Box Frame
- Truss Structure
- Solid Block
- Support Shell

The screening process evaluates some very general characteristics of the concepts in order to narrow down the options for further investigation. Nine criteria were established based on the client's needs. The concepts were scored by determining whether that concept had a positive, negative, or neutral characteristic of each criterion. The evaluation is presented in Table III.

TABLE III
CONCEPT SCREENING ANALYSIS AFTER INITIAL CONCEPT GENERATION STAGE

	CONCEPT VARIANTS							
SELECTION CRITERIA	Geodesic Rib	Small Piece	Box Frame	Supported Shell	Traditional	Solid RP Piece	Geodesic Wireframe	Truss Structure
Assembly Time	+	-	+	+	0	+	-	-
Ease of Assembly	+	-	0	+	0	+	-	-
Mass	-	+	+	0	0	-	+	0
Structural Integrity	+	0	-	0	+	-	0	0
Uniform airfoil surface	+	0	-	+	+	+	0	0
RP utilization	+	0	+	+	0	+	-	0
Cost (RP time considered)	-	+	+	-	0	-	+	0
Away from Traditional rib method	0	+	0	+	-	0	+	+
Potential for other applications	0	+	0	+	-	0	+	+
Total +'s	5	4	4	6	2	4	4	2
Total -'s	2	2	2	1	2	3	3	2
Total 0's	2	3	3	2	5	2	2	5
Net	3	2	2	5	0	1	1	0
Rank	2	4	3	1	7	5	6	8
Continue?	Y	Y	Y	Y	N	N	N	N

The top four concepts were selected for further development. The Geodesic Wireframe, Solid Block, and Truss Structure concepts were eliminated at this stage. The traditional rib spar method was found to have a low ranking; however it will still be carried forward during the analysis for comparison between any new wing structure manufacturing concepts.

A.1.1 Overview of Secondary Design Concepts

After the completion of the screening phase, the top four design choices were taken for further development. A description of each concept is given and accompanied by CAD models in this section.

Geodesic Rib Concept

The first concept begins with making a geodesic wireframe of the wing using very thin carbon fibre rods or strips wrapped around contour of the wing. However it was very quickly discovered that carbon fibre rods and strips are not designed to bend around concave surfaces and would simply fracture. Combining the geodesic wireframe concept with a traditional rib proved to be a viable option as shown in Figure 23.

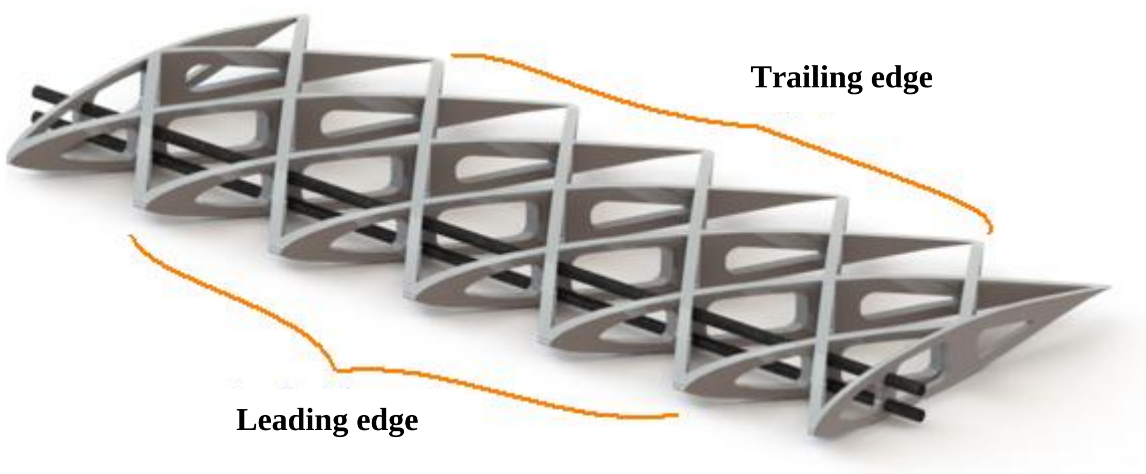


Figure 23. Isometric view of geodesic design

Manufacturing the geodesic wireframe entirely out of RP ABS and supporting it with various carbon fibre rods to increase bending stiffness led to the geodesic-rib design seen in Figure 23. A geodesic pattern that contours the profile of the wing and travels along the span of the wing is a complex geometry. Furthermore the ABS material will need to be thick enough that this complicated shape will not collapse upon itself. The end result for this concept is not a "true" geodesic shape, but benefits from the robustness of a traditional rib construction. Figure 24 shows a side profile of the geodesic concept.

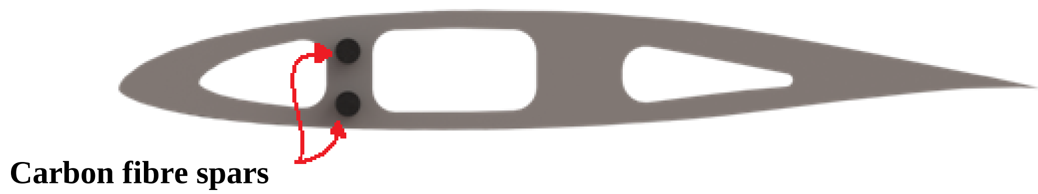


Figure 24. Side profile of geodesic-rib concept

Using ribs is the ideal way to keep the airfoil shape. However, instead of having a series of parallel ribs placed 90° to the span of the wing, there are two separate series of ribs along the span, one set placed at 45°, and the other at -45°. The opposing ribs meet at both the leading edge and trailing edge of the wing, shown in Figure 23. Placing the ribs in this fashion allows them to transfer load along the span of the wing. This whole configuration will be one continuous piece of RP material. Holes for small carbon fibre rods to act as spars will run the span of the structure as seen in Figure 25. The completed wing will be comprised of six to eight of these “geodesic-rib” sections. Each section can slide onto the carbon fibre rods one after the other making for quick and simple assembly.

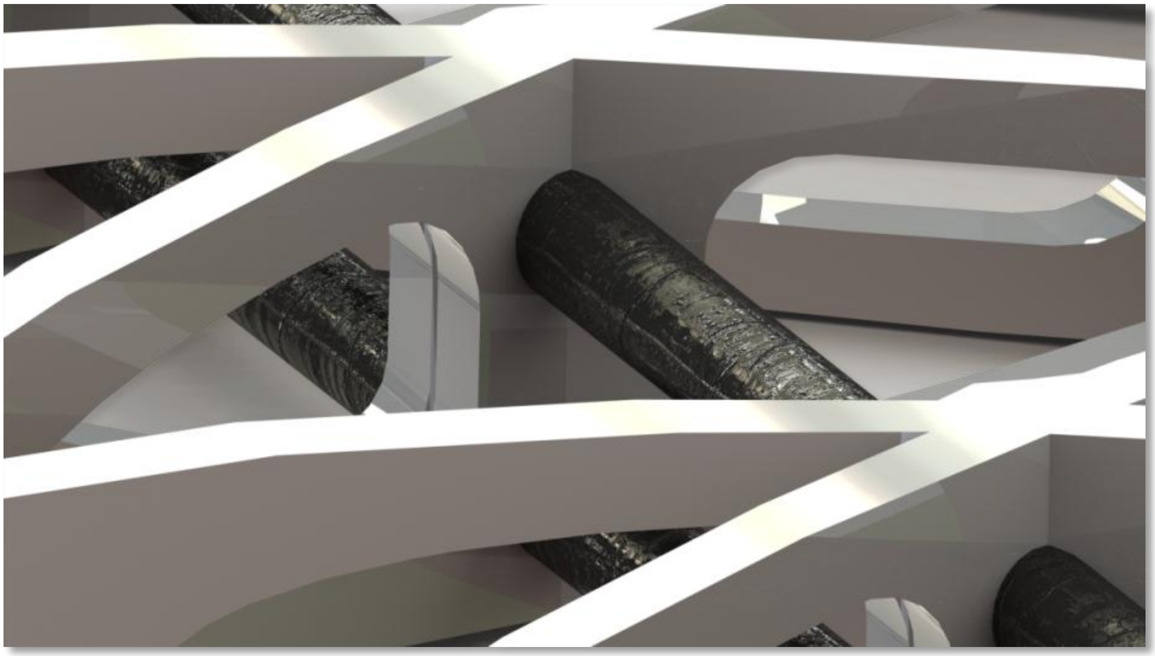


Figure 25. Close up view of geodesic design

Small Piece Concept

The small piece concept involves using RP blocks, shaped in the contour of the wing's surface and connecting them with structural rods. A main structural carbon fibre rod runs along the quarter-chord location of the wing profile. This location is selected for the spar because it is capable of supporting the full load experienced by the wing. Other rods will be used between each of the RP blocks to keep these contour-defining shapes in place. These rods can be glued into the blocks with adhesive. Figure 26 and Figure 27 show the configuration of this concept.

Carbon fibre sheeting will wrap over the profile and be glued to the surfaces of the RP blocks. If possible, the sheets will wrap all the way around the wing. That is, from the trailing edge on the top surface and around the leading edge to the underside of the wing where it terminates and glues again at the trailing edge.

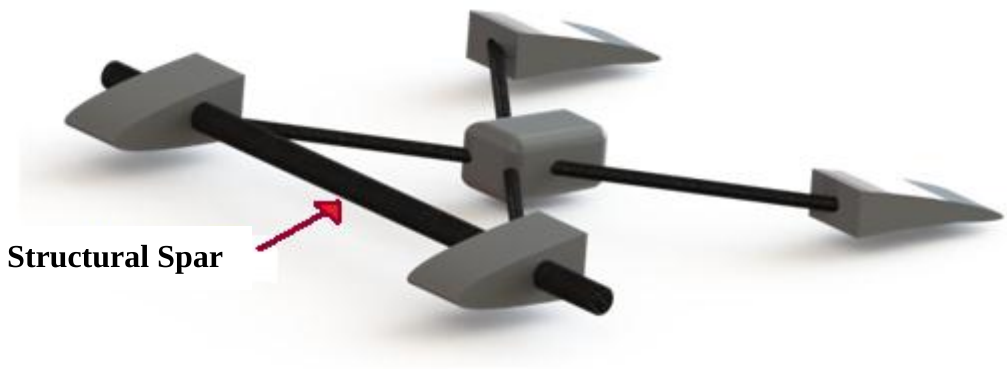


Figure 26. Isometric view of small piece design

Figure 27. Side view of small piece concept

The blocks will be situated in the proper location by an intuitive numbering system. Matching numbers will be labeled on corresponding leading and trailing edge blocks. The wing is symmetric about the fuselage, so there four blocks will have the same number. The rod configuration is designed such that there is only one unique structural rod that is used in every location. The leading edge blocks slide on and are located along the spar by markings provided on this spar. Adhesive is injected into these leading edge RP blocks. This step is done with the flat face of these blocks resting on the surface of a workbench so that all blocks are at the same angle along the spar.

Box Frame Concept

The box frame concept involves using RP box frames, which are connected at the butted ends to form the wing span. The box frame is then reinforced with carbon fibre rods along the length of the wing and carbon fibre sheeting over the wing profile. Two rods provide the main bending resistance about the quarter chord. These two spars are arranged to increase the elastic section modulus. The single rear spar at the trailing edge aids in aligning the overall structure. The overall structure can be seen in Figure 28 on the following page.

The sheeting wraps over the profile and can be glued to the surfaces of the box frame. If possible, the sheets will wrap all the way around the wing. This is done by starting from the trailing edge and proceeding around the leading edge to the underside of the wing where it terminates back at the trailing edge. The leading edge and trailing edge are both formed from ABS. This not only completes the box frame structure, but also creates a surface for the carbon sheeting to adhere to.

Figure 28. Isometric view of box frame concept

Each box frame is different in size, due to the taper in the wing, and thus can only be assembled in one way. This adds the benefit of simple manufacturing. The frames attach at the ends via locking mechanisms and are secured with adhesive. Each end of the box frame also provides shape to the wing via extending supports from the main nodes. The end of the box frame and attachment points can be seen in Figure 29.

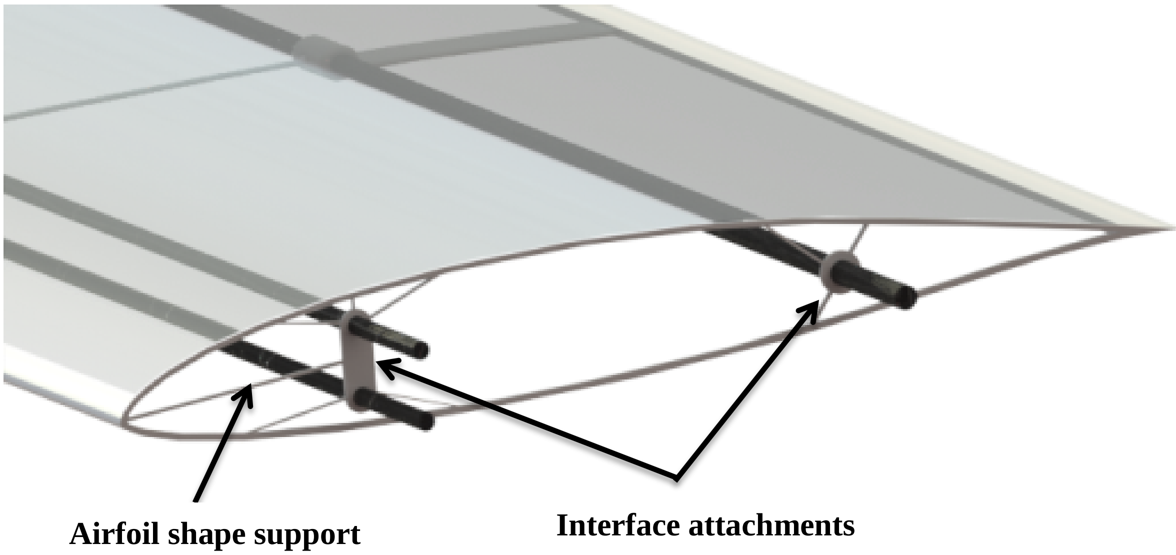


Figure 29. Rapid prototype interface connection point of box frame concept

The centre portion of the box frame provides additional support for the carbon rods. These supports ensure the majority of the bending load is taken by the carbon rods and not the ABS. These supports can be seen in Figure 30.

Figure 30. Center connection and support of box frame concept

The central supports can be formed into different shapes as necessary. The airfoil supports can also be arranged in a more suitable manner for the loads. The variation of structures can be seen throughout the wing at different points in Figure 30.

Supported Shell Concept

The Supported Shell concept kept in mind the desire to use non-traditional wing structure methods while highlighting the ability of rapid prototyping to manufacture complex geometries. Furthermore, it keeps in mind the desire to diversify and scale up the RP nodal structure manufacturing technique in composite applications.

The main RP ABS spar running the length of each section will align and lock each section of the wing structure together. The centre of this spar was left hollow so that a carbon rod with a length that spans the wing could be integrated into the structure. The profile of the wing is laid out by the swiss-cheesed surface. Carbon fibre veneer sheets are expected to contour the wing and will be the main strengthening factor along with the carbon spar. Since the carbon fibre veneer encompasses the functional surface, much of the RP material can be removed to reduce the weight of the part.

Veneer will wrap over the profile and adhere to the surface area available in the design. Ideally the veneer will wrap from the trailing edge, around the leading edge to the opposing side of the wing where it adheres at the trailing edge. The following three figures how different views of the Supported Shell design.

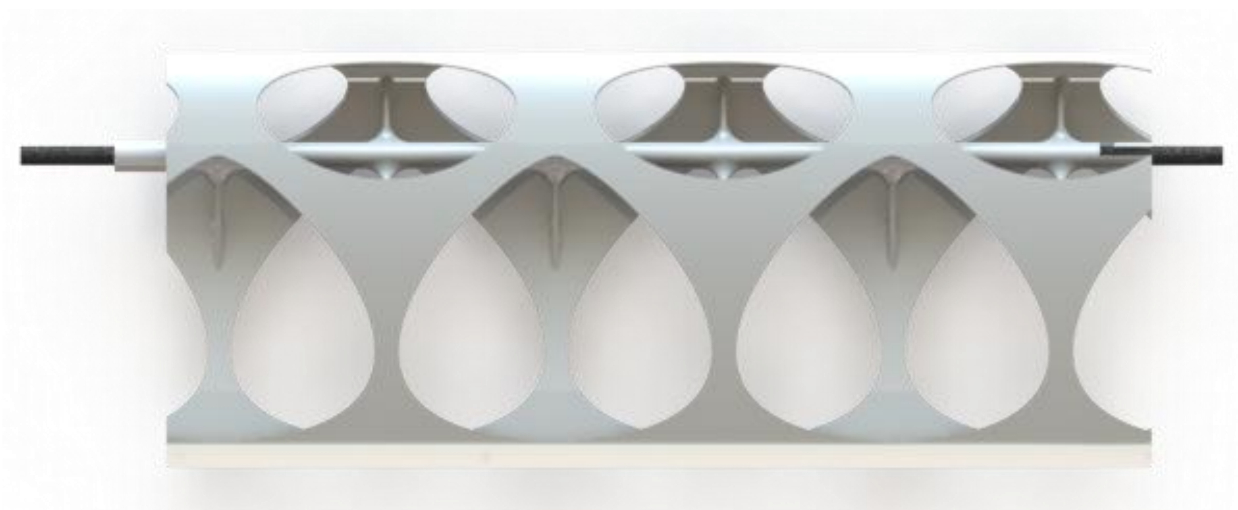


Figure 31. Top view of Supported Shell Concept

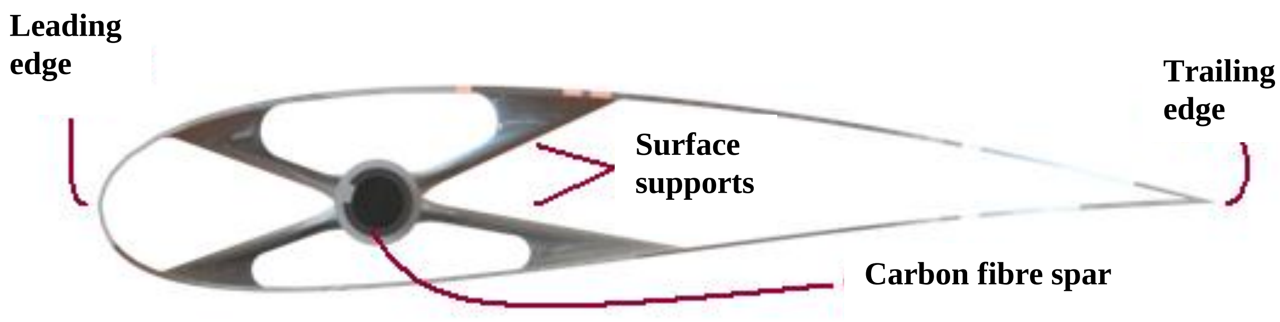


Figure 32. Side profile of Supported Shell concept with labels for all features

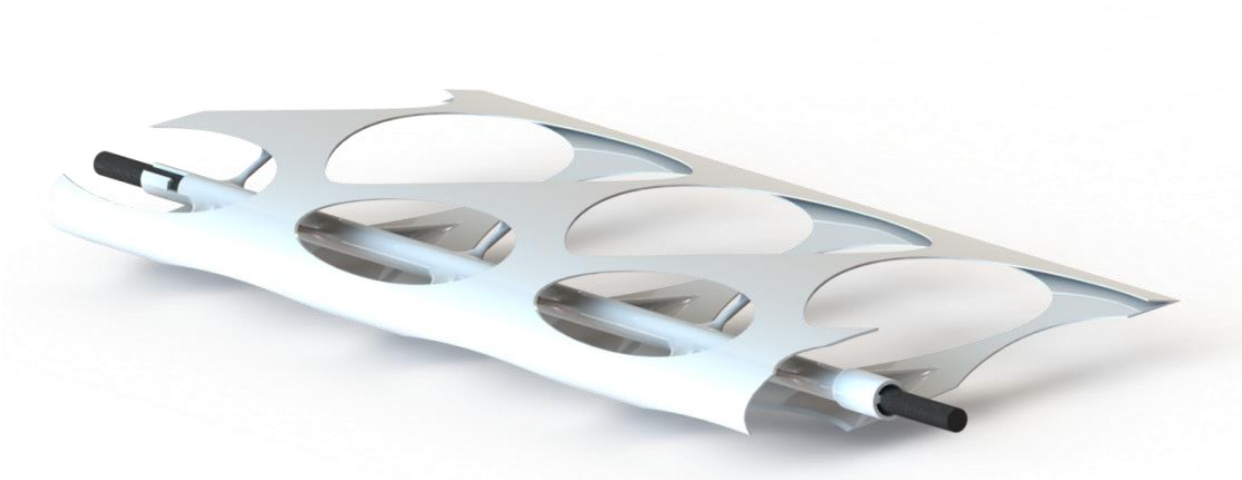


Figure 33. Isometric view of the Supported Shell concept

Traditional Rib Spar Method

The traditional rib and spar method consists of several profile-defining ribs that are perpendicular to the span of the wing. A spar runs along the span at the quarter-chord of the airfoil to support the entire load acting on the wing. Conventional methods for building a wing using this method consist of balsa wood for its low mass, a strong wood such as Douglas-fir for the spar, and a thin plastic wrap (called Monocoat) to stretch over the whole shape to define the airfoil surface. This method was described in detail in Section 1.2.

A.2 CONCEPT SCORING AND EVALUATION

The next phase of concept selection was to evaluate each of the concepts at a moderate level of detail. The evaluation resulted in a score for each concept based on its ability to satisfy the design criteria. Additionally, simple technical analyses and cost analyses were performed to support the findings obtained in the concept scoring process, and to help form a final decision for in the concept selection.

A.2.1 Concept Scoring

The same selection criteria used in the screening process was used for concept scoring. However, at this stage each aspect was evaluated more closely. The concepts were rated on a scale out of ten based on how well the design addresses the needs of the criteria, with a score of 1 being poor and 10 being excellent. Additionally each design criteria was given a weight based on the importance in the overall design. A total score was given to each concept by adding all the weighted scores for that design, and then the concepts were ranked accordingly in the following table.

TABLE IV
CONCEPT SCORING ANALYSIS FROM FIRST CONCEPT NARROWING STAGE

		CONCEPT VARIANTS									
		Geodesic Rib		Small Piece		Box Frame		Supported Shell		Traditional	
SELECTION CRITERIA	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Assembly Time	10%	9	0.9	2	0.2	8	0.8	9	0.9	6	0.6
Ease of Assembly	10%	9	0.9	3	0.3	6	0.6	9	0.9	6	0.6
Mass	10%	4	0.4	7	0.7	10	1	6	0.6	4	0.4
Structural Integrity	15%	8	1.2	7	1.05	4	0.6	6	0.9	9	1.35
Uniform airfoil surface	10%	10	1	6	0.6	3	0.3	9	0.9	8	0.8
RP utilization	15%	8	1.2	4	0.6	10	1.5	10	1.5	1	0.15
Cost (RP time considered)	5%	4	0.2	8	0.4	10	0.5	5	0.25	4	0.2
Away from Traditional rib method	10%	5	0.5	10	1	2	0.2	9	0.9	1	0.1
Potential for other applications	15%	9	1.35	10	1.5	5	0.75	9	1.35	3	0.45
Total Score		7.65		6.35		6.25		8.2		4.65	
Rank		2		4		3		1		5	
Continue?		Develop		No		No		Develop		No	

A.2.3 Concepts Technical Analysis

The four designs are considered from a technical perspective to identify each of their strengths and weaknesses.

In the Geodesic Rib concept it was found that the RP material is bulky and used in excess. Material can be removed from the sections to lighten the structure as the carbon fibre rods are designed to take the bulk of the bending load of the wing. It is a very stable and structurally sound geometry.

The Small Piece concept would be difficult to implement. Numerous short carbon fibre rods would be required to connect the various nodes in this design. Having multiple connection points provides a challenge in ensuring structural stability as each nodal point represents a discontinuity in the load bearing carbon fibre rods. At the nodes, the ABS blocks will need to be designed to accommodate the load. A benefit of this concept is that it can readily be adapted for use in other applications.

The biggest challenge present in the Box Frame concept is that the airfoil shape is maintained by very slender supports extending out from the carbon fibre spars. These supports need to be capable of transferring the aerodynamic loads from the wing surface to the carbon fibre spars. In its current configuration, the Box Frame concept is very fragile and the slender supports would likely fail under normal loading conditions. Additionally, this concept provides a very small bonding surface for the veneer sheeting.

The Supported Shell concept takes the best advantage of utilizing rapid prototyping's ability to manufacture highly complicated shapes. It is lightweight and provides excellent surface area for bonding the carbon fibre veneer. The supports connecting the central spar to the airfoil surface may need to be strengthened as the ABS may not be able to accommodate the loading.