

Preliminary Design of a Composite Wing-sail

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Abstract: An Abaqus/Standard FEA based study was carried out to develop a structural format for a wing sail used on a sailing boat, V-39 Albatross. As well as providing a novel structural solution to meet a challenging set of requirements, the study has given the necessary mass properties and stiffness data required to further progress the preliminary design phase of the overall boat.

The brief for the boat is to set a new world outright sailing speed record at Portland, UK. The choice of location influences the overall concept from the outset, since the conditions are closer to real world conditions when compared to currently favored locations for speed sailing. The boat is configured to add at least 10 knots to the current record by setting a speed above 60 knots (111 km/h). At speed the boat hulls will fly above the surface using a wing in ground effect. The pilot is able to sail on both port and starboard tack and can actively control the craft in roll and height as well as yaw.

The boat has two handed wing-sails to give both lift and power. Each wing-sail is split into an inner and outer plank. Each plank is free to rotate or 'weathercock' about its longitudinal axis into the local air stream. The degree of lift generated by a given plank is set by controlling the upward deflection of a full trailing edge flap. This approach brings an essential weight saving benefit when compared to the conventional approach of adopting a tail surface to provide stability and control; this would necessitate the addition of four booms, tail surfaces and additional counterweights, one for each plank. The overall CG position of the boat is paramount to its stability and control and would not allow this additional structure.

The 'tailless' aerodynamic approach adopted gives rise to a profound structural problem. A wing type structure would typically have a very different in-plane and perpendicular flexural stiffness. This causes the direction of deflection to differ from the direction of applied wing lift. This effect results in a shifting of the centre of lift and causes the outer plank to exert unwanted moments about the axis of rotation to the inner plank. This prevents satisfactory plank stability and control.

The structure developed includes a main tubular carbon fiber spar holding the bearing housings as well as carrying the wing-sail bending and shear loads. The surrounding structure including ribs, skin and secondary spars gives each plank its form and carries local aerodynamic loads into the main spar. However, this additional structure has been partially decoupled from the main spar to prevent it from increasing the flexural stiffness of the main spar in the plane of the plank. The resultant structure has near axisymmetric properties and therefore mimics a purely tubular structure.

Composite modeling techniques used are of a macroscopic nature, i.e. composite lay-ups are represented using thick conventional shells. Angular contact bearings are defined within the interaction module and their weight represented through a concentrated force at the control point. The plank Mylar skins are tensioned by applying a temperature predefined field and including an expansion (contraction) step.

1. Introduction

The work described herein is part of a wider project to design and build a sailing boat, V-39 Albatross to challenge the current world outright sailing speed record. An outright speed record attempt involves sailing a straight course of 500m without the use of powered control systems. As the work began, the project was moving from a conceptual to preliminary phase. At this stage, the wing-sail structure was perceived as carrying the greatest risk to the feasibility of the project. The purpose of the work is to determine preliminary data for the configuration, mass and structural characteristics of a wing-sail structure and to compare this data with assumptions made during the conceptual design process.

The overall concept of the boat involves providing a single crew member or pilot with a degree of active control which compares to that provided to a pilot of a glider or sailplane. At speed, the boat hulls rise free of the surface through aerodynamic lift generated by a wing in ground effect. Once the hulls are free of the surface, the pilot is able to actively control the boat in roll, height and yaw. The high degree of active control enables the pilot to maintain the hulls free from the surface for prolonged periods of time.

In this configuration, only a single keel and rudder with 'T' hydrofoil is penetrating the surface. The maximum speed of the boat is restricted only by the incipient cavitation speed of the keel and rudder surfaces. Since the pilot is able to actively control the height of the boat above the surface, he is in effect controlling the depth of penetration of the keel and rudder surfaces. These surfaces form the largest contributors to the overall drag of the boat, therefore actively controlling the height of the boat is an active form of speed control. This process enables the pilot to maintain a boat speed close to the incipient cavitation speed of the underwater foils for prolonged periods when the boat is subjected to a range of true wind speeds.

The boat is given in figure 1. The boat can sail on both port and starboard tack. It tacks by rolling through 90 degrees as it turns through the wind; the hull forward section rotates between two fixed positions to remain upright. The vertical sail becomes the horizontal wing and the horizontal wing becomes the vertical sail as the boat tacks. The hull aft section has fixedly mounted to it the two wing-sails, the two keels and the two rudders. When the boat tacks, transposing of keels takes place, enabling the use of a fixed cambered section. The use of camber dramatically increases the incipient cavitation speed of the keel.

Table 1. V-39 specification.

Maximum speed (incipient cavitation):	63 – 67 knots (72 – 77mph, 117 - 124 km/h)
Target lift / drag ratio:	3:1
Overall length:	39 feet (11.9m)
Sail area:	23.5 m ² (47 m ² for both wing-sails)
Mass including pilot & ballast:	550 kg

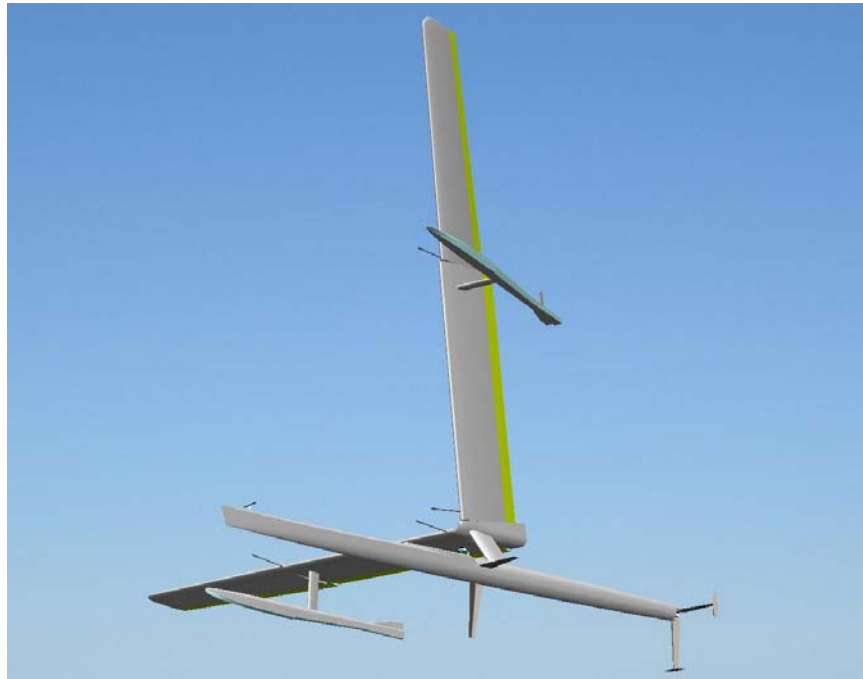


Figure 1. V-39 perspective.

At the time of writing, the world outright sailing speed record holders are the l'Hydroptère team achieving 51.36 knots with their boat, l'Hydroptère shown in figure 2. The hulls are raised clear of the surface using a pair of surface piercing hydrofoils. The V-39 Albatross uses aerodynamic lift as opposed to hydrodynamic lift to both raise the hulls clear of the water and to balance the sailing heeling moment. By making this choice a layout has been reached which shows important advantages over a hydrofoil approach:

Lift and negative heeling moment are generated by a wing running in span dominated ground effect. Where a hydrofoil running near the free surface suffers from a loss of lift with no loss of drag, a wing in span dominated ground effect benefits from a reduction in drag;

A wing in ground effect does not suffer from cavitation and can therefore operate at a much higher lift drag ratio at high speed;

The V-39 has little above water structure when compared to l'Hydroptère;

The V-39 is roll balanced with no net heeling moment so only two points of contact with the water are necessary as opposed to three;

l'Hydroptère suffers from cross coupling between lift and keel side forces, where V-39 has independent lift / keel side forces. The V-39 pilot can independently and actively control the amount of keel in the water;

Finally, a record attempt leads to increasing as far as possible the incipient cavitation speed of the underwater foils, i.e. the keel and rudder. This causes the foil sections to become very thin. Such

thin sections only operate at a satisfactory efficiency across a relatively narrow band of Reynolds numbers. As the incipient cavitation speed moves above 60 knots, as with V-39, the Reynolds number is ideally maintained below $8e6$. This can only be achieved with a chord less than 0.3m. As a result, the overall size of the V-39 is relatively small when compared to l'Hydroptère (l'Hydroptère OAL: 60' ; V-39 OAL:39').



Figure 2. l'Hydroptère perspective.

Referring to figure 3, each wing-sail of V-39 is split into an inner and outer plank (four planks in total). Each plank is free to rotate or 'weathercock' about its longitudinal axis into the local air stream. Each plank is aerodynamically and mass balanced about the axis of rotation. Each outrigger is free to rotate about the same axis described above. When an outrigger is not in contact with the water, it simply weathercocks (aligns) into the local air stream. It is important to note that each wing plank and each outrigger is free to independently rotate about its axis. The pilot has no direct control over the wing planks nor the outriggers. With a given wing plank, the degree of flap deflection controls the angle of attack relative to the local air stream.

Referring to the cross-section through the wing sail (figure 3), with zero flap deflection, a wing plank produces zero lift. With an upwards deflection of flap, a wing plank produces lift depending on the degree of upwards deflection. Increasing upward deflection of the flap leads to increasing lift, up to the stalling point of the airfoil.

This aerodynamic characteristic is achieved by careful design of the wing plank airfoil section. The section is designed to have a zero pitching moment with zero flap deflection and an increasing positive pitching moment with increasing negative (upward) flap deflection. The position of the axes of rotation is important and is stationed at approximately 22% chord.

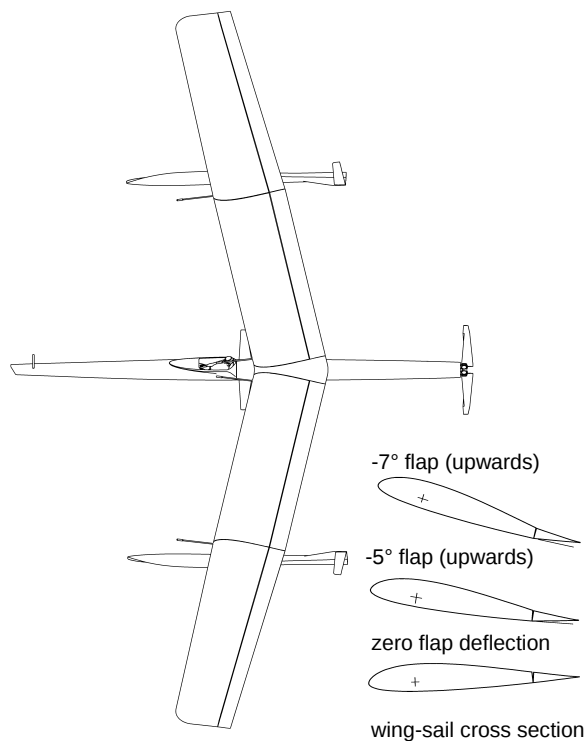


Figure 3. V-39 wing-sail planks.



Figure 4. Greenbird.

The overall CG placement of the boat is very important and places a very tough weight budget on the wing-sail structure. Equally, the aerodynamic design which has been adopted makes it necessary for each wing plank to have the same stiffness in all directions. This requirement is essential to prevent each plank from adopting a preferred orientation. A tubular structure (or one which behaves as such), which is free to rotate about its longitudinal axis, has no motive to rotate under bending loads. This is naturally not the case for a wing type structure, which would deflect in a different direction to the applied load. This would cause both unwanted shifting of the centre of lift and the outer plank to exert unwanted moments about the axis of rotation to the inner plank. Both effects prevent satisfactory stability and control of each plank. These unwanted moments could be easily overcome if the conventional aerodynamic approach were to be adopted, by where a tail surface is employed, one for each plank. This would, however, necessitate the addition of four booms, tail surfaces and additional counterweights, which would move the overall boat CG off limits. Figure 4 shows the single tail surface with boom and counterweight employed to control the single rotating wing-sail surface of the Greenbird - the world's fastest wind powered vehicle.

Abaqus/Standard has been used to explore a number of alternative approaches to meet these requirements, before the chosen structure came about. The structure developed includes a main tubular carbon fiber spar holding the bearing housings as well as carrying the wing-sail bending and shear loads. The surrounding structure including ribs, skin and secondary spars gives each plank its form and carries local aerodynamic loads into the main spar. Giving each wing-sail plank the same structural characteristics as a single tubular spar is achieved by partially decoupling the secondary structure, i.e. ribs, membrane skins and secondary spars, from the main spar. The secondary structure is then prevented from contributing to the bending stiffness of the overall structure. Careful design of the secondary structure enables it to remain structurally sound even though it is partially unconstrained from the main spar.

Wing-sail bending moments and shear forces are prepared using Sage-math and Excel. Composite modeling techniques used are of a macroscopic nature, i.e. composite lay-ups are represented using thick conventional shells. Angular contact bearings are defined within the interaction module and their weight represented through a concentrated force at the control point. The plank Mylar skins are tensioned by applying a temperature predefined field and including an expansion (contraction) step.

The resultant structure has been shown to have near axisymmetric properties and therefore mimics a purely tubular structure. The mass of a single wing-sail (inner and outer planks) as modeled within Abaqus/CAE is 68.8kg. This does not include the trailing edge flap, nor nose counter-weighting which are estimated to add 15kg. The V-39 concept design assumes a total mass of 75kg including the trailing edge flap and counter-weights. The structure is therefore 9kg overweight. However, the work has remained within a preliminary stage of design and further work to optimize the structure should yield a degree of weight loss.

2. Provisional wing-sail requirements

The following set of requirements were generated during the boat concept design phase:

Wing-sail mass (inner & outer plank excluding outrigger): 75kg;

Each plank to freely and independently pivot about axis;

Each plank to be mass balanced at the axis of rotation;

Each plank to adopt similar structural characteristics of a purely tubular structure. This is to ensure there are no tendencies for each plank to rotate about the axis of rotation under the influence of bending loads.

The overall wing-sail configuration is given in figure 5.

As part of the V-39 concept design process, a series of discrete vortex Weissinger computations were carried out to investigate approximate span-wise lift distributions for the wing-sail in both sail and wing configurations. Wing twist, angle of attack and effective sweep were set to provide overall balance of the boat for roll, lift and thrust. Figure 6 shows the design span-wise lift distribution experienced when the wing-sail is in a wing configuration which will result in the maximum wing-sail bending loads. Figure 7 shows the resulting design shear force and bending moment curves which were prepared using Sage-math and Excel.

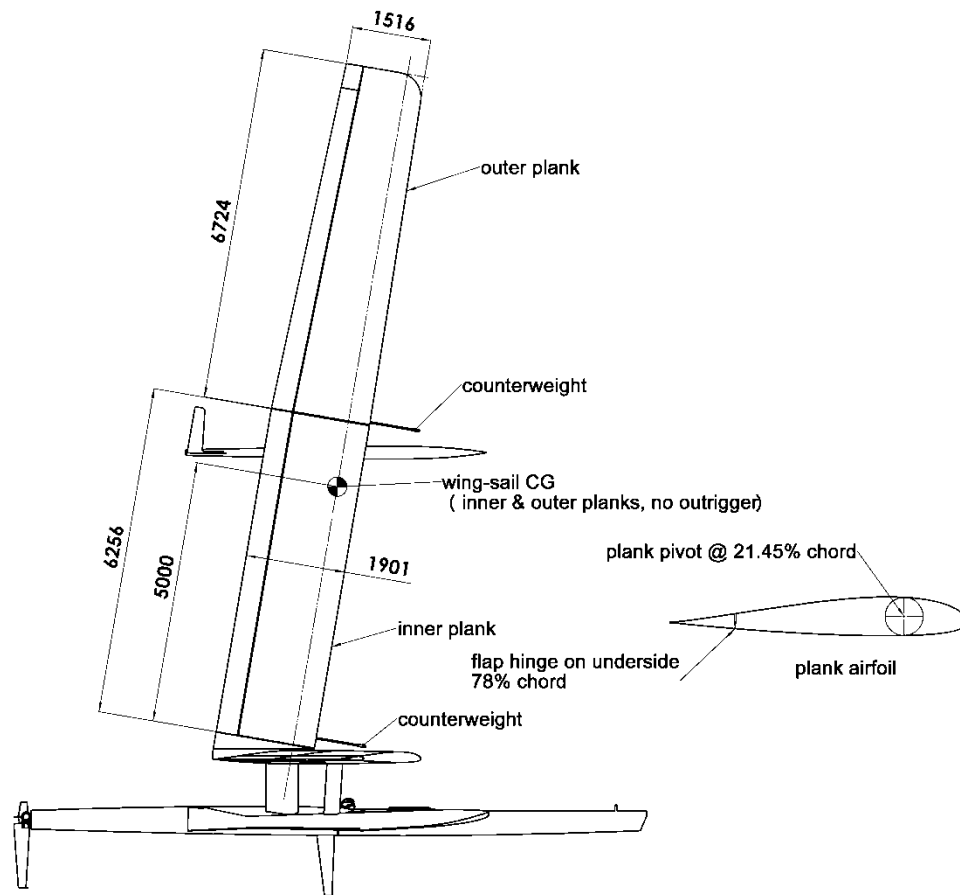


Figure 5. Wing-sail configuration.

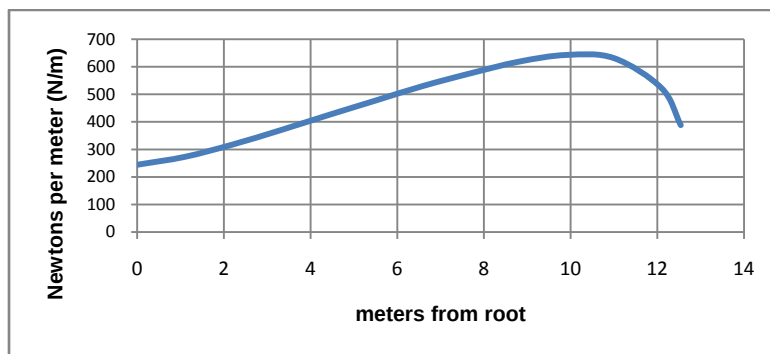


Figure 6. Span-wise lift distribution.

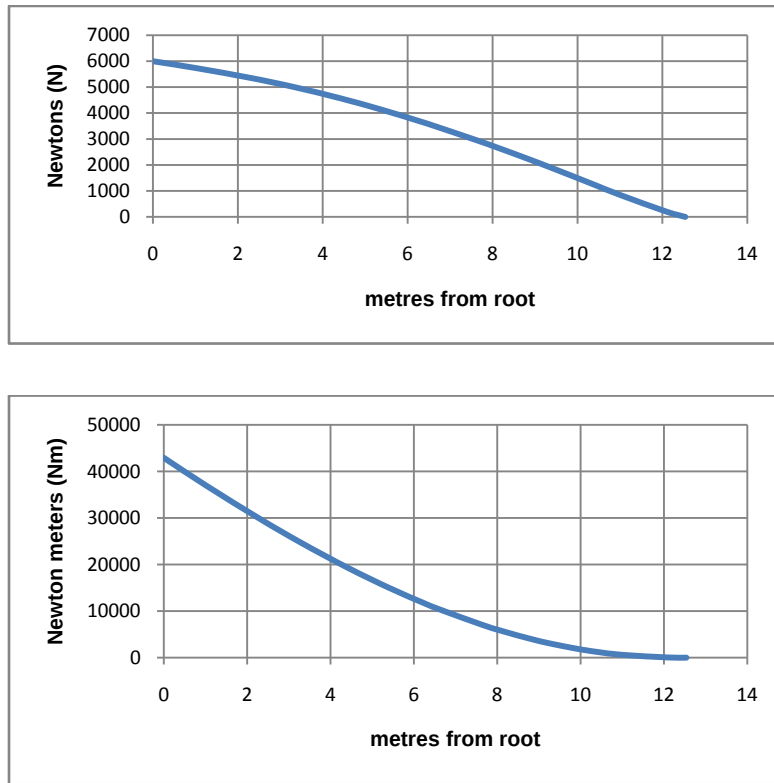


Figure 7. Shear force & bending moments.

3. Material mechanical data

3.1 Carbon fiber epoxy prepreg - unidirectional high modulus fibers

Table 2 - all are normalized values based on fiber volume fraction declared in last column. Fiber volume fraction taken as 55% for cured ply thicknesses of 0.06mm and above. Fiber volume fraction taken as 40% for cured ply thickness of 0.04mm

Table 2. Carbon fiber prepreg properties.

Material	σ_{11} MPa	E_{11} MPa	ν_{12}	E_{22} GPa	σ_{11}^c MPa	G_{12} / G_{13} GPa	G_{23} GPa	ρ kg/m ³	V_f %
M46J UD MTM49-3/36%	1709	235000	0.27	6.87	875	4.09	3.20	1535	55
M46J UD MTM49-3/36%	1243	168000	0.27	6.87	636	4.09	3.20	1436	40

3.2 Isotropic materials

Table 3. Isotropic materials properties.

Material	E MPa	ν	ρ kg/m ³
Rohacell 31 IG PMI foam	36	0.38	32
Mylar	3790	0.38	1400

4. FEA modeling - Abaqus/CAE

The analysis was split into three stages and results obtained at each.

4.1 Stage 1 - Main carbon fiber composite spar assembly

The wing-sail main spar assembly comprises a tubular carbon fiber composite structure. The spar consists of three separate tubes as shown in figure 8:

the inner tube internal diameter is 8.500" and runs the entire length of the inner plank. This tube houses thin section angular contact bearings at both ends of the tube. At the root of the inner plank, two sets of three bearings are arranged in a face-to-face configuration approximately one meter apart. These bearings allow the inner plank to rotate relative to the boat main hull. At the inner plank to outer plank junction, a pair of bearings are arranged, also in a face-to-face configuration, approximately 0.88m apart. These bearings allow the outer plank to rotate relative to the inner plank. In each case, these bearings have a section of 0.750"x0.750" with a 7.000" bore;

the centre tube outer diameter is 6.843". It lies within the outer plank;

the outer tube diameter is 4.724". It lies within the outer plank. A sleeved joint exists between the center and outer tubes. This join fully constrains the outer tube relative to the center tube.

Each tube is tapered, such that the wall thickness varies with the bending loads carried.

At the two intersections (ball bearing intersection between the main hull and inner plank, ball bearing intersection between the inner plank and outer plank) the inner and outer tubes have the same flexural stiffness where they lie between the angular contact bearing face-to-face pairs. This is necessary to prevent tilt misalignment of the bearings.

The tube layups comprise of axial layers locked between layers of off axis helical windings. At least 20% of the layers are off axis by volume.

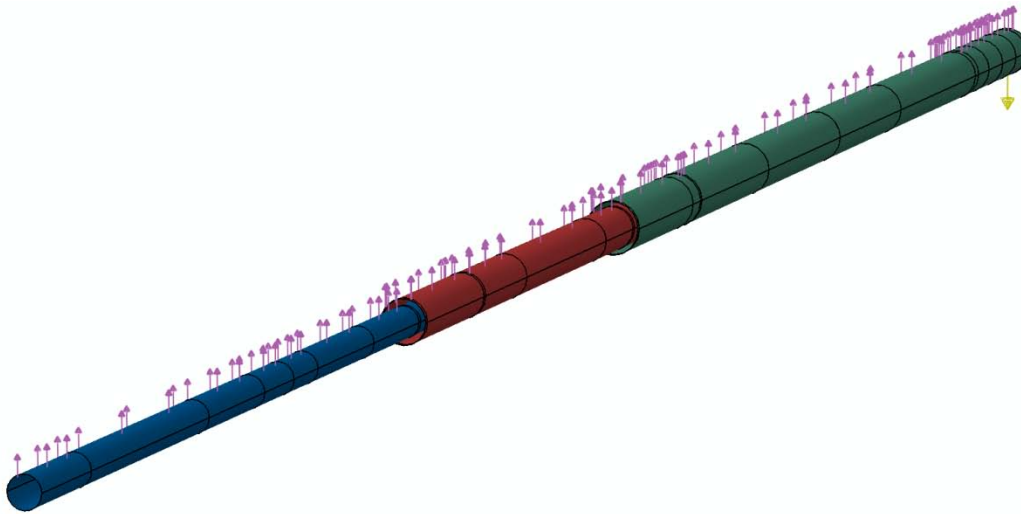


Figure 8. Wing-sail main spar.

Surface traction loads are applied directly to the spar assembly in accordance with the design load case (figure 6). The spar assembly is fully constrained using a kinematic coupling at the root of the shaft of the bearings housed at the root of the inner plank.

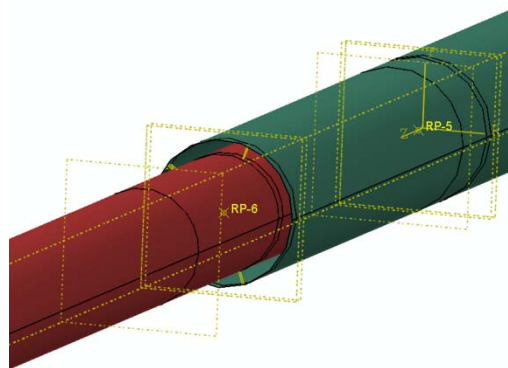


Figure 9. Inner / center tube junction.

Angular contact bearings are defined within the interaction module and their weight represented through a concentrated force at the control point (RP-5/6, figure 9). Each bearing is unconstrained in UR1 & UR2 within a distributing coupling. This is to ensure each angular contact bearing is unable to carry moments.

Gravity load is applied to the entire model.

4.2 Stage 2 - Secondary structure added (figure 10)

The secondary structure forms the shape of each plank and allows local aerodynamic loads to feed into the main spar. With this analysis stage, the skin is omitted and the aero loads remain as traction loads applied directly to the main spar. The secondary structure comprises of ribs, leading edge spar and trailing edge spar. The inner plank secondary structure is not connected to the outer plank secondary structure.

The first and last ribs of each plank have a box section for stiffness. The leading and trailing edge spars pass through each simple rib and are built in to each box section rib at each end.

A surface to surface interaction is applied between the main spar and each simple rib. Since the hole in each simple rib is elongated in the X-direction, the main spar can slide in the X-direction and rotate about the Y-axis relative to each simple rib.

Each box section rib can rotate about a Y-axis which is fixed to the main spar. Within Abaqus/CAE, the box section ribs are constrained using couplings to a control point. One of the two box ribs is unconstrained in the Z-direction, relative to the main spar.

This method of coupling the secondary structure to the main spar ensures that the secondary structure does not increase the flexural stiffness of the overall structure, particularly in the XZ plane.

The carbon fiber leading edge and trailing edge spar layups comprise of axial layers locked between layers of off axis helical windings. At least 20% of the layers are off axis by volume. The ribs are from Rohacell 31 IG PMI foam with carbon fiber skins and carbon fiber caps.

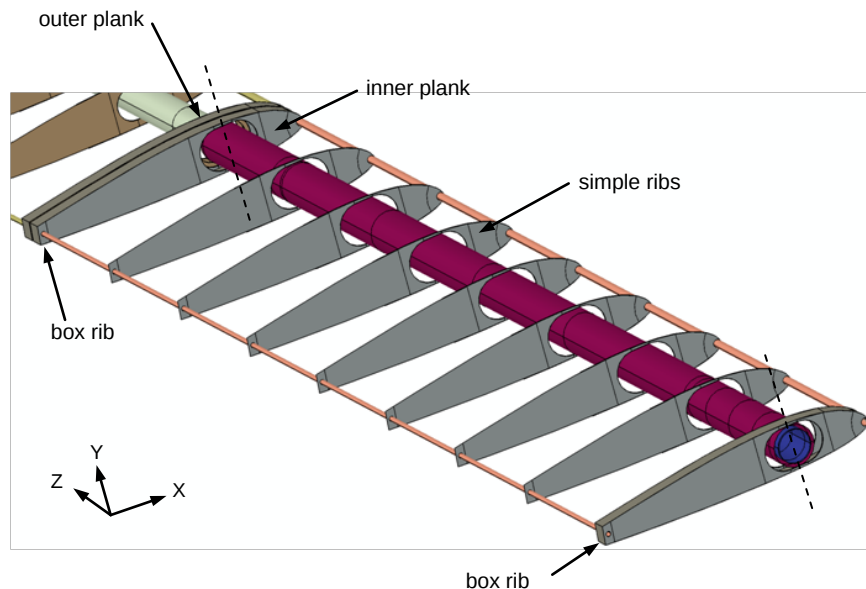


Figure 10. Secondary structure coupled to main spar.

4.3 Stage 3 - Full assembly (figures 11 & 12)

Rohacell structural foam is added to the trailing edge spar to give the trailing edge its correct form. However, this foam may simply be from hot wire cut Styrofoam. This foam is represented using solid elements. Wire bracing of the secondary structure is simply represented using rigid beams. This wire bracing enables the secondary structure to remain structurally sound even though it is partially unconstrained from the main spar. Each beam shown will in reality be two wires diagonally opposed and pre-tensioned.

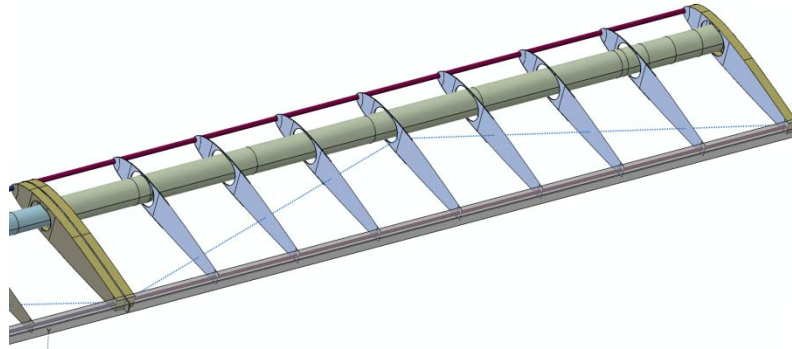


Figure 11. Full assembly excluding skin.

Finally, the Mylar / foam skin is added to the model. 0.05mm thick Mylar skin lies over a layer of Rohacell foam which ranges from 6 to 10mm thick. This foam may be from Styrofoam. The Mylar / foam layer is represented by a single layer of thick conventional shell elements with a composite layup. A temperature predefined field is added to the skin and a thermal expansion (contraction) step is resolved to give the Mylar component of the skin a degree of tension. The aerodynamic loads are now applied to the skin using traction loads. The load distribution is realistic in the direction of span (refer to figure 6). In the direction of chord, the load distribution has been kept a simple approximation, with the load shared between the lower and upper surfaces and applied to give aerodynamic balance about the axis of rotation. Penalty friction formulation is added to the interaction between the simple ribs and main spar since there will now be a transfer of load between these surfaces.

Figure 12 shows the entire model within Abaqus/CAE. Note, the slight taper of the outer plank has been ignored to greatly speed up the modeling process (refer to figure 5).

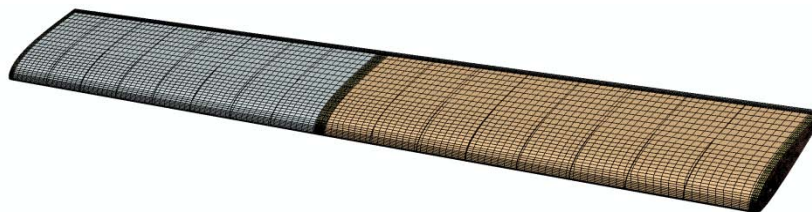


Figure 12. Entire model.

5. Results

5.1 Stage 1 results - main carbon fiber composite spar assembly

The main spar deflection under load is given in figure 13. The maximum deflection at the tip is just over one meter. This is approximately 7.7% since the total span is 13 meters. The unloaded angle between each wing-sail will be set greater than 90 degrees to compensate for this deflection under load.

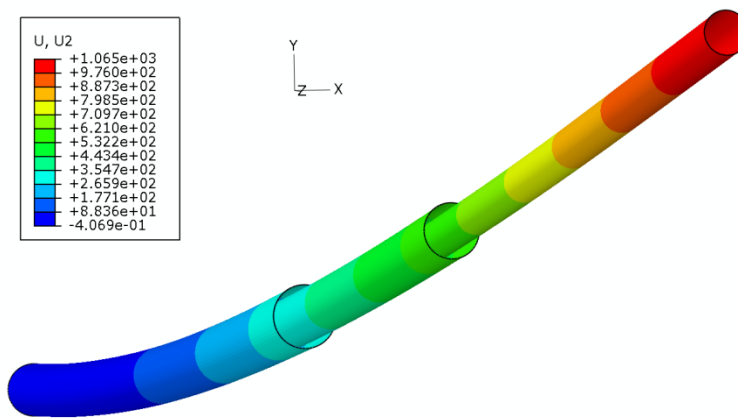


Figure 13. Main spar deflection.

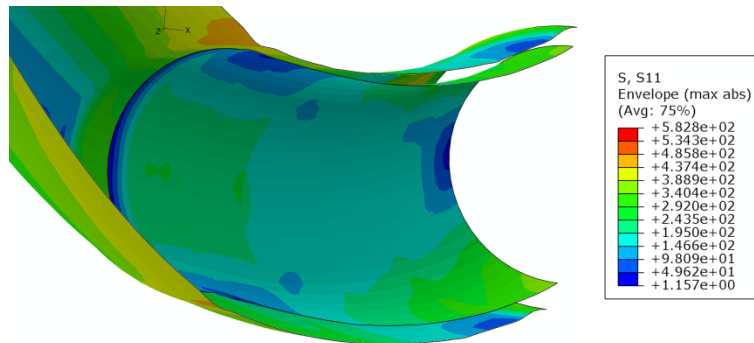


Figure 14. Bearing alignment.

Figure 14 clearly shows the curvature under load of the inner and outer tubes at the wing-sail root (deflection scale factor x20). Angular contact bearings exist at both ends of the overlapping region. These bearings do not carry moments. It can be seen that the inner and outer tubes have the same bending stiffness to avoid tilt misalignment of the bearings.

Figure 15 shows an envelope plot of the absolute maximum stress which lies within the inner axial layers of the tubes. The maximum stress (tensile and compressive) is 583MPa. This gives a reserve factor of 1.5 for compression and 2.9 for tension.

The main spar mass including angular contact bearings is 44.8 kg.

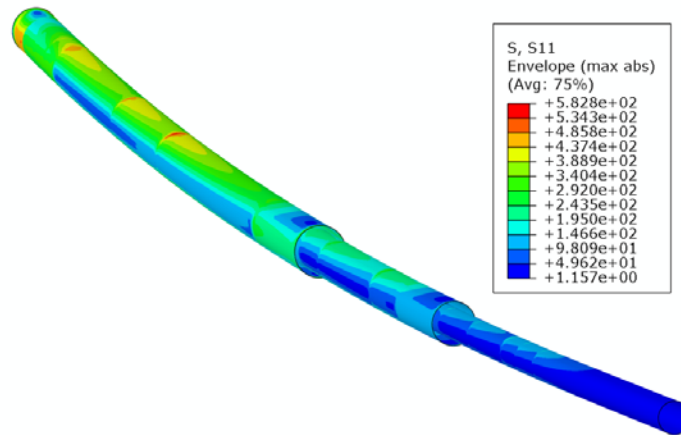


Figure 15. Main spar axial layer stress.

5.2 Stage 2 results - secondary structure added

The purpose of stage 2 is to test the structure's characteristics to ensure it mimics a purely tubular structure, i.e. the bending stiffness does not change with the direction of applied load. The aero loads act in the positive Y-direction as shown in figure 16. The surface of the wing is tilted 15 degrees to represent a wing producing lift at a high angle of attack configuration. Figure 16 shows the resultant deflection of the wing-sail. Deflections perpendicular to the direction of applied load, i.e. X-direction, range from +5.8mm to -15.4mm. These deflections are 0.5% and 1.4% of the maximum Y-direction deflection respectively.

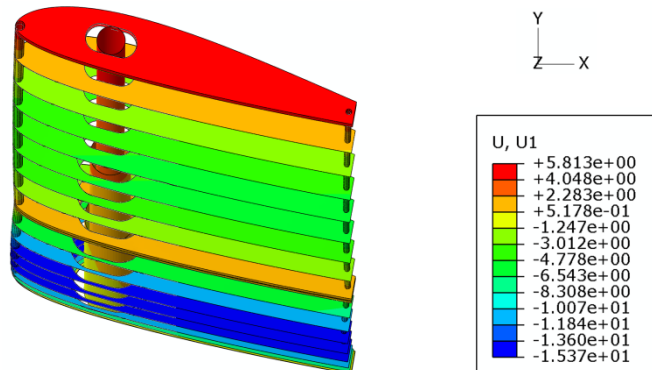


Figure 16. Perpendicular deflection.

5.3 Stage 3 results - full assembly

the structure's characteristics are checked to ensure it mimics a purely tubular structure, i.e. the bending stiffness does not change with the direction of applied load. The aero loads act in the positive Y-direction as shown in figure 17. The surface of the wing is tilted 15 degrees to represent a wing producing lift at a high angle of attack configuration. Figure 17 shows the resultant deflection of the wing-sail. Deflections perpendicular to the direction of applied load, i.e. X-direction, range from +4.5mm to -18.6mm. These deflections are 0.4% and 1.7% of the maximum Y-direction deflection respectively.

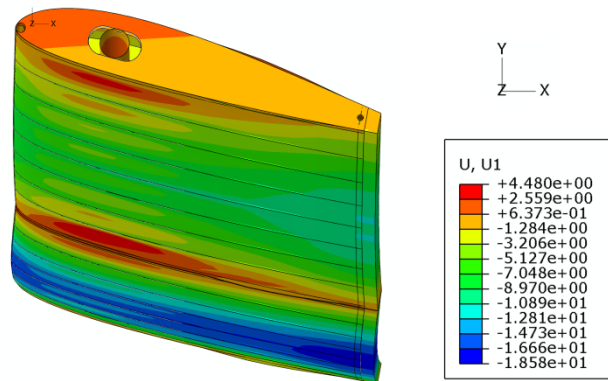


Figure 17. Perpendicular Deflection - full assembly.

Figure 18 shows an envelope plot of the absolute maximum stress within the secondary structure.

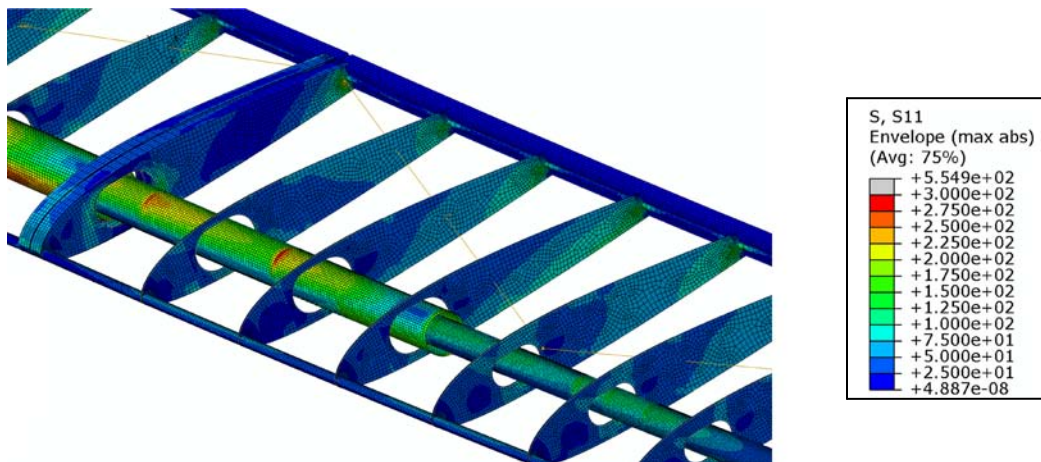


Figure 18. Secondary structure stress.

Figure 19 gives an indication to the degree of local deflection of the skins under local aerodynamic loading.

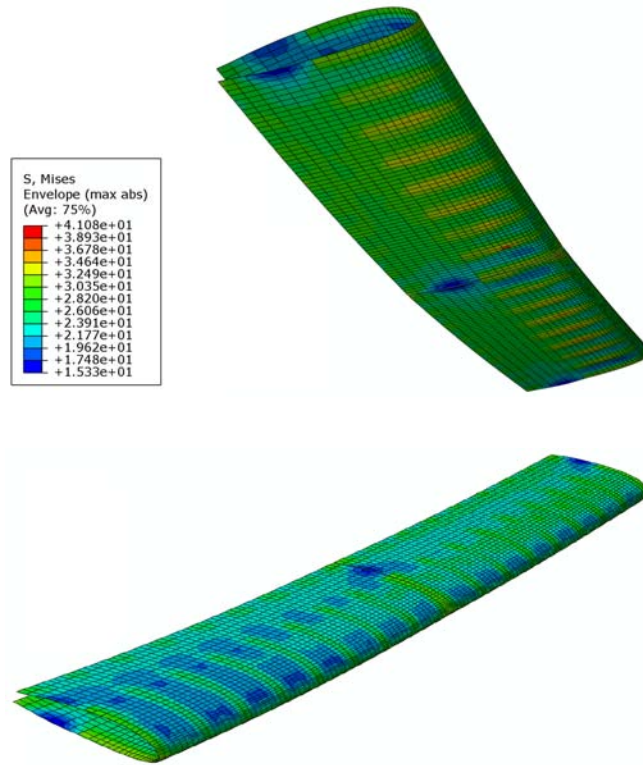


Figure 19. Skin deflection under aerodynamic loading.

The mass of the complete assembly including angular contact bearings is 68.8 kg. The centre of gravity of the complete assembly acts 5233mm outboard of the wing-sail root.

6. Conclusions

6.1 Mass

The mass of a single wing-sail (inner and outer planks) as modeled within Abaqus/CAE is 68.8kg acting 5233mm outboard of the wing-sail root. This does not include the trailing edge flap, nor nose counter-weighting which are estimated to add 15kg. The V-39 concept design assumes a total mass of 75kg including the trailing edge flap and counter-weights, acting 5000mm outboard of the root. The structure is therefore 9kg overweight. However, the work has remained within a preliminary stage of design and further work to optimize the structure should yield a degree of weight loss.

6.2 Stress

The target reserve factor within the main spar when subjected to the design load case is 2. The results show a reserve factor of 1.5 for compression and 2.9 for tension.

The main spar layups as modeled are tapered in thickness to maintain an efficient structure. At this preliminary stage of the design process, the axial plies are tapered in a relatively stepped fashion. This has led to stress concentrations which can be clearly seen in figure 15. With further optimization of the specified layup, it will be possible to even out the stress contours leading to a reduction of maximum stress. Carbon fiber tube manufacturers are stating fiber volume fractions of 70% giving an increase in strength and stiffness. Within this study, a fiber volume fraction of 55% has been assumed.

Stresses in the main spar towards the tip tend to be low, since it is difficult to design down to the very low bending loads experienced near the wing-sail tip, without the tube wall thicknesses becoming very thin.

6.3 Stiffness

The principle requirement of maintaining a structure which experiences no moments about the axis of rotation under bending loads has been achieved. Figure 17 shows the overall assembly is mimicking a purely tubular structure and is deflecting only in the direction of the applied load (perpendicular deflections remain below 2% of overall deflection).

The overall wing-sail deflection under the design load case is under 10% of span and can be compensated by adjusting the unloaded position of each wing-sail.

The results also show that tilt misalignment of the angular contact bearings can be avoided by stiffening up the inner tube to increase the stiffness to that of the outer tube at the bearings.

6.4 Skins

At this preliminary stage the foam backed Mylar skins have not been optimized. The modeling technique has been shown to be successful and it has enabled the loads to be applied to the skin. This in turn has allowed the secondary structure to carry local aerodynamic loads into the main spar and has allowed the effect of frictional drag resulting from the relative movement between the simple ribs and main spar to be considered.

The modeling technique of the tensioned foam backed Mylar skins can be used to optimize the wing skins to give a good balance between weight and rigidity. It will be possible to adjust the foam density and thickness, Mylar weight and tension to minimize the distortion of the aerofoil under local aerodynamic loading, whilst saving on weight.

7. Acknowledgment

I would like to show my gratitude to Max Leadley-Brown, Tom Bianchi and Chris Smith of Simulia for their continued interest and support with the project.

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