# STRUCTURAL DESIGN GUIDELINES FOR WIND TUNNEL MODELS MADE BY RAPID PROTOTYPING

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**Keywords**: *wind tunnel testing, rapid prototyping, aerodynamic testing*

## Abstract

*Design guidelines are presented to help in designing subsonic wind tunnel models fabricated by rapid prototyping. The focus is on the structural design and manufacturing aspects, which include the overall model architecture, attaining adequate stiffness and strength by reinforcing the polymer models with metallic inserts, realization of suitable connections between parts, and issues related to the design of the individual components. Four aircraft models designed by students as part of their final-year aerospace engineering project have been produced. The testing results indicate that aerodynamic data of acceptable quality can be collected from rapid prototyping models while offering significant cost and production time advantages over machined metal ones.*

## 1 Introduction

The technology of Rapid Prototyping (RP), which has been around for over 20 years, allows the fabrication of a physical object directly from the CAD model in an additive, layer-by-layer manner. The prototypes are made of various materials, such as polymers, metals and paper, using different technologies. A promising application of RP is the production of wind tunnel models for checking, verifying and generating data such as lift and drag coefficients, pressure distributions, etc. Traditional wind tunnel models are made of aluminum or steel by 5-axis CNC milling, take weeks or months to fabricate, and cost tens, even hundreds of thousands of dollars [1]. Several case studies show that making wind tunnel models by RP can produce good results in terms of aerodynamic performance and characteristics, while incurring a five- to tenfold reduction in cost and a significant shortening of acquisition time.

Landrum et al. [2] tested three ~30-cm span by ~10-cm chord airfoil models in a low-speed subsonic wind tunnel: a conventional cast polyurethane model and two photopolymer models made by stereolithography (SLA). All three models were identical except for the light sanding of one of them to produce a smoother surface finish. They reported comparable fabrication times and dimensional tolerances for the RP and conventional models, with the biggest difference being in the drag coefficient for both the RP models, which was about half the value measured for the cast model. They attributed this result to the rougher surface of the RP models inhibiting the formation of laminar separation bubbles.

Springer and Cooper [3] compared the static stability aerodynamic characteristics obtained in a trisonic wind tunnel over a range of Mach numbers from 0.3 to 5.0, for models made by three different RP technologies, and one control model made of aluminum. They tested models made of ABS plastic by fused deposition modeling (FDM), photopolymer resin made by SLA, and glass reinforced nylon made by selective laser sintering (SLS). All the models were of a wing-body-tail configuration launch vehicle with area $S_{ref}$ = 8.68 in$^2$ and length $L_{ref}$ = 8.922 in. They concluded that at the present time (1997), only preliminary design studies and limited configurations could be used due to the RP material properties that allowed bending of model components under high loading conditions. However, for obtaining preliminary aerodynamic databases, the RP models offered significant cost savings and fabrication time reductions at acceptable fidelity.

Hildebrand et al. [4] and Tyler et al. [5] described two wind tunnel models, a 4-ft span by 3-ft long X-45A UCAV, and a 20-in. span lambda wing-body configuration Strike Tanker, made by SLA (plastic) and SLS (stainless steel) techniques. They investigated issues such as the integration of pressure taps (small holes on the surface and internal airtight passageways to the transducers), model sagging under load, dimensional accuracy and cost and time of fabrication. They found that it was necessary to stiffen the Strike Tanker plastic model to prevent excessive wing deflection, and did it by building the model parts around a 1/4-in. thick support plate. This construction principle was also described by Heisler and Ratliff [6], where a steel tube constituted the strong back of missile models, and plastic RP parts (made by FDM) were attached to it to establish the outer shape.

A 2-m long model (1:8 scale) of the European Tiltrotor aircraft was built and tested at speeds up to 50 m/s [7]. RP technology was used to fabricate the external fairings of the model out of a composite aluminum- and glass-filled polyamide-based material (Windform® GF). These components were mounted onto a machined metallic central frame. Satisfactory results were reported with only two drawbacks identified: wider dimensional tolerances and worse surface finish of the RP parts compared to conventional composite lamination models.

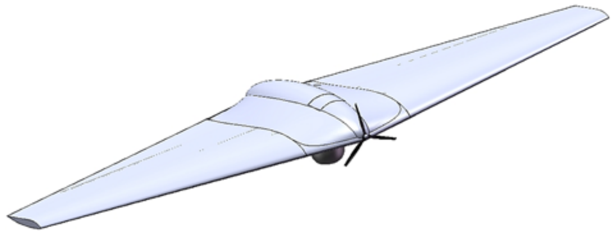
Nadooshan et al. [8] tested a wing-body-tail configuration of a polycarbonate model made by FDM against a conventional machined steel model over a range of Mach 0.3 to 0.7 and angle of attack range of –2 to +12 degrees. The model's length was $L_{ref}$ = 200 mm and area $S_{ref}$ = 48 $cm^2$. The results were a generally good agreement between the metal and plastic models up to about 10 degrees of angle of attack, when the plastic model's deflection under the higher loading produced more noticeable differences.

The current paper presents briefly the design of four wind tunnel models made by RP as part of final-year aerospace engineering students' projects at the Technion, and a sample of the aerodynamic testing results obtained. A more detailed description of the testing results and their use in the preliminary design process of aircraft appears elsewhere [9]. The emphasis of this paper is on the guidelines for designing the wind tunnel models that we were able to state after gaining considerable experience with the particular RP technique.

## 2 Wind Tunnel Models Description

Four models, of which three shared the flying-wing configuration, were manufactured and tested over the last two years. ILAS (Fig. 1a) was a low-altitude, quiet, fuel-cell powered observation aircraft carrying a 2.5-kg electro-optical payload. It had a wing span of 3 m and was designed to fly at 20-25 m/s. ILAS's wind tunnel model had a scale of 1:5.5. CERBERUS (Fig. 1b) was a low-RCS, long-range (1500 NM) UAV, carrying two 500-kg bombs and a variety of sensors. Its wing span was 13.2 m and cruise speed M=0.8. Its wind tunnel scale was 1:22. The "Flying-car" (Fig. 1c) was a four-passenger vehicle with telescoping wings and canards, capable of flying at up 250 km/h (cruise speed 215 km/h) and maximum range of 600 km, and travel on roads at a top speed of 160 km/h and a range of 400 km. The maximum wing span was 8.5 m, and the wind tunnel model scale was 1:17. MORPHEUS (Fig. 1d) was similar to CERBERUS, with an extended range of 3,000 NM and a 1,200-kg payload, except for its morphing wing, which allowed varying the wing span, sweep and camber.

One of the lowest cost RP technologies, known as 3D printing or PolyJet™ and PolyJet Matrix™, was used for this work. The model is built in layers from the bottom up, by accurately depositing liquid photosensitive polymer droplets and curing them by ultra-violet light. Another, gel-like material is used as temporary support for overhanging features, and is washed away by high-pressure water jet when the fabrication process is finished. No other post-processing is necessary. Machines used in this study were Eden250™ and Connex350™ made by Objet Geometries Ltd. (24 Holtzman St., Science Park, Rehovot 76124, Israel). Model materials were FullCure® 720 and VeroBlue.



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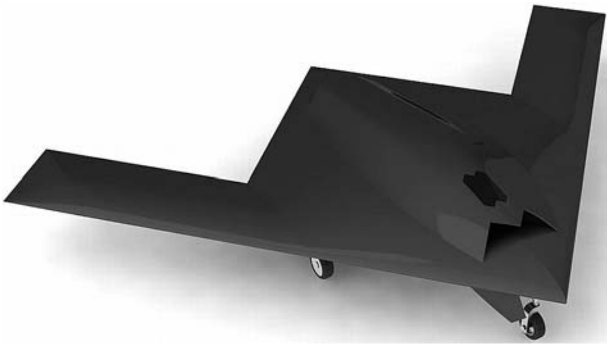

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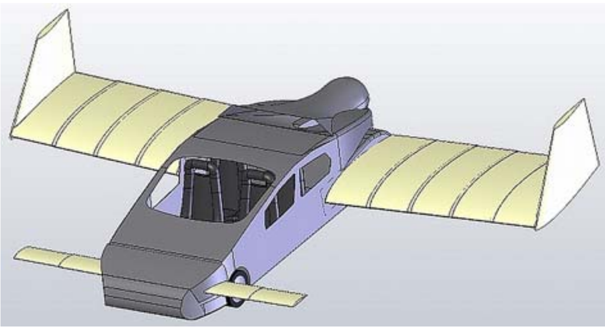

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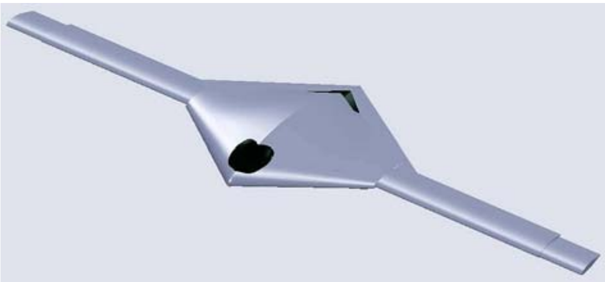
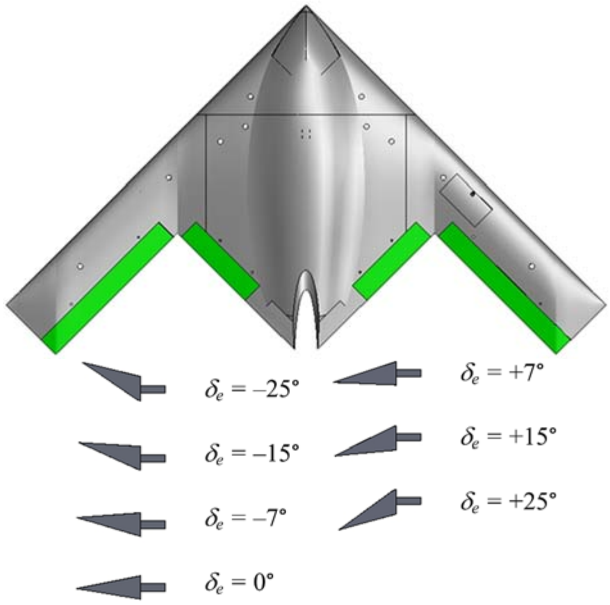


(d)

Fig. 1. CAD models of (a) ILAS, (b) CERBERUS, (c) "Flying car" and (d) MORPHEUS

Model fabrication was carried out at the Technion, Israel. All models were tested in the Technion's subsonic wind tunnel, which is an open circuit tunnel with a 1x1-m cross-section, 400 kW motor driving a single stage centrifugal blower, and capable of air velocities up to 90 m/s. The level of turbulence is less than 0.5%, atmospheric stagnation pressure, and the air is at ambient temperature.

Ailerons, elevons and spoilers in the models were manufactured as separate parts, each representing a different position of the control surface. For easy changing of these parts, the models incorporated slots and other locating features, and means of securing the interchangeable parts: pins or screws. Fig. 2a shows the pitch and roll control surfaces (elevons), and Fig. 2b shows the yaw control surface (spoiler), all for the CERBERUS model.

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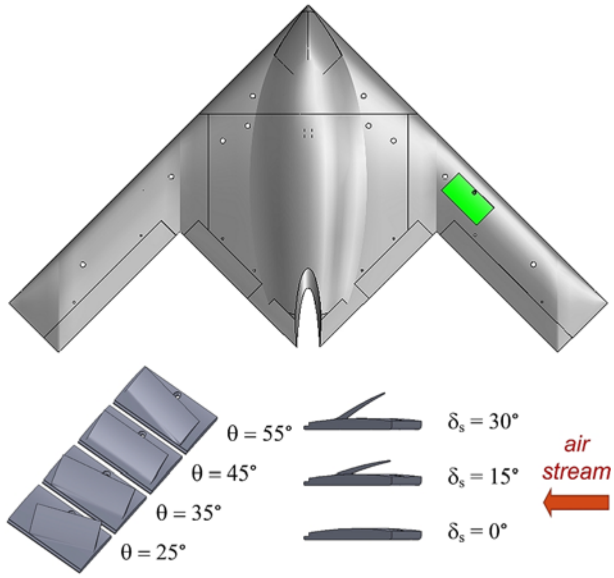


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Fig. 2. CERBERUS control surfaces: (a) elevons for pitch and roll control, and (b) spoilers (only one side made for testing) for yaw control

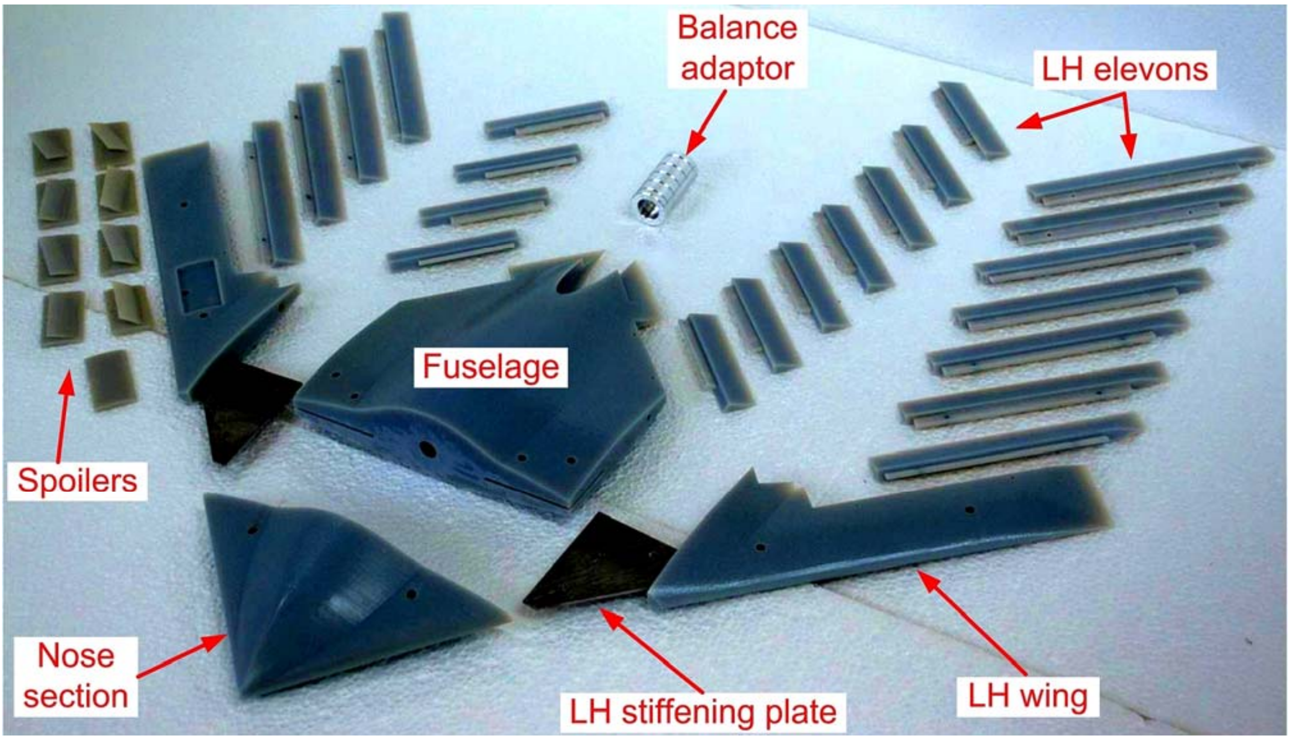


Fig. 3. CERBERUS model parts

Fig. 3 is a photograph of the CERBERUS model showing the main parts, stiffening plates (see explanation below), and the complete set of control surfaces. Fig. 4 shows this model mounted in the wind tunnel for testing.

## 3 Testing Results

Aerodynamic analyses with the Tornado program of vortex lattice method code and the DATCOM program were performed prior to the wind tunnel testing. The wind tunnel test results usually showed very good compatibility with the theory and similarity to the analyses results, which indicates that using the RP technique for production of wind tunnel models is adequate and sufficient for obtaining quick and accurate enough results.

Fig. 5a presents the wind tunnel test result and the calculated (linear) lift coefficient, $C_L$, as a function of the angle of attack, α, for the CERBERUS model. Fig. 5b shows the measured lift coefficient including its maximum value. The wind tunnel test and the calculated (quadratic) results for the drag coefficient, $C_D$, as a function of $C_L$ are shown in Fig. 5c. All the results indicate a very reasonable and predictable behavior.

After establishing the level of confidence and proving the adequacy of the RP models, several tests for the controllability of the air vehicles have been conducted. Fig. 6 presents the wind tunnel results for the evaluation of the control surfaces of CERBERUS. The elevons' effectiveness in controlling the pitch is plotted as the pitching-moment coefficient, $C_m$, as a function of the elevon angle, $\delta_e$, in Fig. 6(a) for several angles of attack. Next, two tests were conducted to determine the optimal spoiler's hinge centerline angle, θ. The yawing-moment coefficient, $C_N$, was plotted against the yaw angle, ψ, for several spoiler centerline angles in Fig. 6(b), all for a specific angle of attack and spoiler opening. This test showed that the highest yawing moment was produced at $\theta = 35°$. Then, the spoiler's influence on the roll was checked by plotting the rolling-moment coefficient, $C_R$, as a function of ψ, for specific angle of attack and spoiler opening angle, Fig. 6(c). The reasonably low and relatively constant effect of the spoiler when its centerline is at 35° strengthened the decision to set the spoiler centerline at this optimal angle.

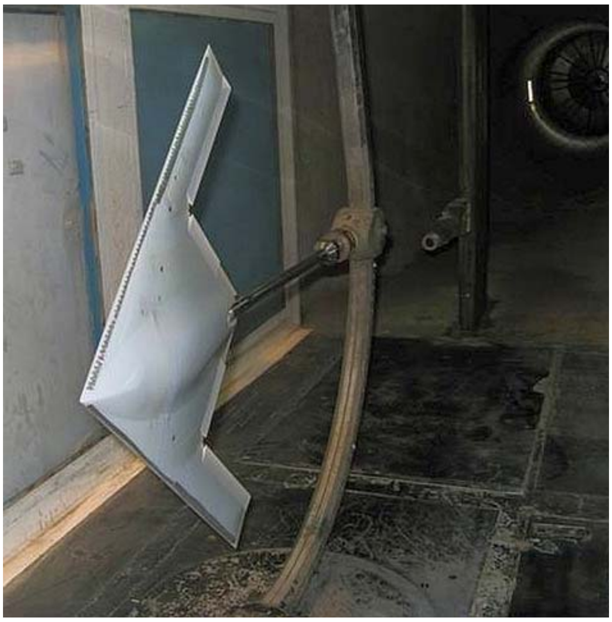

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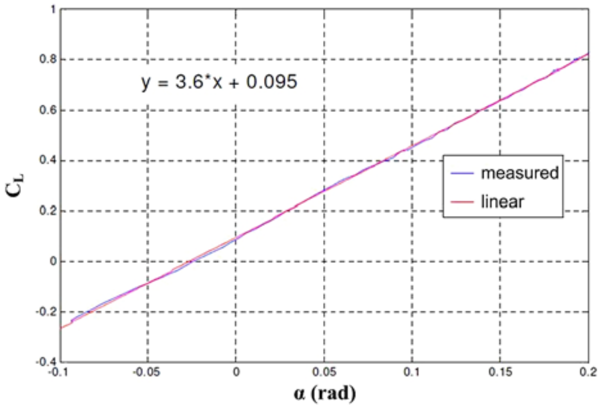
Fig. 4. CERBERUS model mounted in the wind tunnel for (a) pitch and (b) yaw measurements by carrying out a horizontal sweep of the model

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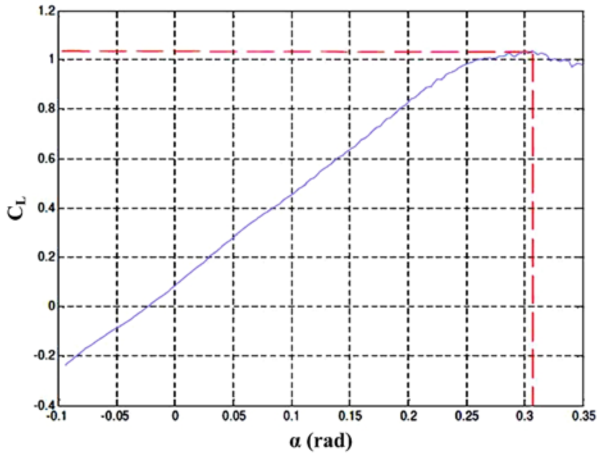


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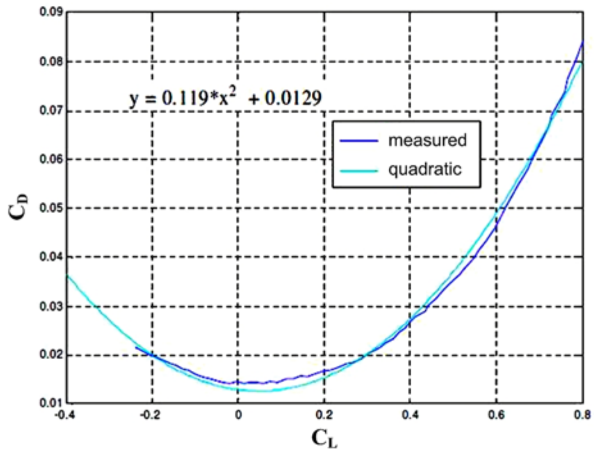



(c)

Fig. 5. (a) Comparison between the measured and calculated (linear) lift coefficients as a function of the angle of attack, (b) measured lift coefficient as a function of the angle of attack ($C_{Lmax}$ = 1.04 at α = 17.6°), and (c) measured and calculated (quadratic) drag coefficient vs. lift coefficient, all for the CERBERUS model

## 4 Design Guidelines

Designing an RP model for wind tunnel testing involves consideration of the overall model architecture, provision for adequate stiffness and strength, choice of fastening methods, and proper part design. The RP technology offers some unique characteristics, capabilities and limitations that need to be taken into account.

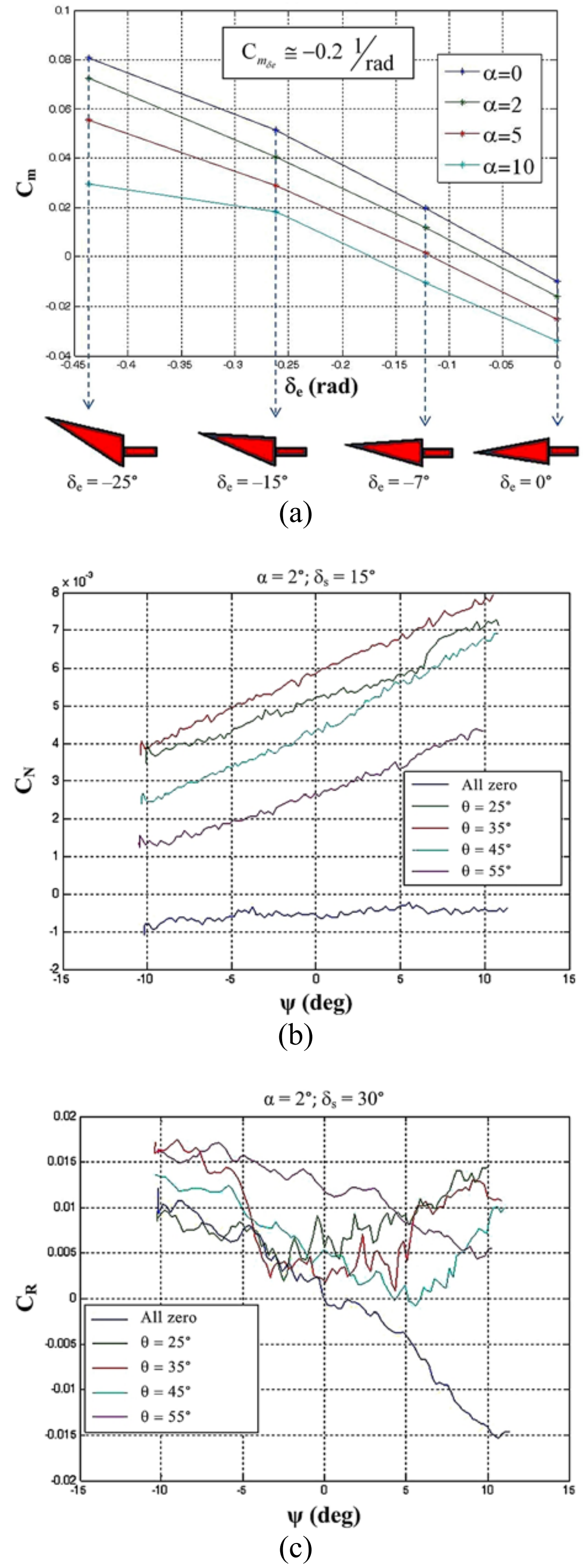



Fig. 6. CERBERUS testing results: (a) the elevons' influence, (b) the yawing-moment coefficient vs. yaw angle, and (c) spoiler's influence on roll for different hinge angles with 2° angle of attack and 30° spoiler opening

## 4.1 Model Architecture

The wind tunnel for our experiments was fitted with a rear-mounted sting-type strain-gage balance, with its forward section tapered (Morse cone) to accept a mounting adaptor for models. Because the model plus cone adaptor are attached to the front of the balance, the design needed to provide this access, both for securely mounting the model in the tunnel and for removing the model from the balance. A second consideration in determining the composition of the models in terms of separate components is the limitation on maximum RP part size, which did not allow fabrication of whole spans as one piece. We used two machines, with a maximum part size of 250x250x200-mm and 340x340x 200-mm, respectively. A third factor in determining model architecture is the need to test interchangeable parts. For the cases described in this paper, and excluding control surfaces which are discussed separately, this was relevant to the MORPHEUS model, which required testing of various wing configurations. All this led to architectures that consisted of four main parts: fuselage, nose section, left wing and right wing. These components are shown in Fig. 7a for the "Flying-car" model, and 7b for MORPHEUS.

When splitting the model in the spanwise direction, it is recommended that the central section is made as wide as the RP build size allows, so that the connection between wings and fuselage does not coincide with the most highly loaded area of the wing, which is at its root, or the fixed end of the cantilever beam.

## 4.2 Stiffness and Strength

The manufacturer of our RP machines quotes 55-60 MPa of tensile strength, 79-84 MPa of compressive strength, tensile modulus of elasticity of 2.7-2.9 GPa and flexural modulus of 1.7-2.0 GPa [10]. These numbers are also confirmed by other experiments [11,12] and our own testing, and are, of course, considerably lower than those for metals. Additionally, these strength figures are in the plane of the layer, while those in the build direction (vertical, z-axis, or perpendicular to the layer), dominated by the intra-layer adhesion, are about one-half of the quoted numbers. This anisotropy must be taken into account when designing the model and when determining the orientation of the built parts in the RP machine.

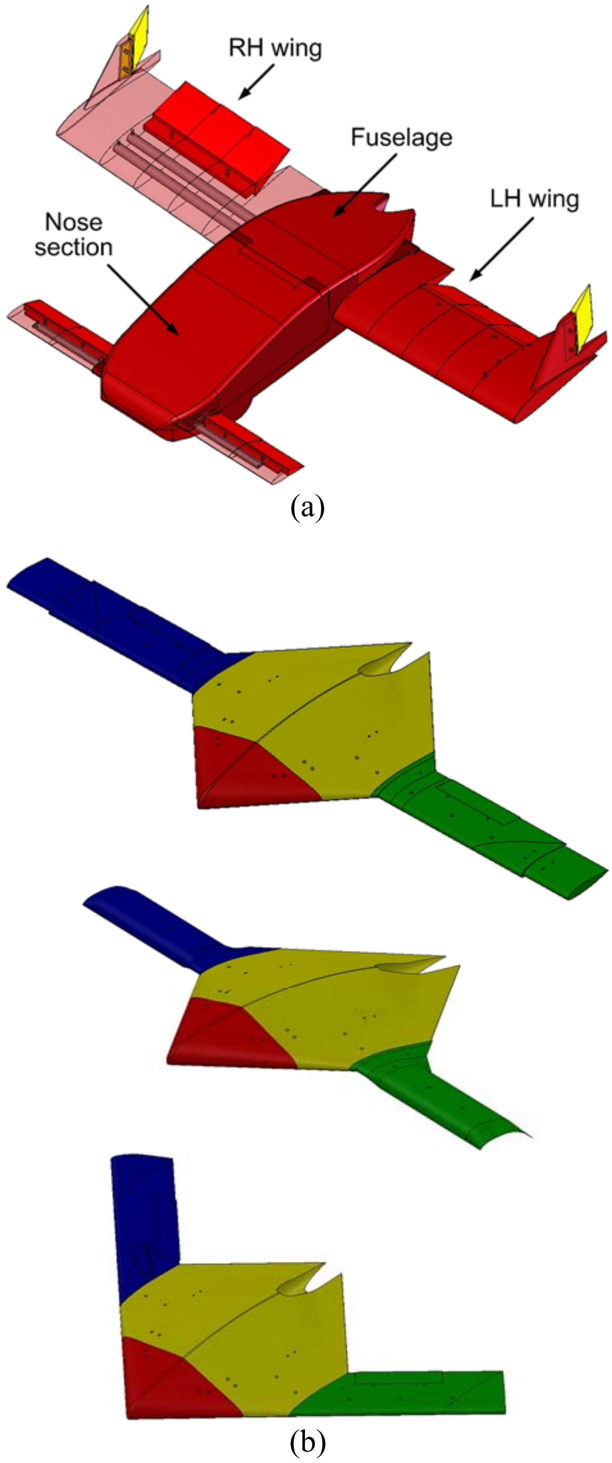



Fig. 7. CAD models of (a) “Flying-car”, and (b) MORPHEUS with the interchangeable wings, showing the four main parts of the wind tunnel models: fuselage, nose section and two wings

Although our tests were conducted at Mach numbers only up to 0.2, the forces generated are large enough to deflect and distort the model and thus adversely affect the fidelity of the experiments. Under stalling conditions, the models tend to vibrate quite forcefully, so strength becomes an issue too. To ensure adequate stiffness and strength, all of our model structures were reinforced with simple metal inserts that are easy and economical to make. The ILAS model was designed to accept five 8-mm diameter aluminum rods as shown in Fig. 8. The rods were inserted into long bores that were part of the RP model and secured in place with small screws.

The CERBERUS model had wings that were too thin for inserting round rods, so 2.5-mm thick stainless steel plates were used instead, as can be seen in Fig. 9. In this case too the model parts were fastened by small screws to the plates. Through holes for the screws were fabricated as part of the RP process, so no additional drilling was required. Similar attachments were used with the MORPHEUS model, and the canards of the “Flying-car”.

We have run some bending tests of 250-mm long, 34-mm wide and 15-mm tall beams made of FullCure® 720: a solid polymer beam, a beam strengthened with a 4-mm thick and 1-in. wide steel plate at mid-section, and a beam strengthened with two 6-mm diameter steel rods side-by-side. In addition to confirming the polymer properties, we used the material constants for tuning our finite element analysis of stresses and deflections, so we could run analyses for the metal-reinforced wind tunnel models. Fig. 10a shows the RP beam with the two steel rods being tested, while Fig. 10b demonstrates the deflection analysis of the same beam, using the material properties from the tests.

In designing such reinforcing elements, they should ideally span from as close to one wing tip to the other. However, as wings usually become thinner towards their tip, the reinforcements tend to be shorter. A more serious constraint was imposed in our models by the presence of the force balance and its adaptor, which interfered with connecting the

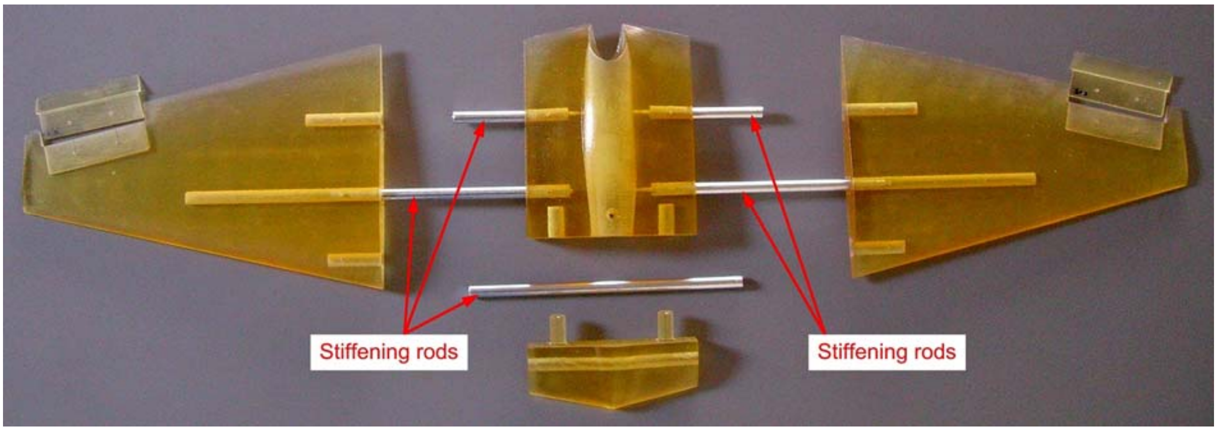



Fig. 8. The ILAS model before final assembly showing the five reinforcing rods

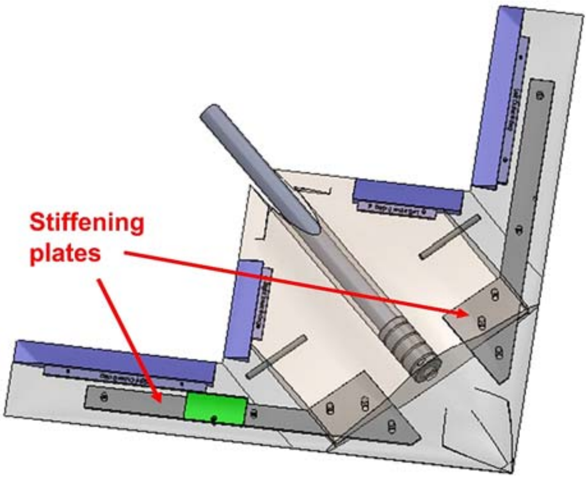
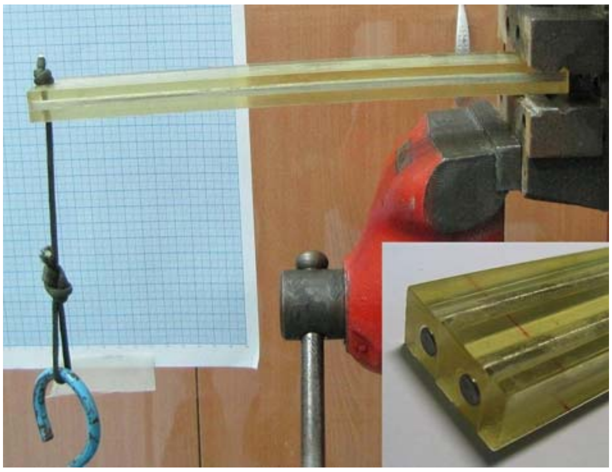



Fig. 9. CERBERUS model showing the two reinforcing steel plates

two wings directly. We therefore had to split the rods or plates into separate wing supports.

In general, it is recommended to use the largest diameter rod, or thickest plate, that are available in stock sizes (to minimize machining) and can fit inside the wings and still reach as close as possible to the wingtips. We generally prefer steel rods or plates to aluminum ones for stiffening purposes, as their Young's modulus is about three times higher. Care should be given in designing the contour of plates to minimize and simplify the required milling.



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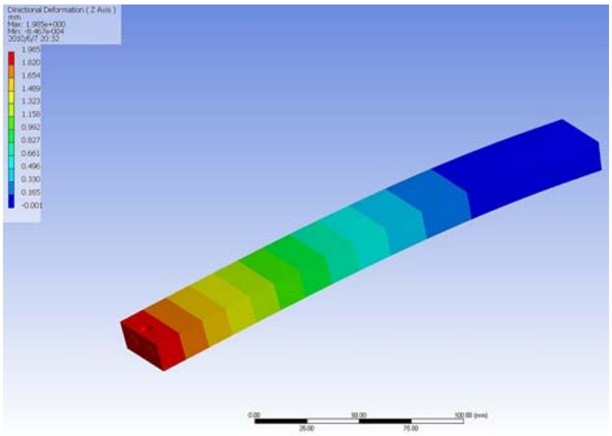

(b)

Fig. 10. (a) An RP beam reinforced with two steel rods (see inset) being tested in bending, and (b) deflection analysis of the same beam

### 4.3 Fastening Methods

The wind tunnel model needs to be securely fastened to the force balance, the main model parts should be fastened to each other, and the control surfaces need to be easy to assemble and disassemble for quick interchanging during testing. Connections should be accurate enough to guarantee the shape continuity of external surfaces, and tight enough to prevent backlash.

The connection to the balance was realized in our models by using a machined metal adaptor with a conical bore that fits onto the force balance and is secured by a screw. The adaptor was fixed in place relative to the plastic models by screws or adhesive plus screws.

Securing the main model parts to each other was done by a variety of methods, depending on whether the connection was permanent or not. For permanent connections we found that adhesive bonding, using either epoxy or cyanoacrylate, worked well. In such cases, guiding features – for example, holes and pegs – were designed into the plastic parts to provide accurate location. For connections that needed to provide for disassembly, fastening was done by means of screws and pins. However, because the plastic used for our models is not durable enough for repeated screwing, we tried to take advantage of the presence of the stiffening metal inserts to thread into them. So instead of directly fastening a wing to the fuselage, for example, we secured the wing to its reinforcing metal part, and the latter was fastened to the fuselage. We also found it possible to drive small screws directly into the plastic after making pilot holes as part of the RP manufacturing process. Small screws used by us were usually of the headless Allen set screws variety. Larger screws requiring a head were mostly with flat heads, so they could be mounted flush with the external aerodynamic surfaces. When we needed to fasten parts with a screw and nut, a hexagonal cavity was formed in the RP part, and a standard metal nut glued with epoxy to the walls of the cavity. This is similar to using threaded metal inserts in injection molded plastic parts, for example, and quite simple to accomplish with RP.

Interchangeable control surfaces were always made with guiding features, mostly a rectangular tab that fitted into a slot, as shown in Fig. 11, and secured with two pins or headless screws. During testing, many different control surfaces need to be disassembled and reassembled while the model is mounted onto the force balance inside the tunnel (to save time and eliminate a source of possible inaccuracy, removing the whole model and refitting it is undesirable). The force balance is a very delicate instrument, and tapping on the model to extract and insert interference-fitted pins might damage it. This unique requirement led us to prefer threaded fasteners instead of pins for this application. Using headless screws to provide shear resistance, as opposed to being subjected to tension, was less demanding on the plastic material, so it managed to tolerate several applications of repeated threading and unthreading into it without excessive wear.

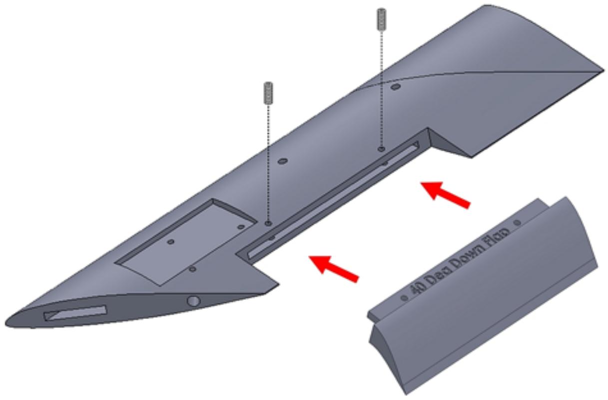


Fig. 11. Detail of an elevon and wing showing the locating features and the fastening by screws. An inscription made as part of the RP process contains the elevon's designation

In designing mating parts, special care should be given to the issue of tolerances. Horizontal (x-y directions) resolution of the machines used is about 0.1 mm, so backlash of a few tens of a millimeter might be present when parts fit depends on several dimensions. For example, when attaching 2 RP parts to each other using two "peg-in-hole" features, inaccuracies might stem from the pegs diameter, the holes diameter, the center distance of the pegs and the center distance of the holes. Slight adjustments were occasionally required by lightly sanding features of the plastic parts. Backlash was always eliminated when mechanical fastening or gluing were applied.

## 4.4 Part Design

RP allows generating complex geometries easily. The major implication for wind tunnel models is that hollowing out the models to reduce their weight, and making internal passages for pressure measurement or for smoke discharge for visualization are readily obtainable. The common double curvature geometry of external aircraft surfaces, which is makes complicated and expensive to machine, does not present any added difficulty for RP.

While we have not yet fully realized the potential of making hollow parts, we did benefit from a significant weight reduction compared to metal models. The relative density of the RP polymer is about 1.1, making the model much lighter than similar metal models. This, in turn, allows using a more sensitive force balance for testing, thus improving the data fidelity, and also reduces model vibrations during testing. An important byproduct of making the model lighter by hollowing out its bulkier areas is that its cost becomes lower, as less material is consumed in the fabrication. In our RP process, hollow areas are usually filled with temporary support material that is washed away later with water, and the cost of the support is about one half that of the model material.

In terms of accuracy, we have not carried out a thorough assessment, but feel that the 0.1-mm horizontal resolution and 16-µm layer thickness are very satisfactory. However, all RP techniques approximate the original computer-aided design geometry as small facets (i.e., planar surfaces) through the conversion of the model data to STL format, and this introduces some inaccuracy. At the expense of very large file sizes, the resolution in converting CAD data to STL can be set very high, but this may not improve the final model accuracy as the RP machines only support certain resolutions. The thin layers also assure a relatively smooth finish. Although "step marks" can be seen and felt, they do not seem to represent a roughness that is greater than with fine machining. Light sanding can easily be applied to the polymer if smoother surfaces are desirable.

The RP machines manufacturer reports an Izod impact strength of 24 J/m [10]. This means that small features may be quite vulnerable to accidental impact by other objects and consequently, to fracture. Our experience was that the trailing edges of wings and control surfaces were the most sensitive, as their geometry converges to sharp edges. Care should be given to making such edges blunt by filleting the CAD model at those locations.

A known problem with some RP techniques is long-term stability. The photo-polymers used in our models lose their strength when temperatures rise. Kim and Oh [11] report that the room temperature strength drops by 25% at 30°C, and by 50% at 40°C. We have also observed distortion of RP models (not the wind tunnel models of this paper) over time. Models stored at room temperature sagged noticeably under their own weight over a period of several months from the date of manufacture. This clearly presents a problem when repeated testing over a long time period is desired; however, our metal-reinforced models did not show any visible distortion after more than a year from the date of manufacture. In addition, due to the low cost of producing the RP models, damaged parts can easily be replaced if needed.

## 5 Conclusion

New RP techniques and materials provide a means to reduce the cost and shorten the time associated with the acquisition of a wind tunnel model. Our work in this area is related to students' projects and therefore has to follow a rigid academic timetable. Typically, the final configuration of the aircraft being designed is modeled in CAD towards the end of the project, and little time is left by then to design, fabricate and test the model in the wind tunnel, and evaluate and present the results. Together with having a limited budget for this academic activity, we have found the opportunities offered by RP very useful. The models of this paper were built for a fraction of the cost and time required for a similar traditional steel or aluminum model.

For our sting-type back-mounted models, their shape and size (about 60-cm span), the configuration with four main components—fuselage, nose and two wings—seems appropriate. It allows mounting the model from the front, and easy integration of stiffening metal parts. Ideally, the stiffening rods or plates should run from one wing to the other; however, the force balance and its adaptor might not leave enough space for this arrangement, resulting in separate stiffening elements.

The major structural difficulty that we have encounter is in ensuring a tight connection between the wings and the fuselage. Tolerances for RP parts cannot, at the present time, be as tight as with CNC machining, so some creative solutions need to be incorporated in the design, or adhesives must be used for the final locating of the parts. Clearly, this problem could be avoided by using a central machined strong back and using RP for external fairings only, but this would not fully utilize the cost and time savings inherent in an all-RP model. In addition, the RP polymer is not suitable for direct screw threading, so other fastening means need to be employed or the screws should connect to the metallic stiffening members.

We did not check the dimensional accuracy or the surface finish of the RP models scientifically, but can state that the models look and feel very satisfactory from this perspective. We also did not fully explore the possibility of making hollow models because of our lack of experience regarding the model stiffness issue, but even with the solid models we could benefit from their lower weight and thus higher measurement sensitivity.

In terms of the aerodynamic data, the quality of the test results is clearly acceptable for preliminary design and justifies the use of RP technologies, at least for models of a size similar to ours in a subsonic wind tunnel. The good dimensional accuracy of the models, combined with the high quality of the testing results, suggest that RP can be used for quick, low-cost evaluation of new aircraft and for verifying analyses results in industry and academia. Obtaining wind tunnel results in a short time can also contribute to the marketing of the aircraft during its development phase.

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