Future Airframe Technologies

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Abstract

When looking to the future, it is often best to review the important developments of the past. This paper will review the variety of aircraft designs and the wide range of construction methods utilized up to the present. It will discuss how some of the design requirements have changed over time and how the current marketplace and the regulatory environment will tend to drive the design of future aircraft. Future airframe shapes and construction methods will be proposed for regional, business, and small private aircraft.

Introduction

The airframe is the most fundamental element of an aircraft because it is the primary structural piece, and it holds all of the other pieces in place. There is quite a variety of designs and sizes for aircraft, as well as a wide range of construction methods.

Designing an aircraft is a balancing act between performance, utility, manufacturability, and cost. It is very easy to focus on the performance and utility of the airplane and not give enough thought to how to manufacture the plane and how to control the cost. This cost can be incurred both during the initial construction and throughout the life of the aircraft. The cost and frequency of maintenance directly affects the utility of an airplane. Meeting the performance goals alone does not insure success in the marketplace.

Airframes have evolved significantly over the past 100 years. Advances in materials and manufacturing methods now allow complex aircraft to be built efficiently and reliably. Still, not all aircraft are made from the same materials or in the same way. If there were a single, optimal way to build an airplane, we would see absolute uniformity in the design and in the method of manufacture. If there is one thing about airframes that can be said for the future, it would be that no one airframe-construction method will be adopted universally. There are far too many variables that can be optimized, and too many individual designers, to result in a single, 'perfect', design solution.

This paper will examine the progression of airframe-construction methods. This topic is interesting because there are a wide range of materials, assembly methods, and tooling involved. It is also instructive to understand why these different methods were chosen.

This paper will then examine some of the 'high-tech' materials and construction methods currently in use. Potential development trends will be proposed for airframe construction over the next quarter of a century.

Efficiency in a Commercial World

What is efficiency? Obviously, efficiency is tied to the performance and utility of an aircraft. For an aerodynamicist, efficiency may be seen as reducing the drag of the wing by a fraction of a percent to obtain the needed range or maximum cruise speed. For the structural engineer, efficiency may be measured as reduced structural weight to carry the design loads in the structure. For the aerodynamicist and structural engineer in combination, they would tend to define efficiency as a low-drag, smooth, aerodynamic shape with a low-weight structure that carries the load. The airframe designer would remind the aerodynamicist and structural engineer that their concerns for performance and structural efficiency must be balanced with the complexity and cost to build that airframe and make it maintainable.

During WWII considerable research was carried out in order to understand aircraft performance and how manufacturing methods might affect it. Much of this research focused on laminar flow, because if laminar flow could be obtained over even a fraction of the surface, the drag would be greatly reduced and would directly yield large benefits in performance or would indirectly result in reduced engine size and weight.

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The key to actually obtaining laminar flow is manufacturing a very smooth surface that is free from steps and gaps. It was shown that with the right shape, the use of flush rivets, and careful attention to smooth all joints, a metal airplane could produce laminar flow over a considerable fraction of the external surface. The limiting factors in actually achieving the low-drag benefits are the way in which manufacturing tolerances are handled, how access is made for inspection, and how flush fasteners are installed.

In all of the years since WWII, however, there have been very few production, metal aircraft that have utilized that research to produce laminar flow. Flush rivets have been used on many metal planes, but the cost and effort of additional work to further smooth the surface in order to obtain laminar flow, was not considered by most to be worth the payback.

Fiber-reinforced composites have offered another manufacturing option to produce the smooth skins that are required for laminar flow. A variety of reasons, the most significant being cost, has kept these composites from being accepted for most production airframes.

Despite possible weight savings or improvements in performance, the primary driver for the long-term success of a program is the cost. A successful design is one that can be produced at a cost that allows the plane to be sold at a price that the market can support. In considering a technological question like laminar flow, while it is definitely possible to achieve it, is the cost worth it? Can the careful assembly and handwork to fill and smooth all the edges be done without incurring unacceptable cost? The key to being able to bring a technology into the mainstream, is in being able to demonstrate that it is economically viable.

Airframe Evolution – Materials and Methods

One should not look to the future without evaluating what lessons can be learned from the past. Why were specific materials chosen? How were the pieces assembled? Is a given method still used today?

The Beech / Raytheon factory makes a good case study since it has been producing aircraft for more than 70 years. It is interesting to examine the evolution of the aircraft that have been produced here and the corresponding changes in production methods. Examples will come from the Beech factory along with other sources where appropriate.

The earliest airframes were made from wood and fabric because those materials were light and easily formed with simple hand tools, and the airframes could be built in most any shop. The down side of typical wooden airplane construction was the sheer number of parts requiring assembly, which led to considerable hand labor. Because of the craftsmanship required, homebuilders are the only group that still make airframes using wooden construction. Homebuilders value the craftsmanship and will take the extra time, especially if it can reduce their need for expensive tools and materials.

One of the first airframe elements to evolve to a material other than wood, was the wing rib. A wooden-trussed rib would be built from many small sticks with gussets. Each rib would be constructed on a form board using glue and nails to connect the pieces. Many ribs were needed to build a wing and each rib took a fair amount of time to construct. It was found that by using a formed piece of aluminum, in place of a wooden rib, many individual pieces could be eliminated, and thus the time and cost to build the wing could be reduced. The tooling for these aluminum ribs could be as simple as a wooden form and a lead strap to physically hammer the shape into the part. In a factory, it is more likely that a set of durable metal form blocks and a hydraulic press would be used to form large numbers of ribs at once. Figure 1 shows examples of the wooden-trussed rib[1] and the formed-metal rib[2].

The wooden boards that were used to form the framework of the fuselage were another airframe element that changed to a different material. It was easy and convenient to replace these with steel tubing. While a similar tooling jig would be used for either the wood or metal construction, the steel tubing had very uniform characteristics and provided better crashworthiness protection when compared to a simple wooden fuselage.

The Beech Staggerwing utilized a steel tubing fuselage with wooden battens to provide a smooth shape for the fabric covering. The Staggerwing was the first aircraft developed by Walter Beech when he established Beech Aircraft in the Travel Air factory buildings. This biplane was fast for its day and carried four people in comfort. The wings were constructed mainly with wood, again all covered by fabric. This airplane relied heavily on the skill of individual craftsmen to insure the fit and finish in order to achieve its performance. The performance was excellent for the time, but the methods used were very labor intensive. Figure 2 shows the Staggerwing fuselage assembly line.

The next major improvement in construction was the utilization of a stressed-skin or monocoque design. In the 1930's, thin aluminum panels were formed in presses and then stiffened with stringers, frames, and ribs to form fuselages and wings. During World War II, there were even some stressed-skin aircraft built with molded plywood, because of shortages of aircraft aluminum. The design of the AT-10 showed ingenious use of wood in a time in which the use of aluminum was reserved for combat aircraft. Plywood, stressed skins were formed in heated concrete molds. 1,771 of these aircraft were delivered to the Air Corps for training, but when the material restrictions were removed after the war, this construction method became a footnote in history. A paper describing in detail the design criteria of this airplane, was written by Herb Rawdon[1]. Figure 3 shows a busy AT-10 assembly line.

The Bonanza replaced the Staggerwing in 1946 and incorporated the metal, mass-production lessons from WWII into a new commercial product. These two airplanes were totally different visually from one another, yet they served the same mission (see Figures 4 and 5.) The Staggerwing used a large radial engine while the Bonanza took advantage of the smaller frontal area of the Continental, horizontally-opposed engine to reduce the size and drag of the aircraft. The Bonanza was a major step forward, rather than a small evolutionary step. The metal–working machines that were installed during the wartime to build the AT-11's and C-45's, made it possible to make a rapid shift in the manufacturing technique when the war ended. The Bonanza was designed to use stressed aluminum skins with many hydro-formed ribs and frames along with machined spars. The intelligent use of machines in the production of aluminum parts, both increased the utility for the customer and reduced the cost to build for the manufacturer. The fact that one or more models of this aircraft have been in production for over 51 years, testifies to the quality of the design.

In the early 1960's, the development of the King Air added turboprop engines, as well as pressurization, to the Beech airframe designs. The King Air is part of what may be the most successful evolution of an airframe that began with the Bonanza. The turboprop engines improved the utility, when compared to its predecessors, and allowed the new aircraft to be successful in several markets, including corporate transportation for business customers, commuter airlines, cargo hauling, transportation of military personnel, and military surveillance. Construction techniques are similar to those of the Bonanza, however, there are areas that utilize bonded aluminum assemblies to replace rivet joints. The empennage control surfaces of the King Airs are one of the first applications of bonded ribs in the factory. This construction method, using truss-grid ribs and a skin that wraps around the trailing edge, is very efficient in weight and cost.

The majority of production aircraft since WWII have used aluminum, stressed skins. These skins were initially relatively thin in wing construction, and depended on the internal structure of spars, stringers, and ribs to provide the necessary strength. Today, a number of aircraft designs use thicker skins that are carefully sculpted with milled pockets to remove material. More of the load is then carried in the skin, and these thick skins produce smoother surfaces under load.

As aluminum became the design norm, a new class of materials began to develop, composites. In the mid 1960's, the sailplane community began investigating the use of fiber-reinforced plastics for structure. By the late 1960's, Alexander Schleicher Segelflugzeugbau was producing the standard-class, Ka-6E wooden sailplane in its factory along side a new design, the standard-class, ASW-15 fiberglass sailplane. The cost of the materials for the new glider was higher, but the surface finish was better with the new method and allowed substantial runs of laminar flow. For a competition glider manufacturer, the improved performance of these new gliders alone would push a production decision to implement the new method, even if the cost were higher. Even for lower-performance gliders, the skill, time, and cost to assemble the many pieces of a wooden glider took its toll, and by 1970 the end of wooden production sailplanes was on the horizon. A mix of carbon, aramid, and glass fiber is now the norm for most production sailplanes.

Powered aircraft lagged behind in moving to composites; however, in the early 1980's, a concentrated effort was made to develop an all-new, turboprop aircraft, the Starship I. This revolutionary airplane was designed entirely using carbon-fiber composite. The technology for this design was very new and required the development of a significant database of material properties in order to satisfy both the FAA and Beech that the product would be safe, reliable, and maintainable. Unfortunately, the economics of the hand-lay-up, manufacturing process, along with the unusual configuration and only slightly better performance than other turboprop aircraft, made the airplane unsuccessful in the marketplace. It could be noted, however, that two other turboprops designs of that time, the Lear Fan and Piaggio Avanti, also had difficulties.

While competition-sailplane manufacturers could justify the new materials to obtain laminar flow at nearly any cost, the economics were not as convincingly strong for powered aircraft. Many companies were unwilling to invest in a new technology that lacked a comprehensive, material database, and in the large molds and autoclaves that would be required to produce the major parts. Today, computer-controlled milling machines allow these molds (or plugs to make the molds) to be made very accurately and quickly, but still not inexpensively. Autoclaves that are big enough to process a wing or fuselage require very-large, capital-equipment expenditures.

In the mid 1990's, the Premier I design team examined and considered methods for both metal and composite construction. While the Starship held to an all-carbon design for the airframe, the Premier team examined the various elements of the airframe and chose a combination of metal and composite to reach their design solution.

The Premier has a relatively thin wing with some sweep, in order to have a high cruise speed with good handling qualities and the chance for significant runs of laminar flow at cruise. An aluminum structure was chosen for the wing design to allow for fuel compartments without bladders and a lower level of risk for the design. Because of the wing thickness, a multiple spar layout was chosen. A more conventional two-spar wing with stringers was first proposed, but the thickness of the wing caused the upper and lower stringers to be so close to each other, that they were changed into full-depth spars. With the increased number of spars, the ribs were spaced further apart and thus reduced in number. High-speed machining was used to reduce part count and thus labor cost. All of the spars and rib pieces were made using high-speed machining with each spar from centerline to tip being a single piece. Thick, machined skins were used as well and required shot peening to form them to the required contour. Figure 6 shows the internal structure of the Premier wing.

One of the most striking usages of high-speed machining on the Premier is in the construction of the forward pressure bulkhead. This component is machined from a single block of material. Figure 7 shows the Premier fuselage shell with the installed forward pressure bulkhead.

Composites are still more expensive than aluminum, but there are two technologies that are used on Premier that hold promise for dramatically reducing cost. These are resin-transfer molding (RTM) and computer-controlled, fiber placement. The chief benefit of these two techniques is that they produce parts with repeatable dimensions, which enable lower assembly costs when compared to traditional riveted assemblies. They also reduce labor hours significantly.

The Premier uses resin-transfer molding (RTM) to manufacture the flaps, spoilers, and ailerons. There are substantial costs in putting this system into place, but once done, this technique is quick and has low labor cost. Figure 8 shows the simplicity of the one-piece, RTM spoiler.

The Premier fuselage draws on the experience of the Starship and on a new-technology machine, the Viper from Cincinnati Machine. This robot can accurately place carbon fibers on a mandrel, with the benefit of low labor cost. The robot and the associated mandrels and molds are expensive, but it is anticipated that the reduction in labor cost to build the parts and to fit them to other assemblies will make this process economically attractive in the long term. Figure 9 shows a fuselage being made by the Viper machine.

A number of other technology advances can be seen in products from other manufacturers. These manufacturers range from companies that are very small to the very largest in aerospace. To look at metal aircraft technology, we will begin with the low end of the market. Homebuilt aircraft have become very popular with private aircraft owners and one of the most successful builders of kits is Van's Aircraft, the manufacturer of the RV line of airplanes. An exceptionally high percentage of the RV airplane kits are actually completed, which testifies to the thought that went into the design. One of the newer features of these kits is the use of matched-hole parts. The skins are computer cut and drilled or punched and the frames and ribs, to which they mate, have matching holes already computer drilled. These aircraft can be assembled by inserting clecos into several of the matched holes and then proceeding with the riveting. This method insures that the airplane will be in alignment with an absolute minimum of tooling.

At the high end of the spectrum, automated riveting is now used on Boeing transport airplanes (and by others as well.) Boeing utilizes large robots with laser alignment to assemble accurate assemblies. This technique can build large fuselage panels in an automated fashion with exceptional repeatability of the parts, so that large assemblies can be mated together without the need of any shims.

Boeing is currently using friction stir welding (FSW) in the production of large fuel and oxidizer tanks for the Delta rockets. An automated, computer-controlled, friction stir welder produces error-free joints very rapidly. Eclipse Aviation is also planning to use FSW to produce their fuselage assemblies to reduce production cost. Although it is still very new, this method shows promise for aircraft construction.

Composite construction, another promising method, still poses challenges. Part of the difficulty in designing with composites has to do with having the appropriate database of material properties. The properties of aluminum alloys are readily available for designers, but that has not been the case for composites. Much of the composite data had to be developed through testing by the aircraft builder and then be presented to the FAA and approved. Following the NASA AGATE (Advanced General Aviation Transport Experiment) research program, the FAA is about to publish new policies for the control of composite material data. It is assumed that this will enable open databases for material properties. This new policy will enable a company to do minimal material qualification work and then go straight to full-scale testing.

Marketplace Demands

Every year, consumers expect more from all of the products that they use. Even low-end automobiles now have features that were available only on high-priced models a few years ago. The consumer electronics market is growing so rapidly that many of the products available today are completely new within the last ten years. Items such as the phonograph, cassette recorder, and even the videotape machine are being rendered obsolete. The technology utilized in our aircraft designs will be judged with respect to what the customer has available in other product areas, especially in electronics.

The customer will also expect more in terms of cabin comfort. The levels of noise and vibration in a modern automobile are very low. Private and business aircraft will be held increasingly to those same standards. Corporate aircraft will also tend toward larger cabins that allow the passengers to move around the plane more easily.

The speed and cruise altitude of corporate aircraft will match or exceed those of the airliners. Private aircraft may lag behind in order to maintain lower cost. Even with slower cruise speeds, the block time for a private flight will be low when compared to the typical times through the hub-and-spoke system of the airlines.

Business aircraft are now considered an extension of the office and must have the same access to computer networks and telecommunications as are available in the office. Private aircraft will increasingly need to have electronic entertainment systems available for the seats behind the cockpit, and the latest displays for navigation and aircraft monitoring for the pilots.

The communities, which aircraft fly in and out of, are already requiring reductions in noise level. In the future, the government will be more involved in setting regulations for community noise, safety, and other issues that impact the environment. Regulations, and the market, may push propeller aircraft to utilize shrouds to control noise. In the extreme end of the market, there is considerable research into designing the shape of a supersonic business aircraft to an acceptably low noise level for flight over inhabited landmasses.

The Future

I believe that a large design driver in the future will be cost. We currently have good methods to make metal aircraft and composite airplanes. There are many suppliers of aircraft, all operating in the same global market and trying to differentiate their products to the potential customers. Although there is some differentiation of features and performance among the various aircraft in a market segment, the manufactures try to minimize these differences to avoid loss of sales. The primary driver for sales is the reliability and maintainability of the aircraft and how the manufacturer supports the aircraft after the sales. It is also important, however, that the products have similar costs of acquisition and operation. If either of these costs can be reduced, it can represent a benefit in market share through increased sales because of reduced price, or a benefit of increased corporate income from increased margin.

It has been suggested by McMasters and Cummings[3] that the mantra, “Farther, Faster, Higher,” that existed throughout the cold-war era has been replaced with a new one, “Leaner, Meaner, Greener.” An interesting comment in their paper referring to future design work was, “ .. the laws of economics can be bent to some degree, the laws of physics cannot.” This is very important when considering design optimization with cost constraints.

In a classical, performance-oriented, aircraft-sizing exercise, the airframe material is one of the design variables and it appears primarily in the weight equations of the analysis. For future designs, the sizing models will need to also consider the costs of manufacturing, which depend on material and method choices. Since there are a number of options for building with either metal or composites, more tailoring of the sizing models for cost will be required.

- How will the airframe of the future be manufactured?

The majority of low-end aircraft for use by private owners will continue to be built with thin aluminum skins for the next several years. Aluminum is well understood by most mechanics and homebuilders and is easy to maintain and repair. But because of the recent Diamond, Cirrus, and Lancair composite aircraft, mechanics will gain more exposure and real-world experience with composites, which in turn will make them more comfortable in dealing with them. This will tend to change the dominance of aluminum toward composites within the next ten years. Private owners are already expressing an interest in the added performance that some of the smooth composite designs have to offer.

Composites will be used more widely in secondary structure and also in some primary areas. Improved, low-cost methods for lightning-strike protection of composites will be developed along with improved, composite-sandwich structures and other non-sandwich options that both reduce cost and provide better noise-transmission characteristics. These improvements will result in composites being considered by more designers.

Business and regional aircraft will continue the move toward thick, machined, aluminum skins. For the interior metal frames, ribs, skins, and spars, high-speed machining will become more commonplace. This combination will produce better repeatability of the pieces and assemblies so that cost can be driven down. It is also efficient for weight and produces a smoother aerodynamic surface than is possible with thin skins.

There are two reasons why laminar flow is unlikely to be obtained in the higher-speed business and regional aircraft, cruise speed and aircraft maintainability. High cruise speed is typically obtained by increasing the sweep of the wings. Once the leading-edge sweep exceeds about 20 degrees, it becomes increasingly difficult to maintain laminar flow due to crossflow instability. If the sweep is kept at or below 20 degrees, the second reason, maintainability, becomes important. Business and regional aircraft have high utilization and thus have requirements for frequent inspection. These inspections require access to the interior of the airframe to examine both structure and subsystems. This implies the need for removable inspection ports. Given the tolerances on the ports and on the basic structure, it is difficult to manufacture an airframe that has these inspection holes and that can readily achieve laminar flow, unless there is significant handwork to smooth and fill the joints. These aircraft also typically have an ice-protection system with a removable leading edge for maintenance. This compounds the joint problem and extends it the length of the wing or tail surface. These joints will make laminar flow unlikely without a fundamental change to the manufacturing process that allows smooth, gap-free seams to be made. Composites would face the same challenges as metal in dealing with these joints and would also be more expensive.

Secondary structure will see increased usage of RTM composites primarily due to reduced cost from labor. Flaps, fairing, and control surfaces will be prime candidates for this low-labor technique. It may even be possible to build entire wings and tail surfaces with new mandrel concepts.

Automated fiber placement still holds the potential for affordable primary structure. There will be continued research into a variety of methods to stiffen large panels in other ways than with a sandwich core. If the sandwich cores can be removed, even greater manufacturing speed should be possible, and less ultrasonic checking of panels would be required. Fiber placement can also lead to a wider range of composite subassemblies, such as landing-gear struts or springs, doors, and floors.

Besides advances in composite manufacturing, methods for easy and thorough inspection are critical to safety and reduction of scrap. Developments in ultrasonic inspection allow efficient searches to be made for flaws within a composite laminate, mostly voids or delaminations. In the Raytheon factory, large composite parts are automatically inspected by multi-axis, ultrasound scanners. Smaller parts can be inspected with hand-held detectors, equipment that will likely become commonplace for non-destructive inspection in the field.

Stereolithography (SLA) is currently being used to build prototype parts and speed the production of tooling. There will definitely be an increased use of SLA to do these tasks in the future. Current SLA rapid-prototyping allows the manufacture of complex 3D parts out of plastics and starch-based materials. The material is deposited in successive thin layers with each layer being solidified by a laser. New machines under development can use metals rather than plastics or starch. Titanium parts could be 'grown' one layer at a time from powder. Once grown, the part could be finish machined very quickly. This method greatly reduces the amount of titanium material and machine time that is required to cut a part using traditional methods. This method is most attractive with difficult-to-machine, high-cost materials. This technology is unlikely to supplant high-speed machining, because grown parts have poor surface finish and currently require heat treatment, but the two technologies should compliment each other.

- What will the airframe of the future look like?

Looking through a sketchbook that chronicles various Beech preliminary design studies from the past, one can see a number of styling studies that draw distinctly on the automotive industry. Figures 10 and 11 show studies from 1955 and 1963. In fact, in the post-WWII years there were many magazine advertisements that tried to sell the image that light planes were much like a four-place automobile. For today's buyers, the automobile images that come to mind would be a sporty coupe or a popular SUV. Figure 12 shows a concept for an airplane based on today's automotive styling.

Engine technology has driven the shape of the aircraft. The large radial engines of the 1930's single-engine designs were replaced by the more compact Continental and Lycoming flat four and six-cylinder engines, which allowed the entire nose to be reshaped. The development of small turboprop engines allowed the aircraft with large twin radials to be redesigned with much smaller nacelles that had lower drag, while maintaining the thrust. These turbine engines also could provide bleed air with which to easily pressurize the cabin. Where the Bonanza replaced the Staggerwing, similarly, the King Air replaced the Model 18 Twin Beech. The development of fanjet engines in smaller sizes will logically continue the changes in the personal-aircraft market. While propellers will not likely disappear completely, the number of personal-jet aircraft will increase significantly once the engine manufacturers can show that they have a mature product suitable for widespread use. And as two or more engine makers reach that level, the competition will bring down the cost and the usage will further increase. Figure 13 shows a sketch of a small, cabin-class, jet aircraft.

Those airframe makers that choose to continue with piston products, will finally replace the 1940's-technology, air-cooled, horizontally-opposed engines with modern, water-cooled engines based on the latest automotive technology. These aircraft will be easy to start, run smoother, have standard turbochargers to allow flight at higher altitudes, and have much longer service times between overhaul. The latest Wankel-type rotary engines have good fuel economy and will offer advantages in package size and smoothness of operation. To match these new automotive-based powerplants, the aircraft will have the sleek and smooth styling of modern cars, because molded composites will allow complex compound curves to be easily manufactured.

Will aircraft continue to have wings or depend more on powered lift? Aircraft designed primarily for short trips could benefit from the lower weights of the new powerplants and the carbon, but winged aircraft are likely to remain dominant for trips of a hundred miles or more, simply because of the efficiency and speed.

Composite airframes will become the standard for small private airplanes. In the homebuilt market, the kits will become even more modular, similar to a plastic model plane in construction concept. The traditional configuration with the aft tail, will likely remain the norm since this layout offers advantages in wetted area and performance over most canard aircraft.

Business and regional aircraft already use turbine engines and have well-developed designs. It is likely that future models will be an evolution of the current ones, because they already have optimized structure and utilize some automated manufacturing techniques. Large winglets or sheared wingtips will become more common in order to avoid induced drag penalties associated with the normal evolutionary modifications and modest increases to gross weight.

Conclusion

All in all, it is likely that the lines of future aircraft will be visually traceable to the most modern ones that we see today. The design of these airframes will use more sophisticated optimization techniques to increase both the performance and manufacturability of these products. Business and regional aircraft will evolve more slowly, with personal aircraft leading the way in new technology. The new engine options that will be available in the next decade at affordable cost, will create new airframe-layout options for the individual owner and pilot.

References

1. Rowden, Herb, “Wood vs. Metal Construction in Aircraft,” SAE Journal (Transactions), Vol. 53, No. 12, pp. 691 - 713, Dec. 1945.
2. <u>Metal Aircraft Design and Construction</u>, Willis L. Nye, A Cadet Series Publication by Aviation Press, San Francisco, 1935.
3. McMasters, John H. and Cummings, Russell M., “ From Farther, Faster, Higher to Leaner, Meaner, Greener – Future Directions in Airplane Design in the New Century,” AIAA 2003-0553, Jan. 2003.

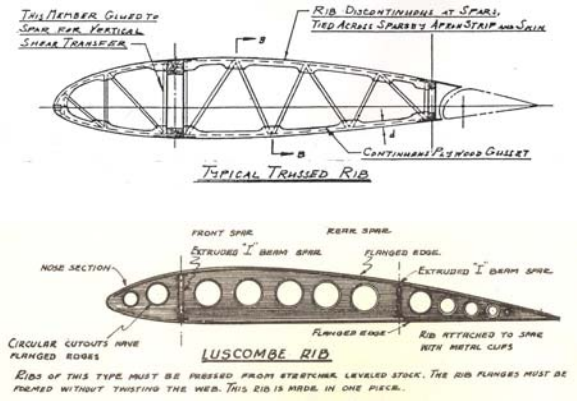

Figure 1 – Typical wooden-trussed and formed-metal ribs (from References 1 & 2)

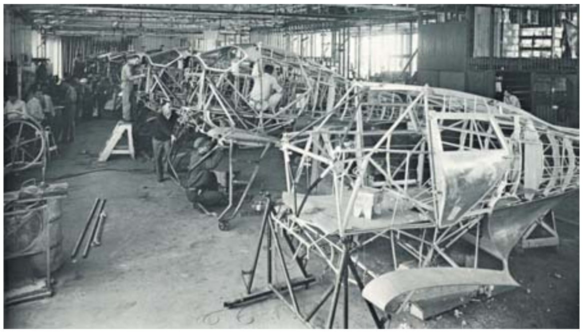

Figure 2 - Staggerwing fuselages on the Production Line.

Figure 3 – Production line for the AT-10 (July 1942)

Figure 4 – Beech Staggerwing

Figure 5 – Beech Bonanza prototype

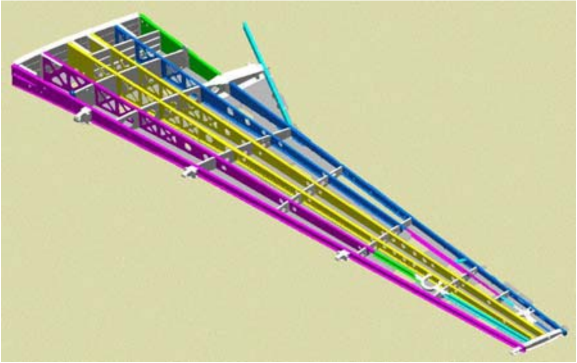

Figure 6 – Internal structure of the Premier I wing

Figure 7 – Premier I fuselage shells with bulkheads

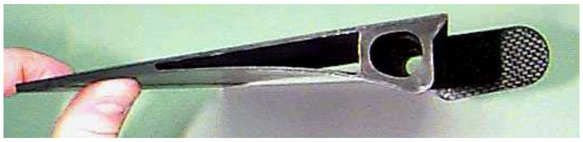

Figure 8 – Resin-transfer-molded (RTM) flap

Figure 9 – The Viper placing carbon fibers on a fuselage

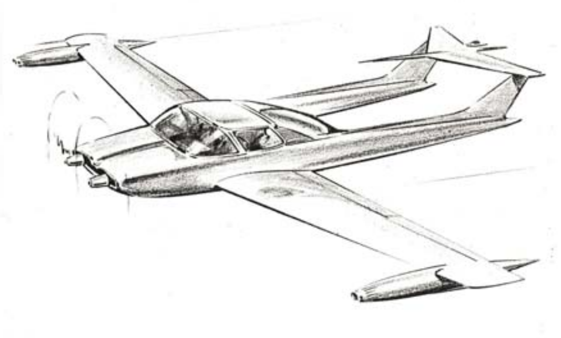

Figure 10 – Styling concept from 1955

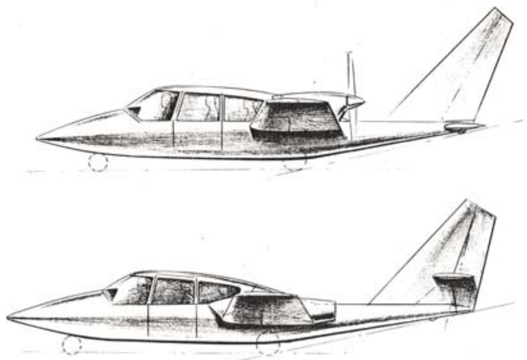

Figure 11 – Styling concepts from 1963

Figure 12 – A modern, auto-based, styling concept

Figure 13 – Concept for a cabin-class jet aircraft

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