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Future of Flight Vehicle Structures (2002–2023)

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The journey in advancing flight is far from complete. Challenges to improve performance while reducing costs to acquire and operate air vehicles to fully exploit the potential benefits of flight for humankind remain formidable. Toward this goal, what progress can we anticipate in the next 20 years? The authors attempt to answer this question, sharing their collective vision for advancements in structures technology within the allotted timeframe. Their coverage spans experimental, general, military, and commercial aviation.

MAN'S desire to fly has seen manned flight grow from a dream 100 years ago into the creation of vehicles that currently enable us to explore our solar system and safely transport people/goods rapidly from one point on the Earth to another. Today we do this in hours vs days and months.

The journey in advancing flight is far from complete. Challenges to improve performance while reducing costs to acquire and operate air vehicles remain formidable, to fully exploit the potential benefits of flight to humankind.

Nature shows us the potential, packaging payload/unit of energy to levels far in excess of today's state of the art. Thus, the challenge is clear. Achieve more with less—carry more payload for less weight, improve fuel burn, and do it for far less cost.

So, toward this goal, what progress can we anticipate in the next 20 years? The authors attempt to answer this question, sharing their collective vision for advancements in structures technology within the allotted timeframe. Their coverage spans experimental, general, military, and commercial aviation. We hope you enjoy the read. May it stimulate you into contributing to the advancement of powered flight.

I. General Aviation

Improvements in general aviation structures over the next 20 years will be primarily driven by economical, rather than technical, limitations. For the last 70 years, improvements in the structures of private piston-powered aircraft and business jets have been the result of trickle-down technology from military and commercial aviation. The trend is likely to continue for the foreseeable future.

A. Conventional Composites

Over the next 20 years, composites are likely to continue gaining ground on aluminum as the dominant general aviation structural material. All of the new piston-powered aircraft introduced in the last decade have had composite structures, and this trend will likely continue with few exceptions. Until now, most of the piston-powered aircraft have been made with fiberglass/epoxy composites—either wet layup or prepreg. Raytheon has been the only business jet manufacturer to make large primary structures, such as fuselages, with composites, and they have used carbon/epoxy laminates almost exclusively. Because of the superior performance of carbon over fiberglass in both weight and strength categories (and the relatively small cost increase as a fraction of the overall aircraft), both business jets and piston-powered aircraft will realistically make the transition over the next 20 years to carbon/epoxy prepreg laminates.

Advanced composite materials have several inherent benefits over aluminum, including lower density, higher strength, and much greater fatigue resistance. However, the ability of composite materials to be formed into complex shapes inexpensively (and the consequent overall cost savings) is probably the greatest of all claimed benefits for composite materials. More important than even improved aerodynamic contours, this ability to form complex shapes has allowed radical part count reductions in aircraft structures. It is reasonable to believe in the possibility of even further part consolidation, which has the greatest potential for reducing the cost of general aviation structures.

Composite aircraft structures of the future will probably consist of a small number of very large carbon/epoxy prepreg parts that can be built quickly with almost zero assembly time. At that point, the time required to install systems will limit the ability of small aircraft companies to deliver aircraft, and considerable emphasis will be placed on integrating systems assemblies with structural assemblies and eliminating the semicustom installations common in the aircraft industry today (relative to the automotive industry). Most companies still develop aircraft structures and systems in relative isolation. Integration of these components, with complete systems that snap into place on a structure without tooling or

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fixtures, will require a radical departure from current development processes.

Another primary benefit of composite materials is the relatively low initial tooling and equipment cost. This factor, along with the smooth contoured shapes, is probably the driving reason that most recent startup general aviation companies have selected composite structures over aluminum structures.

Another significant factor in the growth of composite structures might be the entry of Japanese automakers into the general aviation arena. Toyota and Honda have both built general aviation aircraft in the last decade with composite structures. Both companies have the necessary financial backing and long-term outlook on the industry to successfully make composites for this class of aircraft. Whether composites gain a clear lead over aluminum will depend on which aviation companies are able to survive, rather than on the purely technical advantages of composites. The signal indicating the end of the aluminum era will sound when one of the dominant general aviation manufacturers finally produces an all-composite aircraft, and this will likely happen within the next 20 years, and hopefully, much sooner.

B. Aluminum

All aviation manufacturers will increasingly use the high-speed machining process for aluminum, whether their structures are primarily aluminum or composite.

Tooling and equipment for aluminum aircraft are expensive. Each of the hundreds or thousands of parts must have its own tool. Large, expensive equipment, like large hydroforms, brakes, presses, and shears are required. But computer automation is changing that. High-speed machining can inexpensively make complex, integrated aluminum parts; and with matched-hole assembly methods, the tooling costs are also drastically cut. Initially developed for the large aircraft companies, this technology has proven so cost effective that it has even transferred to experimental home-built companies that have little risk or aversion to trying new techniques.

In short, high-speed, low-cost machining has given aluminum many of the same advantages afforded by composite structures. By replacing dozens or hundreds of parts with a single component, for example, on a complex aluminum bulkhead, assembly time and assembly tooling can be reduced or eliminated, and the reduction in part variation allows for even further assembly time reductions for follow-on operations. In addition, the reduction of parts counts saves significant costs in engineering support, document control, manufacturing, and quality assurance oversight.

High-speed machining is gaining ground in even the lowest-cost general aviation aircraft for one primary reason: low-cost computing. Complex machined components reduce parts count and thus assembly time; accuracy generally improves, resulting in reduced overall cost. But to make complex machined components, a company needs four things: 1) CAD software capable of defining three-dimensional solid components, 2) computers capable of running that software, 3) software capable of generating NC cutting paths, and 4) Numerical control machines with computers fast enough to process the tool paths. As the cost of computing has come down, the software vendors have reduced the price of their software to drastically increase the size of the potential customer base. Now, every general aviation company can afford high-speed computers and three-dimensional solids CAD software. Almost every general aviation company has NC equipment, as do all of their suppliers. Twenty years from now this trend will probably be even more entrenched, with more complicated and integrated designs included in every aircraft in production.

Friction stir welding of aluminum joints is a relatively new development in general aviation structures and has only been made possible by a huge investment on a new aircraft. The high initial cost promises to drastically cut assembly costs, but it is still too early to determine if friction stir welding will be a success. Just like advancements in composite materials, the future viability of friction stir welding will hinge more on the success of the company implementing it than on the pure technical benefits it provides.

C. New Materials

It is doubtful that there will be any new materials incorporated in general aviation structures in 2023 that have not already been invented today. History supports the long development period necessary to include new structural materials in general aviation aircraft.

Almost 40 years ago, boron/epoxy structures were conceived, which led to advanced composite materials on fighters of the early 1970s. Ten years later, the LearFan unsuccessfully struggled to simultaneously incorporate composite materials in general aviation aircraft and convince the Federal Aviation Administration of their safety. A few years later, Beechcraft further advanced the state of the art with the Starship before canceling production. Finally, in the late 1990s Lancair and Cirrus were able to certify two piston-powered aircraft with all composite structures, and now Raytheon has come back with composite fuselage business jets. It is too early to tell if any of these projects will be financially successful.

This saga implies that we already know the names of new materials that will be incorporated in future general aviation aircraft. Perhaps those materials are sheet-molded composites or bulk-molded composites that encapsulate short fibers, like carbon or glass, in an epoxy or other plastic matrix. These materials provide extremely fast processing times with little or no labor. However, the short fibers limit the ultimate strength of the material, resulting in weight penalties to survive the same loading environment. Tooling costs are relatively high, as well, but. . . .

Another possibility for future development is thermoplastic materials. Commercial and military aircraft have attempted to develop cost-effective thermoplastic materials for the last 20 years. However, the more stringent requirements for military aircraft, particularly high-temperature performance, might have limited the chances of success. General aviation structures, with common structural limitations of only 180°F, might prove more suitable for thermoplastic development, but only if significant research funds are made available with the necessary time to develop a successful application.

Resin infusion is gaining ground in the high-performance marine market, both for the high fiber volume ratios possible (similar to prepreg composites) and the reduction in expelled volatiles as mandated by the Environmental Protection Agency. Resin infusion can allow structures even more complex than today's highly integrated composite structures, but with reduced layup times and labor costs that are the result of ease of placement of dry fabric in an open mold.

All of these new materials and processes promise great strength and durability, but it is the lower costs and faster processing times that make them attractive. Each of these systems could easily reduce the cost of wing ribs, gussets, and other complex detail parts on both aluminum and composite aircraft with little or no weight penalty. However, each material still needs considerable development, both in terms of money and time, neither of which is likely to be available because of the general lack of pure research dollars, the perceived lack of potential payoff, and the high risk associated with general aviation.

D. Summary

The future of general aviation structures will depend heavily on the financial stability of some of our more recent startup companies, like Adam Aircraft, Lancair, Eclipse, and Cirrus. If some of the many new composite companies survive, then 20 years from now composite aircraft will be the norm for new light planes. If Eclipse survives, the probability of friction stir welding being applied to multiple aluminum aircraft will be high. But if the startup companies do not survive, then the future of general aviation structures might look very much like the past.

II. Experimental Aircraft

A. Introduction

Twentieth-century aircraft can be grouped into three categories based on the power of their engines: 1) flying objects powered by less than 1000 W (which compose the majority of aircraft), 2) aircraft operating between 1 and 1000 kW, and 3) aircraft powered above 1000 kW.

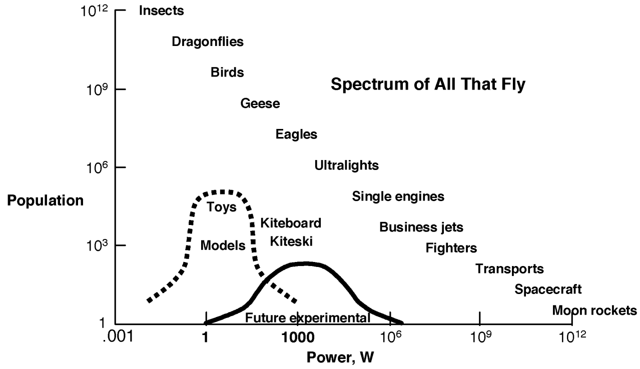

Fig. 1 Flying creations.

The first category includes all flying objects powered by less than 1000 W and can be considered a great incubator for structural concepts applicable to the remaining two categories of larger aircraft. Examples include the new toys found at spinmaster.com. They are made of expanded polystyrene wings with polyvinylchloride pressure tanks, electric motors, and rechargeable batteries and are available at toy and discount stores for less than $100/lb.

The second category comprises approximately one million aircraft currently operating between 1 and 1000 kW. The majority are lighter-than-air, wind-powered sailplanes; ultralights; and experimental aircraft. These are largely unregulated, privately funded, and built by amateurs using a variety of organic and metal structures. The cost of design, fabrication, and assembly runs less than $1000/lb. Over the next 20 years, hundreds of new electric-, piston-, jet-, and rocket-powered aircraft with equally varied structures will be created in this second category. Increasing sensitivity to global air quality will guide most of this experimental aircraft activity, so that the vast majority of these aircraft will be powered below 100 hp. Figure 1 shows the spectrum of flying creations.

The third category consists of government-funded X planes (X-31, -32, -33, -34, -35, -36, -37, -38, -40, -43) and a handful of foreign and domestic aircraft, such as the X Prize rocket planes, which are powered above the 1000-kW range. Structures of these aircraft will be mostly metal and carbon/epoxy, which are the contemporary materials for most of the regulated aircraft developments. Some smart structures, self-healing structures, nanocomposites, and new refractory materials will occupy the high-speed end of this spectrum; but most of the innovation above 1000 hp will be in the aeroshape and in the propulsion systems. First-unit cost of these airframes will exceed $10,000/lb.

1. History of Experimental Aircraft

Experimental aircraft of the past 20 years have been designed and built for the different roles demanded by military and space customers. The X-32 and X-35 concept demonstrator aircraft for the $200B Joint Strike Fighter program were built to demonstrate transition to vertical flight, low-speed handling qualities for operation from the deck of an aircraft carrier, and a high degree of commonality and affordability.

Paul MacCready developed the human-powered (gossamer) aircraft for the Kremer Prizes 20 years ago, building lightweight and low-cost structures strengthened only when failures during flight test indicated structural weakness. The privately funded experimental aircraft of the next 20 years will build on a similar philosophy using more basic structures, systems, and propulsion than in government programs. Another segment of the aircraft industry—the wind-powered kiteboard industry—is also characterized by flights of altitude and duration similar to the first unpowered flights by Lilienthal and Chanute between 1869 and 1900.*

*More data available online at www.cabaretekiteboarding.com.

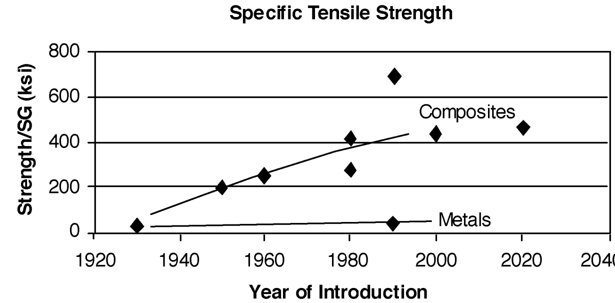

Fig. 2 Strength of materials, composites vs metals.

Fig. 3 Gaastrakites.com.

2. Propellant Tanks

The $1B X-33 and X-34 spacecraft featured the mostly round fuel and oxidizer tanks required to improve the propellant mass fraction on modern spaceplanes. Carbon/epoxy honeycomb sandwich was used to provide structural efficiency and thermal insulation, but the huge delta T between the stress-free state at 350°F in the autoclave and the −350°F of the cryogenic inner wall proved too much for the structure, and severe cracking and leakage resulted. Hence, we will continue to see metal liners or all-metal tanks on the X planes of the next 20 years, especially those containing high-pressure gases or cryogens.

Figure 2 shows the tremendous improvement in specific tensile strength achieved since 1920. More progress is likely in translating these improvements into real structure rather than in dramatically improving fiber strength.

3. Inflated Structure

The case for inflated structures is being proclaimed in general aviation as well as in spacecraft. The Gaastra kite (Fig. 3) combines unicarbon reinforcement of the inflated urethane/Dacron main wing spar to deliver structural efficiency above 10 ft^2/lb while controlling first unit cost below $200/lb. This modern marvel is at the cutting edge of current wing technology. The ocean-racing catamarans and monohulls have pioneered many innovations in wing and hull technology that will show up in experimental aircraft in 20 years.

4. Soft Wings

The 8000-ft^2 stowable wing deployed by the X-38 test vehicle (Fig. 4) explores the upper size limit of this soft wing technology. More than a million modern stunt kites under the 10-ft wingspan continue to push the state of the art. A hundred thousand powered parafoils are delivering millions of flight-hours each year below the 10,000-ft altitude. The next 20 years will see more development in soft wings.

5. Rigid Wings

Classes of modern composites characterized by high compression efficiency will maintain aeroefficiency and predictability of

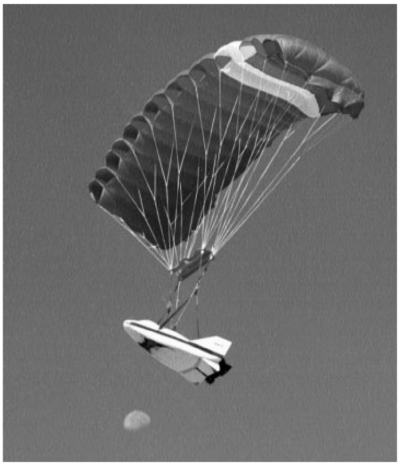

Fig. 4 Soft wing.

Fig. 5 L/D > 30 at cost < $200/lb (www.windward-performance.com).

rigid airfoil shapes and planforms. The Lithuanian gliders with main wing spars of pultruded carbon/epoxy rods from Avia in Hickory, South Carolina, are at the cutting edge of this technology. These 300-ksi carbon/epoxy pultrusions are now available for less than $100/lb from Aircraft Spruce. They represent the best bargain for strength/weight and stiffness/weight for main spar chords and stiffeners. Another experimental aircraft standard for wings might be the application of commercial floor panel technology. These remarkable panels are as stiff and strong as any parts on the $1B Stealth Bomber or the $100M Boeing 777, but the cost is about the same as for marine plywood.

6. Substructure

Aerovironment is pioneering the use of innovative ribs and skins to fly for days on human and solar power. These structures are built at structural efficiencies greater than 10 ft^2/lb and can maintain wing lift-to-drag ratio (L/D) above 20. The first unit cost of the early human-powered planes of the past 30 years was less than $1000/lb, whereas current aircraft are flying above 90,000 ft. Unicarbon truss elements are finding their way into internal ribs where they can be protected from impact damage. Orienting all of the carbon fibers in the most beneficial direction can obtain remarkable levels of structural efficiency.

The typical aircraft wing structure of the past 50 years has an efficiency of less than 0.2 ft^2/lb. In 20 years, carbon sandwich skin panels with little substructure will dominate. The SparrowHawk benchmark of nearly 2 ft^2/lb will be typical of the high lift-over-drag rigid wings of the next 20 years (Fig. 5).

For larger airplanes, sandwich panels supported by sparsely spaced truss ribs and stiffened spars will deliver aeroefficiency above current levels and structural efficiency above 0.4 ft^2/lb.

7. SparrowHawk

The benchmark structure for modern sailplanes is SparrowHawk, which features a 36-ft carbon wing of 70 ft^2, weighing 40 lb. The 35×25-in. cockpit features a one-piece transparency, four carbon longerons, and four transverse bulkheads. SparrowHawk's remarkable features include its 155-lb empty weight and retail price of $25,000—less than $200/lb for the highest performing ultralight sailplane on the market today, with a structure molded exclusively of oven-cured carbon/epoxy prepreg. Electric-powered versions of efficient, high-aspect-ratio aircraft like Silent In from Italy will begin to emerge, some of them using flapping wings based on piezoelectric actuators and active aeroelastic software. Fuel cells also might emerge as early as 2010.

8. Lancair

Lancair homebuilts are the best current examples of competitive composite structure in experimental aircraft. With a structural weight of only 1000 lb and a kit cost (less engine and avionics) of only $100,000, the remarkable Lancair 4P has created a new standard for performance. Cruising at more than 300 kt above 20,000 ft, this experimental homebuilt provides useful transportation to the most discriminating pilots and engineers. Its carbon sandwich structure is based on marine-grade prepregs oven cured below 200°F. Rumor has it that larger companies, like Toyota and Honda, might soon exploit this structures technology and combine it with the latest engine and electronics from motorcycle and auto racing. The cost of the four-place, pressurized, turbocharged, single-engine aircraft could drop from more than $300,000 to less than $100,000, which would create a global market well over a million units and a gross revenue of $100B.

9. Safety

Safety for commercial jets is one hull loss per million departures. The hull loss rate for the X planes is close to 1 for every 100 departures—about the same as the early space shuttle flights. The safety record of all experimental aircraft generally falls between these two extremes. They are more dangerous than commercial aircraft per flight and certainly per seat-mile, whereas commercial aircraft are two orders of magnitude safer than the motor vehicle. Experimental aircraft, however, are generally safer per flight than the space shuttle, which is considered acceptable by most test pilots. The hull loss rate in the new kiteboard industry is around 1 in 10,000 departures, but most of these do not result in pilot injury.

10. Case Study—X Prize Homebuilt Spacecraft

Another smaller band of engineers and dreamers is creating suborbital spacecraft for three orders of magnitude less cost. In the past six years since the X Prize was announced, at least 25 teams of designers have considered how best to put a man in space twice within a two-week period in a 90% reusable vehicle. One team, the Canyon Space team, has defined the experimental aircraft in the following section.

The liquid-oxygen (LOX)-tank is composed of welded stainless because of its low cost and its ability to sustain cryogenic thermals and ability to sustain cryogenic thermals and complex mechanical loading without fatigue cracking or catastrophic failure. The thrust structure is mounted to the aft dome of the 200-gal LOX tank, the wing to the bottom, the vertical tail to the top, and the forward body to the front. The forward body includes a 100-gal fuel tank and a crew capsule, both made of composites: Spectra, carbon, and epoxy. Primary structural loads are the 300-psi tank pressures needed to feed the engine at 20 lb/s. The wing is stressed for 6 g, although it is loaded to only $2g$ in the planned flight profile.

The vehicle shown in Fig. 6 was designed in X plane, a commercial-off-the-shelf (COTS) simulation available on the Web.* This simple program allowed our best engineers to configure the vehicle in less than 100 hr. The most powerful feature of X plane is the way it allows the designer to design the fuselage, wing, propulsion, flight control, and other parts, and then fly the aircraft to see the results. Thousands of changes can be made in real time and the impact of each change measured in minutes.

The COTS engine was developed for replica rocket planes and makes 4000 lb of thrust at 20 pps, with specific impulse (Isp) equal

*Data available online at www.x-plane.com.

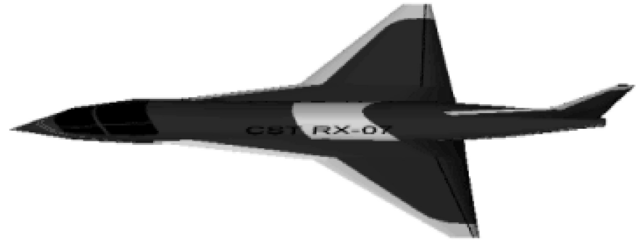

Fig. 6 Designed by Rich Harman in X plane.

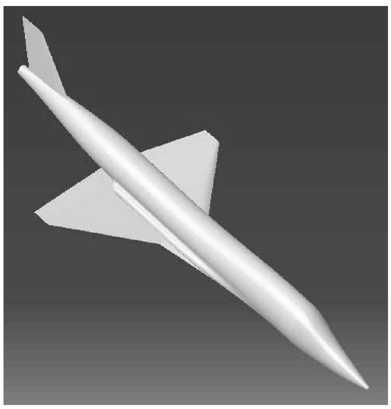

Fig. 7 CAD by Emmanuel Grillos.

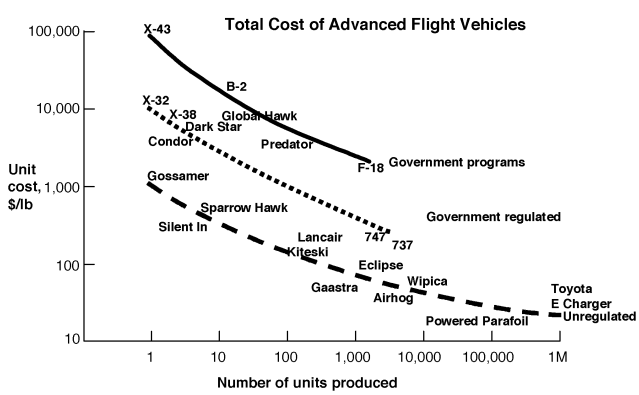

Fig. 8 Unit cost trends.

to 200 s between sea level and burnout above 100,000 ft. When the vehicle leaves the runway at 150 kn, the motor is making only 1800 hp at specific fuel consumption (SFC) of 40 lbf per lb t-hr. But when it leaves 100,000 ft above $M = 2$, it is making more than 20,000 hp at SFC below 4, still worse than the popular internal combustion engines and high-bypass jet engines, which are as low as 0.4—but they cannot go $M = 2$.

The wing is of Gillfab carbon sandwich, a 50-ksi, 8-msi commodity developed as a floor panel material for commercial aircraft. Its COTS availability below $100/lb makes it an ideal candidate for the upper and lower wing surface panels. It is also used for the vertical tail. Press-cured in flat sheets of 0.4-in. total thickness, this 0.5-psf material is elastically bent to the gentle curves of the biconvex wing and tail surfaces. The leading edges are of 2-in. diam, 0.025-wall titanium tube, also commercial aircraft commodities available commercially as bleed air ducts.

The shape of the vehicle was loaded into CATIA Ver. 5 to obtain better three-dimensional visualizations. Note how the position of the high-pressure inert gas tanks is optimized to permit area ruling to minimize transonic drag (Fig. 7).

Figure 8 shows the cost relationships of several types of modern and future aircraft, including future experimental aircraft. Nonrecurring cost is included and is dominant for small fleets like the X planes, the gossamer planes, and most of the development programs that resulted in fewer than 100 production aircraft.

III. Military Aircraft

New design capabilities and manufacturing technologies enable the designer to customize integrated structures for cost and performance in advanced military aircraft structure.

A. Advanced Unitized Structural Systems

Emerging structural concepts provide the aerospace community with an unprecedented opportunity to achieve reduced airframe cost and weight, and improved weapon system performance. Significant reductions in airframe cost will make larger fleets economically viable, and the associated improvements in weight will offer dramatic improvements in range, payload, and maneuverability. Advancements in the design and manufacture of airframe structure will have an impact on fighters, transports, rotorcraft, and new classes of unmanned air vehicles.

Historically, the predominant design and manufacturing approach for composite and metal structure has focused on the fabrication of large numbers of flat or slightly curved parts that are mechanically fastened together. This method offers improved control of tolerances, low porosity with uniform resin content for composite autoclave processes, reduced tooling costs, and lower reject rates of the individual piece parts. However, the reliance on extensive bolted joints for assembly has significantly limited the structural weight fraction of existing air vehicles. To reduce manufacturing touch labor and to improve the efficiency of airframe structures, attempts have been made to eliminate many of these mechanically fastened interfaces by designing and manufacturing "unitized" structural systems. Looking into the future, design concepts and methods with associated manufacturing processes are emerging that will enable the strategic buildup of material where it is needed to carry airframe loads. The expected result will be highly efficient, unitized structures.

1. Advanced Structural Design Considerations

New design capabilities and manufacturing options have resulted in a new level of design flexibility toward unitized structures, such as wing, fuselage, propulsion system, and various control surfaces. A graphical representation of an advanced aircraft structure is shown in Fig. 9. Advanced composite and metallic structures benefit in weight and cost through customized design capabilities from both new design methodologies and manufacturing technologies. New design methodologies based on a probability of occurrence can dramatically reduce actual design weight. This occurs by reducing realistic design loads based on mission weighed averages, which consider mission envelope, g-maneuver loads, and other configuration-specific characteristics. These missions can then be rolled up to fleet size and expected service life to determine a statistical probability that is acceptable and in accordance with the Joint Services Government Specification. From here, an effective load can be calculated and applied to structural sizing. An example is a new hammershock

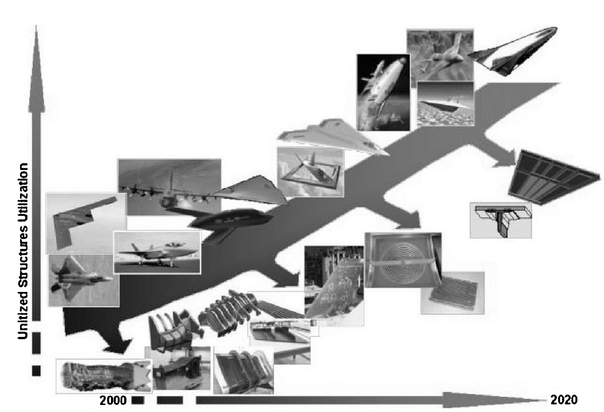

Fig. 9 Graphical represenation of unitized structure.

design methodology, which calculates the probabilistic design load for an inlet system from mission-specific conditions and specific engine compressor stall data. For unmanned aircraft, the acceptable probability of occurrence can increase because the human factor has been removed. The probabilistic inlet hammershock load (for 10^{-5} occurrences per flight) is slightly less than one-half of worst case numbers calculated for Joint Strike Fighter-like missions, 3000 vehicles, 30-year service life, and F-119 engine stall data.[1] The new design load results in significantly lighter integrated composite structures while maintaining an acceptable occurrence rate over the lifetime of the fleet. There are a variety of applications of probabilistic load determination depending on integrated structure type, typical response to loading environment, and vehicle class (manned fighter, unmanned fighter, high-speed strike aircraft, transport, special operations). Advantages for either composite or metallic structures are realized through requirements such as loading type (in-plane vs out-of-plane), loading magnitude, thermal requirements, signature considerations, part geometry, and weight sensitivities of the vehicle.

2. Composite Integration

Composite materials have been used extensively in aircraft structure.[2] These materials have emerged into an extensive number of commercial product forms and have demonstrated significant performance benefits when used in airframe, missile, launch vehicle, or spacecraft structures. These benefits can be largely attributed to mechanical and physical properties, such as high specific stiffness and strength; fatigue and corrosion resistance; tailoring for conductive, nonconductive, and structural properties; and the ability to be formed into complex shapes. These attributes can result in payoffs such as increased payload, endurance, maneuverability, decreased life-cycle costs, and can be used to reduce electromagnetic signature.

Advancements in manufacturing using fiber placement, adhesive bonding, textile structures, and low-cost tooling enable the designer to fully exploit the benefits of composite materials. Naturally occurring composite structural members have evolved with extremely complex, directionally dependent load paths for system performance. This is prevalent in the skeletal formation in bird wings, the damage-tolerant structure of beetle shells, and the directionality of fibers in tree limb to trunk joints. The advent of novel material preforms and processing technologies that exploit simplified manufacturing tooling will allow emerging structural designs to achieve similar levels of complexity as observed naturally.[3] The ability to provide fiber reinforcement tailored for system loads will ultimately eliminate the penalties in structural weight as a result of the presence of out-of-plane loads, turning loads, and intersecting structure. Panel stability will also be improved.

The fiber preform and resin coupled with processing technology represent the building blocks needed for the design and manufacture of composite structure. The overall design freedom and the associated structural efficiency starts with the selection of these constitutive elements. Several material and processing technologies that are being used today are evolving and will be exploited in composite unitized structures of the future. A summary of these is shown in Table 1.

These materials and processes offer the designer a tremendous amount of flexibility in defining how a structure is ultimately developed. Each preform and process has its own unique attributes that must be considered by the designer to ensure that the final article can be fabricated with the appropriate level of quality. The quality of a part, as defined by porosity, uniform resin content, and dimensional stability, for example, will affect the final structural properties and its associated reliability while in service. As we come to better understand these materials and processes, it is anticipated that the composites designer of the future will have design methods available that assess the quality of a finished part and its associated reliability. These tools will provide a means of reducing weight (and therefore costs) by designing for specific life requirements with the cost of quality as a primary design variable. Structural concepts that offer fail-safe performance by distributing loads around damage zones will also have a major impact on design practices, resulting in reduced costs of maintainability and extended service life. There will also be the opportunity to exploit a greater portion of the loading curve, thereby reducing weight.[4] Examples of fail-safe concepts include discrete reinforcements such as stitching, Z-Fiber™, and textile inserts but can also include material attributes such as hispid fibers or toughened resin fillers. Complex cocured/bonded structural geometries have been demonstrated with textile preform inserts for both joint strengthening and fastener elimination. Improved load management can be achieved using intersecting textile joints fabricated with bonded sandwich as shown in Fig. 10.

Table 1 Preform materials, processes, and material lay-down methods

Preform materials	Processses	Material deposition
Prepreg	Resin transfer mokling (RTM)	Hand Layup
Weaving	Vacuum-assisted RTM	Tow placement
Braiding	Induction heating	Filament winding
Pultrusion	Electron beam cure	Programmable powdered preform process
Stitching	Diaphragm forming	Chopper gun
Z-Fiber™	Autoclave	Auto tape lamination
	Nonautoclave	
	Resin film infusion	

Fig. 10 Fuel floor, skin, and bulkhead joint intersection.

Although the use of unitization techniques has demonstrated that significant cost savings can be possible, these design and manufacturing concepts have significant limitations as a result of associated tooling costs. The use of bonded primary structure is a key fabrication approach that is being explored to further reduce the cost and weight of advanced structure, largely because it eliminates the complexity of tooling for large cocured structures. Through the development of design concepts, bond processing methods, and the requisite design methodology, bonding will enable assembly of many small piece-parts into a large, complex low-cost structure. This approach offers the benefit of eliminating the risks associated with curing extremely large parts that require temperature control, resin flow control, and pressure management throughout a three-dimensional component or tool. Assembly concepts are emerging that use autoclave or alternative curing methods for large skins and webs (for optimized structural properties). These panels are then assembled using temporary holding fixtures to assist in joint buildup and adhesive bonding. Alternatively, concepts have been explored that eliminate tooling all together. This has been accomplished by fabricating large panels with integrated female slot features that can be irrigated with paste bond adhesive and then joined with a mating panel. This approach is self-positioning and does not require holding fixtures or the complex tooling associated with cocure. Exploring future low-cost fabrication and assembly techniques will likely become more prevalent, particularly if military vehicle requirements dictate the need for large-scale production of extremely low-cost unmanned vehicles.

3. Metal Integration

Integrated airframe structures requiring metallic mechanical and physical property capabilities benefit from several unique and cost-effective fabrication approaches. These include laser deposition, friction stir welding, and powder metallurgy. These processes are unique in their application to advanced aircraft structure and will play increasingly important roles in manufacturing as the technology is upgraded in both part size and mechanical property maturity. These processes are also very amenable to integrated structure fabrication. Because of their individual advantages, these processes open the door to a new level of design flexibility and ultra-efficient unitized structures.

Laser direct manufacturing (LDM) is a relatively new process. It allows intricate near-net shape part fabrication from a variety of metallic powders and allows design flexibility of part geometry and properties.[5] LDM metallic compositions are deposited by scanning a laser over the surface of the part while injecting metallic powders into the melt region located at the laser focus point. Production of high-quality shapes, including certain "trapped cavity" structures, results in a customized, integrated metallic structure with tailored geometry and physical properties.

Friction stir welding (FSW) provides for assembling large unitized metallic structures without the added cost and weight of fasteners. FSW is a versatile welding technique where like metallic materials are welded together to form a more reliable and stronger weld than possible if conventional techniques were used. FSW uses a highly rotating stirring pin to generate a plasticized region created from frictional heating. This in turn causes a metallurgical mixing of two adjoining surfaces that forges a weld between the two metallic surfaces.

The FSW process will continue to be implemented in future aircraft structures, especially large transport/bomber designs where a significant amount of weight and cost associated with fasteners and their installation can be eliminated. Additional advantages of FSW include the ability to weld a multitude of different materials (such as previously unweldable alloys), better fatigue performance compared to fusion welds, and quality welds for varying part thickness when using NASA Marshall's new retractable pin tool technology.[6] FSW has been used to weld together the various sections of the main shuttle tanks for NASA.

Powder metallurgy (PM) is a highly efficient process for certain classes of part geometry. It allows for both property tailoring and shorter fabrication times. Future PM structures will have less alloy waste, faster detail fabrication times, and significant options for secondary operations for customizing a particular aspect of the finished part property.

4. *Hot Structures Technology (Ceramic Matrix Composites)*

Hot structures integration continues to have an increasing role for the future warfighter. Mission requirements are demanding structural performance consistent with higher speed vehicles, which are subjected to higher temperatures for extended periods of time. Emerging classes of future strike aircraft and space operating vehicles will require structural integration with ceramic matrix composites (CMC) to meet thermal and structural design criteria. High-temperature CMC structures integration imposes unique and complex design requirements to accommodate interactions among the various constituents that make up the structure. Historically, CMC systems have been prone to interlaminar initiated failure modes caused by the relatively weak matrix materials and lack of cross-ply reinforcement. This design limitation is further aggravated when these composite systems carry heavy loads through the joint to skin interface. The most weight-efficient and affordable approach requires that stiffeners be integral with the skin. This structural integration approach reduces weight and alleviates problems such as thermal expansion/contraction mismatch, associated with dissimilar materials at mechanical attachments. To meet the requirement of these emerging classes of high-speed vehicles, integrated hot structure, with effective out-of-plane load-carrying capability, are a primary focus for enabling low-cost and lightweight designs necessary to achieve dry weight fraction requirements for these high-speed vehicles. Hot structures integration for discussion purposes refers to primary and secondary structures exposed to extreme environments where temperatures reach 2200°F.

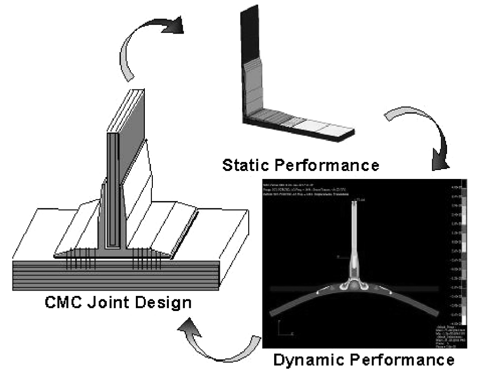

Fig. 11 Candidate primary hot structure CMC joint for 2200°F integrated structure.

New CMC materials and manufacturing technologies enable the structural designer to design integrated hot structures efficiently with emphasis on tailorable joint strength and stiffness for localized load and temperature requirements. Joint requirements for primary structures are defined by specific vehicle and mission requirements and for comparative purposes can be defined by 1000 lb/in. pull-off strength and 2000 lb/in. shear strength at 2200°F for a Mach 10 class of vehicle.[7] Figure 11 illustrates one potential primary structure joint configuration with an expected availability date in early 2006.

Secondary integrated structures are typically support structures for lightly loaded airframe components such as external thermal protection systems. Secondary structure joint requirements are again defined by specific vehicle configuration and mission requirements and for comparative purposes can be defined by less than 500 lb/in. pull-off strength and less than 1500 lb/in. shear strength at 2200°F for a Mach 10 class of vehicle. Secondary structure is typical sized to minimum gauge for weight purposes and requires sizing for acoustic fatigue. A secondary structure joint concept can be similar to that in Fig. 11 with thinner skins and other minimum gauge constituents.

B. Multifunctional Systems

Although unitized structure has been recognized as a way to reduce cost and weight, system requirements (such as the integration of access panels for subsystem maintenance and detachable wings for ease of repair) have inhibited the use of unitized structure. Therefore, system functionality requirements must be addressed as integral to any unitized structure development activity. A key aspect, then, for the successful implementation of unitized structure will be the need to develop multifunctional structural systems, or a structure that carries load and performs system functions. The current design philosophy of developing independent systems and packing them into an airframe has resulted in systems that meet the intended vehicle functionality but tend to be expensive as a result of additional touch labor and tooling. The electrical subsystem of the future will no longer be considered a separate discipline to be "attached" to the airframe. It will instead become an integral element of the structure. Increasing vehicle requirements dictate that opportunities for cost reductions and performance improvements offered by multifunctional structural systems be developed.

1. *Structurally Integrated Thermal Management*

Structurally integrated thermal management is an integration technique where the thermal environment is manipulated either by removing heat or bringing heat to the structure. The structural integration process requires that thermal loads from various sources (such as avionic, propulsion, and new weapons) are cooled through fuel heat exchangers or fan duct heat exchanges and that these systems are integral to the structural arrangement. As these system heat generators evolve, the power consumption, and therefore heating, will increase the load on the thermal management system. Integrating the thermal management function to that of the structure can reduce the thermal load through selective tailoring of the thermal conductivity of either composite (fiber) or metallic materials incorporated into the design. This benefit is realized at the air-vehicle level.

2. *Structurally Integrated Antenna Systems*

The numbers of antennas are increasing rapidly on all air vehicles as the required communication, navigation, and intelligence, surveillance, and reconnaissance (ISR) needs of modern military aircraft increase. In addition, larger antennas and large antenna arrays are needed to meet range, directivity, and rf performance requirements. Current antenna installations are limited to parasitic and nonload-bearing installations such as blades and cavity-mounted antennas. Blades protrude into the airstream and increase signature, drag, and supportability costs. Cavity-mounted antennas require complex support structures and integration schemes that add manufacturing cost and weight. The structural inefficiency of the parasitic nonload-bearing approach limits the size and number of locations where antennas can be located on airframes. These limitations compromise rf performance in terms of range and field of regard and compromise structural efficiency by interrupting load paths.

Conformal load-bearing antenna structure (CLAS) development is directed at structural systems that not only carry airframe loads but also perform antenna functions. Historically, these two disciplines have been considered separate system functions in the sense that each were designed largely independently of each other and then came together during the systems integration of the vehicle. This has resulted in air vehicles with antennas added to existing airframes, requiring the accommodation of large radomes. The upshot is increased drag from poor aerodynamics and inefficient load paths, as well as increased weight from antenna frames and hard points. An increased number of sensor functions and greatly improved rf capability can be achieved by taking advantage of the increased antenna area afforded by the available load-bearing skin of the aircraft. This has provided an opportunity to put apertures in nontraditional locations that increase antenna gain and field of view and reduce vulnerability.

Several recently completed CLAS concepts have been demonstrated for broadband data and communication functions. Under these efforts, rf antenna elements and feeds were embedded within the lamina of composite skin structure. Also, the antenna elements are multifunction, or broadband, which requires only a single antenna installation to perform multiple compatible functions. Two concepts have been demonstrated: a fuselage installation and a vertical tail installation, which are shown in Fig. 12. These two CLAS systems were designed, analyzed, fabricated, and tested. The fuselage demonstration article is load-bearing, multifunction (uhf/SATCOM) antenna 35 × 37-in. panel subjected to combined axial and shear loading, which replicated realistic flight conditions. Ultimate failure loads imposed on the panel were 1800 lb/in. axial loading and 600 lb/in. shearing loading, after successfully withstanding a single lifetime (6000 hr) of fatigue. Electrical performance was validated using anechoic chamber measurements. This system provides a broadband, structurally integrated, low-cost antenna for communications, navigation, identification and electronic-warfare applications in the 0.03–2.0-GHz range. The vertical tail concept was a structural excitation multifunction (vhf/uhf) antenna element that can be tailored to fit in virtually any end cap vertical tail configuration. Designed to endure the severe acoustic environment associated with empennage noise sources, the end cap was

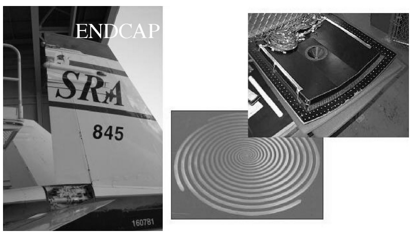

Fig. 12 Structural end cap and broadband spiral panel antenna.

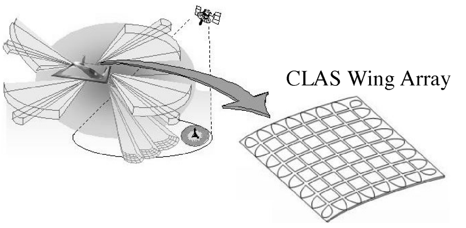

Fig. 13 CLAS phased array.

successfully flight tested on NASA Dryden Flight Research Center's systems research aircraft to validate the structural and electrical performance.

As the know-how and associated complexity of integrated antenna systems mature, the opportunity to explore low- and high-band, phased-array systems has become possible. To develop effective arrays, new capabilities (such as beam forming) must be addressed. Beam-forming is challenging for large CLAS arrays because of the number of channels, subarray techniques, electronic deformation compensation, and integrated position sensing systems that need to be developed. Additionally, phased-array antenna complexity and integration represents a major cost center and is challenging because of element, circulator, transmit/receive (TR) module, and rf/dc power distribution requirements. Reliability of these electronic systems has improved significantly, making CLAS arrays a viable opportunity to be explored.

The development of large phased arrays is currently focused on uhf and high-frequency (x-band), load-bearing, phased-array antenna concepts for foliage penetration, air-moving and ground-moving target indicator capability. A notional wing installation is depicted in Fig. 13 as part of a conceptual "joined-wing" ISR vehicle. These systems are structurally integrated and can exceed 30 ft^2 per array. They feature integrated electrical and structural design, improved antenna performance, improved aerodynamics, and structural efficiency at reduced cost. Challenges require modification of structural and antenna design practices. These include thousands of integrally networked elements, antenna feeds, and elements subject to the aircraft load and fatigue spectrum. Moreover, some structure must be electromagnetically clear. The antenna array requires development of rf circuitry compatible with the structural integration concept that will include buried waveguides and striplines, thermal management considerations, and possibly electrically conductive polymer-based materials. Additionally, structural shape sensing for antenna beam-forming will require mathematics, algorithm development and an integrated sensor suite to determine the position of the antenna elements. Developing flexible arrays with an integrated deformation compensation system for beam-forming provides an opportunity to achieve significant weight reduction. Advanced printing of rf electronics is an emerging technology area that will be exploited in the future for antenna systems and will greatly reduce costs. This technology allows the printing and direct writing of electrical circuitry and radiating elements directly on almost any dielectric substrate that can then be integrated directly into a CLAS system.

3. *Integrated Actuation Systems and Reconfigurable Structure*

The use of conventional actuation can be eliminated by using integral material actuation or distributed actuation technology. This will be possible by developing load-bearing fibrous material fabricated with actuation capability and by using miniaturized discrete systems. It is anticipated that this will result in revolutionary advancements in flow control and structural shape control.

New multipoint design capabilities for future aircraft might require certain aspects of the vehicle configuration (and therefore its structure) to reconfigure during flight. These design features can potentially allow a single vehicle to perform multiple missions without significant performance penalties. Because structural reconfiguration requires physical geometric changes in the outer moldline, the structural integration approach could potentially include integral

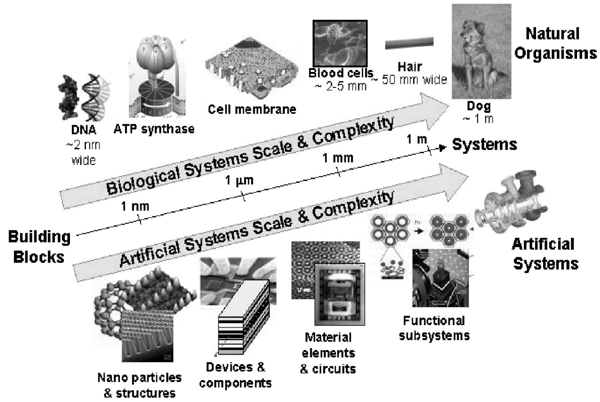

Fig. 14 Artificial and biological system complexity.

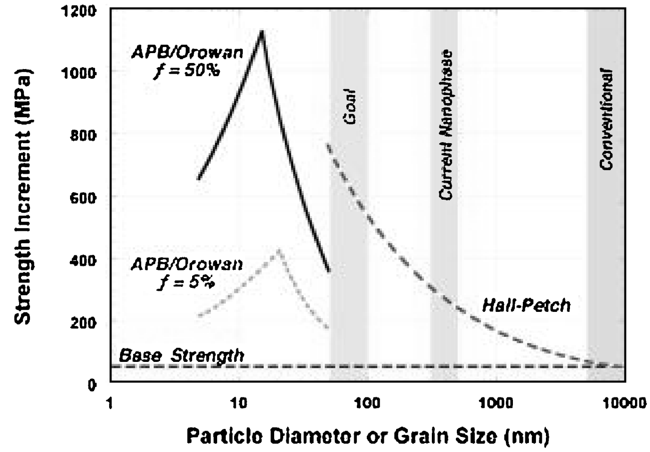

Fig. 15 Effects of refined grain size.

piezoelectric actuators, micro-electro-mechanical systems, or more traditional actuators if large displacements or geometric changes are required. These systems can include distributed control systems that allow independent control for localized regions, while being maintained through the main flight-control computer.

C. Future Influence of Nanoscience and Nanotechnology

Nanoscience and nanotechnology will affect all aspects of air vehicle development in the future. This will be especially apparent in the development of nano-based electronics, electromechanical devices, and materials engineered with specific properties for structural performance and high-energy release rate fuels and propellants. These technologies will be used to provide the building blocks of advanced military vehicles that offer revolutionary war fighting capabilities. The scale of integration[8] of nano-based artificial systems compared with biological systems is shown in Fig. 14.

1. Distributed Sensing and Feedback Control (Influence on Design Process)

A key area of near-term interest in nano-science is the development of sensing systems for real-time diagnostics of airframe structures. Nanoscience will enable the integration of novel noninvasive sensing systems integral to the airframe. Active sensing of the state of strain in the structure, coupled with a neural network used to define the flight-control limits of the envelope, will allow aircraft to have revolutionary capabilities, but with reduced weights. Strain sensing will provide feedback control to limit the maneuver loads applied to the airframe. The aircraft will be able to essentially train itself over the course of its life, making adjustments as a result of environmental degradation or impact damage or real-time adjustments to limit airframe maneuver loads resulting from combat damage. It is anticipated that this nondeterministic flight-control methodology (as opposed to the use of conventional design practices) will be the basis for new design methodologies leading to reductions in weight. This might eventually lead to reduction or elimination of design factors and enable the limits of the flight envelope to be achieved.

2. Future Micro-Air-Vehicle Opportunities

Micro-air-vehicle (MAV) research has received significant interest and investment from the government, universities and industry over the last several years. Research has primarily focused on the miniaturization of flight systems, characterizing aerodynamics, and evaluating conceptual designs for short-range intelligence, surveillance, and reconnaissance missions. Missions could include looking behind walls, over hills, under trees, or even flying ahead of troops to sniff for biological agents. As electronic subsystems and computational capabilities are enhanced with emerging nanodevelopments in electronic materials and device research, the functional capability of MAV systems will be extended as a critical battlefield weapon system. Long-term opportunities for MAV systems will involve the implementation of collision-avoidance algorithms and position control using nano-based telemetry systems to enable swarming missions. Hypothetically, these missions could involve hundreds of MAV systems deployed from a high-altitude vehicle to provide a phased-array antenna system that would be largely nonvulnerable to ballistic threats. In this concept, each MAV would provide an antenna node. Therefore if any one node were to be shot down or malfunction, the array would still perform with limited impact on beam width.

3. Designer Materials

The development of designer nanomaterials will promote a new class of structural materials with tailored strength and stiffness properties as well as self-actuation. The materials could also have integrated electrical and thermal conductivity, which would dramatically reduce electromagnetic and infrared vehicle signatures. Today, military-air-vehicle technology is generally limited to a structural weight fraction of approximately 0.2, with the use of primary sandwich structure and high-strength composite materials. During the National Aerospace Plane program conducted in the 1980s, studies indicated that a structural weight fraction of approximately 0.1 coupled with advanced propulsion technology would enable single-stage-to-orbit (SSTO) capability. SSTO capability can be realized with the use of nano-based designer materials. Significant research is now being conducted to characterize the performance improvements possible through the development of nano-based materials. The theoretical strength associated with refined grain size grows goes as 1/(precipitate size or spacing) for the Orowan strengthening mechanism, and as 1/SQRT(grain size) for Hall-Petch, as shown in Fig. 15 (Ref. 9). The main mechanism for Orowan strengthening is from strengthening precipitates, which block the motion of dislocations. The primary mechanism for Hall–Petch strengthening is from the refinement of grain size. This implies that nanomaterial performance can improve by an order of magnitude. It is likely that other factors (such as fabrication) will limit the achievable threshold; however; if only a fraction of the theoretical capability can be translated to the structural level, the SSTO capability might become plausible.

4. Certification and Durability of Self-Healing Structures

Structural self-repair is a concept the nanocommunity is exploring. This capability will provide a basis to extend the life of a vehicle airframe to the limits of system usefulness. If these concepts mature, it is possible that durability and fatigue will no longer limit the life of an airframe. Instead, the aircraft could remain in service without major structural modifications as long as the overall system performance was needed. As an example, one concept currently being investigated uses micro balloons filled with self-healing material,[10] as shown in Fig. 16. If a microballoon cracks (a structural microcrack or from an impact event), the healing agent ushers into the failed region. This fills the crack nucleation zone before it can grow into a major structural anomaly. It is anticipated that major changes in the traditional certification process will be achieved with the advent of materials that offer this capability. Such a capability will enable

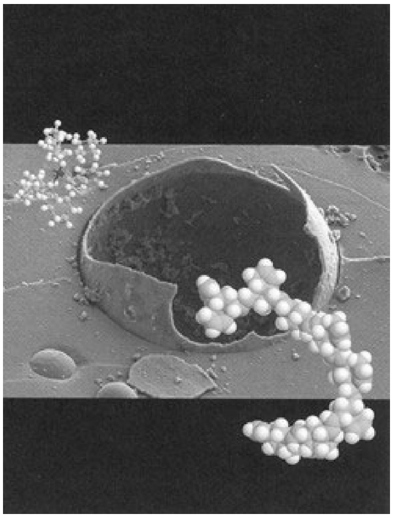

Fig. 16 Microballoon with self-healing agents.

revolutionary reductions in the design and development cycle time that present systems must undertake. The result will be breakthrough cost reductions. In addition, safety factors incorporated into the conventional design process for in-service performance degradation can be eliminated/reduced by exploiting this technology.

IV. 2020 Commercial Airframes Input

A. Introduction

Over the past 20 years, improvements in commercial airframes have been driven by the need to establish the largest possible market share to ensure a program's financial success. One of the most effective ways of doing so has been to reduce airframe weight to improve an aircraft's operating efficiency over a larger segment of city pairs. This in turn has led to additional sales beyond the optimum payload-and-range design point of the aircraft. As manufacturers expanded their offerings to accommodate from 100 up to 450 passengers, it became more difficult to capture incremental sales in a crowded field without offering substantial improvements in technology. Even today, the resulting competitive products utilizing conventional technologies offer airlines highly optimized designs for given payload and range combinations. This makes it difficult to introduce all new aircraft, or even new derivative designs, capable of displacing existing models with their fully amortized infrastructures.

As was witnessed in the race to launch the next super jumbo, the level of advanced technology required for the all new A380 design was much higher than that proposed for the competing 747-X derivative designs. Development decisions such as these were driven by the airlines, which stipulated that a 20% improvement in direct operating costs was necessary to justify introducing an all new aircraft like the A380 into their fleets. Although many system-level enhancements are necessary to meet this stringent criterion, the weight savings afforded by an advanced-technology airframe is an important part of the overall solution. The weight-savings factor has thus forced manufacturers to continually upgrade their airframes with better materials and structures to field competitive aircraft: those capable of becoming market leaders within their given payload and range categories.

When considering the overlapping portfolio of commercial transport designs already in production, manufacturers found they had a diminishing number of options for launching more competitive designs. As airframe advancements have matured through the incorporation of improved aluminum alloys with superior strength and durability, and the use of composite primary structures has expanded, most of the relatively low-risk improvements have been exhausted. Although these earlier improvements will continue to be refined, the difficult question is whether the next goal can be realized: to economically fabricate larger composite primary structures (like the wing or fuselage) and introduce them into commercial airline service by the year 2020 in the over-150-passenger transport category.

Because wing and fuselage elements typically account for about two-thirds of the airframe weight, the associated 20% weight savings that would result from switching from an aluminum-based to a composite-based design would yield untouchable operating economics in an all new aircraft. However, the difficult question is whether enough incremental sales would be generated to justify the higher inherent technical and cost risks associated with developing and certifying the first all-composite wing or fuselage on a large commercial transport. Or, are there other more advanced airplane configurations beyond conventional wing-and-tube designs that would offer higher levels of performance, that is, those levels needed to justify the insertion of these or other high-risk airframe technologies?

How the existing duopoly of commercial airframers reacts to these questions, and the extent to which each is willing to protect its market share, will ultimately determine the level of technology that is embraced in the commercial airframe of 2020. Depending on how the interplay between world economics, airline profitability, competitive positioning, and technology readiness unfolds over the next 20 years, it appears that three distinct types of aircraft could emerge:

1) Improved derivative models are the first type. Incremental product improvement would replace older components with newer technologies as a means of reducing fabrication costs or slightly improving aircraft payload and range. However, these models would not realize the benefits of resizing the entire airplane to achieve an overall system-level savings or benefit.

2) All new conventional models are the second type. Clean-sheet designs of a conventional-looking airplane would use advanced lightweight composite materials for a wing or fuselage primary structure, or both, to achieve a large weight savings that would be cycled back through the system-level optimization to reduce the overall weight of the aircraft.

3) Revolutionary models are the last type. Clean-sheet designs would move beyond conventional wing-and-tube transports and use advanced airframe technologies to gain direct aerodynamic benefits rather than improve performance primarily through a reduction in airframe weight.

Although the structural technologies required to support these three scenarios have already been demonstrated in various research efforts around the world, the tempo of production implementation will be governed primarily by the competitive concerns of the executives at Airbus and Boeing. In a competitive assessment, each company must quantify the potential risk and reward of new technologies to balance the development risks against the productivity benefits that will ultimately be enjoyed by the operators.

B. Improved Derivative Models

Through extensive design, testing, manufacturing, and maintenance of their products, manufacturers have maintained a high level of safety and reliability while introducing advanced technologies onto their airframes. In addition to refinements made in 2000- and 7000-series aluminum alloys (resulting in incremental improvements in fracture toughness and higher yield strengths), composite technologies have also aggressively been introduced. Early composite technologies, led by military applications and NASA-funded research programs,[11] provided the risk reduction necessary to implement today's' state-of-the-art composite applications in many secondary and some primary structural applications. Third-generation transports like the A320 and 777 (Fig. 17) now baseline large primary structures like the vertical and horizontal stabilizers as carbon fiber materials. These transports still maintain all of the secondary structural applications pioneered by second-generation transports. This has increased the composite material structural weight fraction from 3% on second-generation transports to 9% on today's 777, resulting in an airframe weight reduction of 2600 lb (ref. 12).

Continuation of these trends would also be expected in the future. Just as the initial T300/5208 fiber/resin systems used on second-generation transports were improved, material suppliers are

Fig. 17 Advanced composite material utilization on the 777.

Fig. 18 Conventional model with composite wing box.

currently developing new material systems with mechanical properties that exceed state-of-the-art materials like the T800/A-276 systems used on the 777. Although these improvements will reduce airframe weight and cost to some extent, these improvements will not be capable of creating a paradigm shift in how composite materials are used on the airframe.

Continued incremental improvements in aluminum alloys should also be expected as material suppliers continue to refine their products by offering improved grain structures with better durability, strength, and stiffness. Improved assembly methods will also continue to be incorporated. Just as advance automated drilling and fastener installation methods became common practice, new technologies (such as laser drilling, precoated fasteners, and possibly even friction stir welding) should find their way onto the 2020 airframe.

Another important aspect in improving airframe efficiency will be increasing the analytical fidelity of the design process. Just as the introduction of digital computing enabled a more accurate determination of loads and stresses (by enabling a higher precision of design integration), the next surge in computing will facilitate more timely dissemination of information. It will also facilitate the capability to structurally optimize the airframe designs across a wider array of disciplines (e.g., aero, structures, manufacturing). Through the use of advanced simulation and visualization tools, coupled with improved finite element codes, more accurate and easier-to-interpret design data will be evaluated and optimized earlier in the design process, resulting in more accurate parts that are analyzed with increasingly sophisticated methods. Such methods would include probabilistic design and analysis variables that affect everything from the external load cases to the statistical basis of the materials allowables used in the analysis. Reliability-based design optimization will enable part designs without excess margins and should become the basis for replacing or repairing critical structural components during their service lives.

Although the airframe discussed in this category will be more durable, damage tolerant, and profitable for the airlines to fly, their outward appearance will be nearly indistinguishable to the traveling public from the airframes of today. Although the prior 20 years brought us some remarkable changes with the introduction of high-performance composite structures and improved aluminum alloys, the changes discussed in this scenario for the next 20 years promise to be less dramatic—absent the economic incentive for change and the lack of government-supported aeronautics research.

C. All New Conventional Models

Moving beyond an evolutionary approach is the technology advancements necessary to materially affect an airline's operating results, namely, a newly designed aircraft that would yield operating profits beyond what is possible by simply operating incrementally improved, third-generation transports. Achieving this level of performance is possible by introducing a composite wing box as shown in Fig. 18. Although component weight savings of 20% is technically feasible using this approach and has been demonstrated on numerous smaller aircraft programs, commercial airframers are reluctant to apply these technologies to large primary structures because of their high development and recurring costs, as well as the airline industry's reluctance to maintain these unfamiliar structures. As such, the next logical step in commercial airframe evolution has yet to be taken.

Although numerous composite wing and fuselage studies have been completed over the last 25 years, what remains clear is that an adequate level of risk reduction has not been achieved. Moreover, it might not be achieved within the next 5 to 10 years to facilitate the certification of an all new aircraft that launches either a composite wing or fuselage into passenger service by 2020. What is painfully obvious at this point is that, although both manufacturers have a thorough understanding of composite design practices, long in-service histories, and exhaustive manufacturing cost databases, neither is confident enough to introduce these technologies into service. Had the technology been ready, the material and structural concepts for the recently launched A380 would have moved beyond the incremental approach that was baselined (Glare upper fuselage skins, a composite center wing box, and aft pressure bulkhead).

Rather than overcome the last remaining technology-readiness challenges for a composite wing or fuselage and be assured of composite wing or fuselage, and be assured of meeting the component weight targets allocated for the configuration, Airbus chose a more conservative design approach that ultimately shifts risk back to the operational performance. Consequently, as the design matures and airframe weights increase beyond their intended targets, the baseline range and performance degrade beyond the minimum-guarantee levels promised to the airlines, resulting in substantial contract penalties for the manufacturer.

The baseline concept selections made for the A380 indicate the difficulties and risks involved in fully exploiting existing composite fabrication technologies for large commercial aircraft. Until the fabrication costs and structural durability concerns are adequately resolved for larger and more highly loaded composite structures, they will not enter commercial service. The problem with existing prepreg composite processing techniques [such as hand layup, automated tape layup, or advanced fiber placement] is that they are all ill-suited for large structures because of their high material costs, slow lay-down rates (lb/hr), and high capitalization costs. Ultimately, their size is limited by the autoclave (more structural joints required). All of these factors conspire to make production of large composite components much more expensive than conventionally built-up aluminum structures. Additionally, the structural interfaces become much more difficult to design and fabricate as the load levels increase because conventional composite joining methods (such as adhesive bonding and cocuring) are not scalable. This, in turn, leads to bolted-joint designs with their associated stress concentrations and higher costs.

Although most prime and tier 1 subcontractors are perpetually studying new ways to improve the cost competitiveness of composite structures, few new approaches possess the fundamental attributes needed to meet the demanding operational requirements of a

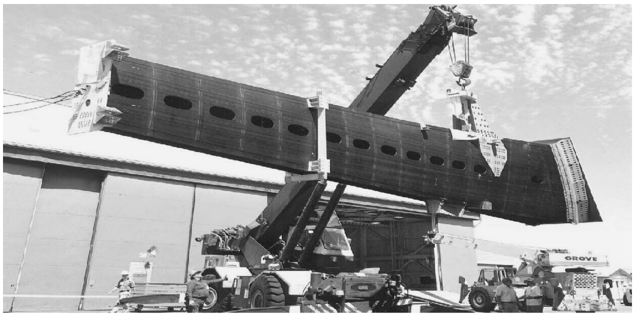

Fig. 19 ACT 42-ft semispan wing test component.

large wing or fuselage component. In principle, the goal is to design large integral structures to reduce assembly weight and cost, which leads to lower overall flyaway costs when compared to traditional aluminum designs. Many of these methodologies are successfully employed by nonaerospace composite fabrication industries (personal aircraft and boating) to yield fastenerless designs, improved fly-to-buy ratios, and faster fiber lay-down rates with lower material costs. Many of these new approaches show promise for efficiently fabricating very large, highly loaded, composite primary structures for commercial aircraft.

One such combination of technologies is vacuum-assisted resin transfer molding and dry carbon-fiber preforms that are reinforced with stitching. In this method, dry carbon-fiber mats are combined with integral stiffening elements and then reinforced with z-direction stitching to create unitized preform assembly, which is then infused with resin and cured in an oven at low pressure. The resulting integral structure exhibits higher notched properties and is more damage tolerant than conventional prepreg bonded, cocured, or even mechanically attached designs. In addition, the near elimination of metallic fasteners through the skins results in more uniform load transfer and is also an important feature for the lightning strike considerations of a fuel-filled wing box structure.

For large aircraft applications, the first generation of dry-fiber preform development was completed by NASA Langley Research Center and The Boeing Company under the Advanced Composite Technology research program.[13] This program demonstrated that large-scale wing structures (Fig. 19) could be fabricated cost effectively with structural properties and design features that were capable of meeting the stringent fail-safety requirements of a transport aircraft wing box. Through extensive analysis and testing, a more resilient structure was developed, one with higher allowable dent depths (0.10 in. to enable visual inspection) and with the ability to arrest damage propagation at critical structural interfaces without "chicken fasteners."

The capability of stitched structures to arrest damage was an important breakthrough in developing the full load-carrying potential of large carbon-fiber structures. Structural interfaces were a traditional weak link for conventional composite structures because they relied on bonded or cocured interfaces that were not particularly effective at arresting damage and thus limited the allowable working strain levels that could be achieved. As loads levels increase and mechanically attached joints are deployed, additional stress concentrations are encountered that require further material buildups that add weight and cost to the structure. Breaking this viscous cycle was a key element of the stitched-design approach. As was witnessed in the stringer pull-off test for the stitched specimen shown in Fig. 20, the out-of-plane loads generated at the skin-to-stringer interface were sufficient to cause a local bending failure in the skin prior to stringer separation. This enabled the panel to meet fuel overpressure load conditions for the wing box without requiring the addition of fasteners along the interface that would have reduced the in-plane axial, load-carrying capability of the panel. This vital ability to suppress out-of-plane failure modes both within the laminate and at common structural transitions (joints, cutouts, runouts, buildups) was a tremendous advantage for stitched structures as compared to conventional prepreg material designs.

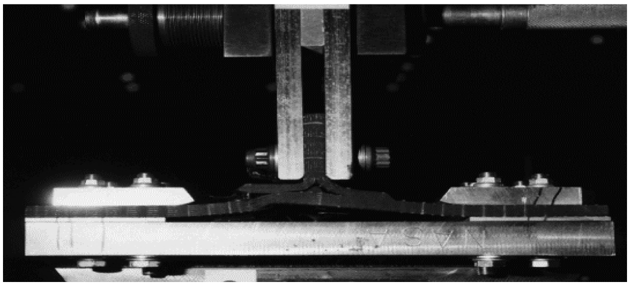

Fig. 20 Stringer pull-off testing of stitched element.

Fig. 21 Blended-wing-body transport concept.

Next-generation composite fabrication technologies are currently being developed that will further improve the economics and structural efficiency of these designs. Out-of-autoclave processing, higher toughness resins, lower-cost fibers and materials, interlayer toughening, advanced fiber lay-down methods, and new infusion techniques will all lead to improvements that ultimately will tip the balance between risk and reward in the favor of a new aircraft design that uses a composite wing, or fuselage, to obtain superior operating performance.

D. Revolutionary Models

The future could also hold a revolutionary concept with higher risk and payoff, like the blended wing body (BWB) shown in Fig. 21, which offers lower fuel burn by shaping the airframe in a nonconventional manner to enable dramatic improvements in aerodynamic performance at the expense of higher structural weight. Although technically feasible, such a bold undertaking would require an outside catalyst before either manufacturer would undertake such an endeavor (for example, an abnormal event like skyrocketing and sustained fuel prices or the introduction of an advanced military version that would help defray initial development costs).

Unlike conventional wing-and-tube designs, the BWB airframe represents a significant challenge for the structural designer. Although the spanwise load distribution is spread more uniformly than in conventional designs,[14] the large flat fuselage panels of the passenger cabin will experience large secondary bending forces during pressurization, which would render conventional aluminum skin and stringer designs unusable. Alternative structural concepts, such as sandwich designs, might be more attractive to minimize the bending-induced weight penalties. Such designs, however, could lead to additional testing and certification costs beyond those associated with a conventional transport design.

Most certainly, the BWB configuration will require an all-composite airframe and with it the litany of challenges, both structurally and financially. To keep the fabrication costs reasonable, the airframe would have to be constructed of large integral assemblies produced without vast rows of fasteners, and preferably outside the autoclave. The airframe would have to be extremely damage tolerant with a higher level of safety than today's conventional aluminum structures to compensate for the higher intrinsic risk of a noncircular passenger cabin. To ensure airline acceptance, maintainability and reliability should be equivalent to that of conventional aluminum structures and significantly better than available prepreg composite repair techniques, which are frequently criticized by the airlines as expensive and tedious.

V. Conclusion

Over the next 20 years, proponents of powered flight will accept the challenge to achieve more with less: carry more payload for less weight, improve fuel burn, and do it for substantially less cost. The timing of these advancements will depend directly on the financial strenght of the industrial sector and the creation of a national aerospace vision with the necessary funding to enable the US to retain its dominant position in aerospace. Dominating this period technologically will be a holistic (systems) design approach with emphasis on micro and nano technology. Composites will become the material of choice for airframes as cost competitive manufacturing processes are realized, Designs will enable the advantages of orthotropic properties to be fully exploited enabling more robust, lighter weight structure than today's "black aluminum" designs offer. Probabilistic design processes will contribute to the lighter weight designs, replacing the conventional factor of safety methodology. Joining will remain the most significant design challenge. Fastening will be minimized. Welding and bonding processes will become more robust, enabling their wider use with confidence. Overall, weight and cost reductions of 30%–40% vs today's best design and cost processes will be possible. Jump on board and enjoy the excitement of the journey!

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