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Design-to-Cost with Advanced Composites and Advanced Metallics

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New structural concepts, which include integral structure of advanced composites and superplastically formed/diffusion-bonded (SPF/DB) titanium, promise to produce significant advancements toward reducing airframe costs and weights. This paper illustrates the results of design studies using both types of structures on a new-generation aircraft when compared to conventional materials and methods of construction. These new processes contribute materially to the challenge of materials, manufacturing, and structures interfaces in the design-to-cost environment.

Introduction

THE aircraft industry, which is charged with the development of advanced structural airframes for high-performance fighter aircraft, has been required continuously to conceive new structural concepts that are lighter in weight than their predecessors. These requirements have led to the utilization of new materials (advanced aluminum alloys, titanium, advanced composites) and more efficient structural forms (honeycomb sandwich, waffle grid) in order to meet the never-ending challenge of airframe weight reductions.

These materials and concepts have led to lighter airframe weights but, unfortunately, increases in airframe costs. The reason is typified by aircraft that span almost four decades of development (e.g., the P-51 of the 1940's and Concorde of the 1970's), which illustrate the point that aircraft structures have historically consisted of high piececount metal strutures mechanically attached by multitudes of fasteners.

These designs lead to numerous subassembly operations and associated inspection requirements, which have resulted in few changes in the man-hours per pound (MH/LB) required to produce aircraft structures. This fact is illustrated by Fig. 1 where the MH/LB of typical airframe structures is shown plotted against the Aircraft Manufacturer's Production Responsibility (AMPR) weight for various aircraft. These man-hours have not shown any particular improvement with time, resulting in steadily increasing costs of producing aircraft because of inflationary factors. Therefore, MH/LB is the primary reason for increased airframe costs and is the major area that must be addressed if the price of airframes is to be reduced.

Although much progress has been achieved in present-day airframe designs in terms of lower weight and increased damage tolerance, it is expected that continuation of present designs will not satisfy the airframe requirements of future fighter systems. It is predicted that the higher aircraft performance of future aircraft will not only demand substantially lighter airframe weights, but will require significantly lower costs in order to provide new affordable systems. These cost reductions must not only involve acquisition but cost of ownership as well.

The airframe designers at Rockwell believe this challenge can be met with the utilization of efficient low-cost structural forms of advanced metallic and composite structures. The advanced metallic structures combine superplastic forming and diffusion bonding (SPF/DB) of titanium into a single process that promises to revolutionize titanium fabrication and structural design. New design concepts, such as that illustrated in Fig. 2, heretofore considered impractical because of high costs and fabrication difficulties, are now possible using the SPF/DB process. Studies to date indicate that SPF/DB titanium structures offer cost savings of up to 70% over conventional titanium structures and can be cost-competitive with aluminum structures in some areas. A titanium SPF/DB structure was incorporated in cost reduction applications on the B-1 aircraft, as shown in Fig. 3.

The application of advanced composite structures to systems is not new, for example, F-14, F-15, F-16, and B-1; only the form discussed is new. Figure 4 illustrates the application areas of advanced composites for the B-1 aircraft. These applications cover the gamut of complexity, from the rib/skin/spar construction for the horizontal stabilizer to full-depth, thin-skin sandwich for most of the secondary structure applications. Past application of composites has been limited to material substitution designs where the metal parts and methods of attachment are replaced by corresponding composite parts. These applications, although lighter in weight and sometimes cost-competitive with their metal counterparts, have not realized the potential of highly efficient conceptual composite designs.

This paper explores the utilization of such designs through the application of integral composites coupled with the judicious application of advanced metallic structures. Such structures result in fewer pieces, less fasteners, and associated

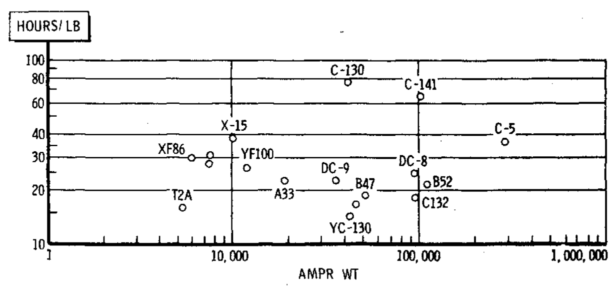

Fig. 1 Manufacturing h/lb for past aircraft.

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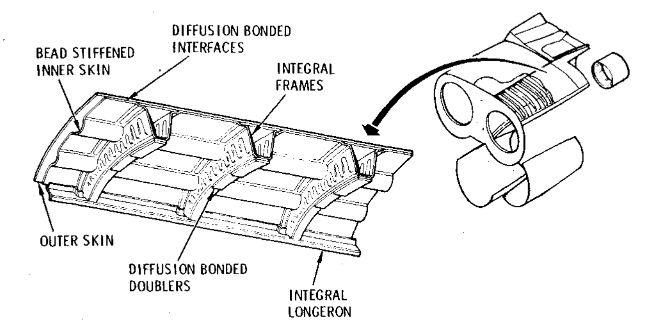

Fig. 2 Fuselage-type structure using SPF/DB with integrally formed frames.

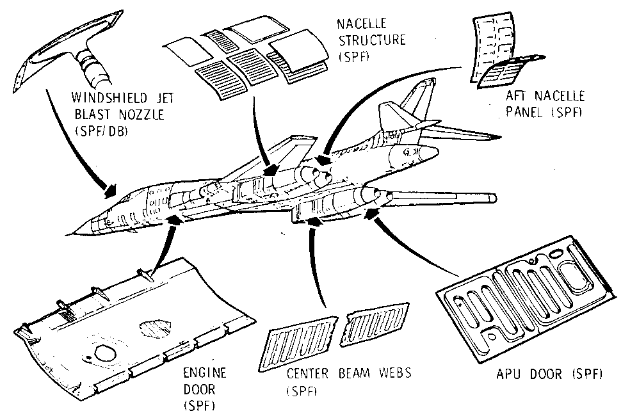

Fig. 3 B-1 production usage (SPF and SPF/DB).

higher operating stress levels, resulting in increased cost and weight savings.

It is the intent of this paper to explore the potential payoffs associated with the attainment of an optimum mix of the advanced metallic/composite structures for a typical future fighter system. Such data will also include the benefits derived from increased corrosion resistance and associated life-cycle cost reductions offered by these structures.

The next-generation aircraft will undoubtedly use substantial amounts of composites and advanced metallic structures, both to meet these demands for reduced costs and to meet required weight targets and performance goals. Figure 5 represents an advanced configuration for a future aircraft and shows the possible distribution of materials within its structure. The most likely use for advanced composites will be in the lifting surface structure, which will also contain aeroelastically tailored wings and canards to provide synergistic improvement in aerodynamic performance as well as reduced weights and fabrication costs. Advanced metallic structures, particularly SPF/DB structures, will be most

Table 1 Average properties of an integrally stiffened SPF/DB part

Tensile strength, F_{ty} 10^3 psi (MPa)	126.9 (875)
Compressive strength, F_{cy} 10^3 psi (MPa)	138 (950)
Shear strength, F_{su} 10^3 psi (MPa)	
Single lap	83.8 (575)
Double lap	83.9 (580)
Static peel 1 lb/in. (kN/m)[a]	1372.5 (245)
Dynamic peel,[a] maximum load lb/in. (kN/m)	Cycles to failure 10^3
590 (105)	9
443 (78)	493
295 (52)	136
263 (46)	182

[a] No failures occurred in bonded areas.

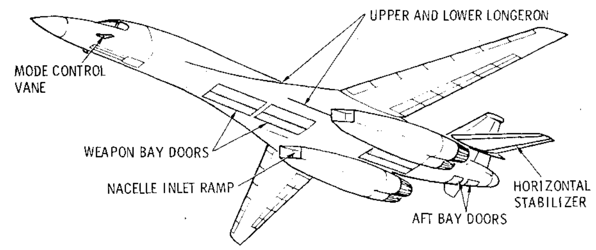

Fig. 4 B-1 composites structure applications.

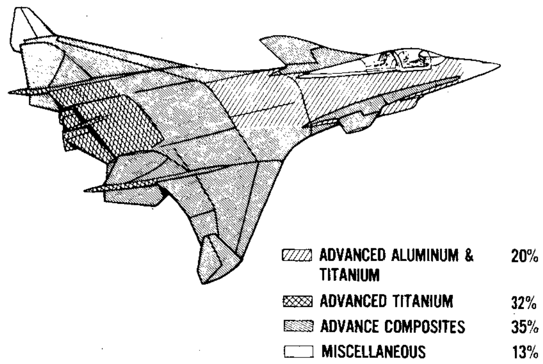

Fig. 5 Structural material selection.

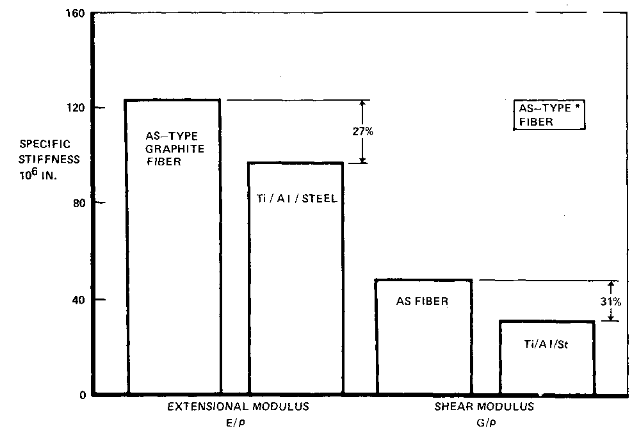

Fig. 6 Specific stiffness (0/ ± 45/90 graphite/epoxy vs metals).

suitable in the hot aft fuselage areas. The substantial efforts presently being pursued are showing such large cost savings that this technology may prove to be less costly than an aluminum structure, particularly when life cycle costs are included.

Composite Structures

On the basis of extensive trade studies and actual design and fabrication experience with composite structures for the B-1 and HiMAT aircraft, it has been generally established that for the class of fighters considered in this paper, graphite/epoxy is the prime candidate material for secondary structures and lifting surface primary structures. As shown in this section of the paper, composite structures result in substantial weight and cost savings over their aluminum counterparts in a production environment.

The numerous lifting or control surfaces on an aircraft consist of both primary and secondary structures. Examples of secondary structures are flaps, slats, rudders, and elevons. Primary structures include the wing and the empennage.

Control or lifting surfaces generally are designed, at least in part, by torsional stiffness requirements to resist wrap-up and torsional/bending stiffness requirements for flutter. The significant weight savings attainable by application of graphite/epoxy vs aluminum or other metallic structures for stiffness-governed designs have been well documented, and savings of 25-40% are generally obtained from these applications. The inherent high-specific stiffness of graphite/epoxy and other advanced composites can be illustrated by considering Fig. 6.

In Fig. 6, specific stiffness properties of a balanced graphite/epoxy laminate (with 25% of its plies each in the 0, +45, −45, and 90 deg directions) are compared to those of steel, titanium, and aluminum. For this case, the specific extensional modulus and the shear modulus exceed those of the metals by 27 and 31%, respectively. Or, put another way, for the same bending stiffness (EI) or torsional stiffness (GJ) requirement, the composite structure results in 27% and 31% weight savings, respectively, for the laminate considered. In practice, the laminate ply orientations generally are not the same percentage, but rather a higher percentage of 0-deg plies is used if greater extensional stiffness is required, and a higher percentage of 45-deg plies is used if greater torsional stiffness is desired, thus resulting in larger weight savings.

Secondary Structure

A great many secondary structures and fighter empennages have aerodynamic shapes that require low thickness-to-chord ratios coupled with high stiffness. A low-weight design for these applications generally dictates a sandwich construction. Composites, with their ability to be co-cured and to effect simple gage changes by ply dropoffs, coupled with corrision-resistant, nonmetallic core, yield significant cost and weight savings over comparable aluminum honeycomb structures.

Figure 7 shows a montage of shapes and complexities for secondary structures recently fabricated for the B-1 and HiMAT aircraft. The data generated by these activities firmly demonstrate that efficiently designed composite secondary structures result in piecepart count reductions, fewer manufacturing operations, and cost savings of 10-25%, coupled with 15-25% weight savings over their metal counterparts.

Primary Structure

Unlike secondary structures applications where the design and manufacturing concepts have been firmly established, optimized composite structural concepts for lifting surfaces, which generally require rib/skin/spar construction for structural efficiency and which contain wet areas, have not yet been achieved. Although the recent development successes of the B-1 horizontal and vertical stabilizer programs demonstrated that an all-composite design (i.e., substructure and skins) can compete cost-effectively with a metal structure through elimination of substructure members and an approximate 40% reduction in part count and fasteners required, these applications, although successful, did not address fuel sealing requirements, efficient low-cost manufacturing processes, and elimination of highly loaded mechanical splices which inhibit the performance of composite structures.

If we are to achieve longer operating life, improved damage tolerance, and higher performance levels for fighter wings, then new composite-design concepts will be required. As a result, an extensive design trade study was conducted to develop a design concept for primary wing structure, including its interface with the fuselage, for a 1980's fighter.

As a result of these studies, an integral (modular) wing/fuselage concept was developed in which all structural splices between the wing torque box and carry-through box, as shown in Fig. 8, were eliminated. The payoffs from this conceptual approach include weight savings from removing a highly loaded splice joint and major cost savings by the elimination of all manufacturing activities associated with a major structural joint, i.e., fit-up, drilling, trimming, and assembly.

An additional aspect of the design is the replacement of the tension-cover-to-substructure joint with an integral joint. By elmination of the stress risers and cutouts in the lower cover, the inherent strength of the lower cover can be utilized fully by allowing up to 5000 μin. of ultimate strain, rather than the current limits of 2500-3000 μin. for primary structures application.

The integral structure/through-wing concept minimizes the number of fasteners required, eliminates fuel sealing concerns for the lower cover, reduces fit-up and shimming efforts, permits higher operating strains for the lower cover, and yields a highly optimized composite conceptual design concept which results in cost/weight savings improvements of 50% or better over current composite design concepts. The upper cover would be closed with blind fasteners and sealed. All access holes for pumps, etc. would be in this upper cover.

Figure 9 shows a typical fabrication and assembly concept for the integral structural design. Initial fabrication studies have demonstrated that the use of castable ceramic tools coupled with rubber pressure molds, as used to fabricate sine wave spars, yields structures of excellent quality. Current studies are underway to address manufacturing scale-up and the associated structural demonstration of large advanced wing structures, including the complexity introduced by aeroelastically tailored covers. These studies are expected to validate the cost/weight savings achievable with integral structures.

Typical cost/weight savings for the integral structure concept vs several metallic designs are shown in Fig. 10.

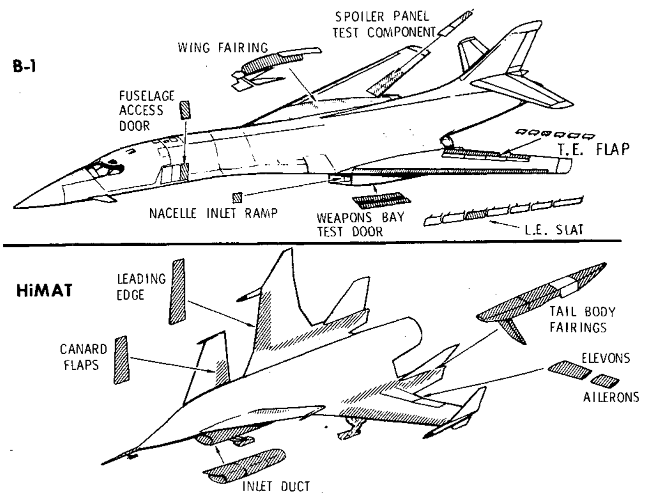

Fig. 7 Summary of Rockwell composites—secondary structures experience.

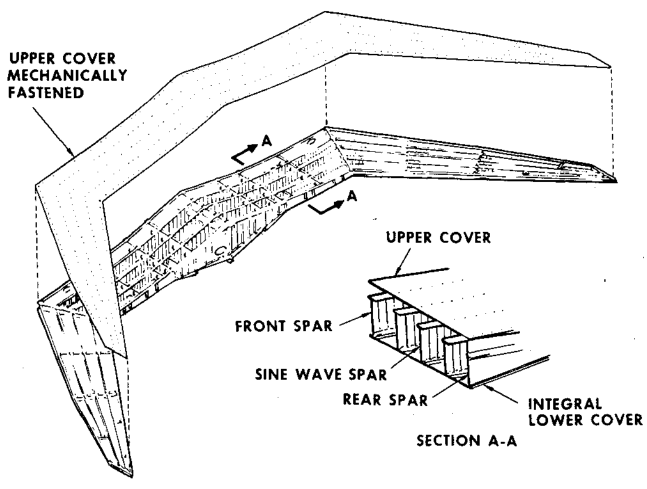

Fig. 8 Integral composite wing/fuselage concept.

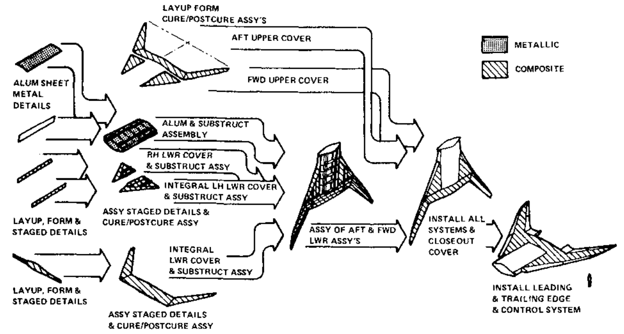

Fig. 9 Integral substructure manufacturing sequence.

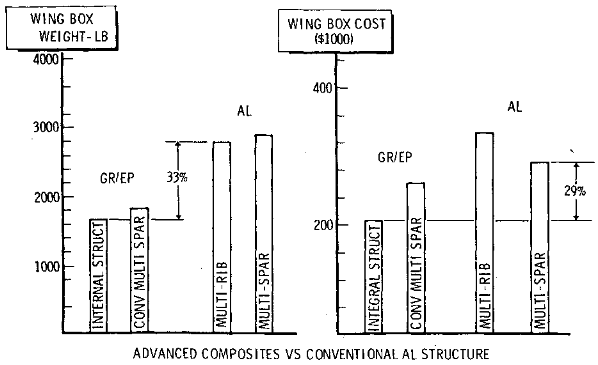

Fig. 10 Wingbox weight/cost comparison.

Advanced Metallic Structure

A new process utilizing the superplastic forming and diffusion bonding properties of metals promises to revolutionize the field of metallic aircraft structural design and fabrication. This process permits the designer to utilize much more efficient structural forms and, simultaneously, significantly reduce piecepart count in a given structure. This results in significant weight and cost reductions over conventional design and fabrication methods. The process takes advantage of two phenomena available in some metals. These include superplasticity, which permits very severe forming of the material, and diffusion bonding, which permits solid-state joining of the materials. These properties can be utilized individually or simultaneously at the discretion of the designer to form an integrated, fastener-free structure.

Superplastic behavior is the absence of localized thinning when a material undergoes extensive tensile strain. Elongations of several hundred percent are typical, some even exceed 1000%.

In superplastic forming (SPF), a metal sheet is heated to its superplastic temperature in a sealed die. An applied gas pressure then forces the sheet to conform to the shape of the cavity. Argon is used in titanium SPF to prevent oxidation of the reactive metal. Springback and residual stresses are not problems with SPF parts.

The optimum temperature for superplastically forming Ti-6Al-4V is 1700°F (925°C). Fortunately, this is the same temperature used for diffusion bonding (DB) titanium structures. This permits simultaneous processing of structures by superplastic forming and diffusion bonding (SPF/DB) during a single heat cycle.

In the SPF/DB process, mating surfaces are brought into intimate contact at elevated temperature. Atomic diffusion across the interface thus produces the bond. Test specimens fabricated by gas pressures in this process produced parent metal strengths across the bonds. Lap shear strengths, for example, averaged 84,000 psi (580 MPa). Typical 6Al-4V shear strength is 78,000 psi (540 MPa).

Independent research at Rockwell has now established three generic types of SPF/DB structures (Fig. 11). In this first type, a superplastically deforming sheet encounters titanium details, preplaced in the tooling, and is concurrently diffusion bonded to them. It is, therefore, possible to add functional members to the formed part. The procedure can also incorporate forming after bonding because both are done during a single-process (heating) cycle.

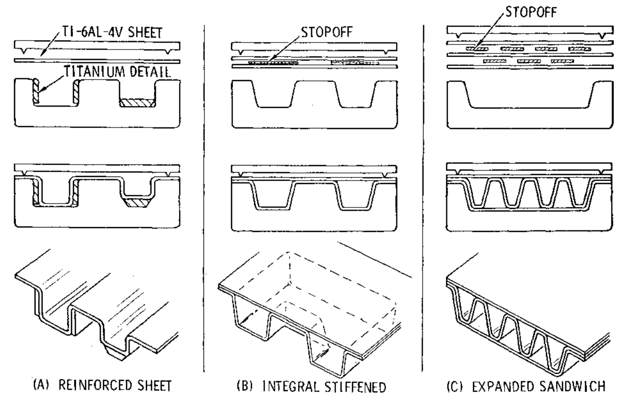

Fig. 11 Three basic types of SPF/DB structures.

The second type of SPF/DB structure—integrally stiffened—is made by the simultaneous processing of two 6Al-4V sheets (Fig. 11b). A stopoff compound applied to one sheet prevents bonding in discrete areas. The stopoff pattern corresponds to tooling cavities. When the pack reaches 1700°F (925°C), pressure is applied and those areas not coated with stopoff are bonded. After bonding, gas pressure is introduced to superplastically form the unbonded areas.

Demonstration parts with "hat section" stiffening, similar to that in Fig. 11b, have been fabricated. Properties of specimens removed from these parts are summarized in Table 1. Note that the lap shear strength values match the experimental average of 84,000 psi (580 MPa).

A prototype similar to the design shown schematically in Fig. 11b has been fabricated under a current Air Force Materials Laboratory (AFML) contract (F33615-75-C-5058).

Sandwich Structure

By using selective bonding and three sheets, the SPF/DB process yields the most exciting form of hardware—expanded sandwich (Fig. 11c).

A variety of demonstration SPF/DB sandwich structures have been fabricated. Although the work is still in an early stage, two important advantages of SPF/DB sandwich can be cited:

1) The external configuration of the fabricated part is obviously determined by the tool cavity and may be a design variable. On the other hand, the core configuration is determined by the stopoff pattern; it may be of infinite variety and can be modified without tooling change.

2) The process inherently provides an edge closure of infinite design. This avoids what is frequently a significant cost factor in applying a conventional honeycomb sandwich. Figure 12 shows typical representative core configurations that have been fabricated to date. These include a truss core, dimpled core (core bonded to face sheets in intermittent spot pattern), and sine wave core (core bonded in a parallel sine wave pattern). The process also readily permits core variations within the same panel, i.e., all types of cores can be utilized within the same panel by varying the stopoff pattern if an advantage can be gained with this approach.

SPF/DB Applications in Specific Airframe Components

The potential for the SPF/DB process is being confirmed by fabricating and evaluating full-scale components. Additionally, the HiMAT airframe uses SPF and SPF/DB hardware in its structure. Figure 13 shows the B-1 hardware

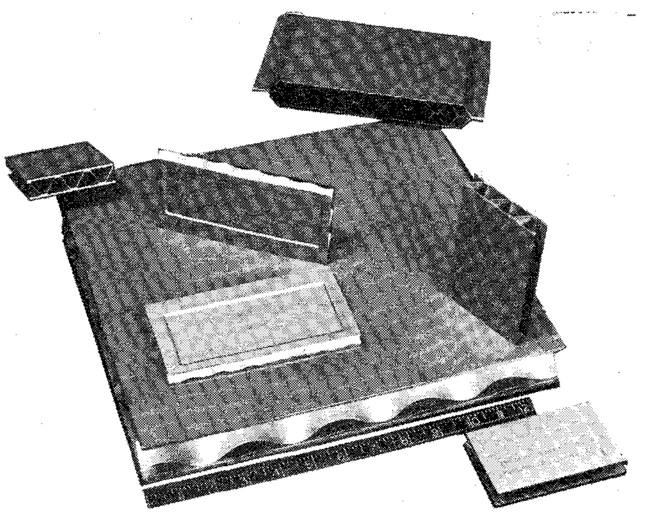

Fig. 12 Example of expanded sandwich hardware.

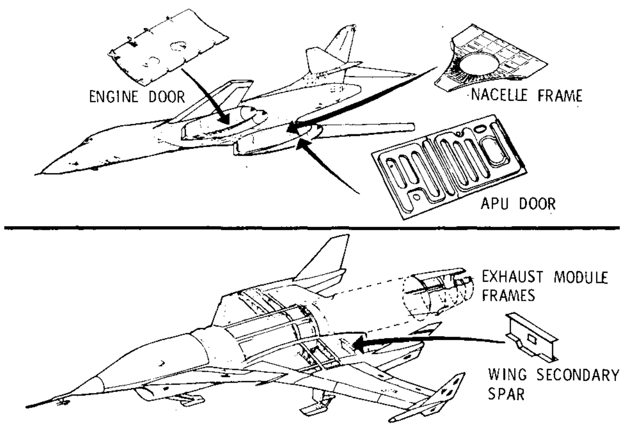

Fig. 13 B-1 SPF/DB demonstration hardware and HiMAT applications of SPF/DB.

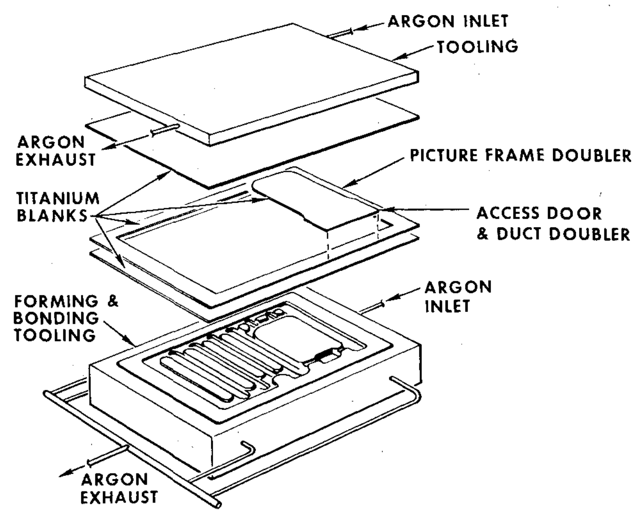

Fig. 14 SPF/DB APU door DF demonstrator.

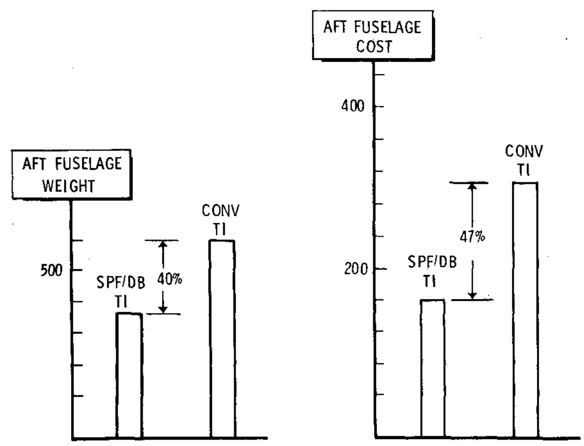

Fig. 15 Fuselage structure comparison SPF/DB vs conventional titanium.

presently being fabricated under an AFML contract as well as the HiMAT applications of SPF/DB.

The first demonstration part under the AFML contract was an integrally stiffened version of the auxiliary power unit (APU) door in each nacelle. The SPF/DB version (Fig. 14) measures approximately 22×28 in. (560×710 mm) with ¾ in. deep (20 mm) hat sections. Two of these doors would replace a single T-section stiffened door machined from plate.

Results of cost tradeoff studies indicate that SPF/DB doors would represent a 50% cost saving in production. A 31% weight saving over the machined version was achieved. The dollar gain derives from a need for less metal and a reduced fabrication cost. The weight advantage stems from the more efficient load-carrying configuration of the SPF/DB part.

The SPF/DB door is more complex that it first appears. The periphery, for example, has a 0.109 in. thick (2.8 mm) "picture frame" doubler bonded in place, a design feature added to increase resistance to acoustic fatigue loading. The flat area of the door accommodates a smaller access door. It is doubled with a 0.060 in. thick (1.5 mm) sheet to provide a 0.120 in. thick (3.0 mm) frame for the smaller door after machining. The large bulge, truncated to accommodate a duct, is also doubled to 0.120 in. (3 mm) and subsequently formed (see Fig. 14).

The second SPF/DB part is a nacelle beam frame, which was originally fabricated as 12 hot-sized and/or machined details, assembled with 81 fasteners. The essentially monolithic SPF/DB design weighs 39% less and would cost half as much in production.

The largest SPF/DB part planned for fabrication to date is also a B-1 component and is part of the same AFML contract. The part, a lower engine access door (Fig. 14), measures approximately 105 in. (2665 mm) long and 55 in. (1395 mm) wide, with a nominal 30-in.-radius (760 mm) compound curvature. The parts used in the HiMAT structure consist of five exhaust module frames fabricated as one-piece ring frames from titanium. Two SPF/DB parts are used in the wing structure. They consist of a spar with spar caps bonded to the web in a concurrent diffusion-bonded application.

One recent study included the comparison of a typical fuselage-type structure consisting of titanium sheet metal and machined ribs, longerons, and chem-milled skins fastened together with a standard riveting system against an alternate design using a concept similar to the expanded waffle (Fig. 2), where diffusion-bonded skins with hat-section stiffeners form the basic skin panel. This structural concept integrates the skin, stringers, and frames into a unitized structure formed and diffusion bonded in one cycle. The results of this conceptual design study are shown in Fig. 15. As indicated, estimated weight savings of approximately 40% and cost savings approaching 50% can be realized with the SPF/DB concept.

Advanced Structures Impact on Performance and Cost

While both advanced composites and metallics have shown substantial payoffs when substituted for conventional structures, their impact on aircraft systems is compounded

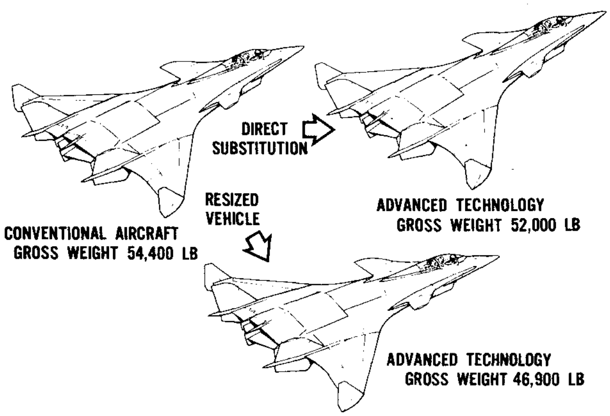

Fig. 16 Weight impact of advanced structures technology.

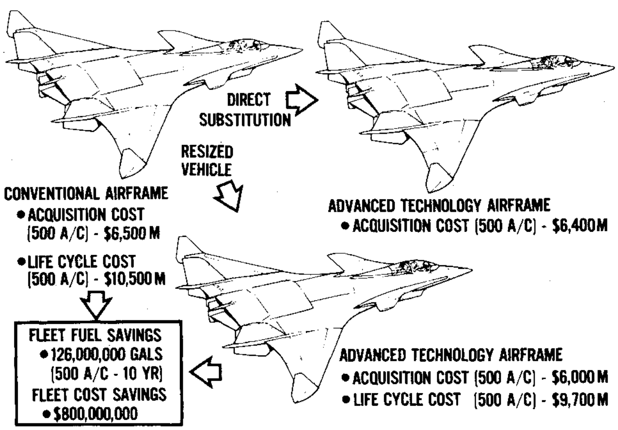

Fig. 17 Cost impact of advanced structures technology.

when applied early in the preliminary design phase because of the effect of growth factor.

In a preliminary design environment, optimization procedures are used to size the airplane configuration geometry, such as wing aspect ratio, thickness ratio, wing area, etc., to minimize the airframe size and/or cost. The air vehicle configurations at this stage are free to grow or shrink along prescribed lines. The final vehicle size is profoundly influenced by the airframe structural weight, which, in turn, is influenced by the technology assumed in the structure.

Growth factor is defined as the ratio of the resulting changes in airplane gross weight caused by a change in weight in some portion of the airframe. For example, with a growth factor of 3, a reduction in structural weight of 1000 lb will reduce the gross weight of the air vehicle by 3000 lb, with corresponding reduction in initial cost and cost of ownership. It is very important, therefore, to apply these new technologies early in the design process of airplane development.

This total impact is shown in the following typicaL example of an advanced fighter design which illustrates the impact of the use of advanced structural technology and conventional metal technology.

Figure 16 shows the difference in gross weight of three airplanes. The advanced technology airplane weighs 46,900 lb, or a difference in gross weight of 7500 lb. In this comparison, the structural weight of the state-of-the-art airplane was 15,800 lb, while the advanced airplane was 11,400. The structural weight reduction resulted from the use of advanced composites and advanced metallics, and included the growth factor effects.

The most important impact of advanced structural technology and growth factor is a reduction in the acquisition and life cycle costs of the airplane. In addition to the cost reductions available through direct substitution of advanced technology, the growth factor effect compounds the cost savings. As shown in Fig. 17, the acquisition cost saving available through direct substitution of advanced technology for a 500-airplane fleet is $100,000,000, while that realized through incorporation of the technologies in the early preliminary design stage is $500,000,000, a substantially larger number.

Additionally, the smaller-sized advanced technology airplane will result in substantially reduced life cycle costs. This is also illustrated in Fig. 17, which shows the resultant total life cycle cost of two aircraft. A fuel saving of 2000 lb per aircraft also results from the smaller airplane. When applied to the estimated life of the vehicle, a saving of 126,000,000 gal is projected over the 10 yr lifespan of a 500-airplane fleet.

Because of this cascading effect, the importance of continuing and introducing new development programs to instill confidence in these new structural technologies cannot be overemphasized. These technologies are a necessity in future aircraft designs and must be pursued to reduce airframe cost and increase their performance. Development programs to reduce new concepts to practice are required before they will be accepted by the industry and Government system project offices.

Conclusion

The studies conducted to date have definitely proven the cost and weight advantages of advanced composites and metallic structures. Their use during the preliminary design stage of aircraft design is a necessity to obtain maximum advantage of these technologies in future aircraft.

Integral composite structure and superplastic forming combined with diffusion bonding are the prime candidates for achieving these goals. Development programs are being sponsored by several government agencies to develop these concepts and reduce them to practice, to reduce their risk, and encourage their acceptance. These programs should continue. They represent the most likely means of reaching the desired goals of higher airplane performance, coupled with reductions in cost of ownership for aircraft.