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Design of Advanced Titanium Structures

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The emergence of new titanium fabrication techniques has opened up new possibilities for achieving high structural efficiency at considerably reduced costs. Superplastic forming/diffusion bonding (SPF/DB), combined with conventional metallurgical joining techniques, has been shown to effect weight reductions in future weapon systems. This paper shows how the basic steps utilized in structural design were altered in the application of SPF/DB to a Mach 2.0 aircraft.

Introduction

ALTHOUGH titanium alloys offer significant structural advantages over other metal alloys, continued use of titanium is dependent on the ability of the manufacturer to compensate for the material's high procurement and fabrication costs by implementing new processing technology. Superplastic forming/diffusion bonding (SPF/DB) and hot isostatic processing (HIP) are two such new emerging technologies. When combined with welding, brazing, and adhesive and weld bonding, they are referred to as BLATS (built-up low-cost advanced titanium structures). This paper will describe the application of SPF/DB to a Mach 2.0 aircraft (Fig. 1).

Thermal Environment

Heating Sources

The primary sources which heat the structure are aerodynamic heating on the external air-passage surfaces, internal heating due to ram air flow in the engine inlet duct, engine compartment ventilation flow, and heat produced by the turbojet engine itself.

Flight Envelope

The operational flight envelope for the ATS aircraft, upon which the temperatures are based, is shown in Fig. 2. The following assumptions were made concerning aircraft capability in regard to this envelope:

1) The aircraft is capable of maintaining V_H for extended periods of time (15-20 min) sufficient to soak all the aircraft structure at equilibrium temperature.

2) After soak at V_H, the aircraft can accelerate to V_L and maintain V_L for 5 min.

3) When flight maneuver load conditions not at V_H or V_L are considered, it was assumed that the aircraft was subjected to the most severe temperature condition at V_L just prior to the subject maneuver.

Propulsion System Heating

It was assumed that the aircraft is powered by a turbojet engine with no bypass flow. The engine utilizes an afterburner combined with an Alben nozzle for thrust vector control and reduced base drag. The engine case itself is a significant source of heating. Engine case temperatures for the maximum power afterburning condition for the ATS engine are given in Fig. 2. The maximum temperature of the case aft of fuselage station (FS) 767 is governed by turbine inlet temperature and is independent of operating altitude for maximum power.

Maximum Structural Temperatures

As shown in Fig. 3 for the hot-day atmosphere, maximum temperature conditions occur when the aircraft is flown at an altitude of 36,000 ft. Therefore, a set of maximum temperatures for the major structural components has been determined, assuming that the aircraft was thermally soaked at V_H ($M=2.0$ at 36,000 ft) and then accelerated to V_L ($M=2.3$ at 36,000 ft) and kept at this speed and altitude for 5 min. The maximum temperature experienced by this structure ranges from 357°F (due to aerodynamic heating) to 700°F (due to engine heating). This is a very appropriate range for the use of titanium alloy.

Loads and Dynamics Analysis

The airloads distribution on the BLATS fuselage structure was derived for symmetric critical loading conditions or load factors (+7.33 and −3.0 at Mach 0.800, sea level).

The load analysis made use of a finite-element model which was used with a doublet-lattice, nonplanar lifting surface program. This program measures air loads from all over the aircraft, redistributes loads for any specified $N_z W$ condition, and applies them at node points on the structure.

Preliminary Loads Estimation and Internal Loads Distribution

The applied loads were then broken down and fed into a finite-element model. The structure was sized by making several iterative runs in a fully stressed design optimization program. Any given member is sized by the worst-case loading of all the loading conditions.

Fatigue Loads

With completion of the preliminary loads and availability of the internal loads distribution, a fatigue loads spectrum was generated from static conditions consisting of three basic maneuvers: pull-up, pushover, and roll. The pull-up maneuver produces a 7.33 g positive N_z and pitch moment. The pushover maneuver gives a negative 3.0 g and reverse pitch movement. The roll maneuver provides maximum loading from an abrupt roll reversal at 4.7 rad/s, −12.0 rad/s^2, and $N_z=5.846\ g$ at $M=0.8$ and at sea level.

The fatigue spectrum is based on internal loads taken from the mathematical model, which is generated from the static conditions. Derivation of the fatigue spectrum from these loads follows the format established for the F-111A and is based on the test aircraft, see Fig. 4.

With the internal loads available from the mathematical model, the load values for each condition (pull-up, pushover, and roll pullout) were compared at several points on the

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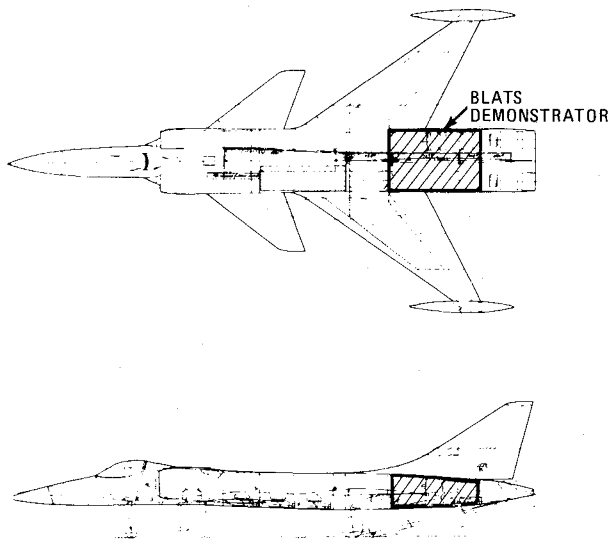


Fig. 1 ATS/BLATS structure.

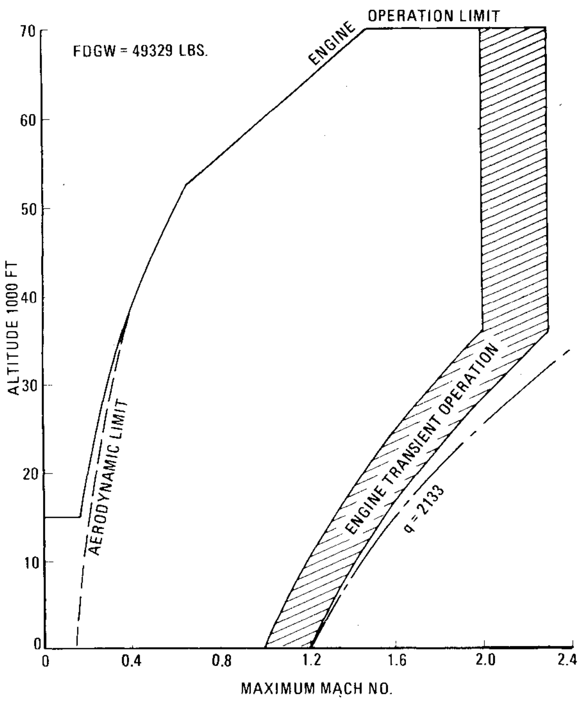


Fig. 2 Operational flight envelope of ATS.

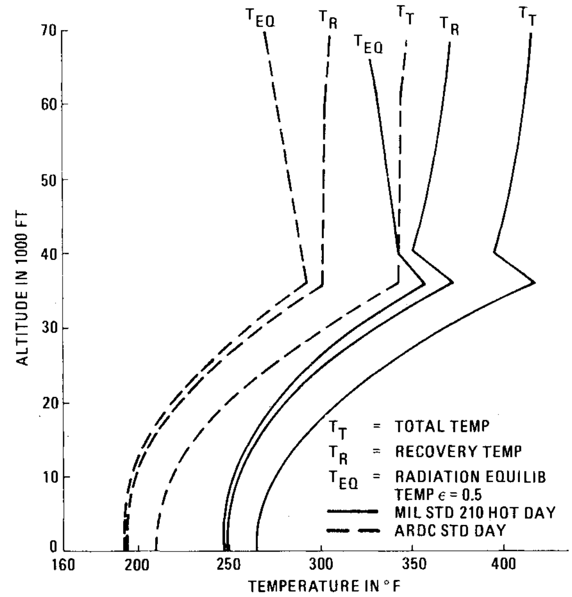


Fig. 3 Temperature variation with altitude for V_L flight envelope.

CURVE NO.	PROPORTION OF PULL-UP		
	PULL-UP	PUSH-OVER	ROLL
1	1.00	-0.58	±0.32
2	1.00	-0.58	±1.00
3	1.00	-0.58	±6.00

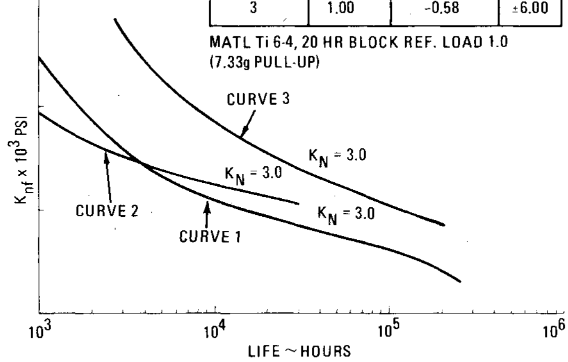


Fig. 4 Fatigue conditions.

structure. These included longerons, frames, forward and aft engine, and fin mounts. Relationships were then derived between conditions (see Fig. 4). This allowed the fatigue curves to be reduced to three.

Fracture Mechanics Analysis of SPF/DB Structures

A study was made to evaluate the proposed design on the basis of fracture considerations, applying the requirements of USAF Specification MIL-A-83444, Airplane Damage Tolerance Requirements. This work was greatly facilitated by the use of the Grumman-developed CRACKS computer program. This program accepts load spectral data along with experimental crack-growth data for a given material, and calculates various quantities pertinent to crack growth, such as crack length vs time or load cycles and residual strength as a function of crack length or load cycles. It is capable of taking into account the interaction between load cycles, that is, the effect of previous load cycles in retarding or accelerating crack growth in a current load cycle.

It can be stated at the outset that the monolithic character of SPF/DB structures can be expected to make them less damage-tolerant than corresponding built-up structures with bolted or riveted joints.[1]

One of the purposes of this study was to evaluate the use of beta-annealed Ti-6Al-4V titanium alloy in place of the mill-annealed alloy. Figure 5 provides a fracture-life comparison for the two materials on the basis of a load spectrum applicable to the BLATS baseline. It should be noted that the indicated initial half-crack length of 0.125 in. is the value applicable to "slow crack-growth structures." The indicated value of 8000 h for the flight hours to failure is applicable if the structure is "in-service noninspectable," while the value of 2000 h would apply if the structure is "depot- or base-level inspectable."

If the monolithic character of SPD/DB structures is not to be departed from, these structures may necessarily be in the category of slow crack-growth structure, as distinct from a fail-safe structure. According to MIL-A-83444, slow crack-growth structure must be regarded either as noninspectable or as depot- or base-level inspectable. If it is the former, crack growth must be such that the required residual strength of the cracked structure is maintained for the entire design life, which is twice the actual anticipated lifetime. The latter requires that the structure be inspected for cracks at intervals of one-quarter the actual lifetime, with a factor of two applied

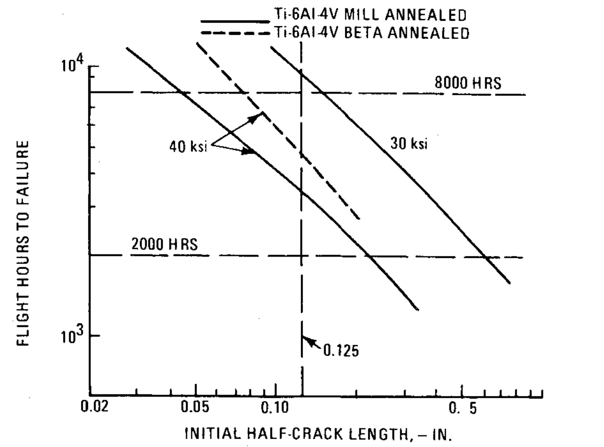


Fig. 5 Comparison of the fracture properties of mill-annealed and beta-annealed Ti-6Al-4V titanium alloy.

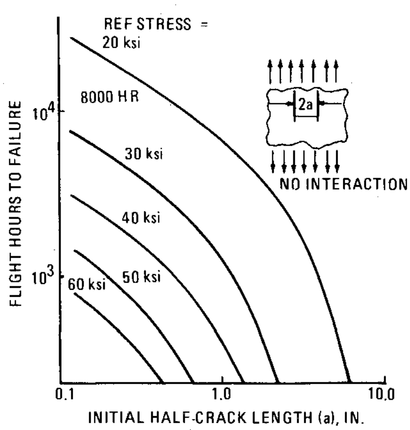


Fig. 6 Crack growth behavior in mill-annealed Ti-6Al-4V titanium alloy plate without interaction.

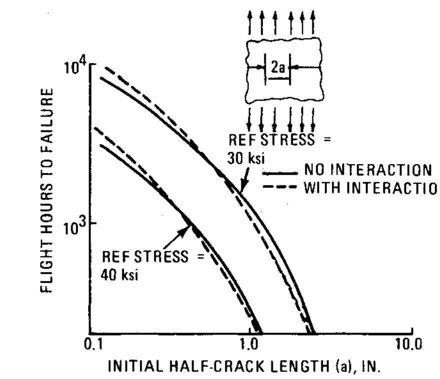


Fig. 7 Crack growth behavior in mill-annealed Ti-6Al-4V titanium alloy plate with and without interaction.

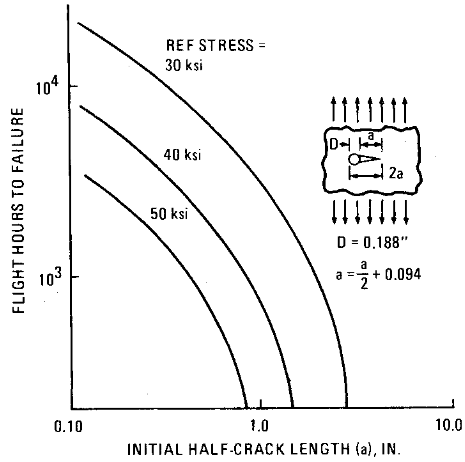


Fig. 8 Crack growth behavior in mill-annealed Ti-6Al-4V titanium.

to this interval for the maintenance of required residual strength. The initial crack length (that is, the length of a crack that must be assumed to exist at the beginning of the life of the structure or at the beginning of an inspection interval) must be at least 0.25 in. at locations other than holes, unless it can be demonstrated that smaller cracks can be reliably detected.

Results for a through-the-thickness crack in an infinite plate of Ti-6Al-4V titanium alloy (mill annealed) in uniform tension are shown in Figs. 6 and 7. It can be seen that for an initial crack length of 0.125 in. and for a design life of 8000 h (noninspectable structure), reference stress corresponding to a 7.33 *g* pull-up condition is slightly less than 30 ksi when load interaction is not taken into account. If this portion of the structure is depot- or base-level inspectable (2000 h intervals), the corresponding reference stress values are 45 and 46.5 ksi. This represents a substantial increase in allowable stress, and provides a strong incentive to design the structure for inspectability. These results also indicate that the effect of interaction is favorable and should be taken into account.

The case of a crack emanating from a drilled hole was also considered to ascertain whether it might be more critical. The hole was assumed to be 3/16 in. in diameter and the initial crack length was taken to be 0.05 in., as specified in MIL-A-83444. Results are shown in Fig. 8 for the same load spectrum used previously and with interaction effects included. It can be seen that the reference stress for a design life of 8000 h is almost 40 ksi, and is considerably in excess of the value previously obtained for the larger initial crack that must be assumed at locations removed from holes.

Development of Geometric Configurations

The purpose of the skin stabilization effort was to optimize skin/stiffener arrangements subjected to axial, shear, and pressure loading. Skin/stiffener optimization began with the selection of various geometric sections after considering the associated manufacturing and structural prerequisites. Innovative designs were considered, e.g., making a slightly beaded skin panel. A Grumman study showed that for configuration 11 of Fig. 9, the stringer section of the skin could be curved into the airstream (0.040-0.100 in. for a stringer width *b* of 1-1.5 in.), significantly increasing the local compressive buckling of that section of the stringer. This effect also improved the overall efficiency of the section.

After a particular skin/stiffener geometry had been developed (considering the above-mentioned factors), the local compressive buckling parameters of the various plate and curved elements that comprise the particular section were calculated and compared. Utilizing the parameter which represented the weakest of these elements, the most efficient Euler column length was then determined and that length was allowed to represent the frame or support spacing. This design philosophy also allowed for optimization of the section geometry from a conventional flexural bending standpoint. The purpose of this procedure was to insure that the material was utilized to its fullest strength capability. Various skin/stiffener configurations, including formed hat sections, truss core, and sandwich panels, are shown in Fig. 9. Many of these configurations were fabricated and tested.

The material gages used in the SPF/DB effort were kept between 0.040 and 0.060 in. whenever possible. This was based on economic considerations, which for most structures showed higher costs for the procurement of gages below 0.040 in. and poor material utilization above 0.060 in. When these material thicknesses and chemical milling were combined, a varied range of load intensity applications was possible.

Detail Design of Major Components

Having established the goals and requirements for the structure, detail design was undertaken. One of the first tasks was to select the skin stabilization method most appropriate for the particular structure. Figure 9 shows the various concepts considered. Several of these were fabricated and tested to determine the structural behavior, structural integrity, fabricability, and cost, as outlined in Table 1.

A total of six structural arrangements were developed, utilizing various skin stabilization concepts and corner joint details. Panel sizes were varied, based on commercially available sheet sizes and prices, manufacturing considerations (i.e., available press sizes), and logical splice locations, such as longerons and bulkheads. Adequate accessibility provisions were made for maintainability via access covers and doors, see Fig. 10.

The joining methods selected included welding, diffusion bonding, automatic riveting, and mechanical bolting, with and without interference fit. The use of welded joints was preferred based on the excellent fatigue results obtained in the F-14A wing and wing center section structures.[2] In addition, welding eliminated potential leak paths in the fuel-carrying aft fuselage.

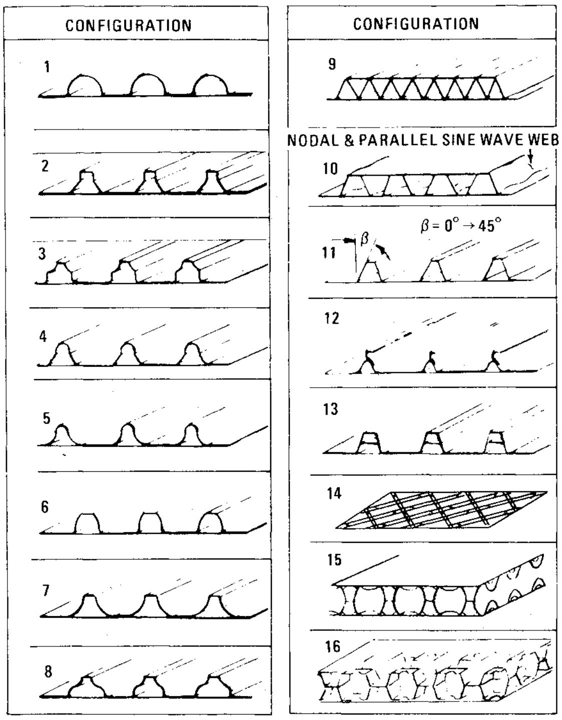


Fig. 9 SPF/DB skin stabilization configurations.

Concept Evaluation

The objective of this analysis was to compare the cost, weight, reliability, and maintainability of the major structural components of the six advanced configurations developed under this program. The ultimate aim was to determine which was the most effective design for an aft fuselage. The analytical tools used in this evaluation included: design-to-cost studies, weight optimization studies, structural finite-element mathematical model, CONMIN optimizer programs to generate optimum geometric configurations, and detail stress analysis.

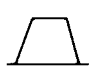
In addition, careful attention was paid to established design practices, with emphasis on structural continuity, including design details which favorably accommodate fracture and fatigue requirements.

Preferred Concept

This configuration (see Fig. 10) is a compilation of the best joint, skin stabilization, and process combinations of the five configurations studied.

The vertical tank wall was designed as a single-sheet SPF corrugation. Tradeoff studies were performed against an assortment of skin-stiffened panels (hat, modified hat, and semicircle) and sandwich-type panels in order to ascertain the most structurally efficient design to carry vertical shear loads and internal fuel pressures. Utilizing a computer program for

Table 1 Summary of compression test results

Specimen No.	Stiffener shape	Failure load average stress, Nx	Theoretical column length, in. (pin ended) $E\text{-}17 \times 10^6$ lb/in.^{2}	Superplastic forming diffusion bond quality of specimen	Failure initiation
A		63,000 74,000 7,300	–	Poor, some delaminations at failure	Buckling of skin followed by stiffener buckling on all faces
S1	 Chem milled pocket	62,400 78,500 7,677	14.75	Good	Skin panel buckled by wrinkling. The onset was premature due to the lack of sidewall stiffening
S2		85,000 91,000 11,921	11.02	Good	Failed across cap
S3		38,000 72,000 6,107	11.71	Good	Local buckling of the hat section cap caused by excessive thinning during forming
S4		37,400 64,500 5,376	16.60	Excessive thinning of skin cap during final chem milling	Skin panel first buckled and cap failed
S5		68,000 76,000 9,513	13.96	Poor, spot welded	Caps buckled
S6		55,900 54,000 7,985	11.64	Poor, spot welded	Caps buckled
S7		63,000 73,600 8,520	16.79	Good	Caps buckled

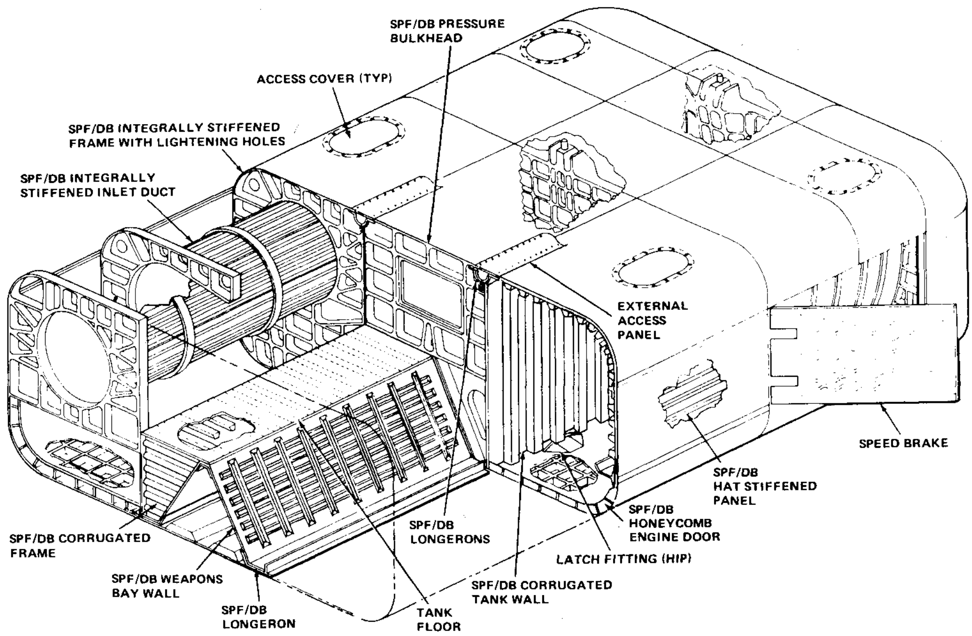


Fig. 10 BLATS concept.

the optimization of compression panels, single-sheet corrugation demonstrated the highest level of efficiency of all the structural elements analyzed. This resulted in a minimum weight design for the tank wall.

The weapons bay wall consists of horizontal corrugations with transverse members to provide an efficient column-type structure. The longitudinal orientation of the corrugation was conceptualized as a means to provide a fail-safe design, in the event that the lower longerons should experience structural failure due to battle damage.

The nacelle inlet duct was conceptualized as a three-sheet, modified hat-stiffened structure. The configurations attempted included a two-sheet design. While the approach efficiently utilizes material, design-to-cost analysis revealed that tooling costs and complexities negated the advantages of this approach. The modified hat configuration generates a skin-stiffened structure through a procedure similar to that utilized when fabricating multisheet-type structures (i.e., truss core). After fabrication, a trimming operation removes excess material, leaving an efficient structural element with material buildups located in the section's flanges. This procedure greatly reduces tooling cost and complexity.

Bulkhead/frame-type structures utilized the pyramid fabrication concept for the structural intersections of stiffeners. This design is so called because of the shape that two equal-height stringers (type 11 in Fig. 9) form when they intersect. In addition, this concept has the highest degree of structural efficiency of all SPF/DB stiffener intersections. Stiffener/flange intersections utilized the "blown member close-out" system, which creates a completely integral connection between bulkhead/flange stiffeners and flanges.

The speed brake was designed as an SPF/DB three-sheet trusscore structure. This type of construction exhibits structural and process advantages of other forms of sandwich construction due to inherent forming characteristics.

The upper longerons were designed as SPF/DB two-sheet y-shaped members fabricated in pairs and cut apart after SPF/DB. This design provides a high degree of structural integrity and facilitates maintainability by integrating structural and systems requirements. The cavity created through the center of the longeron provides access for hydraulic, pneumatic, electrical, and control lines, while generating a high degree of torsional rigidity and a large radius of gyration, thereby improving longeron stability and minimizing weight.

Table 2 Weight comparison

	Conventionally designed titanium, lb	Advanced titanium, lb	Savings, %
FS 659-714			
Outer skin panels	51.7	40.1	22.4
Decks and beams	100.9	80.3	20.4
Longerons	54.5	54.5	0.0
Engine duct	32.0	26.2	18.1
FS 684-714			
Outer skin panels	62.4	61.7	1.1
Decks and beams	124.2	97.5	21.5
Longerons	73.9	73.9	0.0
Engine duct	41.0	28.9	29.5
Equipment door	44.0	42.4	3.6
FS 714-750			
Outer skin panels	74.8	73.3	2.0
Decks and beams	118.0	90.6	23.2
Longerons	74.6	74.6	0.0
Forward engine door	59.0	49.8	15.6
FS 750-793			
Outer skin panels	103.0	82.7	19.1
Decks and beams	148.7	109.6	26.3
Longerons	68.9	68.9	0.0
Aft engine door	70.0	61.7	11.9
FS 798-814			
Outer skin panels	59.6	34.0	43.0
Beams	27.5	23.1	16.0
Longerons	20.4	20.4	0.0
Frames and bulkheads			
FS 659	79.7	69.6	12.7
FS 684	74.8	67.8	9.4
FS 714	99.8	62.0	37.8
FS 750	116.0	72.7	37.8
FS 777	77.4	65.2	15.8
FS 798	168.0	120.2	28.5
FS 814	85.5	73.7	13.8
Total	2110.3	1725.4	18.2

Skin panels were designed as hat-stiffened-type structures in areas void of contour, and SPF/DB trusscore in areas of single and double curvature. Computer optimization analysis revealed that for the type of loading experienced in the BLATS demonstrator, a single-sheet corrugation is the most structurally efficient and cost-effective type of design. Since

Table 3 BLATS cumulative average cost tradeoffs (200 units)[a]

	Conventional cost, ($)			SPF/DB cost, ($)			
Structural component	Factory labor	Tooling (NR & REC)	Total	Factory labor	Tooling (NR & REC)	Total	Savings, %
Engine access door	159,800	4,180	163,980	56,800	1,910	58,710	63
Centerline bulkhead	30,200	3,410	33,610	9,600	995	10,595	68
Speed brake	62,800	1,120	63,920	20,400	600	21,000	67
Nacelle duct	34,200	1,180	35,380	28,240	2,500	30,740	13
Longeron	10,600	1,960	12,560	4,600	850	5,450	57

[a] Not included: material cost and supporting services.

aerodynamic requirements mandate contour surface flushness, application of this design is precluded. The two-sheet hat-stiffened panel was found to be the next preferred type of structure because it blends the requirements of structural efficiency and aerodynamic performance.

Maintainability and Reliability Assessment

Built-up, low-cost, advanced titanium structures offer advantages in many areas. With regard to reliability and maintainability, benefits are derived from reduced labor associated with fastener repair/replacement, and corrosion maintenance associated with conventional materials and construction techniques.

Maintainability of BLATS, with regard to failure detection and repairability, probably will be more difficult than with conventional construction. Although voids and delamination would be detectable with ultrasonics, this technique requires further development before it can be considered reliable for production. Repair of small voids and delaminations may be accomplished with fasteners or doublers using conventional, readily available tools. However, extensive repairs involving large sections of BLATS would require highly specialized equipment and facilities, such as plasma-arc welding and portable plastic vacuum chambers, which are not normally available at organizational or intermediate level maintenance facilities. However, portable chambers are routinely used at Grumman to repair discrepant parts.

Fly-by-wire systems require that control lines be run in three separate ways to provide adequate redundancy. The BLATS concept has two hollow SPF/DB longerons in which equipment lines can be run. In addition, lines can also be installed in the weapons bay. Thus, this arrangement provides three distinctly separate ways to run lines and gives the desired redundancy.

Weight Analysis of Advanced Concepts

A detailed component-by-component weight analysis of the BLATS advanced concept was completed and the results are shown in Table 2. The final advanced titanium weight of 1725.4 lb represents a 384.9 lb or 18.2% net weight savings when compared to the conventional titanium design. A 10% factor was applied to the analytical weights to account for such items as joints, splices, and fasteners too small to appear on a layout-type drawing; radii and fillets; drawing tolerances and dimensions; and sealant and finish applications.

The conventional titanium baseline weights were determined utilizing the Grumman-developed Semi-Analytical Fuselage Estimating (SAFE) computer program. SAFE provides a rapid method for deriving internally distributed applied loads as well as fuselage weights. The theoretical weights represent the upper limit to the efficient utilization of structural material, which can rarely be realized when the compromises of detailed design and fabrication are considered. To account for such items as the penalties associated with load introduction, joints, splices, fasteners, and cutouts, the theoretical weights are multiplied by an empirically determined nonoptimum factor that yields a realistic assembly weight.

Cost Analysis of Advanced Concepts

An analysis was performed to evaluate the cost performance of SPF/DB vs conventional fabrication.

Cost estimates for the five SPF/DB assemblies were generated, using time studies based on a subcomponents fabrication typical of those shown in Fig. 10. These "standard costs" were then extrapolated with respect to area and/or linear dimensions, as required, to account for the size and shape changes of the various configurations. The conventional cost estimates, which represent detailed analyses of each structural component, were developed on a part-by-part basis using the Grumman Design-to-Cost Manual. Estimates for each structural component were generated with a unit 1 value. A cumulative average cost was generated by utilizing applicable learning curves for each process involved. The cumulative average value was taken as the basis for comparing SPF/DB and conventional fabrication approaches for each structural component. Comparison of the cumulative average costs (see Table 3) clearly indicates that substantial cost savings can be realized with the SPF/DB process.

Using this methodology, a cost savings of 66% was estimated by both the weight and area relationships. This cost savings was based on time standards measured in a laboratory environment during the fabrication of test articles. In addition, the estimates for SPF/DB assume that no problems will surface when real-world aircraft complexities are incorporated and test articles are factored up to full-scale parts. Accordingly, the calculated cost savings were reduced by half.

All things considered, it can be conservatively stated that the cost savings will not be less than 30%, one-half of what is being projected at the present time.

Conclusion

BLATS exhibited a high degree of structural efficiency. It was found that complex geometry and a varied set of loading conditions and intensities could be handled at no additional cost. For the aft fuselage considered, a minimum of 30% cost savings and 18% weight savings are anticipated. The real payoff, however, is a new design flexibility in airframe construction, not only in the use of titanium, but in its combination with other advanced materials. Usage would not be limited to aircraft only, but would include present and future missile systems as well.[3]

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