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"CAREFREE" HYBRID WING STRUCTURES FOR AGING USAF TRANSPORTS

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Abstract. *The United States Air Force (USAF) operates a 6000-aircraft fleet with an average age approaching 26 years, while it replaces only about 60 aircraft per year. To maintain flight safety, USAF maintenance crews carry a high structural inspection burden. Breakthroughs at Delft University, Airbus, GTM Advanced Structures, and Alcoa offer a dramatic new approach to the design and development of "carefree" transport wing structures for new aircraft and for the structural life extension of aging aircraft. The carefree structures concept, first proposed by Hinrichsen, suggests that truly optimized structures are not designed for minimum weight; rather, they are optimized for minimum life cycle costs. This requires extremely long crack-free lives and freedom from corrosion, with the attendant savings from greatly reduced inspection and repair. Such a modern wing design based on the intelligent combination of modern aluminum alloys and coatings, fiber-reinforced sandwich materials, and innovative design/manufacturing methods enables a highly supportable, inspectable structure that offers dramatic weight and life cycle cost-saving benefits over legacy all-aluminum wing designs.*

INTRODUCTION

The United States Air Force (USAF) operates the largest fleet of aging aircraft in the world. Unlike airlines that rarely keep aircraft in revenue service past 25 years, the *average* age of USAF aircraft is nearing 26 years. The average KC-135 tanker (modified B-707) is now 48 years old and more than 800 USAF aircraft—14 percent of the fleet—are grounded or have mission-limiting restrictions due to age.[1] Sustaining the legacy fleet includes fighting corrosion and fatigue of alloys like 2024-T3, which was introduced in 1935, and 7075-T651, which was introduced in 1944 and used on a tanker and transport fleet built in the 1950s and 1960s.[2]

Given the large number of transport category aircraft approaching their life limit in this environment, USAF engineers are considering alternative recapitalization strategies to meet the safety, reliability, and availability requirements for its airframe fleet. Advanced hybrid aerospace structures based on the intelligent combination of modern aluminum alloys, fiber-reinforced sandwich materials (like GLARE), and composite materials with innovative design and manufacturing technologies enable large performance and affordability improvements over the current state-of-the-art structures. The dramatic damage tolerance and performance improvements offered by these types of structures provide attractive solutions to pervasive fatigue and corrosion problems and make the concept of "carefree" structures a possibility.[3]

The continued aggressive use of USAF legacy airlifters has elevated the need for service life extensions for the transport fleet, placing a heavy burden on the engineers, structural inspectors, and repair technicians charged with maintaining safety and availability. In many cases, aged metallic components are replaced with drop-in substitutes fabricated from the same legacy alloys called out in the original bill of materials from the 1950s through 1970s.

In the past three decades, the aluminum industry has made substantial improvements in the static strength, durability, and corrosion resistance of alloys.[2,4] Further, the invention in 1980 of the aramid fiber metal laminate (FML) ARALL, and the further development of glass fiber-reinforced GLARE in the 1990s, offer organic composite-like structural performance[5,6] without some of the drawbacks of carbon-fiber-reinforced polymers. Figure 1 shows the FML sandwich form (left) and its tailoring attributes (center and right).

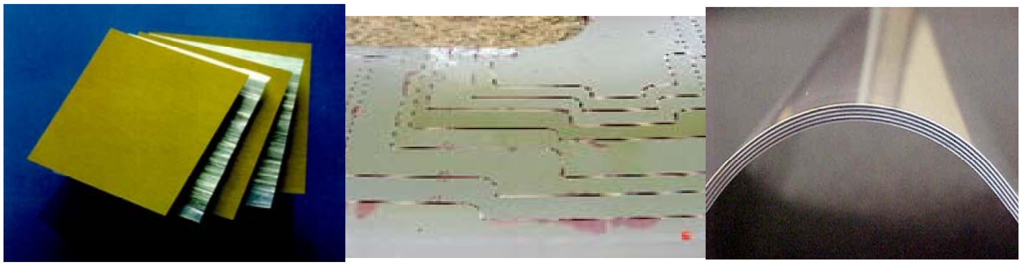

Figure 1. GLARE FML product forms

The USAF may be able to further benefit from the accomplishments of Douglas (now Boeing) on the ARALL C-17 aft cargo door[7] and of Airbus on the A380 GLARE fuselage sections and tailplane leading edges[8] as shown in Figure 2. These lead structural applications of FMLs open opportunities for higher level hybridization of the structure to achieve dramatic improvements in life cycle cost savings for the aging USAF transport fleet.

Figure 2. Applications of FML structures on C-17 and A380 aircraft

BACKGROUND

The USAF follows the damage tolerance concept for ensuring the safety of aircraft structures, as described in MIL-STD-1530C.[9] The premise USAF approach is to integrate slow crack growth design and scheduled inspections to maintain airframe ability to carry regulatory load with partial fatigue, corrosion, and/or discrete-source damage present. The strict inspection requirements in this damage tolerance approach should ensure that damage never reaches a dimensional state that could lead to catastrophic failure. Inspection intervals are set based on the expected damage growth rates such that an inspector has at least two opportunities to detect subcritical damage in time for appropriate repair or retirement of a component.

The damage tolerance certification process for USAF structural components evolved from the 1950s through the 1970s, following in-flight structural failures of the B-47 (1958) and F-111 aircraft (1969). The method was developed at a time when conventional aluminum alloys such as 2024-T3 and 7075-T651 and characterization of fatigue crack growth rates by the $da/dN = C\Delta K^n$ Paris Law were the best that could be achieved. As such, it was common practice to base structural design on slow crack growth, meaning a required inspection at or before one-half of the flight cycles required to grow an initial flaw from just below the detection threshold to critical size (Figure 3).

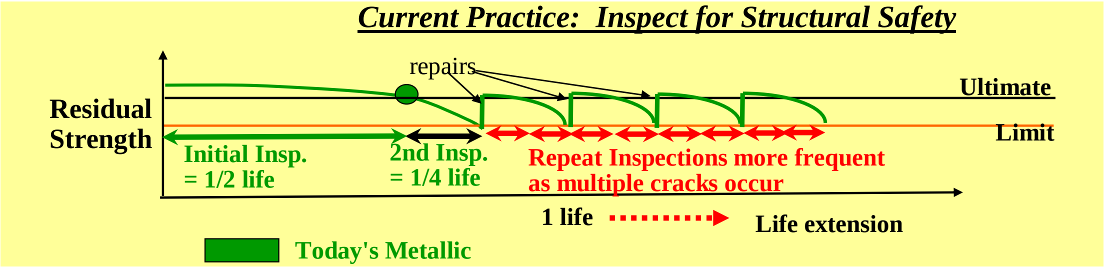

Figure 3. Development of inspection intervals for damage-tolerant aircraft

If operators desired service life extensions beyond the design service goal (DSG), they chose between even more frequent inspections and repairs and/or the replacement of a major structure. For example, following the first Gulf War in 1991, a majority of the C-141 fleet was grounded for lower wing fatigue cracks that were eventually repaired with boron/epoxy bonded patches. Eventually, 120 C-141s received a total of 2,300 bonded repairs.[10] Fatigue failures in commercial service in the late 1980s and early 1990s (e.g., Aloha 737 in April 1988 and El Al 747 freighter in October 1992) illustrated the high cost of underperforming on inspections.

Commercial practice diverged from USAF practice in the 1980s and 1990s, when airlines elected to recapitalize by replacing their older jetliners typically with newer Boeing (757, 767, and 777) and Airbus (A320, A330, and A340) versions. In contrast to commercial jetliners, the usage rates of military transport aircraft are lower, and the USAF elected to fly, inspect, and maintain its aging fleet of Lockheed (C-5, C-130, and C-141) and Boeing (KC-135, 707-derivative, and B-52) aircraft. Fleet viability decisions were based largely on flying hours, with less emphasis on the time-dependent effects of corrosion. In some cases, additional heavy maintenance lines were opened (e.g., the C-130 uses two Air Logistics Centers plus contractor facilities to handle its depot maintenance workload) as maintenance hours per aircraft increased. Emphasis also was placed on finding smaller cracks with higher performance inspection equipment.

This inspection-driven life extension drove higher maintenance workloads and reduced the availability of individual aircraft. As the USAF transport fleet continues to age, costs of inspections, structural repairs, and component replacements are expected to increase. Maintenance categories for USAF aircraft over the period of 2001-2005 are presented in Figure 4. The top three relate to maintenance of aging airframe structures included in the "look phase" of scheduled inspections (focuses primarily on finding cracks and corrosion), airframe repair (including painting for corrosion control), and special inspections (Time-Compliance Technical Orders, where an entire aircraft fleet undergoes a special one-time inspection because an unexpected defect has been found). These top three categories together account for 37% of USAF aircraft maintenance man-hours.

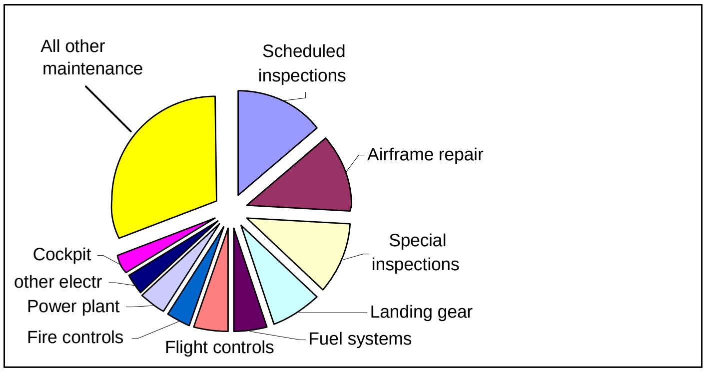

Figure 4. Top 10 maintenance categories in the USAF, 2001-2005

Given the increasing USAF fleet age, it is not surprising to note that the top three categories have grown every year. By contrast, engine maintenance (4 percent of the five-year total) has decreased over the same time period, benefiting from a strong investment in research into better automated inspections and a condition-based approach. In 2006, the USAF spent 87 percent more on aircraft maintenance[11] than it did in 1996, while fleet availability has declined.

TECHNICAL NEEDS FOR AGING STRUCTURES

USAF Secretary Michael Wynne has challenged the research community to deliver solutions to the aging airframe problem, instead of the status quo: increasing restrictions and groundings, increasing maintenance costs, more frequent inspections, and reduced aircraft availability rates. New materials and structural concepts promise 3 to 10 times longer crack-free lives and greatly reduced inspection intervals, while still decreasing structural weight compared to conventional aluminum structures. Hinrichsen's concept of carefree structures[12] suggests that truly optimized aircraft structures should not be designed for minimum weight; rather, they should focus on minimum life cycle costs. The carefree concept requires materials exhibiting high specific strength and tailorability of properties, extremely slow fatigue crack growth rates, relative freedom from corrosion, and excellent tolerance to damage from impacts. Proper material selection, when combined with attention to design detail to avoid abrupt change in load paths or other eccentricities,[13] complements the carefree structure concept to enable significant maintenance cost savings and downtime reductions though greatly simplified inspection and repair requirements.

Visual inspection over the entire DSG is an attractive design alternative for attacking the high costs of maintenance and repair. Further cost-saving opportunities would result if the concept required no greater training and equipment investment than traditional mechanically fastened sheet metal repairs. As such, large savings in maintenance would result from a concept that combines ultra-slow crack growth rates and high residual strength so that critical flaw sizes are never reached in 50 or more years of service.

Traditional carbon-fiber composites offer very high specific stiffness and are relatively insensitive to fatigue and corrosion, though galvanic corrosion has occurred in limited cases involving metal and carbon fiber contact. USAF experience on the Northrop Grumman B-2 has demonstrated that carbon-fiber composites perform well in applications where damage from low-energy impact is not a problem. A prevailing argument for the use of carbon-fiber-based composites is that their long fatigue life and relative corrosion resistance generally allow longer intervals between scheduled maintenance than would be required for conventional aluminum structures. For example, the 50-percent composite Boeing 787 "Dreamliner" is being marketed with twice the heavy maintenance interval of the aluminum 767 aircraft it replaces.[14]

Unlike aluminum structures, inspection and maintenance of carbon-fiber structures are driven by unscheduled events such as overheating, low-velocity impact, environmental effects, battle damage, and collisions with ground vehicles. Further, carbon-fiber composites are generally more difficult to repair than similar metal components. Higher levels of training, unique tooling, greater engineering involvement in the design, and strict process controls are required to accomplish a successful repair. Inspections before and after a repair are more difficult to realize due to the anisotropy and low "plasticity" exhibited by carbon composites. As a result, calendar-based inspection intervals for composites remain a non sequitur.

Visual inspection is difficult for thin-walled carbon structures. Impact damage can remain hidden even when fibers are broken and plies have delaminated. Thus, the structural integrity of the composite aircraft relies either on large-scale, frequent inspections using expensive equipment or on structures thickened to account for out-of-plane impact events, which reduce or can even eliminate the weight advantage that made them attractive in the first place.

APPLICATION OF HYBRID STRUCTURES

Finding a better way to build transport structures means designers must resolve the problems of fatigue cracking and corrosion without substituting new failure modes and more complicated inspection and repair schemes. The need for real reductions in the inspection burden faced by maintenance crews argues for structures that are more environmentally neutral, more durable, and more tolerant to impacts, while being easier to inspect and as simple to repair as aluminum structures. Enhancing structural supportability saves life cycle costs and frees up aircraft for flying duty. Longer inspection intervals and virtual elimination of Programmed Depot Maintenance (PDM) cycles equate to smaller fleets due to increased availability of the individual aircraft, freeing up critically needed capital for other priorities.

Authors[3,15-20] recently have described hybrid design concepts for high-performance, highly affordable, next-generation transport wing structures that make use of advanced aluminum and glass fiber/aluminum laminates to deliver the optimum combination of fatigue resistance, corrosion resistance, low structural weight, and minimum life cycle cost. Figure 5 shows the Alcoa Best Wing Box™ concept, which promises as much as 20 percent weight savings over conventional structures.[3,17,18]

A promising concept for the fatigue-critical lower skin of a hybrid wing would be based on the newly developed "CentrAl" hybrid concept in which FML grades (like GLARE) are bonded adhesively between (multiple) thick aluminum sheets. This concept[16,17,19,20] significantly enhances the fatigue performance of the skin and allows the designer to tailor the skin in the span-wise direction. Built on the well-known metal bonding practice that dates from the early 1950s, the concept has seen nearly 50 years of successful service on such aircraft as the Fokker F27, which first flew in March 1958. Upper wing surfaces would likely be built from high-strength, corrosion-resistant conventional aluminum alloys (i.e., unreinforced), while ribs and spars would be conventional alloys chosen for corrosion resistance, ease of manufacture, and stiffness. Ribs and spars would take advantage of increased integration to reduce parts count (including fasteners), weight, and component cost.

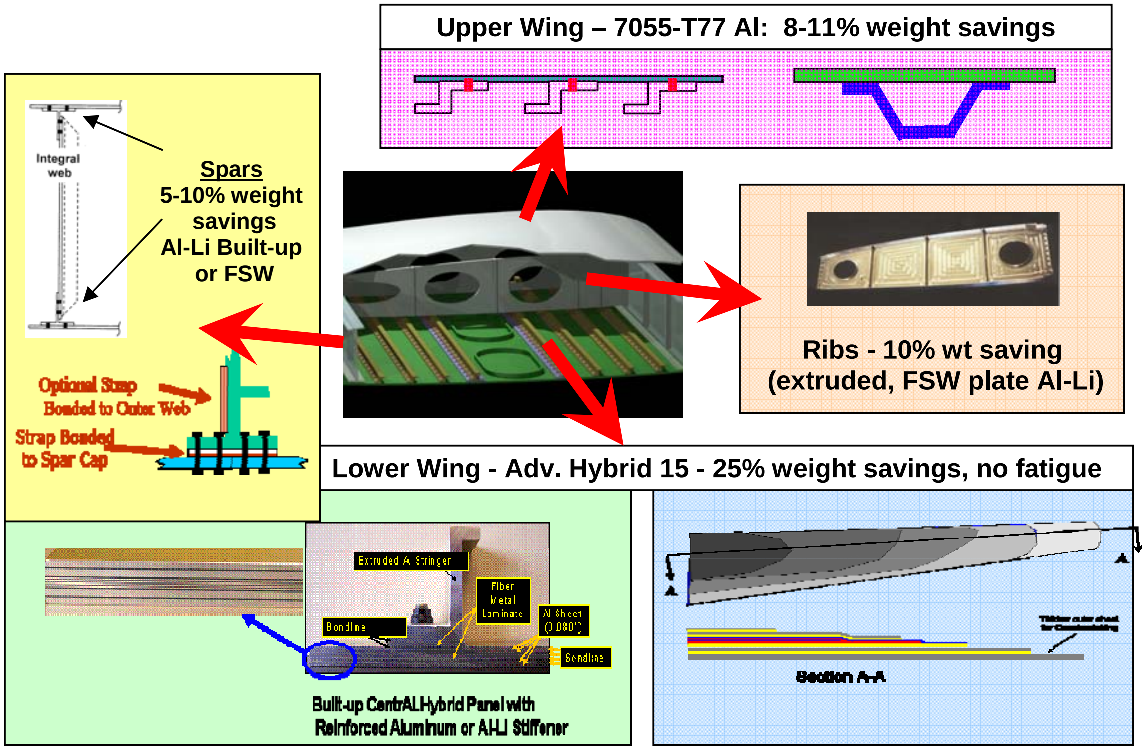

Figure 5. Alcoa Best Wing Box^{TM} concept[18]

If these advanced concepts for a new aircraft design were applied instead to retrofitting a military transport wing with a 50-year service life requirement (versus 20 or 25 years for a commercial transport), the design space would shift. Likely one-half of the substantial weight savings available would be traded for an even longer crack-free service life, offering substantial life cycle cost savings. Taking the C-130 Hercules transport as an example, dramatic reductions in inspections could be achieved, including elimination of the midlife center wing replacement[21] currently underway for the C-130H models. (1960s vintage C-130E models received new wings in the 1970s following hard usage in the Vietnam War and are now facing flight restrictions and grounding as their second wings wear out.) As the newer C-130H models face the need for new wings, they present an attractive opportunity to demonstrate hybrid technologies. Figure 6 shows graphically the effect carefree structures can have on military transport sustainment.

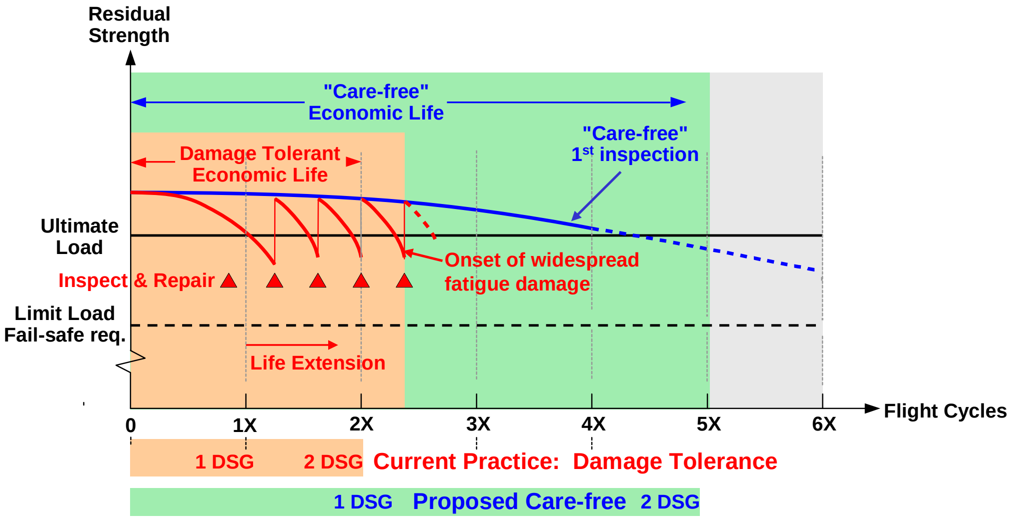

Figure 6. Effect of carefree structures on long-term fleet management

The impact of the carefree concept on life cycle costs is significant. For a typical USAF transport aircraft, structural inspections, corrosion, and structural repairs would fall by approximately 90 percent compared to legacy aluminum airframes. Because of extremely slow crack growth and very large acceptable critical flaw sizes in the hybrid wing, the first structural inspection required by damage tolerance regulations would occur at something like twice the current design service goal of a Boeing 767. Depot maintenance would become much less frequent, and the conventional midlife re-wing being carried out on the C-130 fleet today would vanish. Figure 7 shows a projection of the hypothetical life cycle cost benefit for the hybrid carefree design.

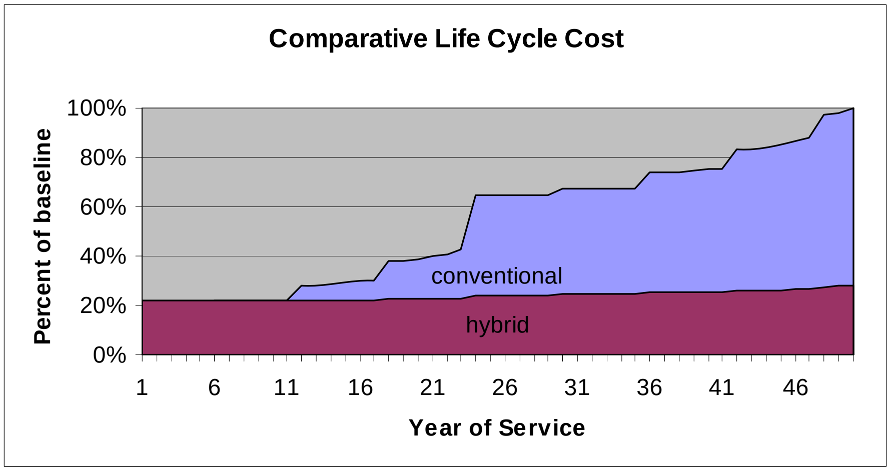

Figure 7. Life cycle cost comparison for notional USAF transport wing

This life cycle cost model shows what should not be a surprise: drastic reductions in inspection and repair actions and the elimination of a disruptive and time-consuming replacement of the wing at midlife of a military transport aircraft save 50 to 70 percent of life cycle costs in a notional transport wing, equating to tens of millions of dollars per aircraft.

Of equal importance to the maintenance community is the enhanced supportability of the FML/advanced aluminum hybrid structure. The key challenges of the past 50 years are met in the high strength and fatigue resistance, coupled with excellent corrosion performance of the concept. Extremely slow crack growth rates (when the rare crack does occur) enable inspection intervals to be set at one service lifetime or longer. Impact damage is readily evident by visual inspection means, and structural repair techniques are the choice of the maintainer: riveted, bolted, or bonded repairs[22] have demonstrated complete success in restoring static strength and durability.

CONCLUSIONS

- The concept of hybrid care-free structures offers major life cycle cost savings for USAF transport aircraft and can result in lightweight, long-life solutions to the legacy sustainment problems without the structural maintenance difficulties of carbon-fiber composites.
- Key improvements available from FML hybrid structures include fatigue and corrosion insensitivity, excellent impact tolerance, and extremely slow damage growth. Moreover, the concept offers significant design flexibility to optimize cost/performance trades.
- Hybrid structures offer new possibilities for cutting sustainment workloads by significantly reducing and simplifying structural inspections for corrosion and fatigue, while retaining ease of damage detection and metal repair practices.
- In addition to new designs, hybrid materials and processes that are qualified and certified on C-17 and A380 fuselage structures offer a low-risk opportunity for replacement of legacy transport wings.
- The significant potential of the aluminum/hybrid wing structure needs to be validated by a design, manufacture, and full-scale test program.

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