AN ASSESSMENT OF THE STATE-OF-THE-ART IN THE DESIGN AND MANUFACTURING OF LARGE COMPOSITE STRUCTURES FOR AEROSPACE VEHICLES

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SUMMARY

An assessment of the State-of-the-Art in the design and manufacturing of large composite structures has been conducted. The focus of the assessment is large structural components in commercial and military aircraft. Applications of composites are reviewed for commercial transport aircraft, general aviation aircraft, rotorcraft, and military aircraft.

INTRODUCTION

The state-of-the-art in the design and manufacturing of large composite structures includes many high-performance aerospace vehicles. This paper reviews the history of composites in commercial and military aircraft with an emphasis on the application of composites in moderate to heavily loaded structural components. Applications of composites are reviewed for large commercial transport aircraft, general aviation aircraft, rotorcraft, military fighter aircraft, and military transport aircraft. The paper concludes with a critical assessment of the state-of-the-art in the design and manufacturing of large composite structure.

LARGE TRANSPORT COMMERCIAL AIRCRAFT

The first composite components on commercial transport aircraft were designed and built as part of the NASA Aircraft Energy Efficiency (ACEE) Program and entered flight service during 1972-1986 [2]. The primary objectives of the program were to obtain actual flight experiences with composite components and to compare the long-term durability of flight components to data obtained from an environmental exposure ground test program. Boeing Commercial Airplane Company, Douglas Aircraft Company, and Lockheed Corporation agreed to participate in the program. A common feature of all three programs was the use of the Narmco T300/5208 graphite/epoxy material system. T300 is an intermediate modulus and intermediate strain-to-failure graphite fiber and the 5208 matrix is a thermoset epoxy that cures at 177°C. In the early years of the ACEE Program, smaller components of lightly loaded secondary structure were designed and entered service. These components included the L-1011 fairing panels, B-737 spoiler, DC-10 aft pylon skin and the DC-10 upper aft rudder. In the later years of the program, larger, more heavily loaded control surfaces were designed and entered service. These components included the B-727 elevator, Figure 1a, B-737 horizontal stabilizer, Figure 1b, DC-10 vertical stabilizer, and the L-1011 aileron. By January 1987, 350 composite components had entered commercial airline flight service.

As of 1993, the 350 components originally placed in service had accumulated over 5.3 million flight hours. The service performance, maintenance characteristics, and residual strength of numerous components were reported to NASA and compared to the data obtained from the 10 year, environmental exposure ground test program [3]. The data indicated an excellent in-service performance of the composite components during the 15-year evaluation period. The airlines reported damage such as ground handling accidents, foreign object impact damage, and lightning strikes. However, there was no degradation of the residual strength of the composite due to fatigue or in-service environmental exposure. Furthermore, there was good correlation between the results of the ground test program and the structural performance of the actual aircraft components.

A comparison of the applications of composites as a percent of structural weight for large commercial transport aircraft is given in Figure 2. These data were obtained from several issues of Jane's All The World's Aircraft [4]. The plotted data shows an increasing use of composites over the last three decades from lightly loaded secondary structure, to control surfaces, to more heavily loaded primary structure in the empennage of the Airbus aircraft and the B-777. The applications of composites in these aircraft are described in more detail in the next paragraphs. The current barriers to significant increases in the use of composites in primary structure are the higher cost of composites relative to conventional aluminum structure and the unreliability in the estimates of the design and development costs of composite structure.

Airbus was the first manufacturer to make extensive use of composites [4] on large transport commercial aircraft, see Figure 2. The A310 was the first production aircraft to have a composite fin box. Composite components on the A310 include the wing leading-edge lower access panels and outer deflector doors, nose wheel doors, main wheel leg fairing doors, engine cowling panels, elevators and fin box, fin leading and trailing edges, flap track fairings, flap access doors, rear and forward wing/body fairings, pylon fairings, nose radome, cooling air inlet fairings and tail leading edges, wing leading-edge top panels, panel aft rear spar, upper surface skin panels above the main wheel bay, glide slope antenna cover, and rudder. The A320 was the first aircraft to go into production with an all composite tail. Also, about 13% of the weight of the wing on the A340 is composite materials.

The Boeing 777 makes extensive use of composites for primary structure in the empennage, most control surfaces, engine cowlings, and the fuselage floor beams. These components are shown schematically in Figure 3. About 10% of the structural weight is composites [4]. As the schematic shows, several different composite material systems were used. Graphite/epoxy composites were used for most secondary structure and control surfaces. A toughened epoxy material system, Toray T800H/3900-2, was used for the larger, more heavily loaded components including the vertical fin torque box and horizontal stabilizer torque box components of the empennage.

ROTORCRAFT AND GENERAL AVIATION AIRCRAFT

Rotorcraft and general aviation aircraft have made extensive use of composites to achieve performance goals. The applications of composites as a percent of structural weight is plotted in Figure 4 for selected rotorcraft and general aviation aircraft to contrast the higher percent of composite in these aircraft relative to the large transport aircraft [4]. The V-22 tiltrotor aircraft designed by Bell has a number of significant applications of composites. Bell used an integrated product team approach to designing the V-22 airframe [4]. The approach is credited with saving about 13% of the structural weight, reducing costs by 22% and part count by about 35%. Approximately 41% of the airframe of the V-22, Figure 5, is composite materials. The wing is IM-6 graphite/epoxy and the fuselage and tail are AS4 graphite/epoxy. The nacelle cowlings and pylon supports are graphite/epoxy. The main cabin has composites floor panels and the crew seats are boron carbide/polyethylene. The fuselage is a hybrid structure with mainly aluminum frames and composite skins. The wing box is a high-strength, high-stiffness torsion box made from one-piece upper and lower skins with molded ribs and bonded stringers, two-segment graphite single-slotted flaperons with titanium fittings, and a three-segment detachable leading-edge of aluminum alloy with Nomex honeycomb core. The rotor also used significant graphite/epoxy (17%) and glass/epoxy (20%) composites.

MILITARY AIRCRAFT

Military aircraft have been designed with significant applications of composites in primary structure. While not all information on military aircraft is publicly available, the data in Figure 6 obtained from reference 4 compares the application of composites as a percent of structural weight for a number of fighter aircraft. For example, the Lockheed Martin F-22 Raptor, Figure 7, is approximately 39% titanium, 16% aluminum, 6% steel, 24% thermoset composites, 1% thermoplastic composite, and 14% other material systems [4]. The fuselage is a combination of titanium, aluminum, and composites. The wing skins are monolithic graphite/bismaleimide. Figure 8 shows the wings being assembled. The wing front spars are titanium and the intermediate spars are graphite/epoxy. The horizontal stabilizer uses graphite/bismaleimide skins with an aluminum honeycomb core. The vertical stabilizers use graphite/bismaleimide skins over graphite/epoxy spars. The wing control surfaces are a combination of co-cured composites skins and non-metallic honeycomb core.

The Northrop Grumman B-2, Figure 9, is constructed of almost all composite materials [4]. Development of the B-2 began in the late 1970's. The first flight test of the B-2 was July 17, 1989. The wing is almost as large as the B-747 with a span of 52 m and surface area of 478 m^2. The wing is mostly graphite/epoxy with honeycomb skins and internal structure. The fuselage also makes extensive use of composites. The outer skin is constructed of materials and coatings that are designed to reduce radar reflection and heat radiation. Boeing Military Airplanes produced the wings and aft section of the fuselage. Northrop Grumman produced the forward center-sections including the cockpit. Boeing completed the outboard wing section of the twenty-first and final aircraft on May 3, 1994.

The original design of the McDonnell Douglas (now Boeing) C-17, Figure 10, uses about 8% composite materials, mostly in secondary structure and control surfaces. In 1994, McDonnell Douglas proposed to re-design the horizontal tail using composites [4]. The tail was redesigned using AS-4 fiber at a 20% weight savings, 90% part reduction, 80% fastener reduction, and a projected 50% acquisition cost reduction. The prototype composite horizontal tail was successfully tested in 1998 to 133% of the design ultimate loads. Orders have now been placed for 70 aircraft with the new composite horizontal tail.

ASSESSMENT OF THE STATE-OF-THE-ART

Aerospace structural components are designed at close to a zero-margin. While the margin of safety is not zero for all the design criteria at each structural location, there is typically one criterion for each structural element that governs the design details of that element. The quest for the lowest weight structure then drives the design margin to nearly zero for the design limit load condition. The factor of safety between design limit load and design ultimate load accounts for the difference between linear, elastic behavior and complete structural failure. Therefore, aerospace structural designs do not have a large factor of safety to accommodate any deleterious structural behavior.

Composite structures fail differently than metal structures. The 65 years of successful experiences at designing metal structure cannot be directly transferred to composite structures. First, composite materials are not isotropic like most metallic alloys. Second, the initiation and growth of materials level damage and the failure modes of composite structure are not well understood and cannot be predicted analytically. Due to these complications, the best design practices are fully understood only by those engineers that are experienced at designing composite structure.

Composite structural design and manufacturing technology is not yet fully mature for all applications. There are 3 key factors that contribute to the lack of maturity of the design and manufacturing technology. These factors are the lack of a full understanding of damage mechanisms and structural failure modes, the inability to reliably predict the cost of developing composite structures, and the high costs of fabricating composite structure relative to conventional aluminum structure. While the technology required to overcome these uncertainties is under development, these factors are barriers to expanding the application of composites to heavy loaded, primary structure. For those applications where development and fabrication costs are not a factor or where risks to aircraft structural integrity are low, there is extensive use of composite structures.

Successful programs have used the building-block approach to structural design and manufacturing process development with a realistic schedule that allows for a systematic development effort. The complexities of light-weight, built-up structure led the industry to develop a building block approach which is the standard practice for both metals and composites. The building block approach relies on tests of elements and subcomponents to establish the effects of local details on structural behavior. The building block approach also must include development tests to address manufacturing scale-up issues. This is particularly critical in processing polymeric matrix composites where curing kinetics are particularly challenging to scale to large component fabrication. The lessons learned by the industry provide strong motivation for practicing collaborative engineering to design composite structure that can be reliably manufactured. Experienced materials and processing engineers should be included in the design phase and must be readily available to correct problems in production processes. The building block approach must be used to avoid overdesigned structure and high risk structural designs.

Maintenance, inspection, and repair technologies are not yet fully mature for all applications. Technologies in everyday use to support metal structures do not apply to composite structure. Furthermore, the long-term, field experiences necessary to develop a support infrastructure does not exist for composite structure. Therefore, support issues must be anticipated in the design phase to help facilitate effective maintenance, inspection, and repair procedures. Structures must be designed that can be repaired in the field. In addition, NDE experts should be part of the collaborative engineering team so that inspectability is built into the structural design.

REFERENCES

1. Aeronautics and Space, Code of Federal Regulations, Title 14, National Archives and Records Administration, U. S. Government Printing Office, Mail Stop SSOP, Washington, D.C. 20402, 1996.
2. Dow, M. B., The ACEE Program and Basic Composites Research at Langley Research Center (1975 to 1986), NASA Reference Publication 1177, NASA Langley Research Center, Hampton, VA 23681, 1987
3. Dexter, H. B. and D. J. Baker, Flight Service Environmental Effects on Composite Materials and Structures, Adv Perf Mat, Vol. 1, 1994, pp. 51-85.
4. Jane's All The World's Aircraft, 1998-99 Edition, Paul Jackson, Editor, Jane's Information Group Limited, Coulsdon, Surrey CR5 2YH, UK, 1998.

a. Boeing 727 composite elevator

b. Boeing 737 composite horizontal stabilizer

Figure 1. Commercial Applications Initiated by ACEE Program

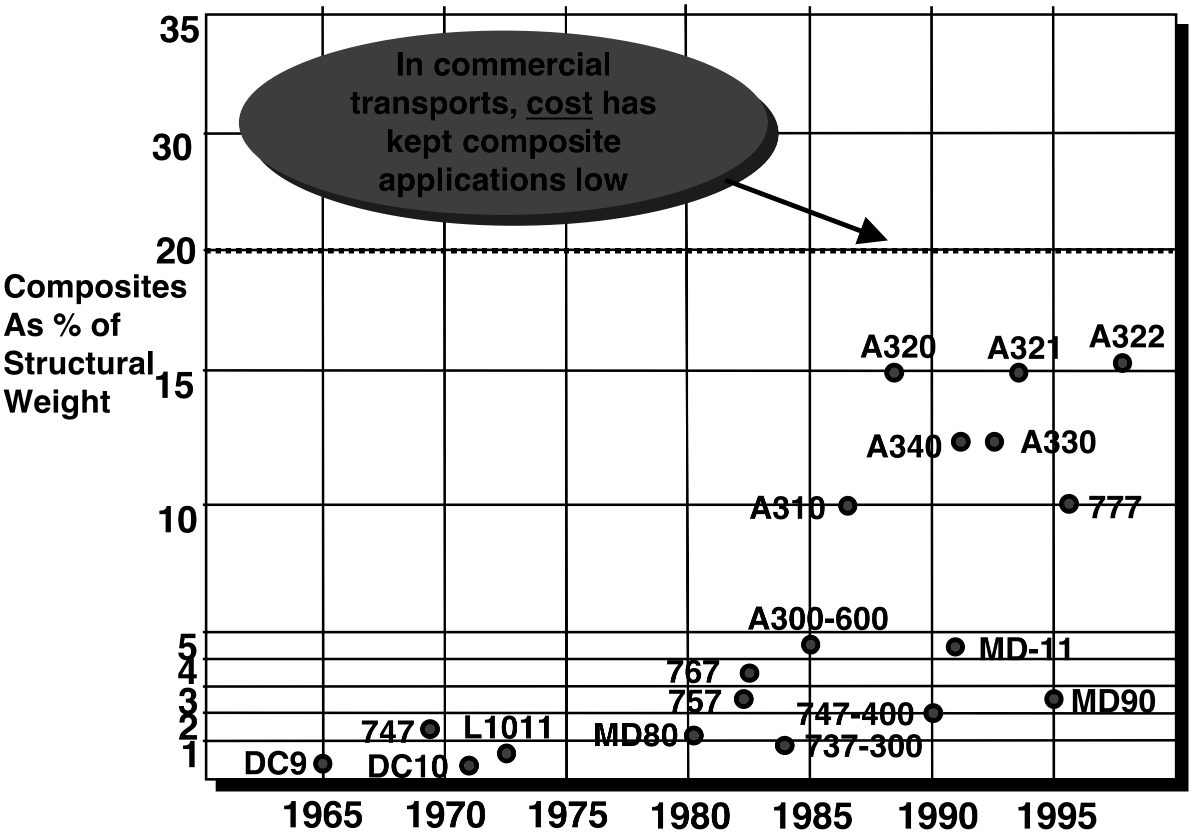
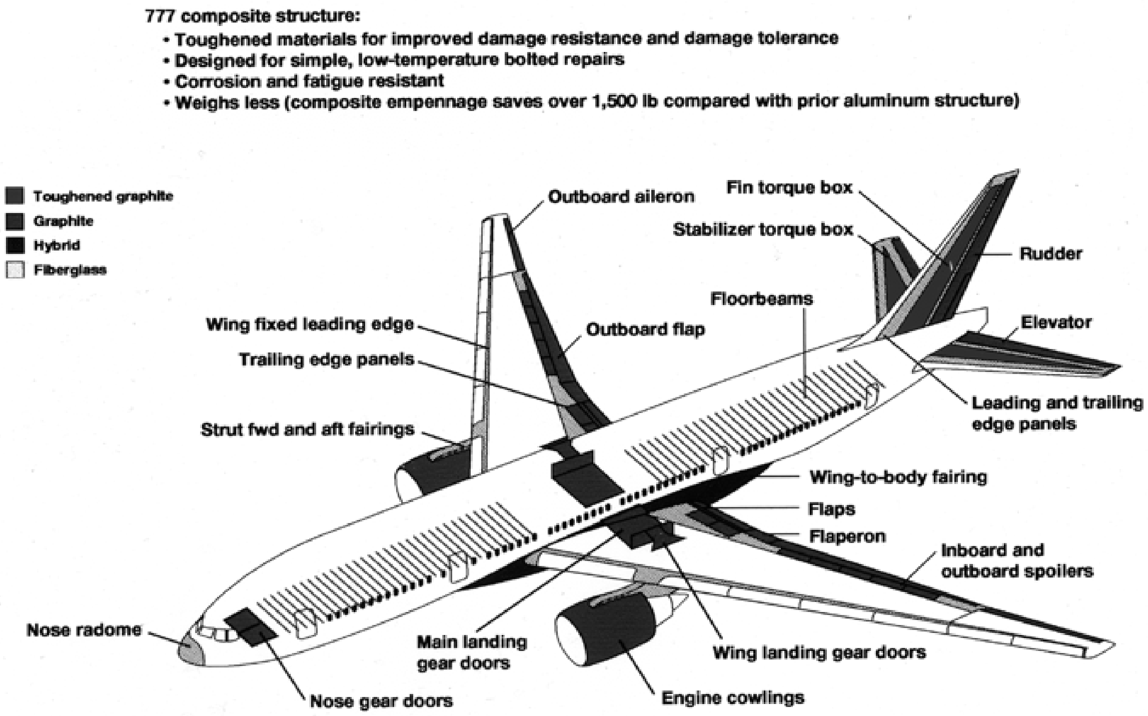


Figure 2. Applications in Commercial Transport Aircraft



777 composite structure:
- Toughened materials for improved damage resistance and damage tolerance
- Designed for simple, low-temperature bolted repairs
- Corrosion and fatigue resistant
- Weighs less (composite empennage saves over 1,500 lb compared with prior aluminum structure)

Figure 3. Structural Composites on the B-777

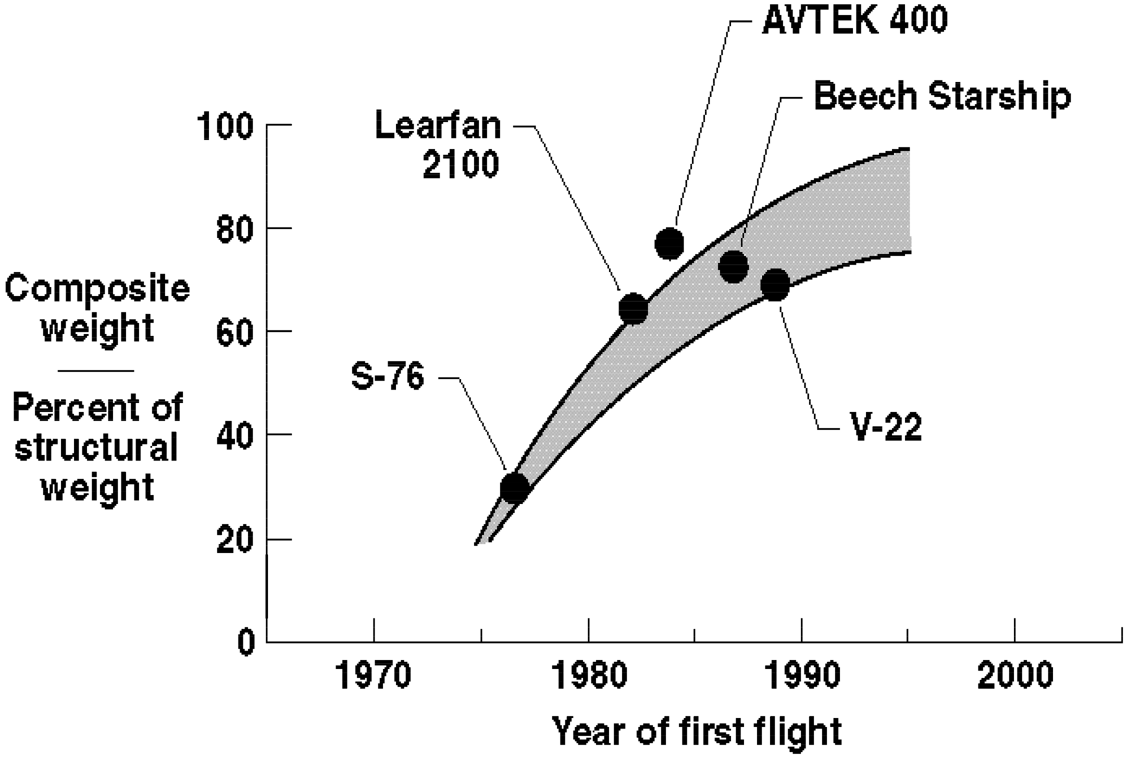


Figure 4. Applications in Rotorcraft and General Aviation

Figure 5. Applications of Composites on the V-22

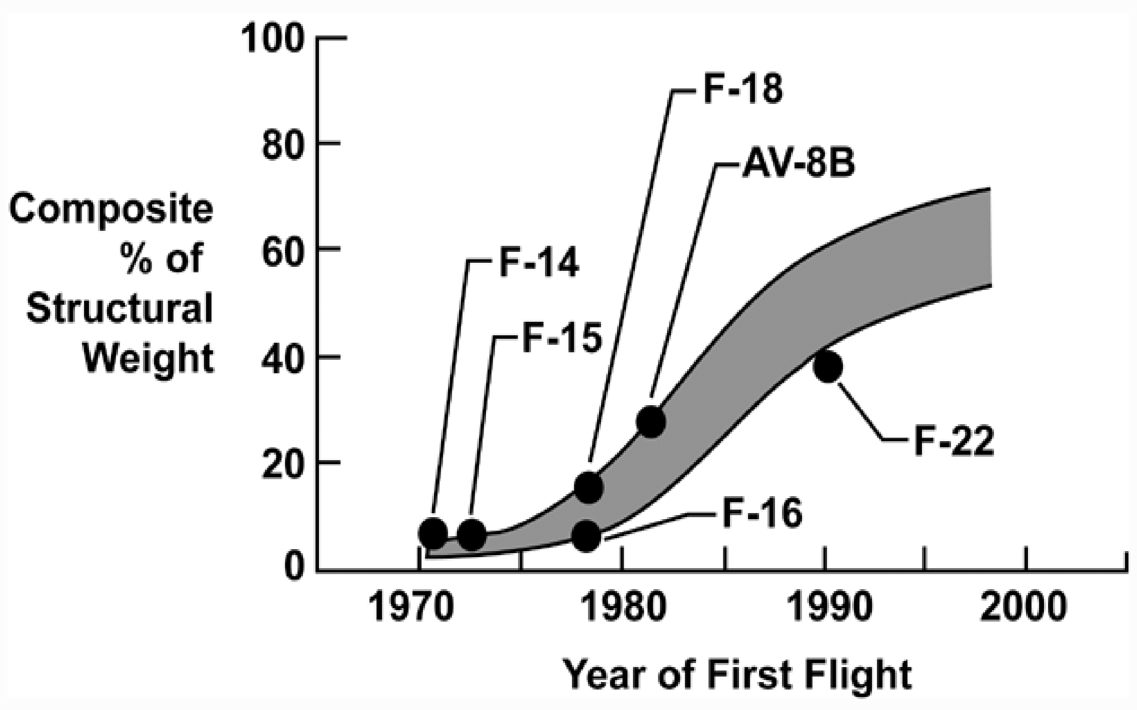


Figure 6. Applications in Military Fighter Aircraft

Figure 7. Lockheed Martin F-22 Raptor

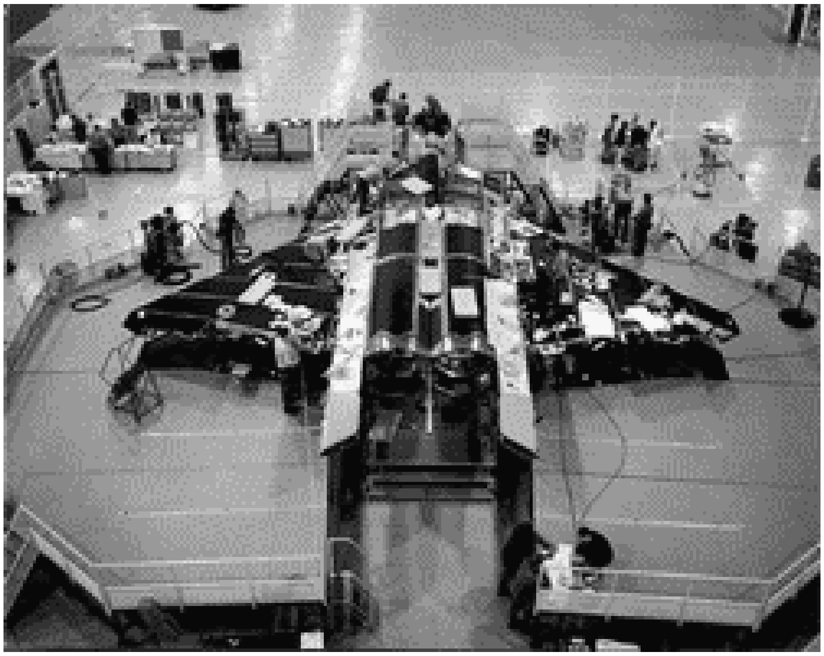


Figure 8. Assembly of F-22 Composite Wings

Figure 9. B-2 Primary Structure Is Almost All Composites

Figure 10. C-17 Horizontal Tail Redesigned using Composites