7. Costs and Aircraft Applications of Thermoplastic Composites

7.1 Costs of Thermoplastic Composites

As is the case with thermoset composites, thermoplastic composites are used in specialty, low volume applications, hence prices are high and will stay high as long as the commercial sales volume remains low. However, the majority of the high performance thermoplastic materials discussed in this report are more expensive than their thermoset counterparts, whether in the form of a neat resin, a prepreg tape or in a commingled woven fabric. Avimid K, Avimid N, Eymyd U-25, Eymyd U-35, Larc-TPI, Cypac X-7005 polyimide prepregs as well as PBI prepregs are amongst the most expensive, at least twice as expensive and in some cases 3 to 4 times more expensive than thermoset prepregs. There are however some prepregs such as reinforced PEEK, PES and PPS for which prices are comparable to some second-generation thermoset composites such as IM6/5245C (US $90-120/lb for a quantity of about 100 lb).

Fortunately, the higher cost for the raw material can be offset by lower processing costs [221]. Thermoplastic composites have indeed the potential for low processing costs. In general, they are more suitable for automated production than thermosets because most of them require only the application of heat and pressure to fabricate laminates and to form parts. No chemical reaction is required, hence no long and elaborate curing cycles are involved. They can be processed with short cycle times. Because they require high temperature and pressure, it is more appropriate to produce them in high volume. Automated processes such as tape laying, filament winding and pultrusion are the most cost effective processing methods for thermoset composites [1] and they are also the key to the cost effectiveness of using thermoplastic composites [221]. Competition from thermoset composites and metal is important and to really pierce the market, innovative cost-effective manufacturing processes for thermoplastic composites have to be developed in spite of their good properties.

Chang and Lees [2] estimated the relative cost of processes to fabricate thermoplastic and thermoset composites. Table 35 contains the relative cost of prepregging which they estimated for thermoset and thermoplastic tows. The cost of prepregging thermoplastic tow is without any doubt higher than for thermoset. Amongst the techniques to combine fibres and thermoplastic matrices, solvent and melt impregnation have the lowest potential cost and powder impregnation and commingling the highest.

Table 36, taken also from Reference 2, compares the cost of part fabrication using filament winding of tows preimpregnated by each of the four prepregging methods already mentioned above. While the cost of thermoplastic prepreg is between 1.8 and 3 times higher than that of thermoset prepreg, it is offset by lower production costs. The final thermoplastic

TABLE 35. Relative Cost of Prepregging for Thermoset versus Thermoplastic Tows [2]

Process	Resin Cost	Throughput Rates	Prepreg Invest.	Added Cost
Thermoset tow	X	X	X	X
Thermoplastic tow				
ex powder	1.5X	0.5X	2X	2.5X
ex commingling	2.5X	4X	1.5X	3X
ex melt	X	0.5X	2.5X	2X
ex solvent	X	X	2.0X	1.8X

TABLE 36. Effect on Downstream Cost for Filament Winding [2]

Process	Prepreg Cost	Part Production	Part Cost
Thermoset tow	X	X	X
Thermoplastic tow			
ex powder	2.5X	0.5X	0.8X
ex commingling	3X	0.5X	X
ex melt	2X	X	0.6X
ex solvent	1.8X	X	0.6X

TABLE 37. Relative Forming Cost of Parts via Continuous Filament Tape/Tow and Discontinuous Drawable Sheet-Thermoset (TS) versus Thermoplastic (TP) [2]

	Continuous Filament Tape/Tow		Discontinuous Drawable Sheet
Type of Part	TS	TP	TP
Single curvature skin	X	1.1X	0.8X
Shaped skin	X	X	0.5X
Hat section	X	0.9X	0.6X
Closed sphere	X	0.6X	N/A
Box beam	X	0.5X	N/A
Complex shape	X	0.8X	N/A

part costs are typically 40% lower than thermoset parts for the melt and solvent processes, and either 20% lower or equal to the thermoset part cost, for the powder and commingled process, respectively.

Chang and Lees also compared the relative forming costs of continuous filament tape/tow for both thermoplastic and thermoset material for various parts. They are shown in Table 37 where relative costs for discontinuous drawable sheet are also included. In general, forming parts with continuous filament reinforced thermoplastic resulted in lower prices than for thermosets. The unique reprocessability feature of thermoplastic composites, that makes them reprocessable and reusable, renders them more attractive from an economic point of view. Parts with defects can be reprocessed and scrap from the fabrication of trimmed parts can be reused.

7.2 Examples of Use of Thermoplastic Composites in Aircraft Applications

Even though the questions of processing techniques, tooling, joining and repairing have not been fully addressed by researchers and designers, applications of thermoplastic composites in aircraft structures are becoming increasingly common. Aircraft thermoplastic composite components have to be designed to the same static and dynamic loading conditions and fail-safe requirements as conventional thermoset composites [1]. As suggested by the National Advisory Board of U.S. National Research Council [1], "the application of thermoplastic composite materials as aircraft structural materials can be expected to build on the data base established for thermosetting composites. Modifications to the evaluation criteria can be expected as experience develops with this family of materials." Selected applications demonstrating the feasibility of using high performance thermoplastic composites in primary and secondary aircraft structures are presented in the following paragraphs.

7.2.1 Westland 30-300 Thermoplastic Tailplane [248, 249, 250]

Westland Helicopters is currently engaged in a project to develop and build a thermoplastic composite tailplane for the Westland 30-300 helicopter. This primary structural component was selected to evaluate and demonstrate thermoplastic composite manufacturing technology as many elements incorporated in the assembly are directly applicable to other aircraft primary structures. The tailplane also gave the opportunity to compare three technologies since it was first made of metal and then changed to epoxy composite.

The materials chosen for the project were carbon reinforced PEEK and woven carbon reinforced PEI. Initially, only carbon/PEEK was selected but since it had not reached commercial maturity during the first phase of the project, being only available in development quantities, a change in material was required. Carbon/Ultem PEI was chosen as a replacement material. Characterization of APC-2 and carbon/PEI, and investigation of the strength of bonded and mechanically fastened joints with these materials has been undertaken. Even though the environmental tolerance of carbon/PEI has been found to lie between epoxy composite and APC-2, results indicated that carbon/PEI and APC-2 materials are suitable for primary airframe structures. They exhibited acceptable properties for structural applications and improved environmental resistance compared to carbon/epoxy composites. Damage tolerance was found to be superior to epoxy based composites. Damage was also more easily detectable.

Figure 60 shows the construction details of the composite tailplane. The construction of the horizontal component of the tailplane was 4 ply (0°/90°/90°/0°) APC-2 skins, with Nomex honeycomb sandwich panels bonded to a spar and rib sub-assembly. The sub-assembly consisted ot two press formed ±45° APC-2 spars, two ±45° APC-2 press formed ribs and two carbon fibre reinforced PEEK injection molded attachment brackets. Leading and trailing edge reinforcements were also press formed from APC-2. The components were assembled using a combination of mechanical fasteners, welding and adhesive bonding to demonstrate a range of joining techniques.

The fins were sandwich panels manufactured from woven carbon/PEI skins bonded to Nomex honeycomb. The edges were closed with vacuum formed polycarbonate capping strips and a woven aramid/PEI frangible cap cold bonded to the lower edge.

The fins were bonded to the tailplane using a mortice and tenon joint. Titanium pins that passed through the injection molded brackets and sandwich panels attached the tailplane to the helicopter. Reinforcing patches were bonded to the upper and lower surfaces at the attachment points.

The different processing methods used included consolidation of flat laminates by compression molding, press forming of the pre-consolidated laminates using matched metal and rubber tooling, press-clave consolidation of prepreg material and contouring of woven fabric components. These were discussed by Griffiths et al. [248]. The equipment needed, the problems encountered and the techniques used to alleviate them were presented. In addition, several types of joining techniques including mechanical fastening, adhesive bonding and welding that have been used in the manufacture of the tailplane were described. Regarding adhesive bonding, the best results were obtained when the surface was pre-treated by corona discharge while the best results for welding were achieved with ultrasonic techniques. In general, the non-destructive techniques for evaluating the quality of epoxy composites, such as X-ray analysis, ultrasonics, thermography, Fokker bond testing and visual inspection were found suitable for thermoplastic composites.

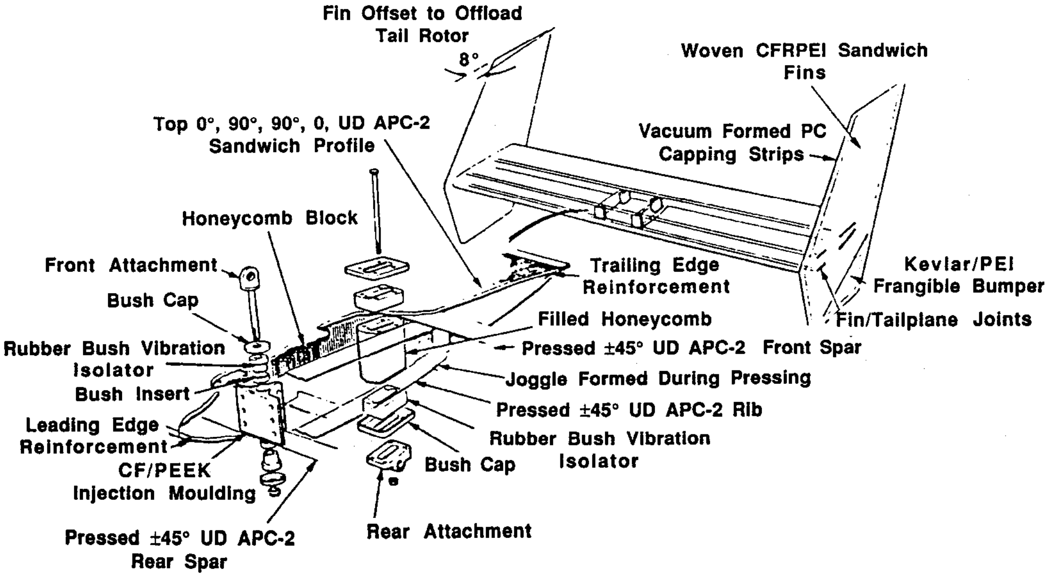


FIGURE 60. Westland 30-300 Thermoplastic Tailplane [249]

TABLE 38. Estimation of the Tailplane Costs Assuming that the Material and Components are being Produced in Volume Quantity [250]

W30 tailplane costs and weights

	Metallic Al-alloy	*Thermoset CFR epoxy*	*Thermoplastic APC and CFRPEI*	*Optimized plastic APC and CFRPEI*
Weight	100%	70%	71%	68%
Manufacturing cost	100%	76%	52%	44%

The estimation of the tailplane costs assuming that the material and components are being produced in volume quantity is shown in Table 38. The cost of the optimized tailplane, which uses injection molded brackets adjacent to the rear spar in place of the filled honeycomb block, is based on the assumption that laminates are tape laid prior to forming. Westland believes that the cost effectiveness of using these materials lies in automation of the processes involved. The major disadvantage in current thermoplastic manufacturing is the two stage process of producing consolidated preform sheets followed by a forming operation, hence an automated process that leads to a net shape component would be much preferable.

7.2.2 Advanced Tactical Fighter (ATF) and B2 Stealth Bomber [158, 251 - 253]

Advanced thermoplastic composites are widely used in developmental military aircraft such as Lockheed's and Northrop's versions of the Advanced Tactical Fighter (ATF), and Northrop's B2 Stealth Bomber[251 - 253]. The all composite B2 bomber measuring about 5.2 m high by 21 m long with a wing span of 52.4 m consists largely of carbon/polyimide and other advanced plastic composite structure that make it virtually undetectable by radar [251]. The ribs for a wing section on the B-1B bomber as well as the ribs, stiffeners, skin and leading edge on the inboard flap of the Fairchild A-10 have been made of APC-2 by the film-stacking method [252, 253]. Film-stacking fabrication was jointly developed under the U.S. Air Force Thermoplastic Composite Development Program.

Materials for the proposed USAF ATF must retain structural performance at temperature up to 176° C [74]. In order to meet the service criteria defined for the aircraft, a material with a Tg of at least 200° C is required [74]. Boeing Military Airplane Company has prototyped an ATF wing with 60% Amoco's Torlon polyamideimide reinforced with carbon fibres. The carbon/PAI prepreg is produced by Fiberite/ICI [253]. Avimid K is being considered for the thick section, large area ATF prototype wing skins by the Lockheed/Boeing/General Dynamics team [158].

7.2.3 Wing of the U.S. Navy/McDonnell F/A-18 Fighter Aircraft [188]

McDonnell Aircraft Co. is conducting research and development work on thermosets, thermoplastics, titanium and aluminum-lithium manufacturing technologies with direct application to future military and commercial aircraft. Presently more effort is devoted to the development of advanced thermoplastic composites than thermoset composites.

To demonstrate the evolving thermoplastic composites technology and to gain manufacturing experience with these materials, an upper and lower outer wing skin for both wings of a U.S. Navy/McDonnell F/A-18 fighter aircraft have been manufactured and will be installed and service tested. The left wing panels are composed of thermoplastic composite AS4/PEEK while the right wing panels are made of epoxy composite IM-7/8551-7E. This thermoset using a bismaleimide resin exhibits improved high temperature performance and improved toughness and resistance to delamination. Although F/A-18s will continue to be produced with carbon/epoxy outer wing panels, these experimental panels will permit comparison between thermoplastic and thermoset composites behavior under flight conditions. The reprocessability feature of thermoplastic composites has been demonstrated in this project. In the first part that was made, a disbond was present because of inadequate pressure. The part was put back into the heated press and reprocessed with correct pressure which fused the disbonded area.

Development is focused at the design and construction of fully automatic manufacturing equipment capable of producing thermoplastic composite structures and will include an on-line non-destructive inspection capability.

7.2.4 Landing Gear Strut Door and Access Panel [254]

The Northrop Corporation initiated and completed a project to design, fabricate and test two carbon/PEEK landing gear strut doors and access panels for the F-5F aircraft [254]. These two non-primary structures were selected because of the complexity of the design for the strut door and to acquire durability data for the access panel. This latter component is a damage prone part since it is often removed during aircraft servicing.

The inner and outer skins of the landing gear door were fabricated with the thermoplastic composite material IM6/PEEK. Sixteen and forty-nine ply lay-ups were required for the inner skin and outer skin, respectively. The inner skin was molded using a pressure forming diaphragm process and the outer skin was formed with a vacuum bag autoclave process. The weight savings for the thermoplastic inner and outer skins compared to aluminum skins were 31% and 33% respectively. Assembly was accomplished with skin-to-skin adhesive bonding. The thermoplastic door assembly has carried the proof-test loads.

The original access panel made from magnesium alloy has been fabricated with a 10 ply AS4/PEEK laminate formed in a hot platen press. Both the landing gear door and access panel have been demonstrated as flight worthy by Northrop Corporation and will be flight tested.

Components for a developmental access door made of woven carbon fabric/ PPS laminate sheets have been thermoformed in one-step for Boeing. Seven thermoplastic composite components were ultrasonically welded to assemble the 55.9 cm hollow access door. The thermoplastic composite door exhibited ten times the fracture toughness of carbon/epoxy [252].

7.2.5 Strut Fairings on the Boeing 757-200's Jet Engines [255]

The four fairings used on the struts of the Boeing 757-200's jet engines (two per engine) are produced from injection-molded glass-filled PEEK. These parts approximately measure 51 cm by 30 cm in size and weigh 2.2 kg. They have to resist to hostile conditions including high levels of moisture, sonic vibrations and high air speeds. Despite daily exposure to these conditions, they must provide efficient performance, give long-term durability and maintain an attractive appearance. PEEK resin was selected after evaluation of a variety of other thermoplastic materials including nylon 6/12, polyetherimide and polycarbonate. The PEEK fairings are about 30% lighter than fairings of conventional aluminum construction and they are 90% less expensive.

7.2.6 Aerosurface Components on Subsonic Missiles [256]

McDonnell Douglas Astronautics Company is investigating the replacement of metallic and thermoset composite structures on subsonic missiles with thermoplastic composites. The components include metal fins and wings for the Harpoon and Tomahawk low speed missiles and the Tomahawk glass/epoxy air inlet duct and radome.

Harpoon Missile

Figure 61 shows the Harpoon control fin design concept. The skins are made with either continuous unidirectional tape or thermoplastic resin reinforced with woven cloth. The cloth or tape prepreg is laid-up and thermoformed. The laminate skins are placed in the mold, and the core material consisting of the same thermoplastic resin as the skin but reinforced with 30% chopped carbon fibre is injection molded forming the core.

Both PPS and PEEK thermoplastic resins have been investigated for this application. Tests conducted on these materials have shown that PEEK is superior, but further cost analysis has to be performed before choosing the final material.

Tomahawk Missile

Figure 62a shows that the Tomahawk fin uses the same design concept as the Harpoon fin. The wings and fins, the air inlet duct, and the radome have all been redesigned with thermoplastics. The proposed wing redesign for optimum strength and stiffness is shown in Figure 62b. The two thermoformed laminate skins will be thermally welded to the core.

The choice of the material to replace the hand lay-up glass/epoxy air inlet duct has not been made yet. PPS, PEEK and polycarbonate with various reinforcement combinations are candidate materials. The proposed molding process is complicated since it includes multi-shot

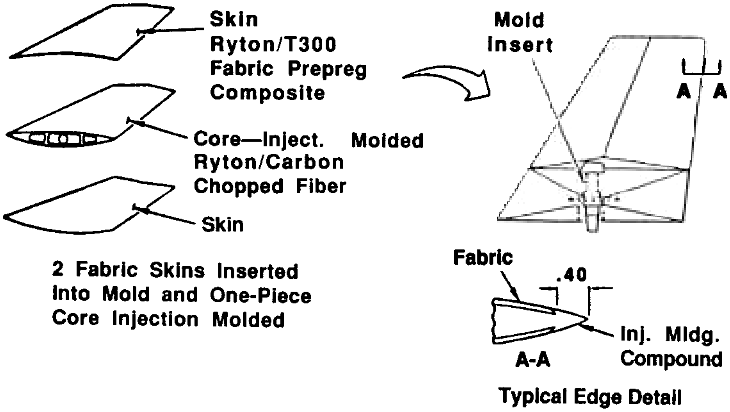


FIGURE 61. Control Fin Design Concept for Harpoon Subsonic Missile [256]

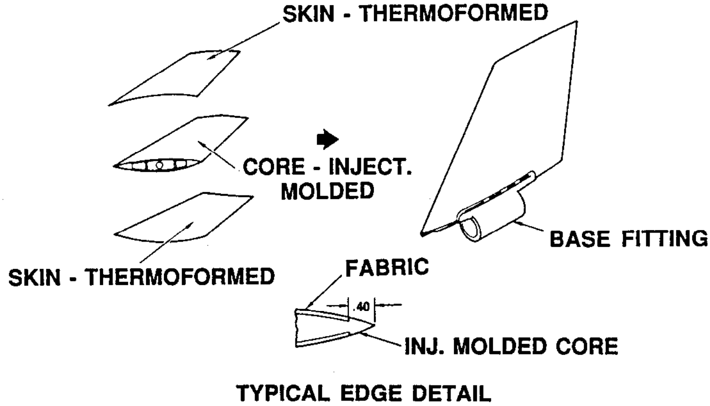


FIGURE 62a. Fin Design Concept for Tomahawk Subsonic Missile [256]

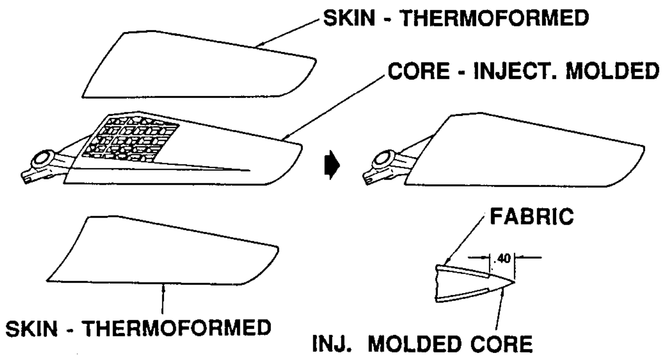


FIGURE 62b. Proposed Wing Redesign for the Tomahawk Subsonic Missile [256]

injection molding and composite material layering. The Tomahawk missile radome is made by injection molding 40% glass filled polycarbonate.

The replacement of these metallic or thermoset composite parts with thermoplastic composites has led to strengths and stiffnesses equal to those of the original designs and with comparable or lighter weight, better solvent resistance and damage tolerance, improved repairability and significant cost reduction. Table 39 presents the relative cost savings for the thermoplastic replacement parts over the metal Harpoon and Tomahawk wings and fins and for the replacement of the present glass/epoxy hand lay-up air inlet duct and radome design.

7.2.7 Glass/PES Hercules Radome [257, 258]

The radome structure for the C-130 Hercules is probably one of the largest continuous fibre reinforced advanced thermoplastic moldings that has been produced. The radome itself is nearly 1 m in diameter and weighs almost 10 kg. The materials used are Grade 600P Victrex PES (in film form) and T2/22 woven glass cloth.

The radome is mounted under the belly of the aircraft. A structure in this location has to be particularly resistant to impact damage. Debris is thrown up from the wheels when operating on unpaved airstrips. The specification states that it has to resist the impact of 25.4 mm diameter stones at a velocity of 100 knots. Results of instrumented impact tests on various thicknesses of PES/glass laminates have shown satisfactory performance while a conventional glass/epoxy was not able to provide the required impact resistance. Increasing thickness in this latter case is not an acceptable solution since it would lead to a weight increase and unacceptable electrical characteristics.

The radome has been fabricated with a film stacking process using matched metal molds with very high pressures in the order of 6.9 to 14.7 MPa and temperatures between 300 and 400° C. The high quality molding required for consistency of electrical performance between components combined with severe processing conditions have led to relatively high tooling costs. "Full electrical and flight testing has confirmed the soundness of the design and construction of this component- specifications being met or surpassed in every respect". A substantial quantity of panels has now been supplied for use on R.A.F. aircraft.

7.2.8 Boeing's YC-14 Carbon/Polysulfone Elevator [1, 259]

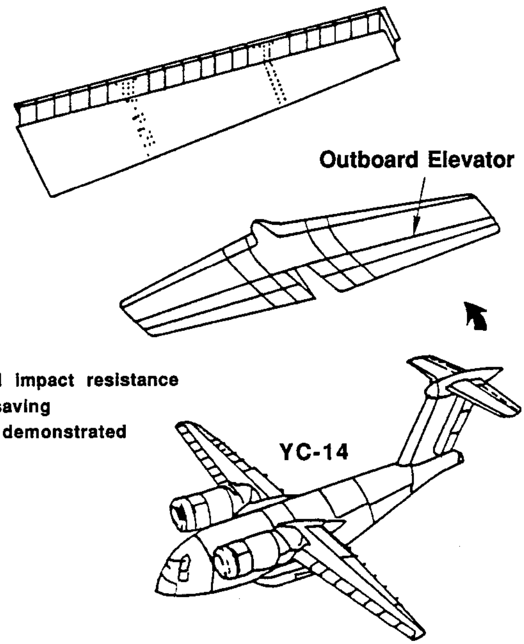
In order to demonstrate the advantages and manufacturing capabilities of thermoplastic composites, Boeing Aerospace Company has fabricated full size elevator boxes for the YC-14 aircraft to replace the existing aluminum elevator. Figure 63 shows the YC-14 outboard elevator. The box has a span of 5.8 m with a maximum chord and front beam depth of 45.7 cm and 33 cm respectively.

TABLE 39. Relative Costs of Aluminum Components and Thermoplastic Composite Replacements [256]

	COST SAVINGS RELATIVE TO FIXED AL CONTROL FINS	
	PRESENT DESIGN COST	COMPOSITE REPLACEMENT
HARPOON MISSILE		
CONTROL FIN – FIXED	1.0	0.1
– FOLDED	0.9	0.1
BOOSTER FIN – FIXED	4.8	0.3
– FOLDED	2.4	0.7
WING – FIXED	2.9	0.1
– FOLDED	1.6	0.2
TOMAHAWK MISSILE		
CONTROL FIN – FIXED (1)	1.0	0.2
– PIVOT (3)	3.0	0.7
WING (LH & RH)	2.1	0.3
AIR INLET DUCT	1.6	0.3
RADOME	1.0	0.1*

ASSUMPTIONS:
1) MATERIAL COSTS INCLUDED
2) LABOR/MACHINING COSTS INCLUDED
3) FITTINGS, HINGES, ETC. NOT INCLUDED
4) THERMOPLASTIC AEROSURFACES HAVE FITTINGS BONDED IN INJECTION MOLDING PROCESS
5) BASED ON 1000 MISSILES EACH TYPE OVER 5 YEARS

*SAVINGS RELATIVE TO PRESENT RADOME DESIGN COST



- Improved moisture and impact resistance
- 25% fabrication cost saving
- Production feasibility demonstrated

FIGURE 63. YC-14 Outboard Elevator [1]

The component was designed to the same load conditions and factors and fail-safe requirements as the metal one. The service life goal is 20 years. The material chosen for the component was carbon/polysulfone because it had an established data base and proven processability. Its chemical resistance is poor but it is considered adequate for the fluids encountered by the YC-14 elevator.

Three full size elevator boxes of carbon/polysulfone were fabricated: one for static testing, one for fatigue testing and a third one for installation on an aircraft. Autoclave consolidation and matched die molding were used to mold and form 4 ply fabric at ±45° into different configurations; i.e. front and rear spar stiffeners, top and bottom covers, doublers for the top covers, spar chords and box splice joints. Fusion bonding and adhesive bonding have been used to join components. Cost and weight savings (25% fabrication cost saving) over the existing aluminum elevator were achieved. Thermoplastic composites permitted more versatility and simplicity in certain fabrication/assembly operations. For example, thermoplastic composites do not require a heat treatment after forming like aluminum and fusing thermoplastic composites does not degrade the parent material as often occurs in welded joints in metals.

7.2.9 Nose-Wheel Door for the Fokker-50 Aircraft [260]

In order to demonstrate the molding process for thermoplastic composite parts, a nose-wheel door for the Fokker-50 aircraft was redesigned and fabricated with continuous Kevlar fibre reinforced Ultem polyetherimide. It consisted of a corrugated laminate cohesively joined to the skin laminates (Figure 64a), forming a "multiple cell torsion box". The laminate lay-up is shown in Figure 64b. The corrugations were progressively formed as shown in Figure 65a, by closing and opening the hot press without intermediate cooling. A panel could be manufactured in approximately 15 minutes. The individual prepreg plies constituting the skin laminates were stacked in the mould without preliminary consolidation (Figure 65b) and the entire product was assembled and consolidated. The static strength of the tested door fulfilled the requirements. After the panel was loaded to failure it was replaced in the mould and reconsolidated in a hot press. No visible damage could be detected in the repaired panel and it exhibited a strength retention of 87% when loaded again.

7.2.10 Thermoplastic Composite Fighter Forward Fuselage [261]

A thermoplastic composite fighter forward fuselage has been designed, fabricated and assembled as part of the Lockheed Aeronautical Systems Company independent research and development program on thermoplastic composites. This program was aimed at developing and demonstrating the engineering and manufacturing technology for thermoplastic composite primary fuselage structure.

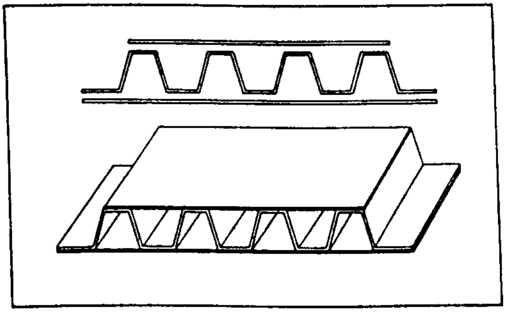


FIGURE 64a. Manufacture of a Cellular Panel [260]

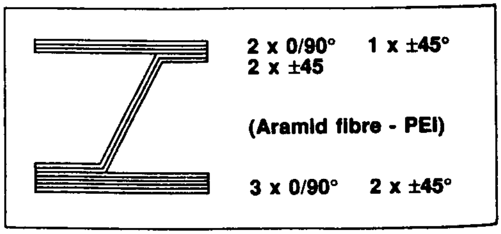


FIGURE 64b. Laminate Lay-Up for the Nose-Wheel Door [260]

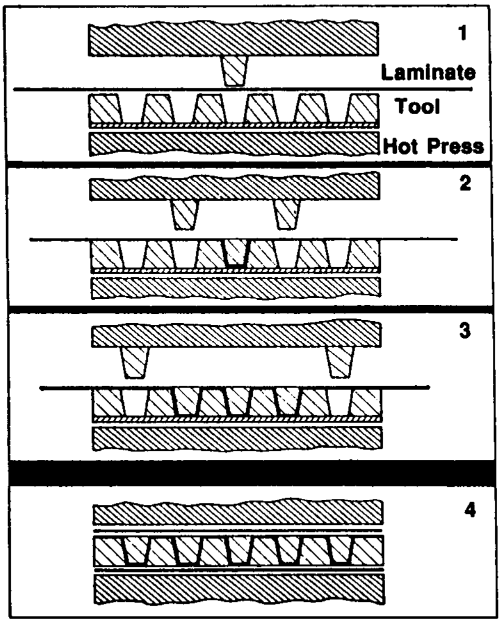


FIGURE 65a. Manufacturing Sequence in a Flat Press, Without Intermediate Cooling [260]

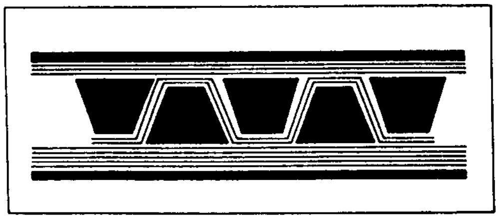


FIGURE 65b. Integrated Manufacturing [260]

The selected fuselage segment is illustrated in Figure 66. It is approximately 122 cm long and 137 cm in diameter, has a complex contour, and is a relatively lightly loaded structure foward of the crew compartment. The fuselage is constituted from ten major assemblies: upper and lower stiffened skins, left and right side panels, forward and aft bulkheads, keelson, intermediate frame and two access doors. Five thermoplastic materials were used: AS4/PEEK unitape, Apollo 43-600/PEI Cypac 7005 unifabric, AS4/PAS-2 unitape, IM8/HTA unitape and T650-42/Radel-C unitape.

A summary of composite materials, tooling materials, forming and consolidation methods, and joining and assembly techniques used in the program is presented in Figure 67. Among the tooling systems used to define the tool surfaces of the individual components, ceramic materials including castable ceramic, castable filled ceramic and integrally heated laminated ceramic were the most promising for high temperature processing of thermoplastic composites.

Several forming and/or consolidation processes were used. Autoclave consolidation was found to be the best method for producing large parts. Rubber press forming was a viable production process having great potential for preforming detail parts that are subsequently consolidated into an assembly. Double diaphragm forming allowed the forming and consolidation of parts in one operation and had the potential to fabricate thermoplastic composite parts cost-effectively.

A variety of joining and assembly methods were demonstrated. Dual polymer bonding (called "thermoplastic amorphous bonding" in this report) and co-consolidation were found to be the most promising for assembly of thermoplastic structural components. Mechanical fasteners as well as adhesive bonding were also used to assemble the components into the forward fuselage assembly. The use of these joining techniques eliminated 73% of the fasteners which would have been required to assemble the part.

7.3 Summary

Thermoplastic composites as raw-materials, in the form of a neat resin, a prepreg tape or a commingled woven fabric, are generally much more expensive than thermoset raw materials. However, the higher cost for the raw material can be offset by lower processing costs. Thermoplastic composites have indeed the potential for low processing costs.

The design, fabrication and assembly of various thermoplastic composite aircraft structures demonstrated by different aircraft companies show that there is major effort and determination to use the new high performance thermoplastic composites and in developing efficient and cost-competitive processing and joining technologies.

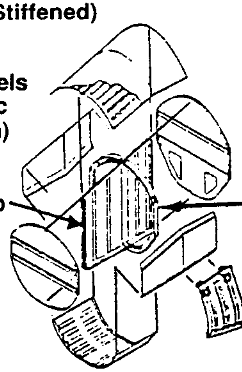


FIGURE 66. Forward Fuselage Demonstration Article [261]

THERMOPLASTIC MATERIALS	FORMING/CONSOLIDATION METHODS
Cypac 7005/Apollo 43-600 Unifabric APC-2/AS4 Unitape APC-HTA/IM8 Unitape Radel-C/T650-42 Unitape PAS-2/AS4 Unitape	Press Forming Single Diaphragm Forming Autoclave Consolidation Double Diaphragm Forming/Consolidation • Superform Process (Alum. Diaphragms) • Diaform Process (Polymeric Diaphragms)
TOOLING	**JOINING & ASSEMBLY**
Steel Aluminum Monolithic Graphite Castable Ceramic Integrally Heated Laminated Ceramic Soluable Mandrels	Mechanical Fasteners Adhesive Bonding Dual Polymer Bonding Co-consolidation

FIGURE 67. Materials and Fabrication Methods [261]