

The Evolution of the Composite Fuselage - A Manufacturing Perspective

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ABSTRACT

A review of critical technologies and manufacturing advances that have enabled the evolution of the composite fuselage is described. The author's perspective on several development, military, and production programs that have influenced and affected the current state of commercial fuselage production is presented. The enabling technologies and current approaches being used for wide body aircraft fuselage fabrication and the potential reasons why are addressed. Some questions about the future of composite fuselage are posed based on the lessons learned from today and yesterday.

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INTRODUCTION

A historical perspective provides an understanding of how the current state-of-practice for composite fuselage manufacturing has evolved. It also provides insight into what the future state of composite fuselage manufacturing might look like. [Figure 1](#) shows a familiar graph that show the increase in composites usage in military and commercial aircraft over time.

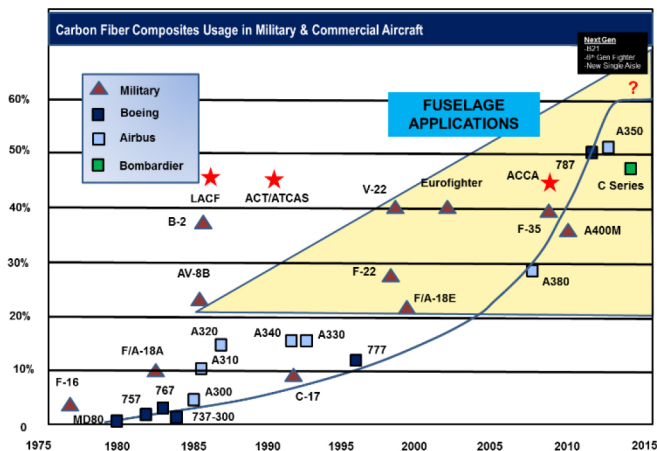


Figure 1. Composites Usage

Initial applications of carbon fiber reinforced composites (CFRP) in both commercial and military aircraft were limited mostly to non-structural applications such as fairings and flight control surfaces. Structural applications for military aircraft began to appear in the 1980's as composite usage grew to more than 20% of the weight of the structure. As the industry continued to mature, material and processes became better understood and cost effectiveness improved to the level that commercial aircraft manufacturers incorporated the technology into the latest generation of wide body and other new aircraft.

EARLY RESEARCH AND DEVELOPMENT

Research and development of high performance composite materials and processes for aerospace applications in the United States was first conducted in the 1940's at Wright-Patterson Air Force Base in Dayton, Ohio [1]. The focus of this early research was primarily for military applications. This research has continued since that time and today, the Air Force Research Laboratory (AFRL), with support from industry, universities and other government agencies such as the Department of Advanced Research Projects Agency (DARPA) and the Department of Energy (DOE), continues to play a leading role in developing advanced materials for military applications. NASA initiated research devoted to the development of high performance composites for commercial aircraft and space vehicles in the late 1960's. Over the years, NASA has worked collectively with industry and academia to develop affordable technologies to improve safety and performance of aircraft and launch vehicles. The paper *NASA Composite Materials Development: Lessons Learned and Future Challenges* provides an excellent historical review of NASA's role in the development of composite materials and processes [2].

A common characteristic shared between AFRL and NASA sponsored programs was the "building-block" approach for research and development programs that progressed through a series of steps, each one having an increase in complexity and cost that built upon the previous step. In general, programs started at a coupon level and looked at a wide range of samples to downselect design approaches, materials of construction, tooling and manufacturing processes to build and test coupons, subcomponents and ultimately full scale components. Not unlike the Technology Readiness Levels applied to describe new technologies today, this approach was used successfully in programs such as the Air Force's Large Aircraft Composite Fuselage Program (LACF) in the late 80's and NASA's Advanced Composites Technology Program (ACT) in the mid 90's.

The B-2 Stealth Bomber program was also taking place during the 1980's and provided many lessons learned related to the manufacture of large composite primary structure. For the B-2, survivability performance was one of the primary reason for the extensive use of carbon fiber composites - cost and producibility were not the most critical factors. Boeing was a prime subcontractor on the program and built the wing skins using Automated Tape Laying (ATL). This program presented the opportunity to demonstrate the productivity that was possible using automated lamination processes such as ATL and AFP.

Another program which derived direct benefit from the ACT program is the V-22. Composites have been used extensively and aggressively in helicopters more than any other type of aircraft because weight is such a critical factor. The V-22 uses composites for the wings, fuselage skins, empennage, side body fairings, doors, and nacelles. AFP technology is used to fabricate the aft fuselage skin in one piece. Both Bell and Boeing also incorporate cocured, hat stiffened fuselage structures, using solid silicone mandrels, on their portions of the program.

Large Aircraft Composite Fuselage (LACF) Program

The LACF program was conducted in part by Northrop and was sponsored by the Air Force Wright Aeronautical Laboratory (AFWAL) during the 1980's. The program was part of an effort focused on manufacturing technology for the Linear Manufacturing of Large Aircraft Composite Primary Structure Fuselage. The multi-phase program was directed toward the definition and demonstration of manufacturing methods for cocuring stringer stiffened fuselage panels using 1. existing, qualified material systems; 2. automated skin fabrication; 3. inner mold line (IML) controlled tooling; 4. non-autoclave curing technology. Like many similar terms, in the 80's "linear" manufacturing was a code word for "lean" and non-autoclave is referred to today as out-of-autoclave or OOA processes.

The program followed a building-block approach through four phases (Fig. 2):

- Phase I - Methods Definition
- Phase II - Manufacturing Methods Establishment
- Phase III - Manufacturing Verification
- Phase IV - Production Demonstration

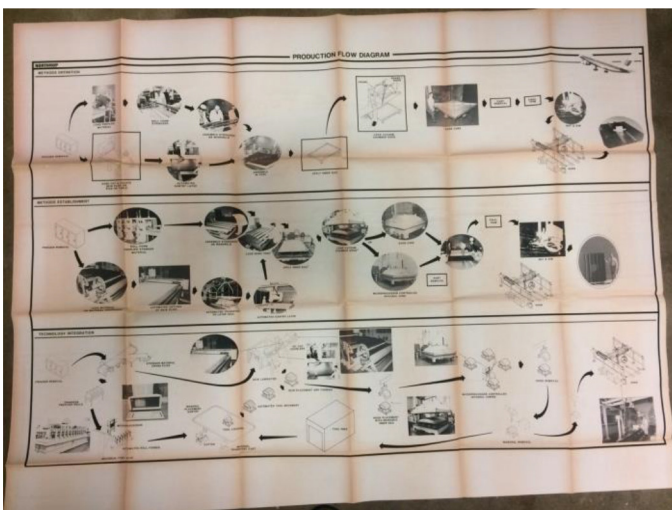


Figure 2. LACF Program

As the program moved through various phases, lessons learned where documented and applied to the next phase. Phase I lessons learned included:

1. raw material required (tow bad, tape good) changes to improve panel quality using automated lamination equipment
2. non-autoclave cured panel mechanical properties were equivalent to autoclave cured panels
3. IML tooling is very good at controlling stringer location and dimensions
4. IML provides very easy tool loading and bagging
5. Continuous roll forming can be used to preform preplied material into "C" channels ready for tool loading (Fig. 3).

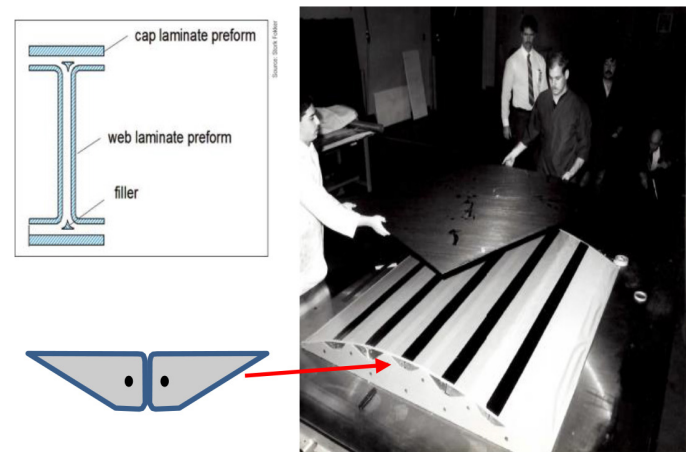


Figure 3. "I" Beam Formed From "C" Channels

Phase II Lessons Learned included:

1. Non-autoclave cure has risks associated with consumable bagging materials
2. Integrally heated tooling strongly supports linear manufacturing
3. Confirmed IML tooling is excellent for controlling stringer/skin dimensions and location
4. Confirmed IML tooling and "I" beam stringer for part and tool removal
5. Flat preplied laminates can be drape formed on gentle contours using IML cure tools
6. Automation can be applied but presents reliability risks and potential equipment downtime
7. Automation can produce a laminate that does not require additional debulking
8. Roll forming of stringer "C" channels is important for linear manufacturing (Fig. 4).

Among the lessons learned as a result of Phase III and IV were the economics related to process scale up for both size and rate. This included ply cutting and kitting time for panel fabrication and backing paper removal and management issues affecting tow placement and stringer laminate preplying (Fig. 5). Another lesson included gaining a better understanding of cocuring longitudinal "I" beams to the skin of a large fuselage panel. One nice feature of the "I" beam construction is that the tooling is not dependent on the

the channel details that form the “C” of the “I” beam can be removed over any length. Disadvantages were also apparent including the number of laminate preform and tooling details needed to construct an “I” beam vs. the simplicity of the hat stiffener (Fig. 6).

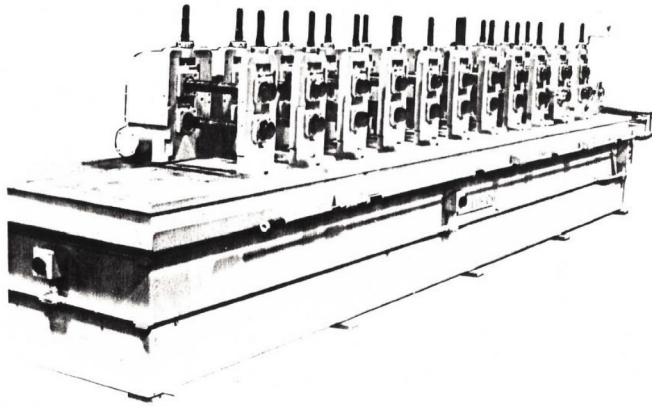


Figure 4. “C” Channel Roll Forming Machine

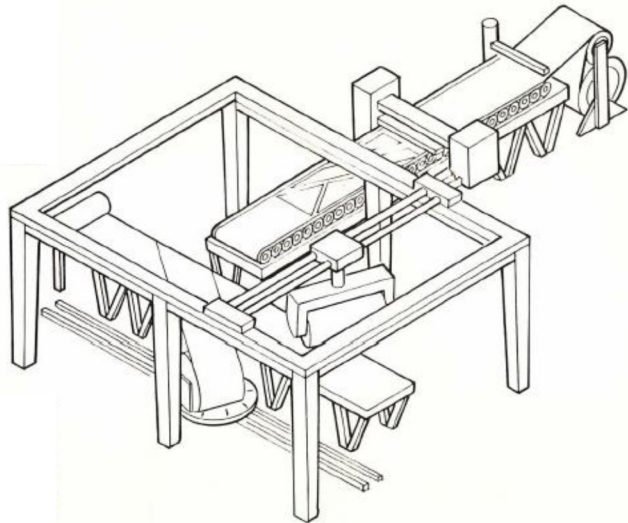


Figure 5. Laminate Cross Ply Equipment

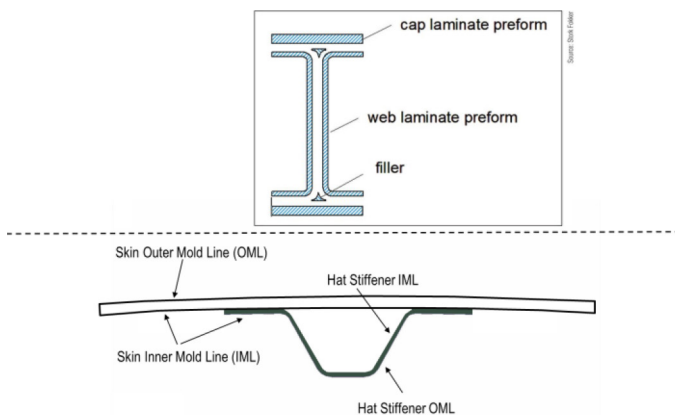


Figure 6. “I” Beam vs. Hat Stiffener

Northrop developed hat stiffened fuselage skin manufacturing technology in support of the YF-23 (Fig. 7). One critical problem to solve was the removal of hat stiffener mandrel tooling from the cured

part. The fuselage tooling was OML controlled and constructed from CRFP prepreg to match the coefficient of thermal expansion (CTE) of the parts. The resin system used for the tooling was bismaleimide (BMI) and the tools were autoclave cured on male, machined monolithic graphite source tools. The hat stiffeners that run longitudinally along the skin were cocured using a silicone mandrel system developed by Northrop using Rubbercraft as a supplier.

The silicone based solid mandrel system included a solid rubber mandrel, a butterfly caul and a resin end dam. The silicone mandrel was designed to be removed from the cured part after pulling and elongating the mandrel to reduce the cross section enough to release from the part. The butterfly caul was designed to help consistently control the OML of the hat stiffener. It also helped to greatly simplify the bagging process which allows for the use of a broader range of operators instead of relying solely on a highly skilled mechanic. The end dam was designed to be cheap and disposable and replace much of the inner bagging process complexity of sealing off the hat stiffener to prevent resin bleed during the cure cycle (Fig. 9). This is not a hard process, but is critical and tedious.

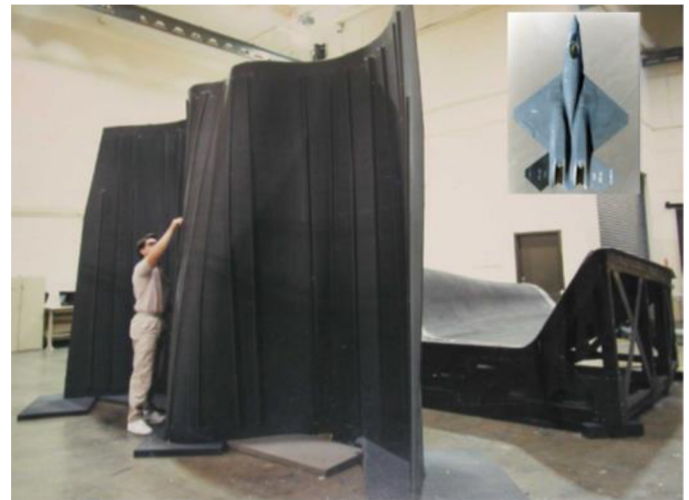


Figure 7. YF-23 Fuselage Structure

Northrop subsequently applied this hat stiffener fabrication process technology to the fuselage of the F/A-18E/F as a prime subcontractor to Boeing on the program (Fig. 8).

During this time period, it was recognized by many of the R&D programs that liquid molding processes presented the opportunity to use resins and fibers in their lowest-cost state by eliminating prepreg from the fabrication process. Other advantages included minimizing material scrap, simplifying raw material storage, and supporting non-autoclave fabrication processes. The development of net shape damage-tolerant textile preforms and the development of innovative liquid molding tooling concepts supported this opportunity. The Advanced Composites Technology (ACT) program included processes such as resin transfer molding (RTM) and pultrusion in the development efforts. The technologies have progressed to state-of-practice processes with both the 787 and the A350 programs using liquid molding and textile preform technology for fabricating fuselage frame elements.

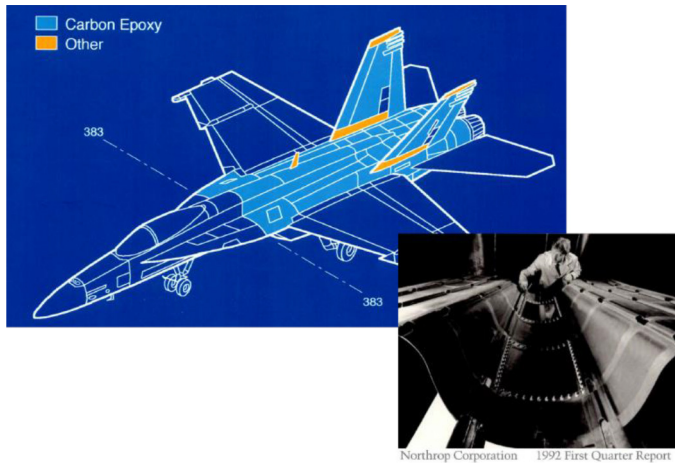


Figure 8. F/A-18E/F Fuselage Structure

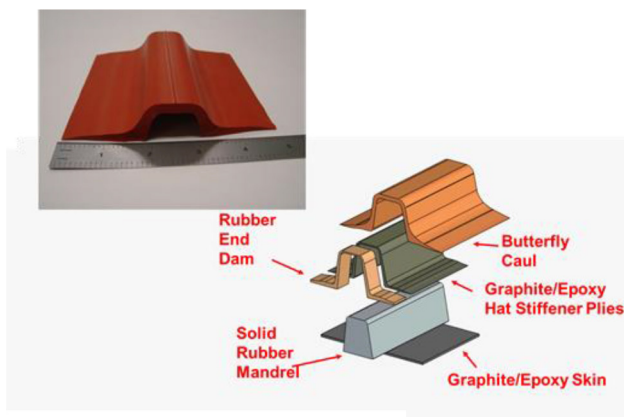


Figure 9. Solid Mandrel System

Advanced Composites Technology (ACT) Program [3]

The objective of the ACT fuselage program was to develop composite primary structure for commercial airplanes with 20-25% less cost and 30-50% less weight than equivalent metallic structure. The Advanced Technology Composite Aircraft Structure (ATCAS) program was performed by Boeing as the prime contractor under the umbrella of NASA's ACT program and focused on fuselage structures. A large team of industry and university partners also supported the program. The primary objective of the ATCAS program was to develop and demonstrate an integrated technology that enables the cost and weight effective use of composite materials in fuselage structures for future aircraft.

The area selected for study was identified as Section 46 on Boeing wide body aircraft (Fig. 10). This section contains many of the structural details and manufacturing challenges found throughout the fuselage. This includes variations in design details to address high loads at the forward end and lower portions of the fuselage. The loads decrease toward the aft end and the upper portion of the fuselage, allowing for transitions in the thickness of the structure that are tailored to match the structural loading.

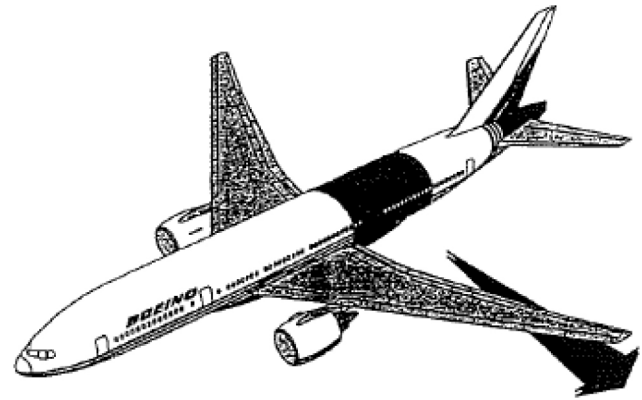


Figure 10. ACT Fuselage Section [3]

A quadrant panel approach was selected for study as shown in Figure 11. The cross section is split into four segments, a crown, keel, and left and right side panels. The circumferential, 4 quadrant panel approach was selected with the idea of reducing assembly costs by reducing the number of longitudinal splices. This built-up assembly approach is baseline to metallic aircraft manufacturing and is similar to the approach Airbus selected for most of the fuselage of the A350.

Manufacturing process development and design trade studies contributed to the development of COSTADE (Cost Optimization Software for Transport Aircraft Design Evaluation) which allowed for defining and evaluating the cost-effectiveness and producibility of various designs. Included in the program were assessments of tooling, materials and process controls needed for future full-barrel fabrication like Boeing selected for the 787.

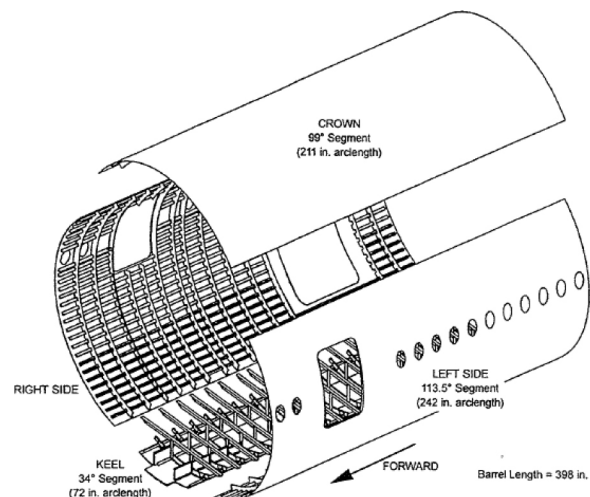


Figure 11. ACT Quadrant Panels [3]

The structural concepts studied included stiffened skin structures achieved by stand alone or combinations of cocuring, cobonding, bonding, and mechanical attachment of stringers and frames to monolithic or sandwich panel skins (Table 1). The crown section study selected fiber placed skins laminated on an IML controlled layup mandrel with the skin subsequently cut into individual panels and transferred to OML cure tools. Hat stiffeners used solid silicone mandrels located longitudinally along the IML of the skin panels for processing.

Table 1. ACT Structural Concepts [3]

DETAILS	PROCESS
Skins	1) AFP (Tow, Hybrid AS4/S2) 2) CTLM (Contoured Tape Lamination Machine, 12" tape)
Frames	1) Braiding / Resin Transfer Molding (Triaxial 2-D braid) 2) Compression molding 3) Stretch Forming (Thermoplastic, discontinuous fibers) 4) Pultrusion / Pull Forming
Stringers	1) Hat – ATLM/Drape forming (Cocured, thickness variation) 2) “J” – Pultrusion
Panel Assembly	1) Cocured/cobonded stringers, cobonded frames 2) Cocured/cobonded stringers, fastened frames 3) Sandwich panels, cobonded frames

The recommended optimized panel design included cobonding of cured frame elements while cocuring the hat stiffeners and the skin. The cured frames were demonstrated using braided textile preforms and resin transfer molding (RTM). One of the main challenges of the crown panel concept was the bond integrity between the precured frame cobonded to a skin panel that is stiffened with cocured hat stringers. Alternative concepts the team considered during the review process included mechanically attached Z-section frames instead of cobonded J's. The mechanically fastened frame approach greatly reduces the complexity of IML tooling needed to cocure the hat stiffeners and cobond the frames. This is especially true at the intersections of the frame and hat. Flexible cauls plates and custom fit reusable bags became part of the tooling system needed to accomplish the fully integrated skin/stringer/frame structure. Producibility issues are complicated by the blind nature of the IML of the skin being completely covered by flexible cauls and the reusable bagging system. The structural arrangement shown in Figure 12 is very similar to the configurations that ended up on both the 787 and A350 programs.

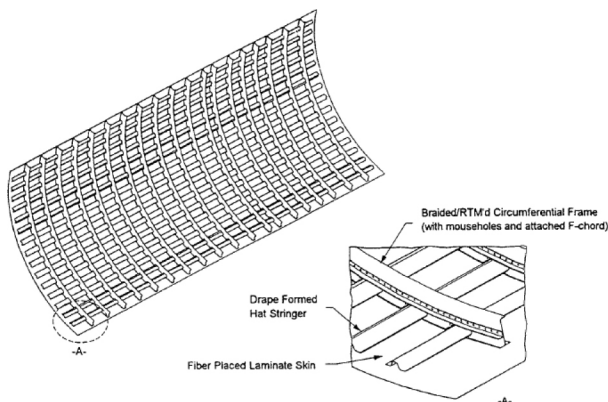


Figure 12. ACT Crown Panel Structural Arrangement [3]

The program studied the pultrusion process for producing skin stringers. Continuous resin transfer molding (CRTM) developed by Ciba Geigy was one of the more promising technologies studied. Improved process control and reduced waste are among the perceived advantages; process maturity, constant cross-section stringers and costs associated with secondary bonding or cobonding are among the disadvantages.

Airbus has studied automating stringer fabrication using both pultrusion and RTM but felt limited by aspects of both processes. As an answer, Airbus developed their version of pultrusion RTM. Figure 13 shows equipment completed in 2011 that is being used to develop and qualify the process [4]. This hybrid fabrication approach allows the use of preform laminates instead of being limited to unidirectional reinforcements like traditional pultrusion and supports continuous production instead of batch processing associated with the traditional RTM. Instead of dipping the preform stack through a resin bath, it is pulled into an RTM tool that is open on both ends. To overcome resin being pushed out at both ends of the open tool, Airbus worked with resin suppliers to develop an epoxy resin with a parabolic temperature/viscosity curve. At 120°C resin viscosity is very low with high flow characteristics, but at both room temperature and at 180°C and higher, it is very viscous. The tool entry is cooled so the resin is too viscous to flow out; the middle is heated to obtain resin flow and cure; more heat is added at the end to increase resin viscosity to make sure it does not flow out and reduce cure pressure.

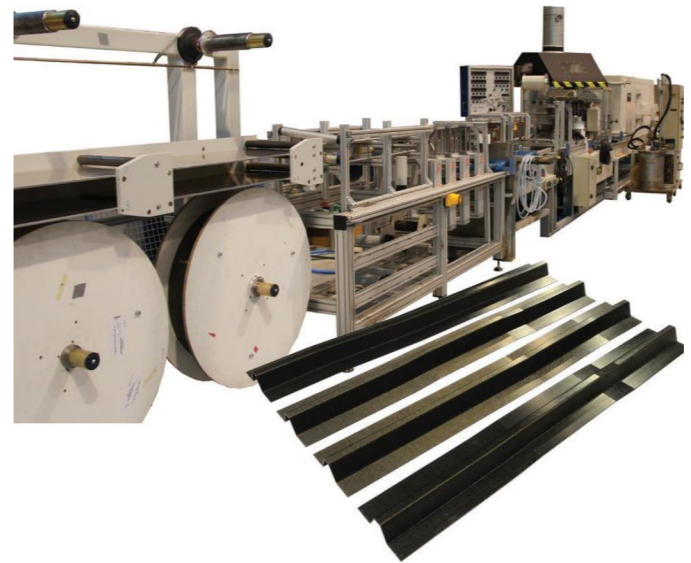


Figure 13. Airbus Continuous Pultrusion Equipment [4]. Source CTC Stade

Follow on efforts to the ACT program that continued to refine composite fuselage construction was the Technology Concept Aircraft Program (TCAP) that focused the development on the High Speed Civil Transport (HSCT) aircraft. Advancements in the current state of technologies were shown to be necessary to meet the manufacturing, maintenance, and operational cost requirement for a HSCT aircraft. In 1994, NASA initiated the High Speed Research (HSR) program to address these challenges. Amongst the goals of the HSR program was to develop the technologies needed to build a commercial transport aircraft capable of flying at Mach 2.4 for 5000 nautical miles at an altitude of 60,000 feet [3].

AUTOMATED FIBER PLACEMENT

Even in the early days of development, industry leaders believed in the possibility of higher layup rates using AFP than was possible with hand layup, but the capabilities and the scale that the industry has