Chapter

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.

Keywords: composites, fuselage, manufacturing, aviation, structures, 787, A350

1. 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 shows the increase in composites usage in military and commercial aircraft over time. Initial applications of carbon fiber

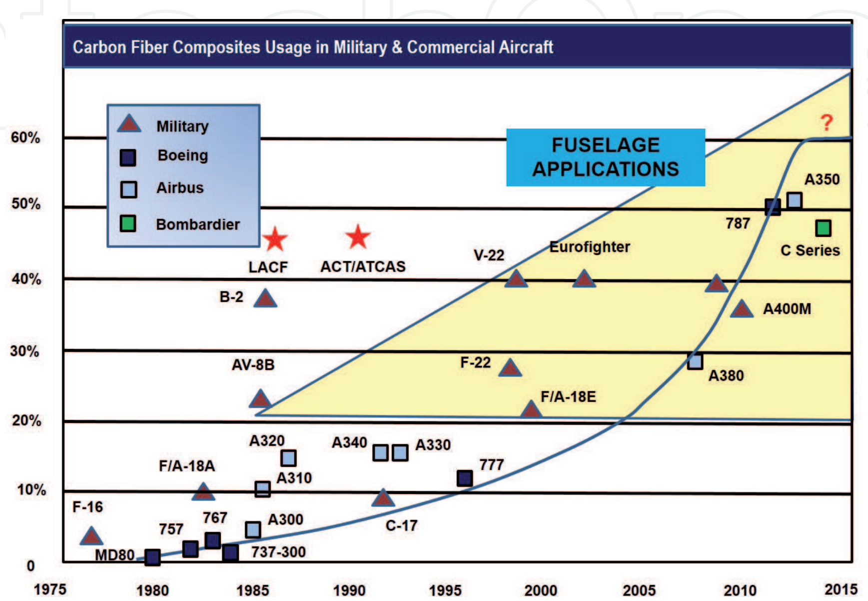

Figure 1.
Composites usage.

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 1980s 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.

2. Early research and development

Research and development of high performance composite materials and processes for aerospace applications in the Unites States was first conducted in the 1940s 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 1960s. 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 down select 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 (LACF) Program in the late 1980s and NASA's Advanced Composites Technology (ACT) program in the mid 1990s.

The B-2 Stealth Bomber program was also taking place during the 1980s 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 reasons 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.

2.1 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 1980s. 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 1980s "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 (**Figure 2**):

- Phase I—methods definition
- Phase II—manufacturing methods establishment
- Phase III—manufacturing verification
- Phase IV—production demonstration

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

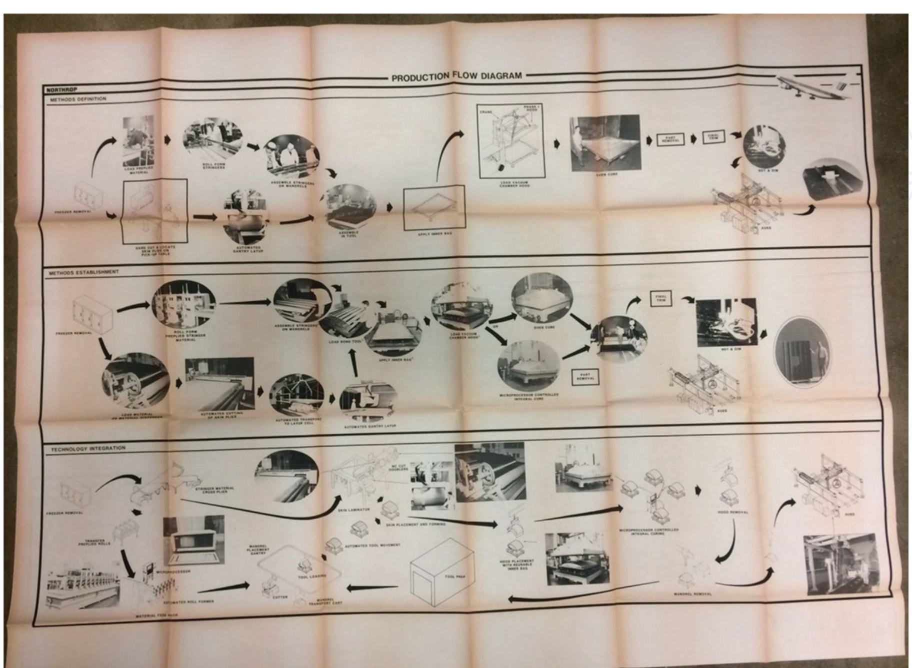

Figure 2.
LACF program.

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 (**Figure 3**).

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 (**Figure 4**).

Among the lessons learned as a result of Phases 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 (**Figure 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 trapped after cure and the channel details that form the "C"

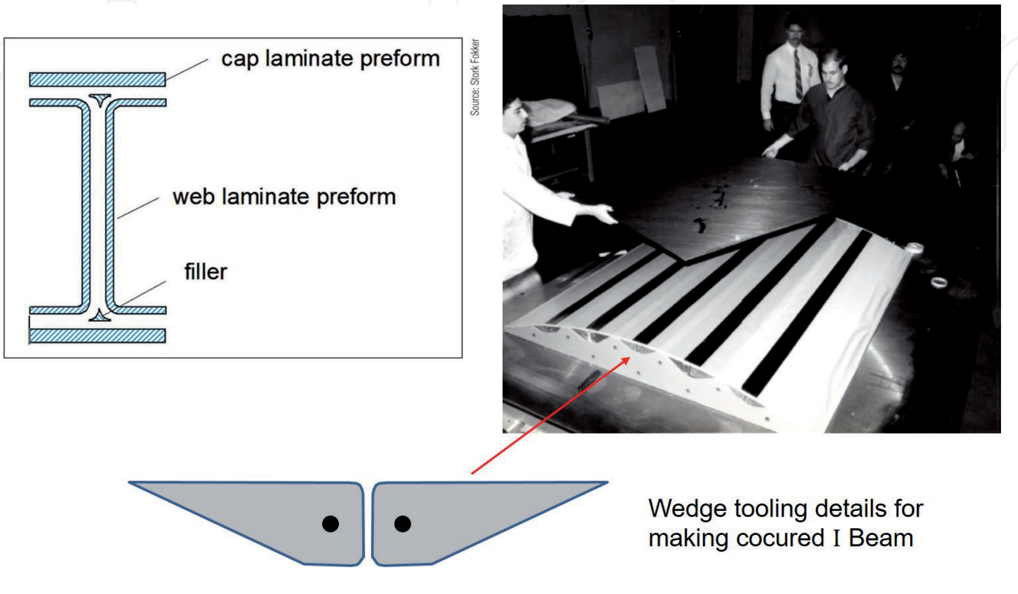

Figure 3.
"I" beam formed from "C" channels.

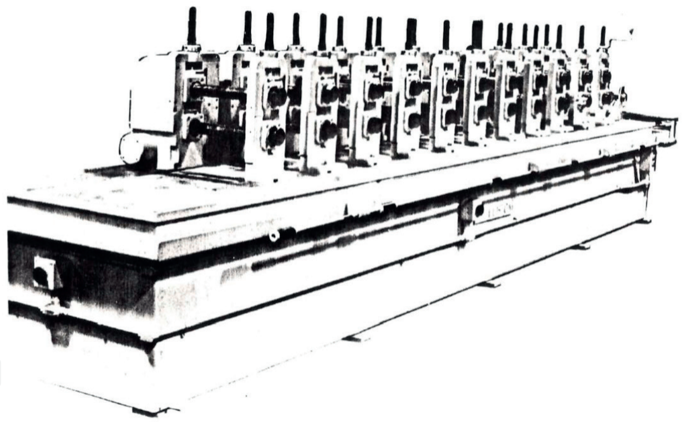

Figure 4.
"C" channel roll forming machine.

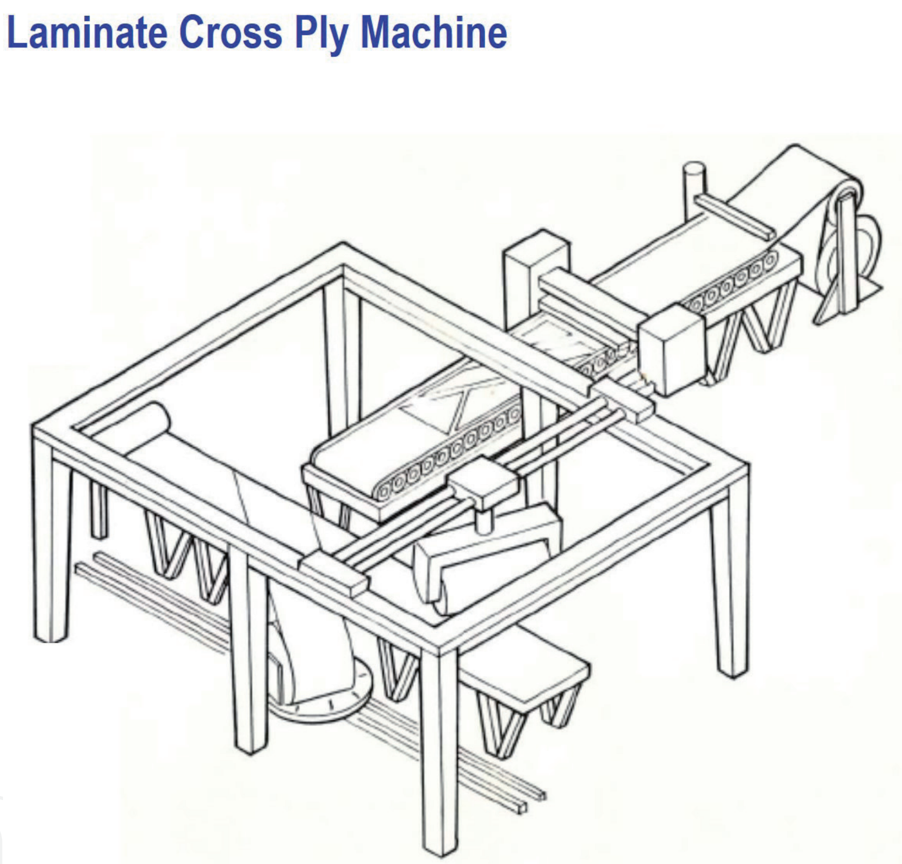

Figure 5.
Laminate cross ply equipment.

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 (**Figure 6**).

Northrop developed hat stiffened fuselage skin manufacturing technology in support of the YF-23 (**Figure 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.

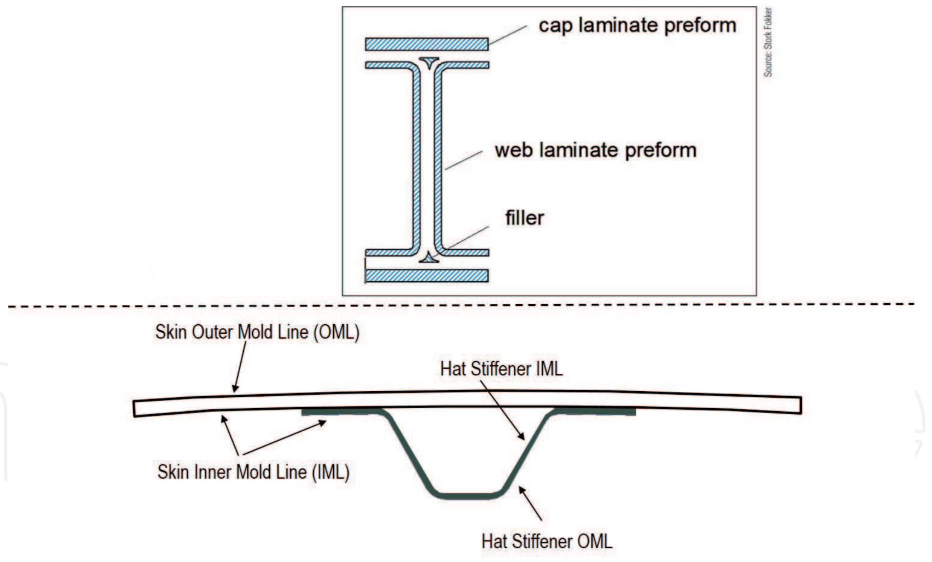

Figure 6.
"I" beam vs. hat stiffener.

Figure 7.
YF-23 fuselage structure.

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 (**Figure 8**). This is not a hard process, but is critical and tedious.

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 (**Figure 9**).

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

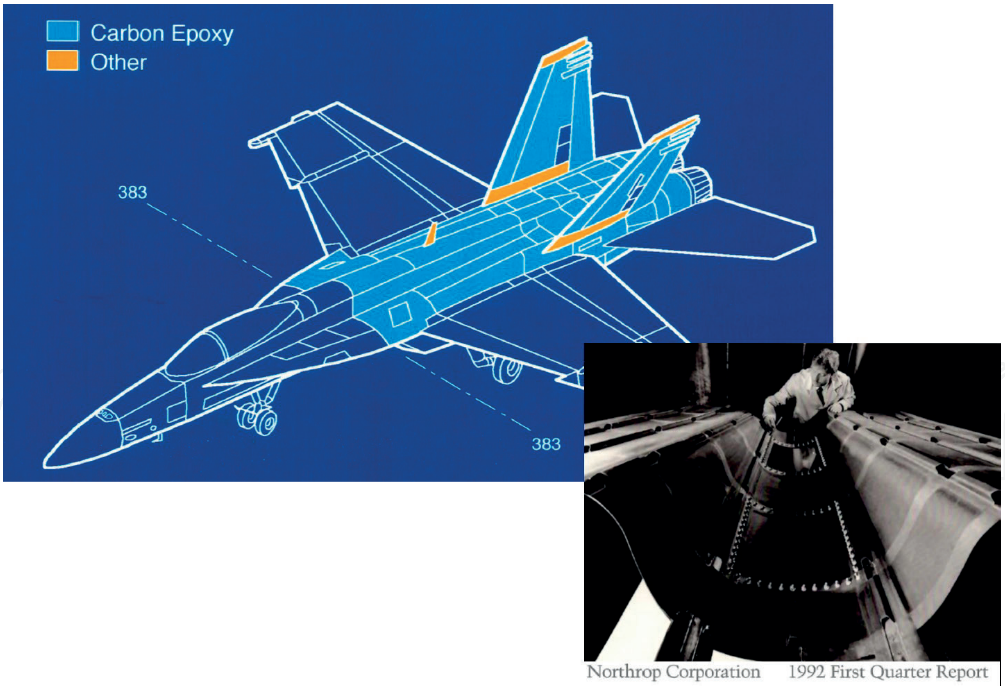

Figure 8.
Solid mandrel system.

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.

2.2 Advanced Composites Technology (ACT) program

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 [3]. The Advanced Technology Composite Aircraft Structure (ATCAS) program was performed by Boeing as the prime

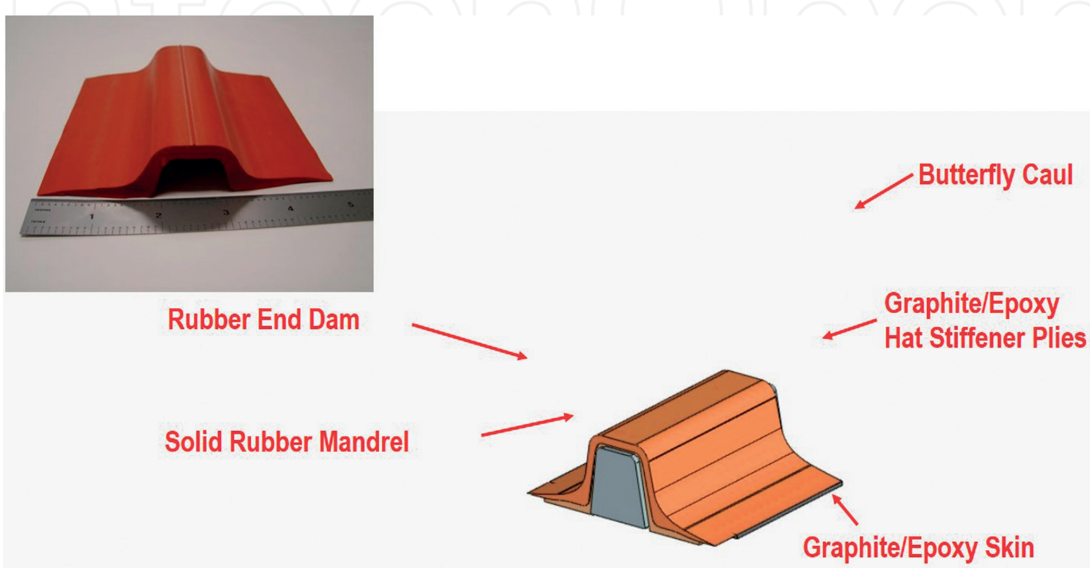

Figure 9.
F/A-18E/F fuselage structure.

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 (**Figure 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.

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, four 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 Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE) 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.

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 cocuring.

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 frames 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.

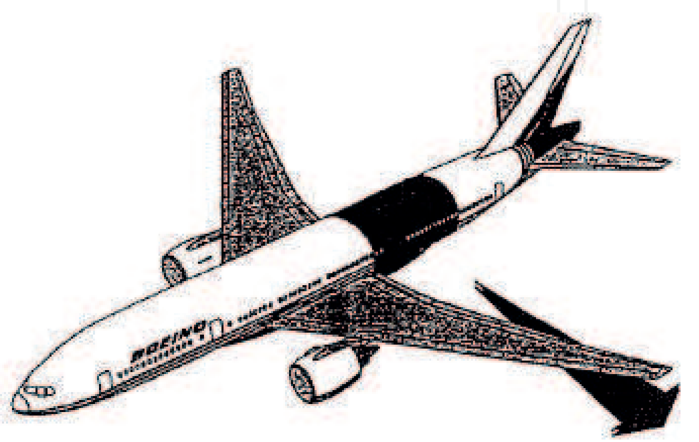

Figure 10.
ACT fuselage section [3].

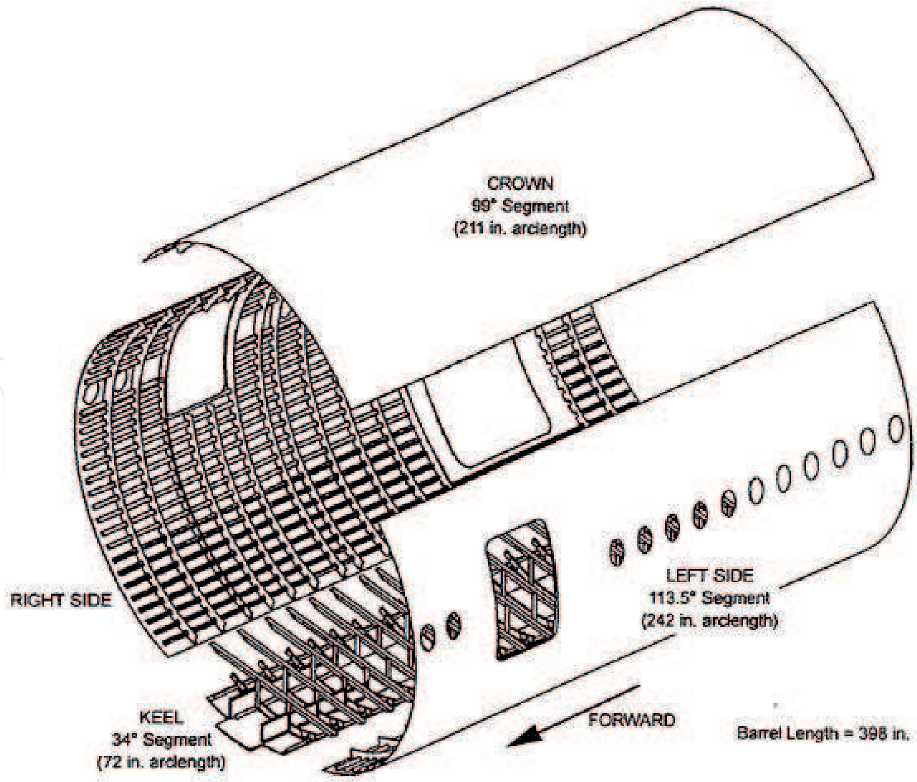

Figure 11.
ACT quadrant panels [3].

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 caul 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.

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.

Details	Process
Skins	AFP (tow, hybrid AS4/S2) CTLM (contoured tape lamination machine, 12″ tape)
Frames	Braiding/resin transfer molding (triaxial 2-D braid) Compression molding Stretch forming (thermoplastic, discontinuous fibers) Pultrusion/pull forming
Stringers	Hat—ATLM/drape forming (cocured, thickness variation) “J”—pultrusion
Panel assembly	Cocured/cobonded stringers, cobonded frames Cocured/cobonded stringers, fastened frames Sandwich panels, cobonded frames

Table 1.
ACT structural concepts [3].

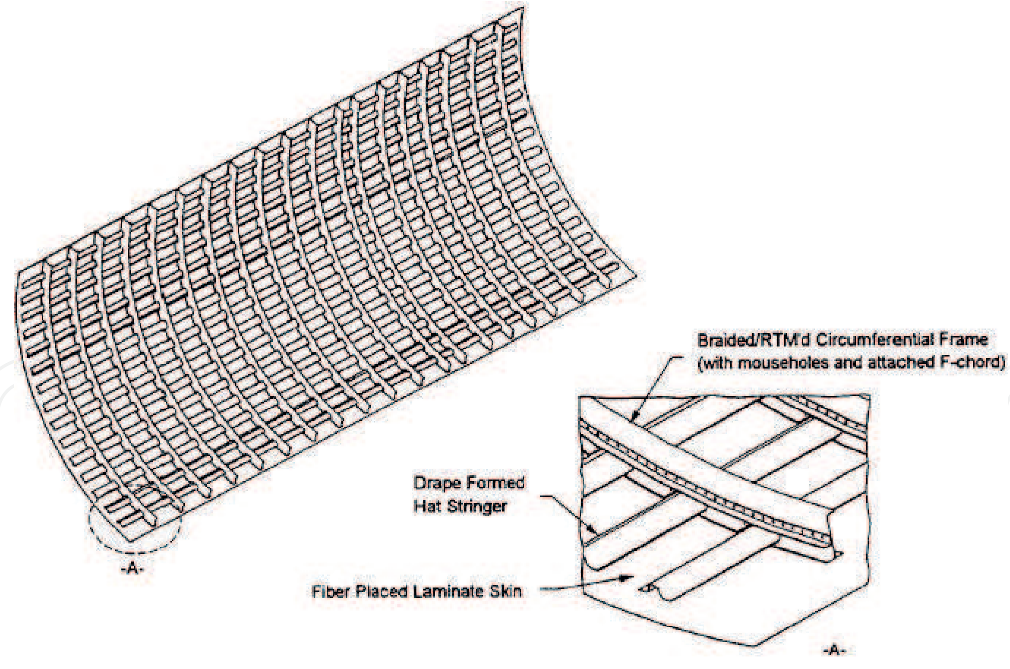

Figure 12.
ACT crown panel structural arrangement [3].

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.

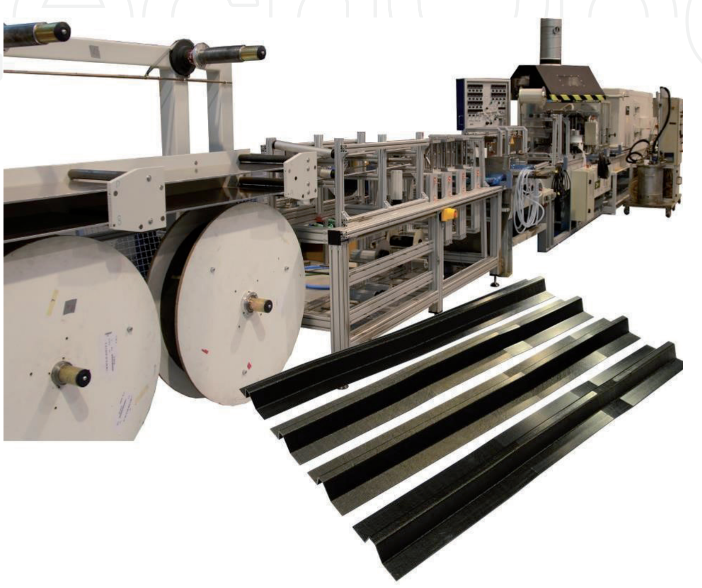

Figure 13.
Airbus continuous pultrusion equipment [4]. Source: CTC Stade.

2.3 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 achieved today is astounding. Almost as astounding as how the industry reinvented itself from a raw material cost saving technology to an enabling technology for large aircraft structural components.

In the late 1980s and early 1990s Northrop and ATK/Hercules worked on several joint projects sponsored by the Air Force which included fiber placement development and application. The technology was in its infancy as ATK was developing tow placement (as it was more commonly referred to originally) from its roots in filament winding technology. The main prize in the early days was $5 per lb. high modulus carbon fiber and $15 per pound high temperature/high performance resin instead of the $60+ per pound price of prepreg. A wet process of running fiber through a resin bath prior to placement onto the layup mandrel was never able to realize the quality and consistency required by the design. This same process has been used in the large wind blade manufacturing process and it reminds us of how challenging (and messy!) that approach can be. In addition, the wind blade manufacturing industry has learned some valuable lessons from those early days of "build it as cheap as you can" using the lowest cost material you can deal with. While those early blades were built with lower manufacturing costs, the argument can be made that many of those blades failed very early in their lifecycle and required costly repairs or replacement to generate electricity. If the blade cannot turn because it has delaminated, it is not generating any electricity in addition to the cost of repair or replacement.

Not only did the technology not realize the cost savings of dry fiber and wet resin, it was forced to adopt prepreg technology into the process—namely dealing with backing paper and ADDING to the cost of unidirectional prepreg tape by requiring it to be slit into prepreg tows. At the time of the ATCAS program, the AFP process was still evolving from what was originally envisioned as a much lower raw material cost build up starting with a dry fiber/wet resin process instead of a costly unidirectional fiber prepreg. The baseline process the ATCAS program selected for fabricating fuselage skins was AFP using prepreg tow. The dry fiber/wet resin tow had evolved to prepreg tow in an attempt to improve process consistency. The process was selected based on several factors including the potential for reduced material cost (compared to prepreg tape), the potential to achieve high lay-up rates over contoured surfaces, and the potential to efficiently support a significant amount of ply tailoring. In addition, the fact that tow material does not require backing paper eliminated a perceived risk of greater machine downtime.

When compared with the quality and consistency of parts made with prepreg tape, tow preg and subsequent prepreg tow, was not acceptable. The variability seen in the quality of the resultant panels would require compensation in the design of the part, resulting in weight penalties. But this did not prove fatal to the technology, instead tow placement reinvented itself (**Figure 14**).

There have been many studies of the AFP process that have helped to shape and refine the characteristics and capabilities that exist in today's equipment offerings. But the ACT program allowed Boeing to better understand, study, define and refine the process to guide the technology development based on the needs of the user community. Everything from tack of the initial plies to the tool surface, to overlaps and gaps in the laminate; the most efficient ways to handle window/door cutouts, laminate thickness transitions, lay-up rates for flat, curved, cylindrical and duct shaped parts, etc., etc. What has ended up on production on the 787 is not the direct result of that ACT program, but the ACT program created the path for subsequent AFP development to follow and improve upon.

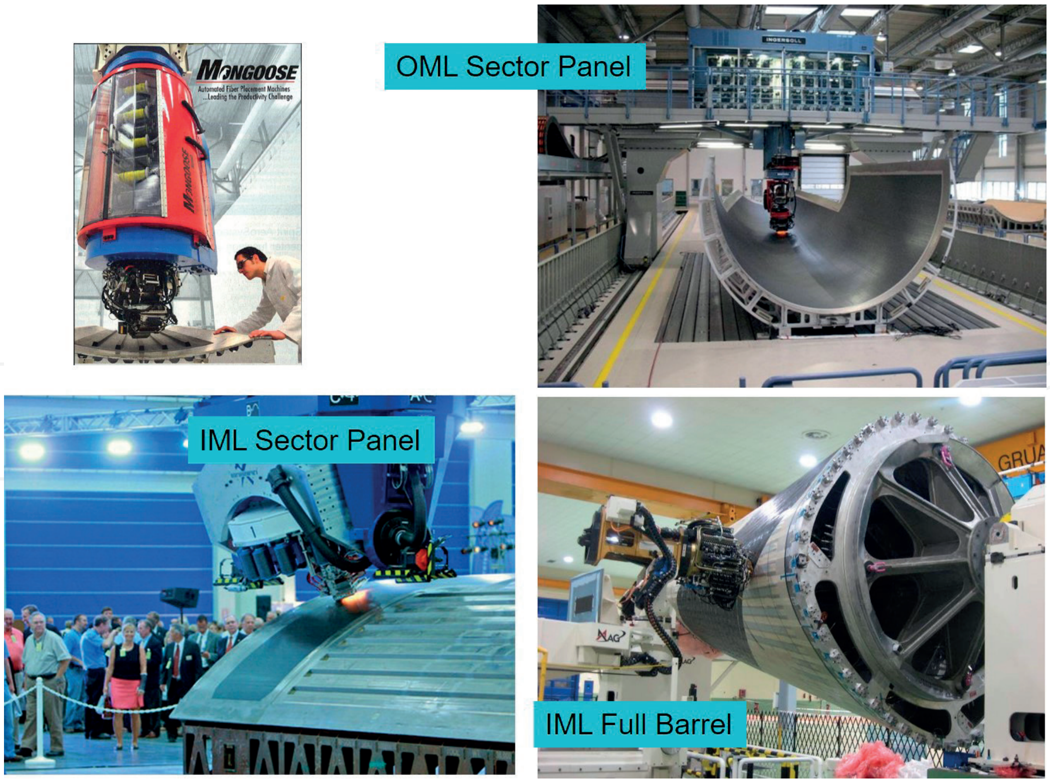

Figure 14.
AFP process and tooling.

2.4 Tooling

One clear thread throughout the development of composite fuselage fabrication processes that was recognized and considered very early on, was tooling. The fabrication of large composite fuselage structures was also enabled by the tooling required to support it. The ability of industry to produce tools using specified materials and built to the size, scale and accuracy required by aerospace and defense applications were critical factors. Large scale machining, laser measuring systems, and innovative thinking supported the transition to today's composite fuselage manufacturing capability.

The ACT program demonstrated how the producibility of large, integrated, composite fuselage structures depend heavily on the tooling to ensure compatibility of the skin cure tool, the cocured or cobonded stringer tooling and the frame tooling. Controlling these elements is necessary to minimize gaps and interference fit between cured detail components. Understanding the effect of tolerance accumulations, warpage, liquid and hard shim allowances and fastener pull-up forces creates the ability to calculate the impact on fuselage structural arrangement and weight, part manufacturing cost and risk and fuselage assembly and integration time. These elements become even more critical as the size of the fuselage grows to 787 and A350 proportions.

One important note was the need for the stringer tooling to be extractable after cure and flexible enough to be able to accommodate skin thickness variations—especially the "joggles" or transitions up-across-down at each of the frame stations. These requirements drove the team toward silicone or flexible laminate mandrels—reusability was also a key consideration. The mandrels needed to be rigid enough for handling or to be used as drape or vacuum forming mandrels; durable and capable of withstanding a 350°F autoclave cure cycle and still be able to conform to skin ply sculpting and tailoring; and be able to be extracted after cure.

While the use of silicone mandrels and the flexible IML tooling proved adequate for controlling hat stiffener shape, quality and location for the demonstration panels, it was also recognized that silicone mandrels presented many challenges in both scale-up and production scenarios. Boeing started to develop hat shaped silicone bladders that fed autoclave pressure into the bladder throughout the cure to provide uniform pressure throughout the stringer. After cure, pressure in the bladder is released making it possible to remove the bladder.

At this same time Rubbercraft was working with engineers on the C-17 program to develop and manufacture inflatable silicone bladders for use on the replacement composite tail (**Figure 15**). In 1991 on aircraft 51, a composite tail was integrated into the program. Rubbercraft produced silicone bladders with FEP film molded to the OML of the bladders that were used in IML tools to cocure hat stiffeners to the skin of the horizontal stabilizers. The tooling, bladders and hat stiffener design allowed for the bladders to be manufactured with substantial excess length that supported multiple cure cycles despite the dimensional shrinkage of the bladder in the longitudinal direction. The reusability over multiple cure cycles is key to the cost effectiveness of the inflatable bladder system. Rubbercraft product improvement was focused on bladder attributes that supported increasing the number of cure cycles the bladder could be used for (**Figure 16**).

While Boeing was developing flexible IML tooling for cocuring hat stringers and cobonding frames on the ACT program, they evolved away from one-piece overall cauls to separate, individual flexible cauls constructed from graphite/epoxy fabric with a layer of Viton® fluoroelastomer and an outer layer of FEP film. The fluoroelastomer was shown to be more resistant to the epoxy resin and thus more durable than silicones or other rubbers. An added benefit—but perhaps not as well understood at the time—is the added resistance to permeability offered by both the FEP film and the Viton rubber. This helps to minimize the amount of autoclave gas on the inside the bladder from being introduced into the laminate through the permeability of the bladder system. Fluoroelastomer bladder development continues today in support of new programs and applications.

A comparison of OML and IML cure tool approaches demonstrates some of the tradeoffs that must be considered. OML tooling is less complex, less expensive, can be initiated as soon as the OML of the aircraft is established and is more forgiving of change than an IML tool. The IML tool requires less labor and risk for locating and maintaining locations of stiffeners and other elements and is much more simple to bag (**Figures 17–20**).

The ACT program also looked at separate male winding mandrels for AFP and then transferring the uncured skin to an OML cure tool. The male layup mandrel improved layup rates and proved to be a less expensive approach to meet production

Figure 15.
C-17 horizontal stabilizer.

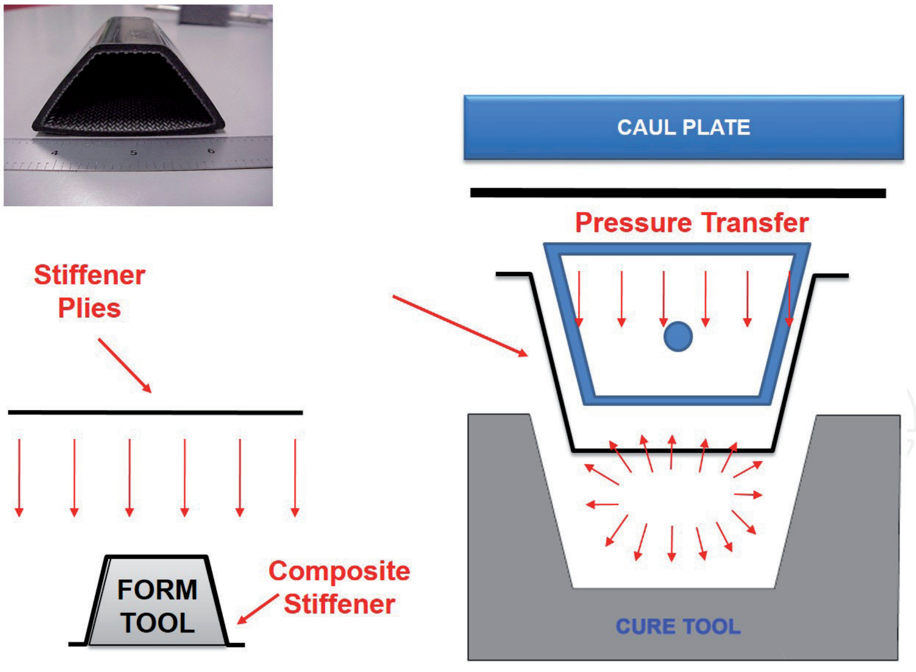

Figure 16.
Inflatable bladder.

Figure 17.
OML sector panel tool. Source: Premium Aerotec.

Figure 18.
IML tool. Source: Boeing.

rate than two cure tools. This also plays to the argument for a combined IML controlled layup mandrel and cure tool—as Boeing selected for the 787 program.

One concern using IML controlled cure tooling is the ability to adequately control the aerodynamic shell of the fuselage. For the ACT program this meant meeting surface waviness criteria of ±0.025″ over a 2″ length using caul plates. The concern

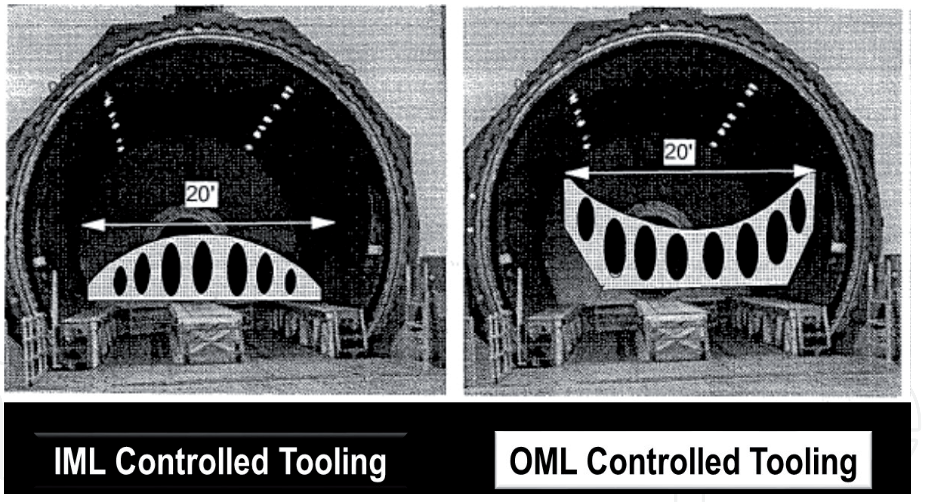

Figure 19.
IML and OML cure tools [3].

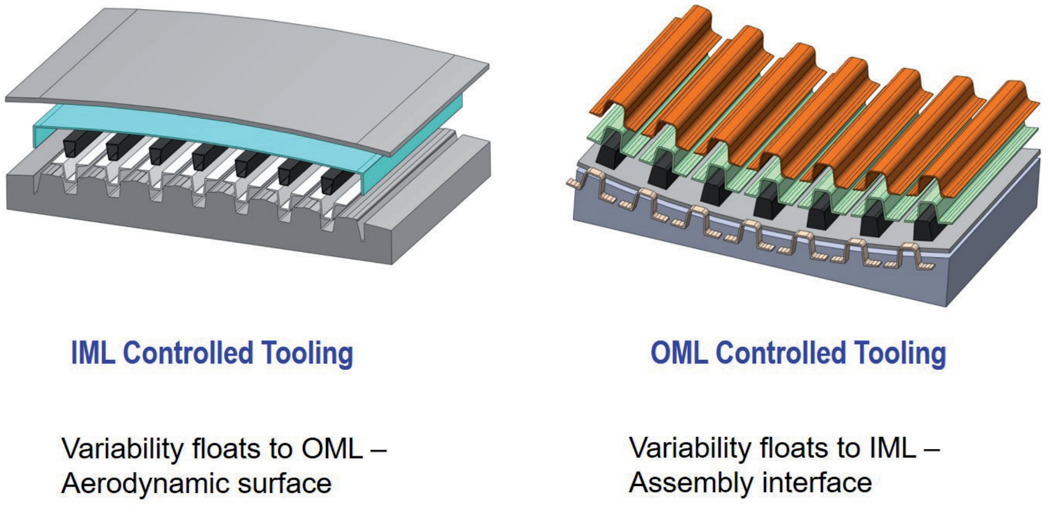

Figure 20.
IML and OML tooling.

over aerodynamic surface control seems to be greatly diminished when you look at what has evolved on the 787 program. The recognition that every airplane has a slightly different OML based on a number of factors such as exact resin content percentage in the prepreg (within the nominal tolerance range of ±5%), the amount of resin bleed experienced during cure and the amount of cured material removed during the sanding, smoothing and preparation for painting process. The skin of a composite fuselage allows for greater tailoring of the skin thickness than is usually incorporated into a metal fuselage. At the base, the fuselage is skin is thicker because it carries more load related to passengers, cargo and landing gear. The structural loads at the top of the fuselage are limited primarily to overhead bins, air ducting, and electrical wiring and this allows for lower weight, thinner skins that predominantly function as aerodynamic surfaces. Regardless of where in space it exists, and even though it varies from aircraft-to-aircraft, the surface is sanded smooth enough to satisfy the surface waviness allowance and negligible difference between aircraft.

The ATCAS team envisioned scenarios that included full one piece barrel fabrication. Significant cost savings were estimated from the elimination of longitudinal splices and the need to compensate for tolerance accumulation in assembly. Material out-time, segmented full barrel cure tooling and barrel warpage were the primary risks identified with full scale single piece barrel fabrication.

The sector panel construction used on the A350 allows for the use of invar for all the fuselage tooling. This includes the IML controlled sector panels fabricated by Spirit for Section 15. The approach Spirit applied is very similar to the one used on the 787 with the exception of the use of sector panels instead of a one piece barrel breakdown mandrel (**Figure 21**).

2.5 Large autoclaves

One enabling capability that supports the evolution of the current state-of-practice for composite fuselage manufacturing is large autoclaves. There are many, many, many, many research and historical, ongoing and planned for the future, development efforts focused on OOA (or non-autoclave as it was called in the 1980s) materials and processes with the goal of eliminating that monument, the autoclave. The goal is noble (and not new) and the development efforts are making great progress and will, someday in the future, represent a significant (if not all) portion of the composite structure on commercial passenger aircraft—just not today. We already see components made from liquid molding processes being used in specific applications and families of parts and components on aircraft like the 787 and A350, just not the primary fuselage panels and stringers—yet. The maturity, forgiving nature, and low risk of baseline autoclave cured systems made it an easy decision for programs like the 787 and A350 to progress knowing that it was just time and money required to build autoclaves large enough to meet the needs of the program. No new technology needed, just scale and incorporation of improvements being realized by the autoclave industry, such as control systems and operational efficiencies. Spirit even built their own liquid nitrogen generating plant onsite to service their large autoclaves (**Figure 22**).

2.6 NDE/I/T technology

The use of composites for high performance applications requires the ability to identify and ultimately eliminate structural defects that occur during manufacture, assembly, service, or maintenance. The entire field of nondestructive evaluation (NDE) has continued to develop and evolve in parallel to the growth of composite

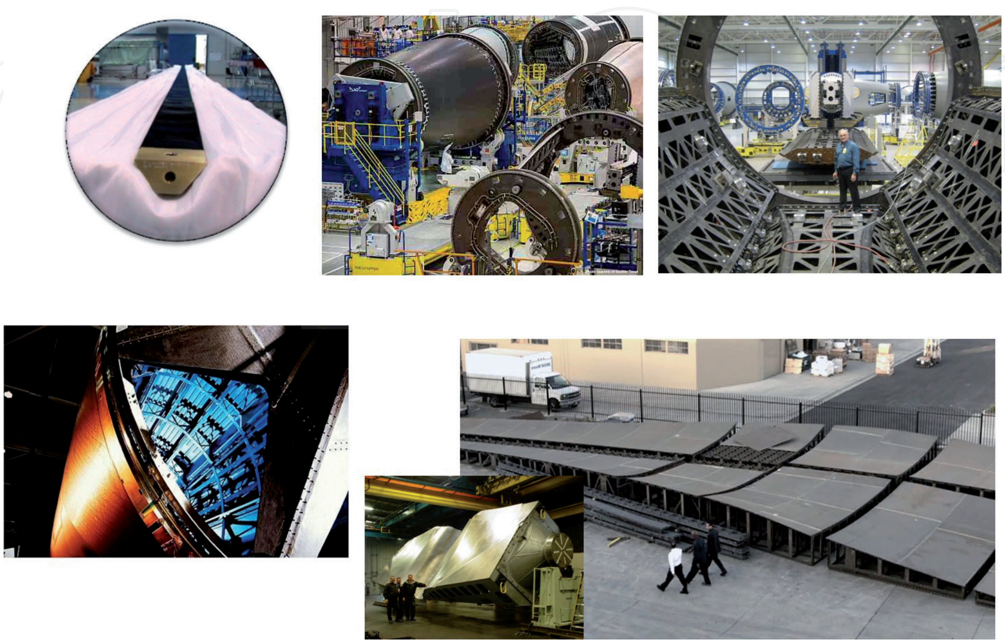

Figure 21.
Tooling. Source: Boeing, Coast composites.

Figure 22.
Autoclaves. Source: Spirit, DLR.

structure applications. It is both an enabling technology and one that has been driven by the market and the need. NDE of composites is a mature technology and has been used successfully for many years, however, the composite structures of today and tomorrow have grown in both scale and complexity. New and improved nondestructive testing (NDT) methods and technologies are necessary to improve detection capabilities, meet growing inspection needs, and address future nondestructive inspection (NDI) requirements. NDT methods currently used in aerospace applications span a broad range of technologies, from the simple coin tap test to fully automated, computerized systems that can inspect very large parts (**Figures 23** and **24**).

Many of the newer NDI methods are "wide-area" inspection techniques, which enable more uniform and rapid coverage of a test surface which can improve productivity and minimize human error. Technical advances in both computing power and commercially available, multi-axis robots and/or gantry systems, now facilitate a new generation of scanning machines. Many of these systems use multiple end effector tools yielding improvements in inspection quality and productivity.

Ultrasound is the current NDE method of choice to inspect large fiber reinforced airframe structures. Over the last 2 decades, ultrasound scanning machines using conventional techniques have been employed by all airframe OEMs and their top tier suppliers to perform these inspections. A limitation of ultrasonic inspection can be the requirement to use a couplant between probe and test part. VACRS (variable automatic couplant and recovery system) has helped changed the way very large area ultrasonic inspections are done [6]. The VACRS system uses a lightweight couplant and delivery/recovery system that makes it possible to conduct a C-scan with large ultrasonic arrays without the large water requirements. It works with Boeing's mobile automated scanner (MAUS®) and other scanning systems on the market.

Shearography and thermography are relatively fast, non-contact methods that require no coupling or complex scanning equipment. Laser shearography was initially applied to aircraft structure in 1987 by Northrop Grumman on the B-2 bomber. Since that time, laser shearography has emerged as an advanced, high-speed, high-performance inspection method.

Method	Advantages	Issues
Coin tap	Low-cost	Large, near surface features only
Ultrasound	Excellent penetration Well-established standards and procedures	Point inspection or scanning required Requires contact, couplant
Radiography	Area inspection Excellent crack detection	Insensitive to many voids or delaminations
Thermography	Area inspection Provides information about flaw type	Operates in close proximity to aircraft Limited depth range
Shearography	Area inspection	Limited depth range Issues at edges and corners

Figure 23.
NDI methods [5].

An enabler for more widespread use of bonded structure in commercial aircraft applications will be improvements in cost and capability related to quantification of real-time structural bond integrity. Adhesive bonds degrade slowly over time and are highly dependent on surface preparation. On older aircraft, the only gauge for bond integrity is age, environmental exposures and statistics — not the actual condition of bonds. The ability to detect weak adhesive bonds, before they disbond will lead to more integration of parts and reduced fastener count and a reduction in everything that is involved with creating holes in cured composite parts. Military air vehicle platforms are more aggressive in this pursuit and the "pay-for-performance" mindset, the lower production rates and the size, visibility, and objectives of the programs allow for more flexibility in bonded structure implementation. The commercial world is different and just like the widespread implementation of composite material on new aircraft, it will not happen unless there are compelling economic advantages and very low risk.

2.7 Logistics

Boeing knew that the transport time required by land or marine shipping methods would not support a supply chain that included major partners located in Japan, Korea and Italy and that air transport would be the primary shipping method [7]. The Dreamlifter started as the Large Cargo Freighter (LCF) program and is a

Figure 24.
Ultrasonic inspection.

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modified 747-400 freighter. The Dreamlifter and follows a historic trail of oversized or outsize aircraft, which includes the Airbus Beluga, that were borne out of the adage "necessity breeds invention". The Dreamlifter is a dedicated transport used to deliver full 787 fuselage sections, wings, and horizontal tail from suppliers located across the US and the world. There are four Dreamlifters in operation supporting the 787 program.

The innovation that was the Dreamlifter (**Figure 25**), also required equipment to support the loading and unloading of such large cargo. Hence was born the largest cargo loaders in the world. The first one designated DBL-100 (DBL has been reported as an acronym for "Damn Big Loader"), were designed for use exclusively with the Dreamlifter.

Airbus was originally a consortium formed by British, French, German, and Spanish aerospace companies. Historically, each of the Airbus partners makes an entire aircraft section, which would then be transported to a central location for final assembly—even after integration into a single company, the arrangement remained largely the same. When Airbus started in 1970, road vehicles were initially used for the movement of components and sections. As production volume grew quickly, a switch to air transport was required. Beginning in 1972, a fleet of four highly modified "Super Guppies" took over. These were former Boeing Stratocruisers from the 1940s that had been converted with custom fuselages and turbine engines. Airbus' use of the Super Guppies led to the jest that that every Airbus took its first flight on a Boeing [8].

Today this need is handled by the Airbus A300-600ST (Super Transporter) or Beluga (**Figure 25**). The Beluga is a modified version of the A300-600 airliner adapted to carry aircraft parts and oversized cargo. The official name was originally Super Transporter, but the name Beluga, a whale, gained popularity based on the appearance of the airplane and has been officially adopted. Interestingly, the Beluga cannot carry most fuselage parts of the A380, which are instead transported by ship and road.

Figure 25.
Beluga and Dreamlifter [7]. Source: Boeing, Airbus.

Airbus has an updated design, The Beluga XL, based on the larger Airbus A330-200. Five aircraft are planned to be built as replacements for the existing aircraft and used primarily for A350 work. The Beluga XL is designed with the capacity to ship two A350 wings simultaneously [9].

2.8 787 vs. A350

The Boeing 787 and the Airbus A350 aircraft share many similarities in size, configuration, manufacturing methods and mission (**Figure 26**). The primary difference between the composite fuselage structures of the two programs is the exclusive usage of IML controlled cure tooling and full barrel fabrication applied by Boeing and the sector panel approach selected by Airbus with a high percent incorporation of cobonded fuselage skin stiffeners. The true results of these decisions will not be known until more information can be collected about actual fabrication and assembly costs being realized by Boeing and Airbus.

2.8.1 Boeing 787

The ACT/ATCAS program had a tremendous influence on the direction Boeing selected for the 787 program. Lessons learned from all aspect of the program influenced everything from the material systems that were selected to the tooling materials, structural arrangement, and the selection of IML tooled, full barrel fuselage structures. Major considerations that influenced that decision were the concerns about the cost of the assembly of very large stiffened structure and the stresses induced on the structure due to assembly.

The program helped Boeing better understand the assembly loads related to composite panel warpage from cured part spring back and cocured and/or cobonded stiffener or frame mislocation. At minimum, these loads need to be understood and accounted for in the part design. Boeing saw an opportunity to minimize these assembly related penalties to the design by the tooling and structural arrangement approach applied on the 787.

Boeing's selection of the AFP process over a male mandrel that serves as both a layup and cure tool is forgiving enough to accommodate different caul plate approaches on different sections of the fuselage. All the fuselage sections use

- One Piece Barrel Construction
- IML tooling

- One Piece Barrel Construction
- Sector Panel Construction
- Cocuring
- Cobonding
- IML tooling
- OML tooling

Figure 26.
787 and A350 fuselage sections.

multiple caul plates that nest together to cover the entire outer mold line of the fuselage. The cauls are floating on the surface of the skin and move with the skin during cure to establish the cured part OML whenever and wherever it is at the time the resin gels and things stop moving. Shared characteristics of the cauls include the ability to be individually and positively located before cure and removed individually after cure. Also the ability to ensure the cauls do not interfere with each other during cure. However, differences do exist in the choice of material (either graphite reinforced composite cauls or aluminum cauls) and in the thickness of the caul. In some cases, the composite caul is very thick and stiff and will behave more rigidly during the cure cycle. In other barrel sections, a thin aluminum caul is employed, which will more closely conform to the surface of the as AFP laminated skin. Both extremes are successfully being used by different fabrication partners.

Invar was the material of choice for Sections 43, 44 and 46 and the tail. Invar tooling was not the right choice for Spirit as it designed the layup mandrel/cure tooling for Section 41. An invar tool of that size and weight would have imposed very expensive requirements on the foundation of the AFP machine that winds the skin. The size of the motors and energy required to turn and manipulate the mandrel during the fiber placement process was also determined to be prohibitive. Instead Spirit elected to fabricate graphite reinforced BMI mandrels fabricated on invar cure tools and then machined to final IML dimensions (**Figure 27**).

Composite tooling is also used for Sections 47 and 48. In addition to lower mandrel weight, faster heat up and cool down rates contributed to this decision.

All the partners on the 787 program follow similar manufacturing processes for fabricating cocured, hat stiffened, full fuselage barrel sections. All use AFP over IML controlled male layup mandrels that also serve as cure tools. Each section (except the tail) uses multi-piece breakdown mandrels which are disassembled and removed from inside the fuselage after cure (**Figures 28** and **29**).

Alenia manufactures Sections 44 and 46 of the 787. Section 44 is a composite half barrel section that covers the main wing box. The lower portion of this fuselage section is mostly metallic and the structure is designed to handle the primary loads from the wings and landing gear.

Fabrication of fuselage barrel Sections 47 and 48 were originally contracted to Vought as part of their statement of work (SOW) on the 787 program. Financial pressures driven by initial program delays led to Boeing acquiring the Vought SOW including partnership in subassembly work with Alenia (**Figures 30**–**32**).

Figure 27.
Spirit 787 Section 41. Photo: Bill Carey.

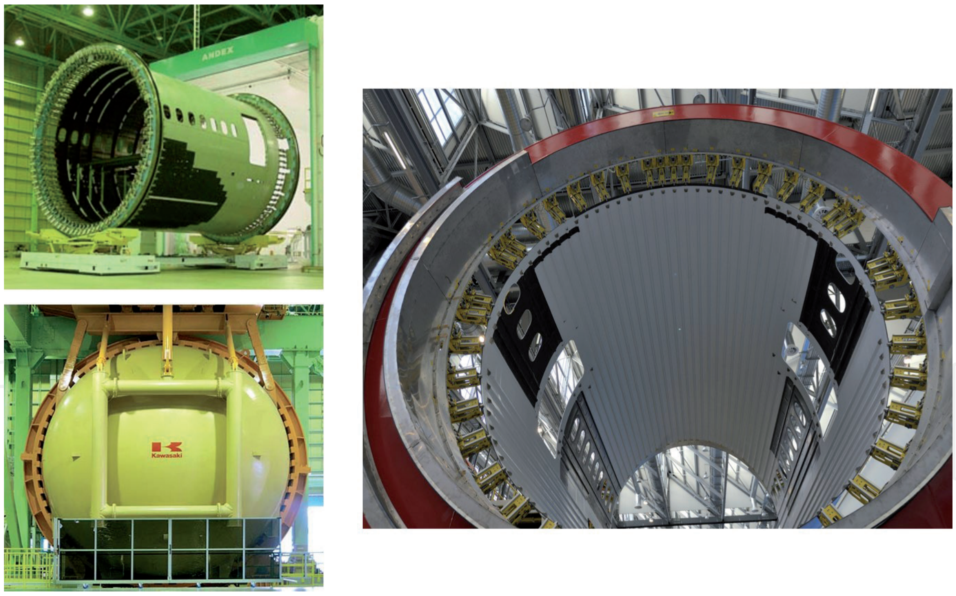

Figure 28.
787 Section 43. Source: Boeing.

The tail is the only barrel section that does not require a breakdown cure mandrel. The natural draft angles allow for cured part removal by simply sliding the cured part off the mandrel.

Boeing achieved stretch version of the 787 by extending the fuselage sections on either side of the wing center of gravity. The 20′ stretch for the −9 was achieved by adding 10′ to Sections 43 and 47. The additional 18′ added for the −10 configurations was achieved by adding 10′ to the forward fuselage and 8′ aft end. When new AFP mandrels were added to meet production ramp-up rate needs and to meet the −9 configurations, the tools were designed to support −10 also.

2.8.2 Airbus A350 XWB

While the focus of this paper has concentrated on developments in the United States, the composites community in Europe was just as active. There were many

Figure 29.
Sections 44 and 46. Source: Boeing.

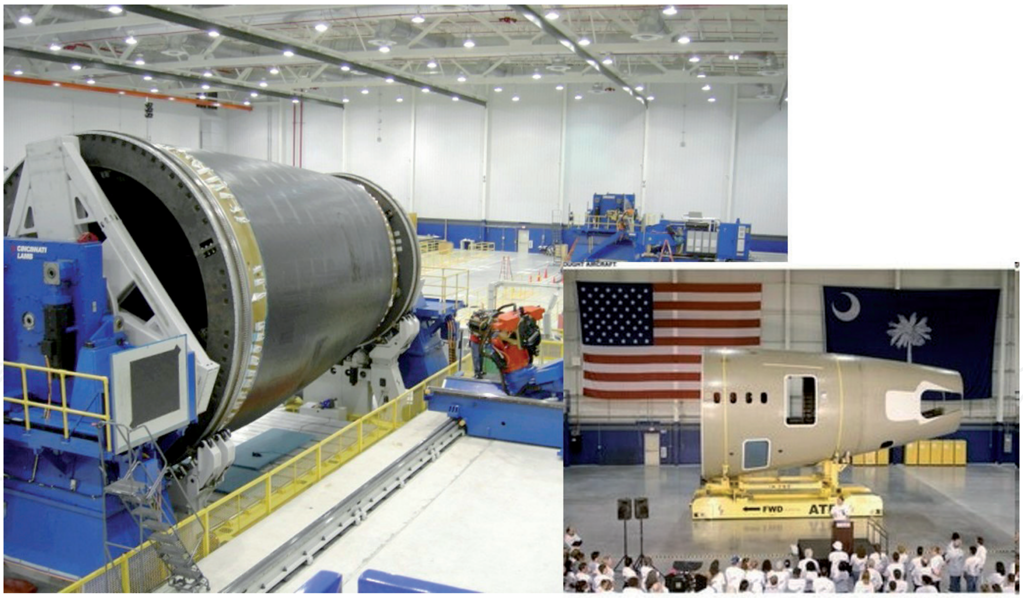

Figure 30.
787 Sections 47 and 48. Source: Boeing.

R&D programs that were directed at high performance composites design and manufacturing activities [10].

The results of this work along with many lessons learned on historical programs fed into the approach taken on the A350XWB program (XWB stands for eXtra Wide Body). The A350 composite fuselage manufacturing approach is not as uniform as the method selected by Boeing on the 787.

The A350 incorporates one complete barrel section, the tail, produced in Spain that uses an approach similar to the one used by Boeing and its partners on the 787 (**Figure 33**). The rest of the A350 fuselage follows a more conventional panel assembly approach, but with some unique manufacturing process used along the way. The use of AFP, invar tooling and longitudinally incorporated omega (like the Greek letter Ω) stiffeners, more traditionally called hat stiffeners, are also common between the programs. The panel approach used on the A350 supports long part lengths and this is reflected in Section 15 which is approximately 65′ in length. How the omega stiffeners are incorporated on the fuselage panels is quite different between sections and suppliers.

Figure 31.
787 Tail. Source: Boeing.

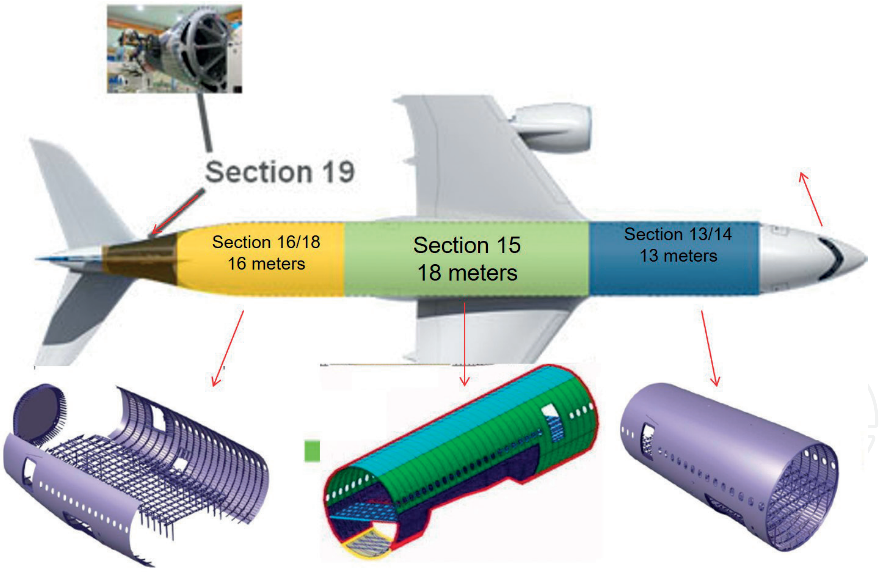

Figure 32.
Airbus A350.

Spirit is a common key supplier on both programs and the fabrication approaches share some key characteristics. Spirit produces Section 15 of the A350 and applies the sector panel approach that is common throughout the fuselage. Spirit cocures the omegas using an IML controlled layup/cure tool with a stiff composite caul plate to control the aerodynamic OML surface smoothness. Uncured omega stiffeners are laminated, formed and located into troughs machined into the invar tool. Inflatable rubber bladders are located on top of the omega laminates and fill the void between the omega and the AFP skin that is laminated on top of over the assembly. The part is autoclave cured and the rubber bladders removed after cure leaving the cocured, and now hollow, omega on the panel (**Figure 34**).

The rest of the A350 fuselage structure uses cobonding to incorporate the omega stiffeners with the fuselage skin (**Figure 35**). Precured omega stiffeners are located onto green AFP skins with a layer of film adhesive between the elements and then autoclave cured (**Figure 36**). During the cobonding cycle shaped tube bags are located inside the cured stiffener and are open to autoclave pressure during the cure/cobonding cycle to ensure the already cured stringer does not collapse or become damaged when subjected to autoclave pressure (**Figures 36** and **37**).

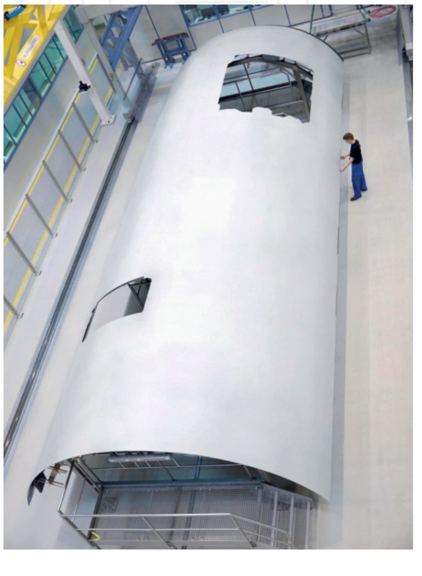

Figure 33.
A350 fuselage panel and tail. Source: Airbus.

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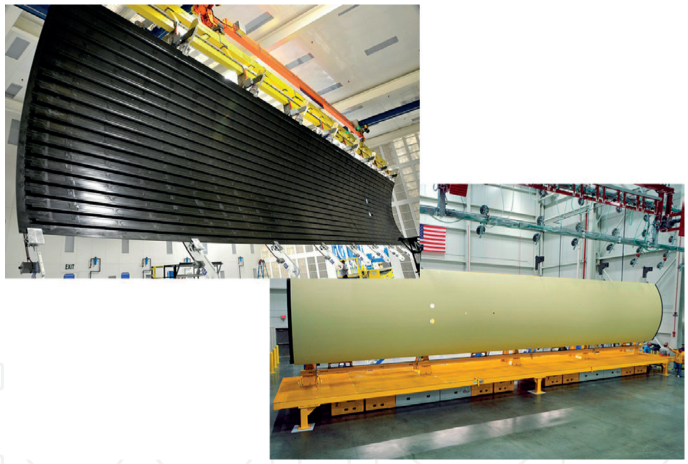

Figure 34.
A350 fuselage side panel. Source: Spirit.

Like the 787 program, liquid molding processes are used to fabricate fuselage frames which are mechanically attached to the skins. The structural arrangements and assembly methods used by both programs are remarkably similar.

One significant difference (if not THE most significant difference) is the frame integration to the fuselage. The 787 incorporates a "mouse hole" in the frame that nests around the hat stiffener and is attached directly to the IML of the fuselage skin. Boeing can do this because the IML surface of the 787 is a tooled surface with features that have controlled heights and locations. This includes hat stiffeners and skin joggles. Both programs use fuselage frames produced using a closed molding process that tools the surface that mates with the skin. On the 787, this creates a

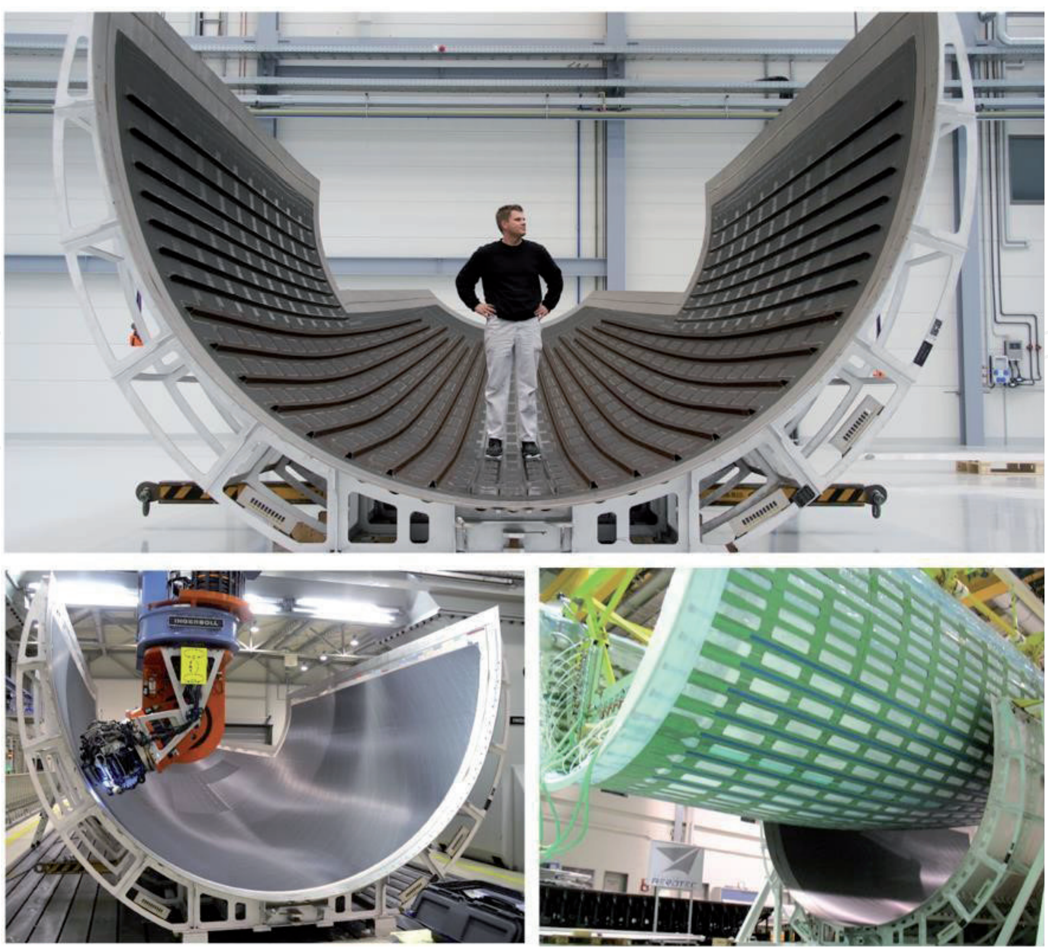

Figure 35.
A350 fuselage panel. Source: CTC Stade.

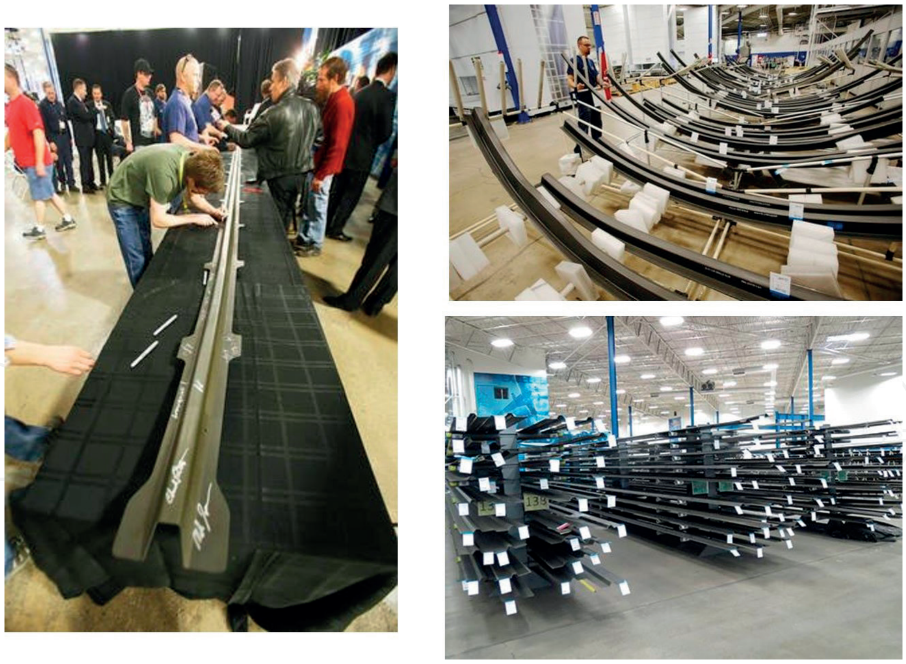

Figure 36.
A350 precured omega stringers. Source: Deseret News, Jeffrey D. Allred; CW/Photos: Jeff Sloan.

tooled surface-to-tooled surface interface creating a very predictable assembly. Components fit together as well as it can be produced because early in the program, it paid the price of being designed for assembly (**Figure 38**).

The A350 fuselage frames are attached only at the crowns of the omega stiffeners using secondary clips. Airbus did not try to attach the frames directly to the skins because the IML of the fuselage skin is not a controlled surface. It is a bagged surface that might use caul plates to create uniform pressure and a smooth surface, but the IML surface “floats” depending on factors such as bagging, resin bleed and initial prepreg resin content. Just as the OML of each 787 fuselage “floats” and is different aircraft-to-aircraft depending on these same factors. Airbus uses a standard carbon fiber reinforced clip, molded from thermoplastic material, to absorb the skin fabrication tolerance in the assembly process (**Figure 39**).

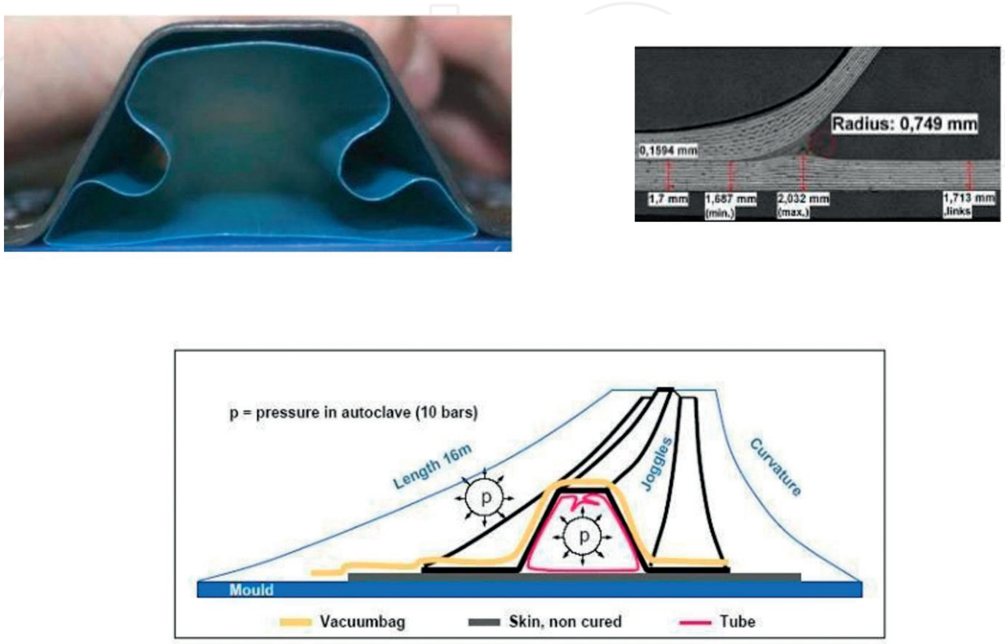

Figure 37.
A350 omega stringer cobonding [11].

Figure 38.
787 fuselage.

Figure 39.
A350 fuselage. Source: Borga Paquito.

3. Future developments/trends

There are several recently developed commercial aircraft, such as the Bombardier C Series, Mitsubishi's MRJ, and Comac's C919, that all have similar overall airframe architecture as the 787 and the A350. However, none of these aircraft incorporate an all composite fuselage. The advantages for composites on large, wide body aircraft have been validated by the short service history of the 787 and even shorter history of the A350. The debate regarding smaller aircraft achieving the same gains continues for Next Generation Single Aisles.

Wide body aircraft spend much of their life cruising at 40,000 ft. and the structure is sized for pressure loads and structural needs—this provides adequate thickness for good damage tolerant designs. The fuselage designs for single aisle aircraft could be more efficient based on cabin pressure and structural loading alone. But, to provide for designs that will be tolerant of many more takeoff and landings and in service hazards such as luggage and catering carts, dropped tools and equipment, hail and bird strikes, the fuselage panels must be thicker and heavier, thus sacrificing weight.

Wings are one area of implementation for composites on the single aisle upgrades and new aircraft of the future. The Boeing 777X has incorporated a composite wing into the design. A composite wing allows for a very high degree of laminate tailoring and can be designed and built for maximum efficiency. This creates an elegant wing that is incredible to watch in-flight, but appears alarmingly thin compared to conventional metal aircraft wings. But composite wings for high rates present challenges. Production rates of 12–14 per month for wide bodies have proven to be achievable. Building composite wings to support production rates as high as 60 aircraft per month for narrow bodies has not. Costs related to rate tooling alone can be daunting.

Remarkable advances in OOA technology might help provide a solution. Bombardier chose an OOA process for wings of the C-series and the MRJ is using an OOA system for the vertical tail wing box, a similar process to what United Aircraft (Russia) has announced for their MS-21 wing. Still, there are complex issues to resolve that will affect the timeline for OOA system usage on next generation, commercial, single aisle aircraft wings and fuselages. The industry is risk adverse and OOA systems are in their infancy compared to autoclave systems. The autoclave process has proven to be very forgiving and tolerant of variabilities that exist in raw materials, support materials, supply chain manufacturing processes and through final part fabrication. The effect of manufacturing variability is well understood and incorporated into efficient designs that contain minimal penalties for the unknown or less well understood. The same will not be true of OOA systems until more lessons learned have been earned. Many of these lessons will continue to come from military applications that are more aggressive in implementing new technologies. The benefit for the military is usually not cost; the benefit for the commercial world is always cost.

On a little longer timeline affecting future composite fuselage construction is sensor and technologies related to structural health monitoring (SHM). This is a very large field with growing interest by many OEM's in many applications by many industries, including aerospace, automotive, and power generation. Advances in this technical arena could be one of the next revolutionary changes or "step changes" (vs. evolutionary) to advance the industry. Advanced sensor technology could supplant many NDT applications by supporting in-situ "structural health monitoring." Installed on or within composite structures, such systems would continuously monitor a component and detects degradation and damage as it occurs. This could eliminate the possibility of damage being overlooked and reduce costly downtime for manual inspections.

The future of SHM and other smart composite structures includes morphing technology that changes part shape in-flight to create optimal flight conditions. Built-in sensing, computing, and actuation are emerging new frontiers for structures that self-tailor their properties for changing flight conditions. Similar developments include multi-functional composites—laminates that not only provide lightweight, load-bearing structures, but also perform additional functions such as energy harvesting and storage. The 20th International Conference on Composite Materials (July 19–24, 2015, Copenhagen, Denmark), featured more than 100 presentations on multifunctional composites [12].

3-D printing is another emerging technology that will impact the future of composite fuselage construction. Already making an impact in prototyping, early design and development, and tooling applications. Small, highly complex parts will follow the path being created by 3-D printed metallic parts. Larger applications are sure to follow. Nano technology may also develop as a viable standalone technology or perhaps integrated with 3-D printing. Remarkable innovations are surely on the horizon.

4. Conclusions

The state-of-practice for dual aisle, wide body commercial aircraft fuselages has evolved over the past generation from minor aerodynamic composite fairings and flaps to entire composite fuselage structures. It has been a methodical, tenacious process that has included determined efforts by resources from the military and defense department, academia and many industry participants. It has been a global race between teams in the US and Europe with both competitors realizing a win-win outcome. Enormous technical advances were required on many fronts, from tooling to transportation. Equally enormous advances were requisite on the cost competitiveness of manufacturing and assembling composite materials in order to earn their way onto commercial aircraft platforms. New mid-market aircraft platforms from both sides of the Atlantic will be the launching pad for the next wave of technologies that have earned their way onto dual aisle commercial aircraft. After that, the industry anticipates direction on long awaited replacement designs for workhorse single aisle aircraft—composite fuselage or not?

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Conflict of interest

No conflict of interest exists with this research.

Notes/thanks/other declarations

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