Commercial Aircraft

Extra large by any measure

Advanced composites play a big role in the success of the world's largest commercial aircraft.

At 555 passengers and a maximum take-off weight of 1,235,000 lb (560 metric tons), "huge" is the most appropriate word to describe the Airbus A380-800, the world's largest jet airliner, set to begin regular service in 2006. The plane itself is an enormous achievement, but so is its impact on the worlds of commercial aviation, advanced materials and composite manufacturing technologies. Over a decade in the planning and design phase, the first flying aircraft is currently under construction, incorporating a host of innovations, including a number related to advanced composites. Based on interviews and information supplied to *High-Performance Composites* by Airbus and its suppliers, the following is a comprehensive overview of the design downselection process employed in the creation of the A380 structures and the processes and materials that are being used to fabricate most of its major composite components. (For competitive reasons, or due to continued evolution of part designs, some details are still confidential.)

Source: Airbus Industrie

First deliveries of the double-decker A380 are scheduled for Spring of 2006. Inset shows relative size comparison between the A380, the wide-body A340 and the single-aisle A320.

According to Airbus' current plans, the A380 will carry 30 metric tons/66,000 lb of structural composites, primarily of carbon-fiber/epoxy, or 16 percent of its airframe weight (approx. 170 metric tons), making it the most composite-intensive commercial aircraft to date. Due to the higher stiffness-to-weight performance of carbon fiber composites, this is equivalent to the replacement of 20 percent of conventional aluminum structure. This figure could rise to 35 metric tons (77,000 lb) as the final component designs near completion. Wing leading edges will take advantage of economies realized in the use of glass-reinforced thermoplastics. And 4 percent of the airframe will be GLARE (GLAss fiber-REinforced aluminum), a multi-layer laminate of fiberglass/epoxy and aluminum to be used in the upper fuselage panels (discussed below and in *HPC* May/June 1996, p. 28). Beyond the structural composites under discussion here, as many as 30 metric tons of composites, mainly fiberglass/phenolic, may be used in each plane's interior.

Airbus' Jens Hinrichsen, emphasizes, "We have selected the most appropriate materials for the structural applications." Currently the leader of the vertical tailplane component management and integration team for the A380, and a strong proponent of composite use in airframe construction, Hinrichsen was previously the director of structures for the Airbus large aircraft division.

A wide range of composite manufacturing processes will be employed in the A380's production, with significant use of advanced fiber placement (AFP), resin film infusion (RFI), and pultrusion. Additional processes will include automatic tape laying (ATL), resin transfer molding (RTM), thermoplastic forming/welding, and hand layup/autoclave processing.

Responsibility for fabrication of major airplane sections has been divided among the principal Airbus partners. Airbus France will manufacture the center fuselage, including the carbon fiber composite center wing box, as well as the nose and cockpit. BAE Systems will produce the main wing sections. A large portion of the A380's fuselage fore and aft of the wings (including assembly of GLARE panels) and fabrication of its vertical tail and rear pressure bulkhead will be performed by Airbus Germany. Airbus Spain will make the composite aft fuselage, belly fairing, horizontal stabilizer, rudder and elevators. A number of secondary structures will be fabricated by partner subcontractors in Europe, the U.S. and Japan.

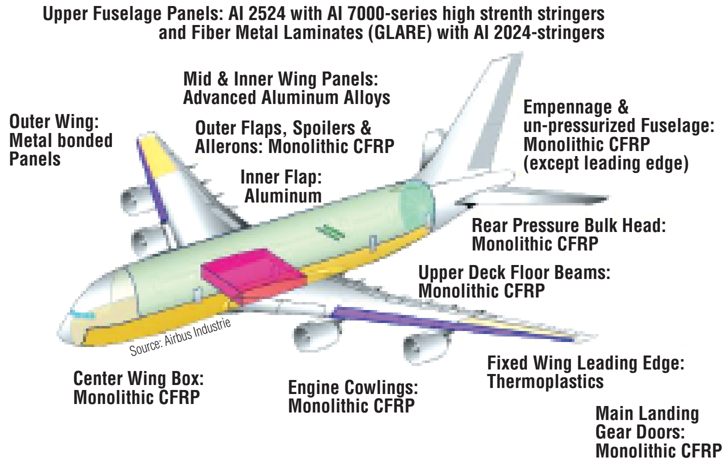
Over a decade in development

Airbus has explored a double-decker fuselage concept since the early 1990s, including joint efforts with Boeing for two years, beginning in 1993. Concluding that the potential market was too small to justify a "jumbo" design, Boeing judged its 747 program sufficient to meet the need and cancelled its participation. Airbus continued alone, initiating the A3XX program in 1994. Airbus began offering the aircraft for sale in early 2000 and, as of the end of July 2002, had received 97 firm orders, including 17 freighter versions, from nine airlines. Airbus forecasts a market for about 1,300 aircraft in the jumbo category over the next 20 years, and expects to capture at least half of those orders. With an estimated investment of $10.7 billion/10.9 billion euro in development and facilities, and a list price of from $239 million/244 million euro to $263 million/268 million euro, Airbus predicts profitability will be attained by the 250th aircraft. Airbus claims operating costs per seat/mile are 15 to 20 percent lower than competing aircraft, such as the Boeing 747-400. Estimated airline breakeven is projected at 323 passengers, or a load factor of 58 percent.

The need to accommodate a record number of passengers yet operate within the current airport infrastructure set some sizable constraints on the aircraft's design. Input from airlines and airports was obtained through a series of workshops and bilateral meetings, beginning in 1996. It was necessary to limit the aircraft height to 24.5 meters/80.4 ft, and to keep overall dimensions within the 80m /262.5 ft square box that most airports allow for maximum aircraft docking space.

By these metrics, Airbus has been successful. The A380's overall length is 73m/239 ft, with a height of 24.1m/79.6 ft and a wing span of 79.8m/261.7 ft. For comparison's sake, the horizontal stabilizer (part of the A380 tail) is equal in size to the main wing of the Airbus A310, a widebody, twin-aisle, 220-passenger aircraft. Since the A380's seating runs two levels the full length of the aircraft, simultaneous boarding bridges for both decks are expected to provide faster turnaround times than today's 747 operations.

The initial passenger version, the A380-800, seats 555 passengers in a three-class configuration



Advanced composites, including carbon fiber/epoxy (CFRP), fiberglass/thermoplastic and GLARE, are used extensively in the A380's primary and secondary structures.

(first, business, economy) and has a range of 8,000 nautical miles (14,800 km) at an economically efficient speed of Mach 0.89 (approximately 675 mph or 1,085 kph). A planned stretched version (A380-900) will transport 656 passengers, and an extended range variant (A380-800R) will fly 555 passengers as far as 8,750 nautical miles (16,200 km). First deliveries of the freighter configuration, A380-800F, start in 2008.

Fabrication of the first A380 began January 23, 2002 at the Nantes, France Airbus factory, with the wing root metal joints and the carbon fiber center wing box. In October 2003, A380 components from Airbus plants in Nantes and elsewhere in Europe will be transported to Toulouse, France, where final assembly will begin in 2004, in an assembly hall under construction in the Aéroconstellation industrial park. Some of the component sections are larger than can be carried by the Airbus Beluga transport (see *HPC* March/April 1999, p. 32), so they will be shipped from production

Source: Airbus Industrie

During the down-selection process for the A380, Airbus extensively tested full-scale demonstration structures, such as this 240m^2/2,583 ft^2 horizontal stabilizer, fabricated from ATL-grade carbon/epoxy prepreg.

sites to Bordeaux, France via ocean from the ports of Hamburg (Germany), Mostyn (U.K.), Saint-Nazaire (France) and Cádiz (Spain). From Bordeaux, they will float by river barge to Langon and finally on to Toulouse by road. After rollout, each aircraft will be flown to Hamburg for painting and cabin furnishings, as specified by the individual airlines.

A GLOBAL SUPPLY BASE

A program as complex as the A380 requires the support of many subcontractors and suppliers. Material selection for the primary and secondary structures is almost complete, with Hexcel Composites (Dublin, Calif., U.S.A. and Duxford, Cambridge, U.K.) and Cytec Engineered Materials (Tempe, Ariz. and Wrexham, Wales, U.K.) serving as the principal suppliers of prepregs, resins and adhesives.

"The A380 program will have a significant impact on the composites industry" says John Stowell, Hexcel Composites' VP of marketing. "We are seeing further penetration of composites into aircraft primary structures, extending from the center wing box, to the rear fuselage and the pressure bulkhead. The A380 program has also encouraged the industry to adopt RTM and RFI, as well as automated fiber placement and automated tape lay-up. The result is a move towards a more industrialized process that takes cost out of the composite component production."

Hexcel's **HexPly M21 carbon fiber prepreg** (high-strength- and intermediate-modulus fiber types, in woven fabric and ATL grade tape forms) has been selected for the center wing box and the skins of the vertical and horizontal stabilizers (select **239**). M21 is a "third generation" toughened epoxy matrix, according to Hexcel, providing superior damage tolerance to that of previous toughened aerospace epoxies. Controlled flow and a simple cure schedule have been incorporated into the product to ease processability.

Hexcel will supply **HexPly 8552/AS4 prepreg slit tape** (select **240**) for automated fiber placement of the aft fuselage skins. HexPly 8552 is a high toughness and damage tolerant prepreg, curing at 180°C/356ºF. JAMCO has selected **HexPly 6376 epoxy prepregs** (select **241**), using **Tenax/Toho HTA fibers** (select **276**) for the pultruded stringers and stiffeners of the vertical stabilizer. **HexPly 913 prepreg** (select **242**) is being qualified for the A380 belly fairing. 913 has the advantage of curing at low temperatures, a standard cycle being 1 hour at 120°C/250ºF.

Hexcel's new-concept, non-crimp **NC2 fabric** (select **243**) has been selected, alongside Hexcel's **RTM6 resin system** (select **244**), to manufacture the corner fittings and the central beams of the center wing box. Non-crimp fabrics are multilayer fabrics in which the plies are oriented for maximum performance. Hexcel reports that NC2 uses novel stitching technology to fix the fabrics into place, allowing full flexibility of ply stack sequence and orientation. Hexcel's RTM6 is a single-component resin system specifically developed for RTM, featuring low viscosity at low temperatures (suitable for low injection pressures) and with a gel time of 30 minutes at 180°C/356ºF. The first RTM resin to be qualified to an AIMS (Airbus Industry Material Specification), RTM6 has a high glass transition temperature, excellent hot/wet properties, and low moisture absorption. The frames of the aft fuselage and the vertical stabilizer C-ribs and front and rear spars are also infused with RTM6, but use non-crimp carbon fiber fabrics supplied by **Saertex Wagener GmbH** (Saerbeck, Germany, select **245**).

Other Hexcel resin products include **HexPly M36 resin film** (select **246**) for resin film infusion and **Redux 319A high-performance film adhesive** (select **247**). M36 is a low-density, low-exotherm matrix suitable for infusion of thick preforms and curable at temperatures as low as 130ºC/266ºF, using an autoclave or by vacuum-assisted infusion, followed by oven cure. Redux 319A is supplied with a woven nylon carrier for peel enhancement and glue-line thickness control, and it cures in 60 minutes at 175°C, providing excellent peel properties and good drape. Hexcel will supply GKN Aerospace (Farnham, Surrey, U.K.) with materials including prepreg and RFI materials for the A380 trailing edge and flap track beam packages.

Hurel Hispano (Le Havre, France) has asked Hexcel to supply special process honeycomb parts for the inner fixed structure of the engine nacelles. Measuring 3.2m by 2.8m/10.5 ft. x 9/2 ft., nacelle parts will each be made from 46 different pieces of **HexWeb PAA honeycomb** (select **248**), some of which will be heat released. HexWeb PAA is made from aluminum foil anodized with phosphoric acid to optimize the bond between the face sheets that carry the bending loads and the honeycomb that carries the shear loads. Hexcel supplies similar parts for the A340-500/600. Socata (Toulouse, France) will use heat-formed and machined **HexWeb aramid paper honeycomb** parts for the landing gear doors (select **274)**.

Cytec's wide range of A380-bound products includes unidirectional prepreg, combining **Cytec's FM 94 adhesive resin** (select **249**), and S-2 glass from **Owens-Corning** (Toledo, Ohio, select **250**), for the fabrication of the upper fuselage GLARE panels. FM 94 cures at 121ºC/250ºF and offers service temperatures to 107ºC/225ºF.

Cytec's **CYCOM 977-2 toughened epoxy resin** (select **251**) is being used on a variety of A380 primary structures, says Frank Nickisch, Cytec's Airbus program manager. For the center wing box and the skin panels of the horizontal and vertical stabilizers, Cytec is qualifying ATL grade tape, using **IM fibers from Toho/Tenax** (select **252**). In addition, 977-2/carbon fabric prepregs and tapes are used for hand layup of the center wing box frames, the intermediate main wing ribs and the leading edge/truss ribs of the vertical stabilizer. For the huge resin-film infused rear pressure bulkhead, 977-2 resin film is being used in combination with **Saertex non-crimp multiaxial carbon fabrics** (select **253**). Nickisch emphasizes that "977-2 is the only epoxy resin qualified for primary structures which also meets Airbus requirements for flame, smoke and toxicity."

In secondary structures, 977-2 is used in mostly hand layup structures, using either carbon fiber fabrics or UD tapes. This includes the nose landing gear doors, flap track fairings, pylon fairing access panels, flaps, spoilers and ailerons. The solid main landing gear doors are produced via fiber placement using 977-2/HTS slit tape. **Cytec's CYCOM 919 epoxy** (select **254**), designed for 121ºC/250ºF cure, is under consideration on carbon and glass fabrics for the belly fairing.

In the aft fuselage skins and the outer nacelles, Nickisch points out that a resin with a higher glass transition temperature (Tg) is required. Cytec is qualifying **CYCOM 997/HTS** (select **255**) in 196 gsm slit tape form for these applications. CYCOM 997 has a dry Tg of 210ºC/410ºF and a wet (moisture conditioned) Tg of 160ºC/320ºF, which is 20ºC/36ºF above 977-2. The trade-off in using 997 is slightly reduced impact performance.

Other Cytec products qualified for use on the A380 include **FM-300 film adhesive** (select **256**) for composite bonding and epoxy surfacing films for composite parts. For metal-to-metal bonding, **FM-73 autoclave** (select **257**) and **FM-94 non-autoclave** (select **258**) film adhesives are Airbus approved.

Early in 2002, Airbus tapped Toray Corp. (Ehime, Japan) to supply **Torayca T800S 24K carbon fiber** (select **259**), and Toho Tenax Corp. (Mishima, Japan) to provide **Bestfight IM600 24K carbon** (select **260**), covering the majority of the A380's intermediate-modulus fiber requirements. Hexcel and Cytec will use the fibers to make ATL-grade prepreg tapes for the center wing box and the vertical and horizontal stabilizers.

Since the first aircraft delivery is still over three years away, final selections of suppliers of some components are yet to be decided. In addition to profiles for the vertical stabilizer, JAMCO will provide pultruded carbon fiber/epoxy prepreg floor cross beams for the A380's upper deck. Qualified interior materials and component suppliers, including **Stesalit AG** (Zullwill, Switzerland, select **261**), **AIK** (Kassel, Germany, select **262**), Hexcel, Cytec, and M.C. Gill (El Monte, Calif.), will support the interiors of the A380.

Candi Burdick, marketing manager for M.C. Gill's interiors business, says the company has proposed novel solutions to save weight on the A380 interior, including a stronger honeycomb, based on N636 Kevlar (see *HPC*, May 2002, p.56) from **DuPont Advanced Fiber Systems** (Richmond, Va., select **263**). Produced from para-aramid fibers, **M.C. Gill's N636 honeycomb** (select **264**), combined with the company's own phenolic/fiberglass prepreg, permits the fabrication of sandwich panels up to 20 percent lighter than first-generation Nomex honeycombs, based on meta-aramid fibers. The company has proposed this system, which meets Airbus ADB0031 FST requirements, for flooring and cargo liner panels on the A380.

Hexcel is proposing a flooring system of **HexWeb HRH-36 honeycomb** (select **265**), based on N636 Kevlar, in combination with fiberglass prepregs using **HexPly M25 modified phenolic resin** (select **266**) and self-adhesive, self-extinguishing **HexPly M26 epoxy resin** (select **267**). Both resins meet ADB0031 FST requirements. **HexPly 250 phenolic prepreg** (select **268**) is being evaluated by Airbus for interior cabin panels, like sidewalls and storage bins. **Cytec's CYCOM 799H phenolic** (select **269**) is under consideration for interior panels, and Airbus is evaluating **Cytec's self-extinguishing thermoplastic composites** for overhead storage bins (select **275**).

The first flight, using an A380 fitted with Rolls-Royce Trent 900 engines, is planned for the end of 2004. The first aircraft powered by Engine Alliance GP7200 engines (the product of a General Electric/Pratt & Whitney joint venture) will take off a year later. The test program calls for four aircraft and 2,200 flight hours over 15 months. Concurrent with flight testing, static tests will take place in Toulouse and fatigue testing in Dresden, Germany.

Certification is expected early in 2006, with entry into service with Singapore Airlines and Emirates in March 2006. The cargo version is slated for initial operation in June 2008. The A380's maximum production rate is expected to be four per month.

Development and down-select

Due to the sheer size of the A380, material supply and manufacturing processes must permit production of much longer and wider panels at twice the average thickness compared with smaller aircraft. A rigorous down-selection process, comparing traditional methods of fabrication with all available options, was undertaken by Airbus, evaluating material performance, manufacturing capability and costs. To reduce risks, Airbus manufactured and structurally tested full-scale demonstration articles to support the decision-making process.

Of course, the selection process is easier if the proposed material or technology has been accepted on other aircraft programs. "One of the most challenging tasks in an aircraft program is to achieve maturity in a new technology in advance of the decision milestones," explains Hinrichsen, in describing the efforts at Airbus to ensure production-readiness of the composite structures for the A380.

Most of the composite applications on the A380 have been proven, albeit in smaller dimensions, on previous Airbus aircraft. In most cases, such applications are still in production, or have flown as demonstration articles to prove out the performance. For example, each Airbus aircraft in production today has a carbon fiber tail. The use of thermoplastic composites for the fixed wing leading edge, solid carbon composite engine nacelles, and a carbon fiber rear pressure bulkhead were introduced on the A340-600. However, none of these applications approached the massive scale of the A380.

Down-selection begins, notes Hinrichsen, with the establishment of a "reference solution": state-of-the-art materials and manufacturing options are defined, which fulfill the requirements specified for the structural concepts of each aircraft component. In the next step, new materials are screened for potential weight savings, cost reduction for manufacturing, and maintainability throughout the life of the aircraft. A 3.2 percent savings in total aircraft weight yields a 1 percent reduction in direct operating costs. But the trade-off between airframe weight and cost requires that new technologies earn their way onto the airplane. Higher material prices for composites must be offset by savings in manufacturing processes at the component level. These savings might include, for example, shorter production times, less scrap, lower-cost forming processes, less heat treatment, or lower assembly costs.


Source: ATS Project Management

The A380's GLARE fuselage panels are layed up on highly accurate metal tooling as large as 10m by 3m/33 ft x 10 ft. Special transporters suspend workers over the panel.

"Benefits can be measured using the reference solution as a yardstick," says Hinrichsen. "Screening is based on knowledge of structural design drivers, for example, compression or tension loading, buckling, residual strength or crack growth, depending on a given set of initial loads and the location within the airframe. As a prerequisite, the structural design concepts must have reached a certain stage of maturity in terms of optimization, load path and load level, respectively."

Despite the benefits of composites, the variations in thickness that occur in the manufacturing process limit to some degree the extent to which they can replace aluminum. "The target for composites needs to be shim-free assembly," says Hinrichsen, adding that "aluminum is making significant progress, with more new alloys and bigger panels." However, the high scrap ratio (due to machining, chemical milling, etc.) makes the average buy-to-fly cost ratio for aluminum structures nearly twice that for composites. For highly complex structures, such as the aft fuselage with its double curvature, using composites results in great material efficiencies.

There are cost/performance trade-offs between composite materials and processes, as well. Airbus has determined that in many applications, more expensive intermediate-modulus fibers do not deliver significant weight savings under a compressive load, especially after impact. As a result, most of the carbon fiber used on the A380 will be standard-modulus. Similarly, non-crimp carbon fiber fabrics infused with RTM-type resins yield a part with an acceptable 10 percent lower material performance at considerably less expense than automated tape layup of prepregs. For example, the resin-infused internal spars of the vertical tail plane (stabilizer) incur a 7 percent weight penalty but cost 40 percent less than prepreg layups, and the ribs of the vertical stabilizer, due to their configuration, are weight neutral between the two processes.

Due to airline concerns over maintainability, honeycomb structures have been minimized, yet some still will be used on the A380, particularly in areas subject to impacts from foreign objects: flap track fairings, and the fuselage belly fairings are a combination of carbon and fiberglass/epoxy skins over impregnated paper honeycomb core. Pylon fairing access panels, fabricated by Goodrich Corporation (Charlotte, N.C.) and the nose landing gear doors are carbon fiber skins over composite honeycomb. The leading edges on the horizontal and vertical tail are also honeycomb structures. Many other traditional honeycomb secondary structures, such as flaps, rudders, elevators and engine cowlings, have been converted to stiffened solid laminate composites.


Source: Airbus Industrie

The A380 wing fixed leading edge will be produced from fiberglass/PPS thermoplastic prepreg supplied by Ten Cate. The technology was first proven on the A340-600 leading edge, shown here.

Down-selection included coupon tests and full-scale component testing in order to validate both structural design concepts and new materials. Because of the A380's enormous size, full-scale demonstrator programs helped validate design principles and assured the maturity of the manufacturing processes. Hinrichsen explains the Airbus reasoning: "Simulation of processes has to occur in a plant environment, not in laboratories. The test articles have to be of equivalent size and surface curvature, and stiffening elements and local reinforcements at load introductions have to be demonstrated in tooling and manufacturing processes, representing a real structure at full scale. For example, performing hand layup of carbon fiber preforms on a mold of real size gives a feeling for the accessibility and for the quality that can be achieved in a real production line." From such trials, development engineers get information about gaps and overlaps of the layup, which need to be in line with structural design requirements. "Different inspection methods can be studied in order to optimize the manufacturing processes and the quality control efforts," Hinrichsen explains. "Subsequent modifications of jigs and fixtures can be performed before the production line starts operations."

CASA (Airbus Spain), for example, completed a large composite horizontal tail skin early in 1999. The huge size of the horizontal stabilizer (240m²/2,583 ft²) and a structural design which requires thick carbon fiber laminates for panels and spars in the carbon fiber composite torsion box were the drivers for a full-scale demonstrator. The specimen underwent fatigue load spectra — testing that varies the frequency and amplitude of loads to replicate typical in-service flying/takeoff/landing conditions, in this case, simulating loads endured during twice an aircraft life. The impact of damages and repairs were studied during the second half of the test cycles, with predictable and successful results.

Blending composites with metal

For the main fuselage design, Airbus considered several critical loading conditions,

Source: Airbus Industrie

A full-scale (5.5m by 6.2m/18-ft by 20.3-ft) A380 rear pressure bulkhead, produced from CYCOM 977-2 epoxy and Saertex non-crimp carbon fiber fabrics using the resin film infusion process.

namely, internal pressurization, lateral gusts and maneuvers, and vertical gusts and maneuvers. Some of the structural design criteria included tension loads in the upper fuselage, which can lead to fatigue cracks (and concerns over crack growth rates), compression loads in the lower fuselage, impact damage tolerance, and corrosion resistance.

In response to these loads, Airbus selected GLARE for much of the upper fuselage skin. Approximately 80 percent of the panels are produced by Fokker Aerostructures (Papendrecht, The Netherlands). The other 20 percent are manufactured in an Airbus plant at Nordenham, Germany. Each A380 will have about 500m²/5380 ft² of GLARE, located forward and aft of the center section, but not in the most highly stressed upper center section, where aluminum alloys will be used. Aluminum-only skin panels will also be used in the lower fuselage, manufactured using a continuous laser-welding process to attach the longitudinal internal stringers, eliminating the riveting process typical of such structures.

GLARE has been in development for 25 years in the Netherlands, with the A380 representing its first large-scale use in aircraft primary structure. It is produced by alternating layers of aluminum and fiberglass/epoxy. The manufacturing process for GLARE is almost identical to that for composite laminates, but the finished product can be cut, drilled, riveted, and repaired

Select 113 (turn to page 35)

Select 114 (turn to page 35)

using techniques originally developed for aluminum. GLARE's key structural property is better tensile fatigue resistance than conventional aerospace aluminum, and in fatigue-critical areas where crack propagation could be an issue it can take 20 to 25 percent greater loads. Airbus projects weight savings of 15 to 20 percent in the upper fuselage skins (where tension is the predominant structural load) versus using aluminum.

Initially, GLARE panels were several times the cost of competing advanced aluminum structures. It took six years to achieve cost parity. As late as 1997, GLARE panels were made flat, then bent to fuselage curvature; they cannot be formed to the degree that aluminum can, but the slight curvature needed for the fuselage skin is achievable. Airbus and its subcontractors attained the needed cost breakthrough on the A380 by assembling the layers with the curvature *built in*, bonding the doublers and many of the stringers into the structure during the same step (see "Applications," in this issue, p. 28.)

ATS Project Management BV (Eindhoven, The Netherlands) has fabricated ten of the large laminating molds used to form the A380 GLARE skins, according to Remco van den Berg, international account manager for ATS. Such tooling is usually produced from either steel or aluminum that is roll-formed and welded together, then welded to a substructure and 5-axis machined to final dimensions. ATS is supplying molds for the A380 as large as 10m by 3m/33 ft by 10 ft. The straightness tolerance of 0.05 mm per meter/0.0006 inches per foot is verified using a laser tracking instrument. Vacuum channels integral to the mold hold the laminate against the curved surface during layup and cure. ATS also worked with Fokker and Airbus to develop special fixturing and layup carriers (which support workers comfortably over the molds during layup) for parts the size of those required for the A380.

Carbon fiber wing box

The A380's largest single structural component is its huge center wing box. Measuring 7m/23-ft wide by 6m/20-ft long by 2m/7-ft high, the wing box runs across the lower fuselage and connects the wings to the fuselage of the airplane. It experiences heavy loading during takeoffs, landings and turbulent weather. In boldly deciding to fabricate the part from carbon fiber composites, Airbus has determined that the state of the technology is sufficiently mature and the risks low enough to go forward.

According to Hinrichsen, the center wing box can be regarded as a fuselage substructure, protected against foreign object damage and direct lightning strikes by the belly fairing. Given this protection and a thorough understanding of the loads, it was a natural candidate for composites. Weighing approximately 9 metric tons (19,800 lb), the wing box is built at the Airbus facility in Nantes, France, using a combination of hand layed prepreg fabrics and ATL, using unidirectional carbon fiber tapes, followed by autoclave curing. Both standard- and intermediate-modulus carbon fiber prepregs are used. Wing box skins and frames are produced separately and assembled using mechanical fasteners.

To match the low coefficient of thermal expansion (CTE) of the carbon fiber composite during the curing process, layup molds for the center wing box skins are

Select **115** (turn to page 35) ***See us at CFA Booth #737***

machined from Invar 36 nickel/iron alloy. Seven of the skin molds, measuring up to 4.4m by 2.6m/14.4 by 8.5 ft were produced for Airbus by UCAR Carbon International (Irvine, Calif.) and shipped by ocean to Nantes, France.

Airbus seriously considered carbon fiber composites for the outboard wing boxes, but a heavy, complex joint would be required between it and the aluminum inboard wing above the outboard engine, negating over half the potential weight savings and increasing costs. As a result, outboard wing boxes will be aluminum structure optimized for damage tolerance.

The wing's composite leading edge, or "D-nose," capitalizes on proven technology originally developed for the A340-600. Formed from Cetex PPS (polyphenylene sulfide)/glass fabric "semi-preg" from Ten Cate Advanced Composites BV (Nijverdal, The Netherlands), the thermoplastic composite saves up to 20 percent in weight over an equivalent aluminum D-nose structure, and has better impact resistance (see *HPC* March/April 2000, p. 27). The PPS resin provides excellent chemical resistance to deicing fluids, hydraulic fluid and jet fuels.

The partially consolidated prepregs supplied by Ten Cate are flexible and relatively easy to cut compared to fully impregnated thermoplastic composites. Full consolidation occurs at the part production stage in an autoclave under pressure at 650°F/343°C, above the melting point of the PPS. The curved D-nose skins are formed directly into the desired shape. The ribs and stiffeners are compression molded, using blanks cut from consolidated, flat multi-layer sheets of thermoplastic composite. The assembly of skins and reinforcing elements is done entirely with thermoplastic welding, eliminating mechanical fasteners. Currently the production source for the A340-600 leading edge, Fokker Specialty Products (Hoogeveen, The Netherlands) is also manufacturing these parts.

"Thermoplastics make sense where thermoplastic welding can be used to eliminate riveting in locations such as the wing's leading edge," says Hinrichsen. However, thermoplastics still lack the stiffness of epoxy-based composites. On the wing leading edge, they not only eliminate rivets and associated labor for drilling and installation, but they also provide greater impact resistance than a thermoset material delivers. "Today, they are a 'niche product' and a price breakthrough is needed," Hinrichsen maintains, noting, "We need roughly a 50 percent reduction in finished part price before thermoplastics can be used more widely."

The use of carbon fiber composites for movable control surfaces on the wing trailing edge is regarded by Airbus as state-of-the-art. Inboard flaps are aluminum, for impact resistance from foreign objects thrown up by the landing gear, but outboard flaps, spoilers and ailerons are fabricated in solid carbon fiber laminates. Flap tracks for the A380 are carbon fiber/epoxy combined with titanium reinforcements. Also originally designed as honeycomb structure, the main landing gear doors have been converted to solid carbon fiber laminate, using automated fiber placement.

The A380 is powered by four engines, each with a nominal 70,000 lbs of thrust in the passenger version and 76,500 in the freighter version. Engines offered include the Rolls-Royce Trent 900 and the Engine Alliance GP7200, each of which will use composites in selected components. Engine cowlings (nacelles), produced by Airbus

Select **116** (turn to page 35)

Spain in solid carbon fiber composite using fiber placement, will complement both engine designs. The A380 has been designed to be quieter than a 747, to meet the latest noise restrictions at London's Heathrow airport (allowing night take-offs with a full load).

Aft fuselage and bulkhead are carbon intensive

Starting with the rear pressure bulkhead, which separates the pressurized passenger and cargo sections of the plane from the unpressurized tail section, or empennage, and moving rearward, composites make up the majority of the aft structure of the A380.

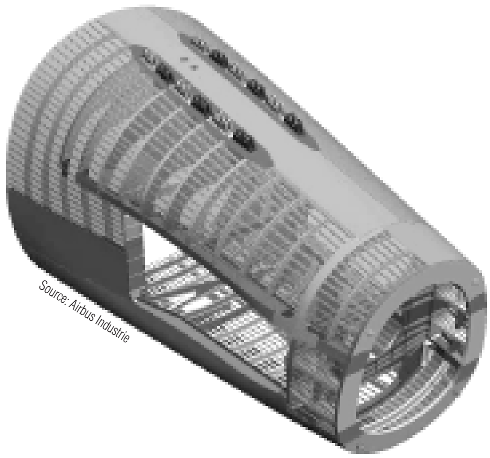
The huge, dish-shaped rear pressure bulkhead is built by Airbus Germany using RFI and non-crimp, high-tensile-strength carbon fiber fabrics in a multiaxial layup scheme. The mating flange to the fuselage has an oval shape that is about 6.2m/20.3 ft tall and 5.5m/18 ft wide, making the bulkhead one of the largest structures in production using RFI. Reinforcing stiffeners produced from the same materials are co-cured to the bulkhead's curved back.

The unpressurized aft fuselage, built by CASA, is defined by the intersection with the horizontal tailplane, or horizontal stabilizer, and the join-up of the vertical tailplane, or vertical stabilizer. For the A380, overall dimensions of this tapered section are approximately 8.2m/26.9 ft in length and about 6.6m/21.7 ft maximum height. Its complex outer contour is the result of an aerodynamic optimization process. In aluminum, 16 stretch-formed panels would be required, due to the pronounced double curvature. Here, composite structures can be cost-competitive with metal panels because processing allows for inherently better material utilization (less waste) and requires fewer joints, provided that the number of skin panels can be reduced.

Hinrichsen notes that by using composites, the aft fuselage could be constructed with as few as four panels, using automated fiber placement (AFP) and achieving a 15 percent weight savings. However, Airbus is choosing to make it with six AFP panels, (still a fraction of the number of joints required for aluminum) because it eases repair after tailstrike. Automated tape laying (ATL) was ruled out for the aft fuselage panels. The degree of double curvature in the mold surfaces prevents the tape layer from applying consistent pressure across the mold surface, potentially resulting in gaps and overlaps. To a greater degree than fabrics or tape, AFP optimizes fiber orientations, although the aft fuselage is principally a quasi-isotropic structure (that is, one with a balanced orientation of fiber directions). This would permit the use of hand layup for either prepregs or non-crimp fibers, but the size of the mold creates excess difficulty for the workers, which may result in deterioration of the quality standard in serial production. The aft fuselage skins are riveted to carbon fiber frames, which are produced by resin transfer molding.

The horizontal tail is also produced by Airbus Spain. ATL is used for production of the tail skins and spars, as well as for the skins of the elevators. In addition to its role in stabilizing the vertical movement of the aircraft, the horizontal tailplane also serves as the fuel trim tank for the A380 because the carbon fiber/epoxy prepreg structure is highly resistant to jet fuel.

The vertical tail is produced at Airbus Germany, with dedicated manufacturing processes, optimizing costs and process stability for the respective structural elements and assembly. ATL is used for the skins of the vertical torsion box and the rudder. The complex leading edge ribs and truss ribs are hand layed. The "C" ribs and the "C"-shaped front and rear spars are resin-infused non-crimp fabrics. Support and actuator fittings are made via RTM. Stiffeners and stringers are cobonded to skin panels during cure. Airbus selected JAMCO Corp. of Mitaka (Tokyo), Japan to pultrude the carbon composite stiffeners, stringers and shear ties for the vertical tail. JAMCO already supplies similar vertical tail profiles for other Airbus aircraft, using ADP (ADvanced Pultrusion)



The complex curvature of the aft fuselage outer skin will be produced using carbon fiber/epoxy slit tape and automated fiber placement. Support frames are produced via resin transfer molding from non-crimp fabrics and Hexcel's RTM6 epoxy resin.

technology, developed in-house. ADP differs from conventional pultrusion in that aerospace-approved prepreg fabrics and tapes are used instead of dry fabrics and resin. The process permits fiber volumes up to 65 percent with void contents under 1 percent. Slit prepregs — in unidirectional and ±45° orientations — are pulled from spools onto shaping rollers, then into a heated compression die where the resin begins to gel. (The process is inline but unlike traditional pultrusion, it is intermittent, not continuous. Movement stops while the parts are gelled in the compression die.) Final cure in a heating zone typically runs two hours at 177°C/350°F for primary structure such as vertical tail components. Process automation, rather than hand layup of prepreg material, results in reduced labor costs. JAMCO recently expanded the Mitaka facility by 1,600 sq. meters (17,220 ft^2) to support the A380 contract.

Overall, the A380 represents an enormous undertaking on the part of Airbus and its suppliers. The project continues to have some elements of risk, especially financially, although Airbus is confident the demand will be there to justify the investment. For the composites community, the A380 represents a culmination of decades of materials and process developments coming together in one place. When the first c cation aircraft takes flight in 2004, the world will be watching.

— Dale Brosius, Contributing Writer

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