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GLOBAL WATCH MISSION REPORT

HYBRIDMAT 3: Advances
in the manufacture of
advanced structural
composites in aerospace
– a mission to the USA

FEBRUARY/MARCH 2006

Global Watch Missions

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Comments attributed to organisations visited during this mission were those expressed by personnel interviewed and should not be taken as those of the organisation as a whole.

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HYBRIDMAT 3: Advances in the manufacture of advanced structural composites in aerospace – a mission to the USA

REPORT OF A DTI GLOBAL WATCH MISSION
FEBRUARY/MARCH 2006

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National Composites Network

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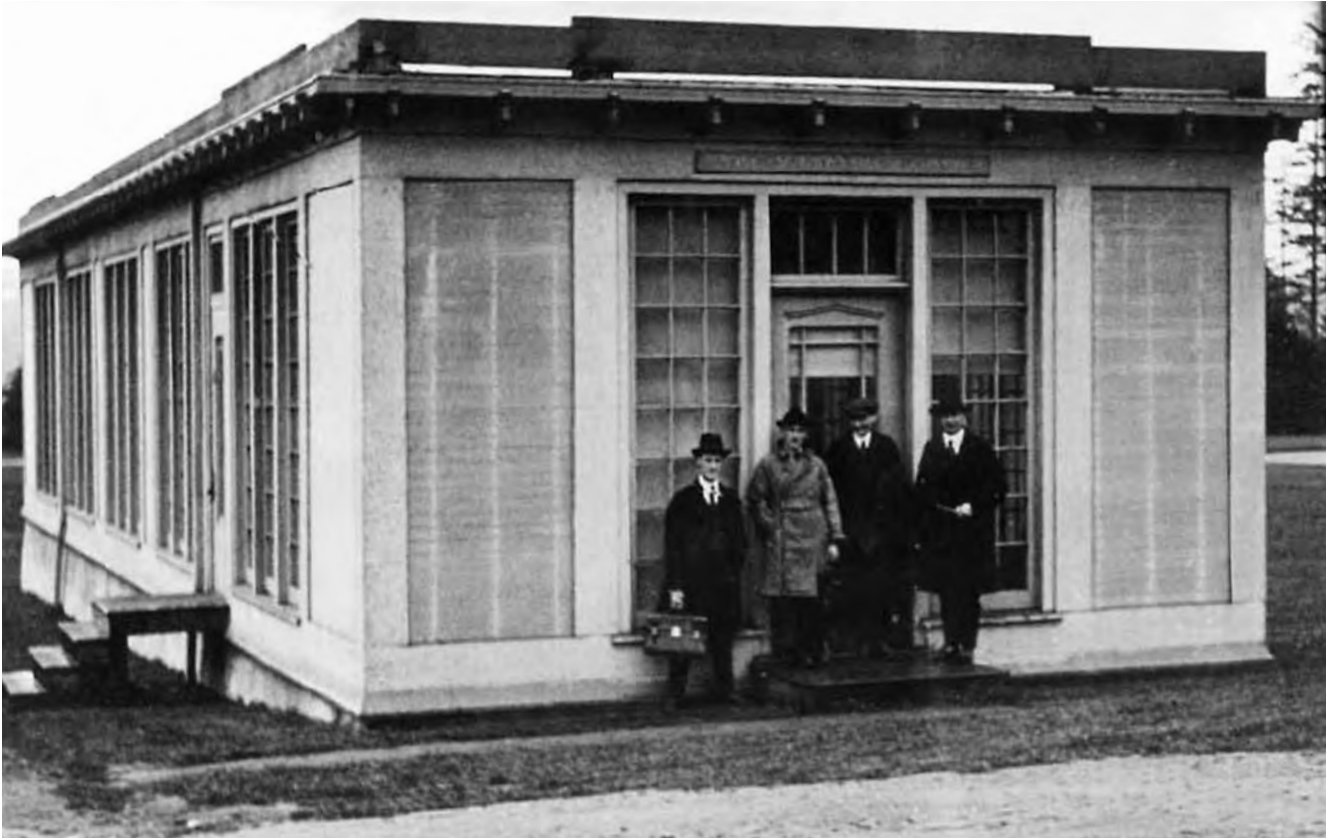


Figure F1 Boeing Aeronautical Laboratory soon after completion in 1917



Figure F2 Mission team standing in front of the historic Boeing Aeronautical Laboratory at University of Washington with Professor Mark Tuttle (Director, AMTAS) and Alan Pritchard (Boeing); L-R: Brian O'Rourke, Chris Beck, John Savage, Roger Duffy, Cliff Young, Andrew Mills, Brian Gilbert, Roger Francombe, Chris Webborn, Mark Tuttle, Alan Pritchard, Sue Panteny

FOREWORD

The global composites market has grown considerably in the last 10 years with current annual revenue for finished parts in excess of £2 billion. This is set to rise by another 25% in the next five years with the aerospace and advanced transport sectors, in particular, contributing significantly to this.

However, increasing economic growth is being achieved by regions with lower labour rates than the West. There is therefore increasing pressure on the UK to draw on the strengths across the whole of its composites industry to maintain competitiveness in this challenging marketplace.

The primary drivers for the selection of composite materials are still weight and durability, but with advances in technology, composites offer greater flexibility in design and affordable component manufacture. This has made a significant contribution to improvements in the total life-cycle cost of products using these materials.

The National Composites Network (NCN) now plays a key role for the UK in signposting existing capabilities and best practice in effective technology insertion for optimised performance and economic improvement. This involves assessment across sectors and global regions. It also seeks to benchmark and identify key gaps in technology vital in maintaining the competitiveness of the UK composites industry on the global stage.

The HYBRIDMAT 3 and 4 DTI Global Watch Missions to the USA, which were managed by the NCN, had the objectives of both promoting UK capabilities and assessing the status of US technology. HYBRIDMAT 3 addressed advanced manufacturing techniques for

composites, while HYBRIDMAT 4 addressed 3-D weaving and near net shape preforms. Findings from these missions will shape the agenda of future technology activities for both the NCN and also government funding initiatives. These will address technology development and transfer in a timely manner to ensure continued improvements in the competitiveness of products for healthy economic growth in the UK.



Ken Wappat
Chairman, NCN

EXECUTIVE SUMMARY

- S.1 Background*
- S.2 The mission*
- S.3 Key findings*

S.1 Background

Aerospace industry composite materials can increase structural efficiency, particularly in stiffness critical applications, resulting in increased range, lower fuel consumption and reduced carbon dioxide (CO₂) emissions. However, weight savings have to be balanced against material and manufacturing costs. The acquisition and through-life costs of composite components can be considerably more expensive than heavier metallic components. More than half the cost of a composite structure is associated with lay-up, cure and assembly. Acquisition and through-life costs can be significantly reduced by low-cost manufacturing and reliable condition monitoring. Recent reviews of the composites industry have highlighted the need for more cost-effective manufacturing processes for high-performance composites.

In composite materials development, the emphasis is now on consistency, longevity and cost-effectiveness, rather than minor increases in mechanical performance. Affordability is the major issue, and manufacturing costs, total life-cycle cost, lack of whole-life performance data and recyclability are issues that are inhibiting composites from attaining their full potential.

Carbon fibre-reinforced polymer (CFRP) composites are now widely used for secondary civil wing structures (leading/trailing edges, flaps, spoilers, fairings, access panels, engine nacelles etc). Airbus led the move into primary structure of large

civil aircraft, first with vertical stabilisers in the late 1970s then with horizontal tailplanes (HTPs) in the 1980s, and keel beams and pressure bulkheads in the 1990s. The A380 will enter service with a composite central wing box and composite rear fuselage sections, but it is the Boeing 787 that will take the next major step forward in large civil aircraft by introducing a complete composite wing and fuselage. Airbus will also significantly increase the usage of primary composite structure by its introduction of complete composite wings on the A400M and the future A350.

In business aircraft, Raytheon has led the way in automated composite fuselage production with its Premier 1 programme.

Traditionally, composite components have been manufactured by curing laminated prepreg layers in an autoclave at high temperature. Cost savings have been sought by automation of the laminating process, but in recent years there have been a number of high-profile programmes aimed at producing large primary structure by 'out-of-autoclave' routes, and at producing smaller complex shaped components by liquid resin infusion of dry fibre preforms.

The progress of alternative low-cost production techniques has been a primary topic of discussion.

S.2 The mission

Consequently a team from UK organisations was brought together to undertake a Department of Trade and Industry (DTI) Global Watch Mission to the USA to exchange ideas on the future directions of

manufacturing processes for aerospace structures with some of the key American industrial and research organisations working in the area. Whilst aerospace organisations were visited, to ascertain the trends in manufacturing processes for composites the synergies with the motorsport sector were studied. The mission, coordinated on behalf of DTI by the National Composites Network (NCN), took place during 26 February to 2 March 2006 and visited the following organisations:

- National Institute for Aviation Research (NIAR), Wichita State University
- Raytheon Aircraft Co, Wichita
- Spirit AeroSystems Inc, Wichita
- V System Composites Inc, Anaheim
- Goodrich Aerostructures Group, Riverside
- Boeing Co, Frederickson
- Center of Excellence for Advanced Materials in Transport Aircraft Structures (AMTAS), University of Washington
- C&D Zodiac Inc (formerly Northwest Composites), Marysville

This report details the main findings of the mission, giving an overview of developments in advances in the manufacture of advanced structural aerospace composite components within the American organisations visited.

S.3 Key findings

There is currently under way a marked increase in confidence and business in the design and manufacture of carbon fibre composite structures in the USA. The timescale for the development of the Boeing 787 is driving massive investment in manufacturing capability. National Aeronautics and Space Administration (NASA) and Federal Aviation Administration (FAA) investment in materials and structural testing at NIAR is removing the barriers of performance and repair uncertainty and reducing the barrier to

new materials introduction by smaller companies such as Raytheon.

Since the last DTI Global Watch Mission in aerospace composites that was undertaken in 1998¹, there is far greater enthusiasm for composites introduction, and designs are becoming less conservative. However, although cost reduction and light weight are still the main drivers, the rapid development of structures required for the Boeing 787 has meant the continued use of prepregs in the short term.

Research and development (R&D) funding has been directed towards development of out-of-autoclave curing processes, resin infusion processes, and integrated stiffened structures with one-stage cure.

The mission team found a wide range of manufacturing, assembly and automation methodologies in use, from legacy programmes such as the Boeing 737 fuselage, to the very latest generation Boeing 787 fibre-placed composites fuselage.

The emphasis for future programmes is very much on major capital investment in facilities and process development.

Innovative solutions to reduce cost and maximise efficiency were evident in the approaches taken by the companies visited. Many of these companies have implemented the principles and culture of lean manufacturing (LM) and statistical process control (SPC), in common with many European companies.

An emerging business model is one that relies on technical development and new product introduction in the developed economies and volume production in low-cost areas.

¹ Aerospace Composite Structures in the USA, DTI, 1998: www.globalwatchservice.com/missions

The majority of applications seen during the mission used the traditional approach of unidirectional carbon fibre, pre-impregnated with epoxy resin, cured at elevated pressure and temperature in an autoclave to give high-quality composite components.

Overall it appears from a tooling perspective that the UK and USA have similar philosophies. Invar is widely used for mould tooling due to its damage resistance and perceived longer life compared to composite, but the weight and heat capacity are becoming increasingly problematic as components increase in size.

There are many similarities in the programmes and work being carried out in North America and the UK and, on balance, technology development is similar between the UK and the organisations that were visited.

The US universities are noticeably involved with industry not only in the R&D undertaken, but also in the day-to-day solving of technical issues for a company, as witnessed at NIAR.

As in the UK, there is a shortage of qualified engineers and trained technical staff. The US universities are addressing this issue by working closely with industry to run courses specific to industrial requirements.

The US Government is aiding its industry significantly with its research programmes and centres of excellence that have been set up in the composites and aerospace sector between universities and industry.

1 INTRODUCTION

- 1.1 *Background*
- 1.2 *Objectives*
- 1.3 *The mission*

1.1 Background

Aerospace industry composite materials can increase structural efficiency, particularly in stiffness critical applications, resulting in increased range, lower fuel consumption and reduced carbon dioxide (CO₂) emissions. However, weight savings have to be balanced against material and manufacturing costs. The acquisition and through-life costs of composite components can be considerably more expensive than heavier metallic components. More than half the cost of a composite structure is associated with lay-up, cure and assembly. Acquisition and through-life costs can be significantly reduced by low-cost manufacturing and reliable condition monitoring. Recent reviews of the composites industry have highlighted the need for more cost-effective manufacturing processes for high performance composites.^{2,3}

Carbon fibre-reinforced polymer (CFRP) composites are now widely used for secondary civil wing structures (leading/trailing edges, flaps, spoilers, fairings, access panels, engine nacelles etc). Airbus led the move into primary structure of large civil aircraft, first with vertical stabilisers in the late 1970s then with horizontal tailplanes (HTPs) in the 1980s, and keel beams and pressure bulkheads in the 1990s. The A380 will enter service with a composite central

wing box and composite rear fuselage sections, but it is the Boeing 787 that will take the next major step forward in large civil aircraft by introducing a complete composite wing and fuselage. The new super-efficient commercial passenger plane will be the first commercial jet ever to have the majority of the primary structure made from carbon toughened epoxy composites.⁴ The 787 is expected to be up to 18 tons lighter than the Airbus 330-200,⁴ with composites accounting for 50% of the aircraft's structural weight – only 12% being aluminium. Airbus will also significantly increase the usage of primary composite structure by its introduction of complete composite wings on the A400M and the future A350.



Figure 1.1 Advanced composite fuselage for the Boeing 787 (courtesy Boeing Co)

In composite materials development, the emphasis is now on consistency, longevity and cost-effectiveness, rather than minor increases in mechanical performance. Affordability is the major issue, and

2 UK Polymer Composites Sector: Foresight Study and Competitive Analysis, 2001

3 www.iom3.org/foresight/hac/wing_summary/DERAWINGSsummary.htm

4 Boeing sets pace for composite usage in large civil aircraft, B Griffiths, High Performance Composites, May 2005

manufacturing costs, total life-cycle cost, lack of whole-life performance data and recyclability are issues that are inhibiting composites from attaining their full potential.

The USA continues to develop CFRP technology. Resin-transfer moulding (RTM) methods are being developed by a number of organisations to achieve greater speed, accuracy and lower voidage than is possible with hand lay-up methods. RTM can give significant cost and weight savings over standard hand lay-up methods. The price of high strength, aerospace quality carbon-fibre tow has fallen since the late 1990s by around 50%, and production worldwide has increased considerably.

Processing trends in the UK are away from hand lay-up towards RTM, resin infusion and thermoforming techniques, whilst a route away from autoclave cure is sought for structural composites. A main recommendation of the DTI-funded composites report was that the highest priority should be given to the development, dissemination and commercialisation of low-cost processing methods.²

This DTI Global Watch Mission evolved to investigate the current and future developments in advances in the manufacture of advanced aerospace composite structures that are being considered by major American aerospace manufacturers and organisations that are already working in this field.

1.2 Objectives

The overall objective was to investigate the current and future strategies for low-cost processing of advanced composite structures in the aerospace sector, through a series of meetings with major US aerospace manufacturers and research organisations that are already working in this field.

This information will be evaluated, condensed and disseminated to the UK composites industry and to the science base, not only in aerospace but to other transport sectors and motorsport. The knowledge will enable UK companies to initiate or refocus research and development (R&D) projects on low-cost structural composite processing technologies that are demonstrating potential success, as well as initiating potential licensing agreements.

Advanced composites in aerospace structures will be an important growth area over the next decade with more composites being used for primary structures.¹ Utilisation of low-cost processes is seen as essential for the UK's advanced composites sector to remain competitive. There is a need to understand current state-of-the-art in low-cost advanced structural composite manufacture and identify future trends.

The overall objective was to investigate the current and future strategies for low-cost processing of advanced composite structures in the aerospace sector. Encompassed within this, specific objectives were identified as:

- Ascertain cross-sector applications
- Investigate increases in systems integration and modelling
- Determine the gaps in current development of low-cost processes and the obstacles to exploitation
- Identify the preferred manufacturing routes, the issues and costs:
 - The current extent of out-of-autoclave techniques, for both civil and military applications, with particular reference to resin film and liquid resin infusion processes (including vacuum infusion)

- Determine the state-of-the-art in predictive modelling tools related to out-of-autoclave processing and control:
 - The process modelling validation required and identification of input data test methods (eg resin impregnation)
- Identify the trends in cure processing:
 - For low and high temperature cures
 - For repair processes
- Assess the current status of near net shape manufacture
- Compare the primary areas of technological development in out-of-autoclave processing to UK capabilities
- Assess technology and research requirements and compare with the UK, eg ultrasonic manufacture
- Describe the UK's work so far in this technology area
- Discuss environmental impact such as whole-life issues, as environmental issues are expected to become major market drivers
- Understand how education and training needs are being addressed compared to the UK
- Identify technology opportunities, exploring areas of potential, mutually beneficial, collaborative work to exploit low-cost composite manufacture
- Ascertain automation and robotic developments and their implication in cost reduction
- Assess what new technologies are being developed and where the competitive advantage will be

- Access technology, knowledge and connections not available in the UK
- Disseminate the resultant findings to the UK composites and aerospace supply industries

The feedback from this mission will give UK companies an insight into the thinking of some of the key American organisations in this area, enabling them to:

- Identify technology gaps
- Focus development programmes
- Initiate potential supply agreements

1.3 The mission

The mission, coordinated on behalf of DTI by the National Composites Network (NCN), took place during 26 February to 2 March 2006 and visited a cross section of original equipment manufacturer (OEM), Tier 1 and research organisations from the aerospace sector:

- National Institute for Aviation Research (NIAR), Wichita State University
- Raytheon Aircraft Co, Wichita
- Spirit AeroSystems Inc, Wichita
- V System Composites Inc, Anaheim
- Goodrich Aerostructures Group, Riverside
- Boeing Co, Frederickson
- Center of Excellence for Advanced Materials in Transport Aircraft Structures (AMTAS), University of Washington
- C&D Zodiac Inc (formerly Northwest Composites), Marysville

This report details the main findings of the mission. Each member of the mission team considered the series of meetings from a different perspective, looking at a specific technology or business area. Those perspectives are reflected in this report, with the following chapters based mainly on the technologies of interest, rather than simply being a chronological sequence of visit reports.

In production terms, and with an eye on lean manufacturing (LM) techniques, there were examples of best practice and less good practice, as would be found on any continent in this industry. It is not possible to make a rigorous comparison between the USA and Europe on the basis of this mission alone, so this report highlights areas where good ideas were seen and may perhaps identify areas where general lessons can be learned about flow and lower cost manufacturing.

It was very noticeable how much more involved universities are with industry in the USA than in the UK, not only in the R&D for a company but also in the day-to-day solving of technical issues. This is seen on a small scale with the materials testing and analysis services that many UK universities now provide.

As in the UK there is a shortage of qualified engineers and trained technical staff but, unlike the UK, the US universities are addressing this issue by working closely with industry to put on courses specific to industrial requirements.

The US Government is aiding its industry significantly with its research programmes and centres of excellence that have been set up in the composites and aerospace sector between universities and industry. The Faraday Partnerships and Technical Centres of Excellence being set up by the UK Government are steps in the same direction and, with the amalgamation into Knowledge Transfer Networks (KTNs), should have enough 'critical mass' to make a difference.

2 ORGANISATIONS VISITED

- 2.1 *NIAR, Wichita State University*
- 2.2 *Raytheon Aircraft Co*
- 2.3 *Spirit AeroSystems Inc*
- 2.4 *V System Composites Inc*
- 2.5 *Goodrich Aerostructures Group*
- 2.6 *Boeing Co, Frederickson*
- 2.7 *AMTAS, University of Washington*
- 2.8 *C&D Zodiac Inc*

The host companies were selected to give a cross section of OEM, Tier 1 and research organisations from the aerospace sector:

2.1 **National Institute for Aviation Research (NIAR), Wichita State University**

NIAR is developing national standards for composite materials used in aircraft manufacturing. Working with NASA's Langley Research Center, NIAR is developing ways to reduce the cost of composite material insertion into aviation programmes. The work on composites standards is highly focused on qualifying a number of new composite materials and advanced processing methods, including RTM, to benefit the aviation community. Damage tolerance, joining, crashworthiness and new nanotechnology for composites are being addressed.

2.2 **Raytheon Aircraft Co**

Raytheon Aircraft is a major manufacturer of business jets and specially equipped aircraft that perform unique and specific tasks, such as photographic, flight inspection, air ambulance, maritime, or electronic surveillance. Raytheon airframes set standards of operational readiness throughout the world, with a long track record of service,

dependability and adaptability.

2.3 **Spirit AeroSystems Inc**

Spirit AeroSystems is the world's largest independent supplier of structures for commercial aircraft. It has designed and built part of every Boeing commercial aircraft except the 717. In addition to the 737 fuselage, Spirit produces the airplane's engine nacelles and pylons, as well as nose sections, nacelles and pylons for the 747, 767 and 777 aircraft. It also designs and produces slats, flaps, forward leading edges and trailing edges for 737 wings, slats and floor beams for the 777 airplane, and wing and fuselage components for the 747. The company also designs and builds aircraft production tooling. Spirit also supplies engine struts and nacelles, vertical fin and horizontal stabiliser, inboard and outboard flaps, and front and rear wing spars for the Next-Generation 737 family of airplanes.

2.4 **V System Composites Inc**

V System Composites specialises in low-cost aerospace composite technologies. The company is a leading production manufacturer and assembler of quality composites using affordable RTM, VARTM (vacuum-assisted resin-transfer moulding) and conventional fabrication technologies for defence, space and commercial products.

2.5 **Goodrich Aerostructures Group**

Goodrich Aerostructures holds a leading share of the world market for its core products and is the world's leading independent full-service supplier of nacelles, thrust reversers and pylons. In addition, Goodrich produces

lightweight, temperature-resistant auxiliary power unit (APU) tailcones for regional jetliners, damage-tolerant rigid cargo barriers for freighter aircraft, and corrosion-resistant structures for tactical military aircraft.

2.6 Boeing Co, Frederickson

Boeing Commercial Airplanes is one of the world's premier commercial jetliner manufacturers with a complete focus on airplane operators and the passengers they serve. Boeing Frederickson Composite Manufacturing Center (CMC) supplies the horizontal and vertical stabiliser assemblies for the Boeing 777 airplane. CMC will provide the vertical fin for the 787 programme through work at its facilities in Frederickson.

2.7 Center of Excellence for Advanced Materials in Transport Aircraft Structures (AMTAS), University of Washington

The University of Washington is working with the University of Manchester, the North West Aerospace Alliance (NWAA), Airbus, Boeing and a wide range of businesses in the UK and USA on the development of composite materials for use in aircraft design and the development of the next generation of materials for aircraft construction. These new materials will lead to significant savings in aircraft weight – thereby saving fuel and reducing emissions.

2.8 C&D Zodiac Inc (formerly Northwest Composites)

Zodiac is a full-service provider of complete aircraft interiors as well as structural and nonstructural composite components. Zodiac is responsible for the design, certification and fabrication of the Boeing 767 interior, and its customer base includes Boeing, Embraer, Bombardier, BAE Systems and all major airlines. The company's R&D centre is continuously developing new processes and methods to expand the capabilities of structural and non-structural composites while reducing overall costs.



Figure 2.1 Jason Scharf (C&D Zodiac) showing Chris Webborn the quality of Zodiac's mouldings

3 MISSION TEAM AND ITP

- 3.1 *Roger Duffy*
- 3.2 *Roger Francombe*
- 3.3 *Brian Gilbert*
- 3.4 *Andrew Mills*
- 3.5 *Brian O'Rourke*
- 3.6 *Sue Panteny*
- 3.7 *John Savage*
- 3.8 *Chris Webborn*
- 3.9 *Cliff Young (ITP)*

The UK mission participants were chosen to make up a well-balanced team of aerospace industry specialists able to make a contribution to the mission. In creating the proposed team, the coordinators deliberately avoided the inclusion of a large civil aircraft manufacturer to maximise the likelihood of open conversations with Spirit AeroSystems, Boeing and Raytheon Aircraft. The team therefore comprised:

3.1 Roger Duffy

*Engineering Manager for
Product and Processes
BAE Systems plc*

BAE Systems is a producer of aerospace and defence equipment, employing 90,000 people – the largest European defence company – and is a top 10 US defence company with an order book of £51.2 billion, £14.8 billion annual sales and £1.2 billion annual R&D spend. At Samlesbury in the UK the main areas of interest are: design, manufacture and qualification of low temperature, low pressure resin systems; infusion processes and processing; automated tape laying and fibre placement; affordable tooling; and assembly methodologies.

3.2 Roger Francombe

*Group Product Manager and
European Aerospace Market
Sector Manager
Advanced Composites Group Ltd*

The Advanced Composites Group (ACG) is a UK-owned company within the UMECO Group that has been at the forefront of advanced composite materials and processing for more than 25 years. The company has a proven track record in developing and marketing application-oriented prepreg materials designed for low temperature and out-of-autoclave processing. These materials find use in a wide range of industries including F1 motor racing, aerospace, automotive, marine, wind energy, recreation, construction, and industrial engineering. ACG is also acknowledged world leader in the design and manufacture of composite tooling. It has production facilities in both the UK and USA, backed up by a state-of-the-art research capability.

3.3 Brian Gilbert

*Senior Consultant and
Project Manager
INBIS Ltd*

INBIS Ltd is a £60 million engineering consultancy company, a wholly owned subsidiary of Assystem, offering wide-ranging engineering experience to a number of diverse sectors and is a leading provider of design and engineering services in Europe, with a pedigree which includes major involvement in many prestigious aircraft projects for both military and civil applications both UK and overseas. INBIS's core business aspects are often combined to provide a turnkey solution, and this match of

component design, tooling design, manufacture and installation allows a seamless service to industry. INBIS's experience covers aerostructures, aircraft interiors, aircraft components, gas turbine components, development and mechanical test equipment, instrumentation, tooling and ground support equipment. For the Airbus A340-600 wing jig, concurrent engineering practices were used throughout the design, manufacture and installation of tooling allowing completion from concept to final client buy-off to be finished within 12 months.



Figure 3.1 Brian Gilbert (R) with Mark Tuttle (Director, AMTAS) at University of Washington

3.4 Andrew Mills

Head of Composites Manufacturing Research
Composites Centre
School of Applied Sciences
Cranfield University

The Composites Centre investigates and develops technology for the cost-effective manufacturing of lightweight composite structures in partnership with industry.

Current large projects with joint EPSRC/industry/Faraday Partnership funding include:

- [Novel design and manufacturing technology for unmanned aircraft](#)

- [Low-cost carbon-fibre composite structure for low-volume sports cars](#)
- [Crash structures for performance cars using novel materials](#)
- [Preforming techniques for composite aircraft structures](#)

The Composites Centre comprises a design/projects office with 20 staff and students and a large laboratory equipped with state-of-the-art equipment for high-performance composites processing. It offers advice in composite materials, design, testing, process technology, automation, manufacturing facilities and costing.

3.5 Brian O'Rourke

Chief Composites Engineer
WilliamsF1

WilliamsF1 is a designer and manufacturer of Formula One (F1) racing cars. The company was formed in 1977 by Frank Williams (Team Principal, co-owner) and Patrick Head (Engineering Director, co-owner) and currently employs more than 490 people. It has been nine times World Champion Constructor and winner of 113 Grand Prix. Work has, in the past, also covered the design and build of rally, touring and sports-prototype vehicles. The composites workforce comprises over 80 people engaged on design, analysis, research, testing, quality assurance (QA), tooling and production prepreg/autoclave work.

3.6 Sue Panteny

Mission Coordinator
National Composites Network (NCN)

NCN is part of the new and unique Materials Knowledge Transfer Network, jointly funded by government and industry, that embraces the entire UK composites industry and its supply chain. NCN is a company limited by guarantee, with a board drawn from organisations with prominent composites interests. The UK has an impressive global

reputation for innovation and research in composite materials and recognised high skills and quality based manufacturing, which is heavily led by implementation of new technologies. Driven by improvements in business economics and the technical performance of materials, industry will inevitably seek further advances via the use of composites. NCN has established a number of regional centres of excellence where companies can obtain hands-on support and expert advice.

3.7 John Savage
Technical Authority – Composites
 Smiths Aerospace

The Smiths Aerospace facilities in Hamble (UK) and Suzhou (China) design and manufacture airframe structural components and assemblies and associated systems in metallics, advanced composites and acrylic materials for the world's prime aircraft manufacturers. In addition to the aerospace composites products, Smiths Aerospace has also developed a specialised composites facility currently producing high-performance structural automotive composite components.

3.8 Chris Webborn
Managing Director
 St Bernard Composites Ltd

St Bernard Composites is one of the leading UK suppliers of manufactured composite components and subassemblies to the aerospace industry. Major clients include Airbus, Rolls Royce, Aircelle, Goodrich and GKN. Products include fan case linings, thrust reverser doors, skins and acoustic panels, airframe components, wing components and ribs.

3.9 Cliff Young
International Technology Promoter – Manufacturing Industries, North America
 DTI Global Watch Service

The DTI Global Watch Service helps British businesses to identify, and learn from, leading technology developments around the world to improve their competitiveness. International Technology Promoters (ITPs) help UK companies to learn more about, and access, technologies and partnership opportunities in key overseas territories. The ITP network covers the Asia-Pacific region, West & Central Europe, Israel, Russia and North America.

4 DEVELOPMENTS IN RESIN INFUSION MATERIALS AND PROCESSES; STRUCTURAL UNITISATION AND COMPONENT INTEGRATION TECHNIQUES

Andrew Mills – Cranfield University

Resin infusion was pioneered in the UK for low-cost automotive bodies. In recent years many research projects and production aircraft components have been manufactured, particularly by the matched mould resin transfer moulding (RTM) technique. Resin infusion processes can provide materials cost and assembly cost benefits, through component integration compared to pre-impregnated material processing, but can also incur much higher tooling costs and process development time. The experience of the US aerospace industry with its greater enthusiasm for higher cost tooling investment was of particular interest.

The issues of assembly cost reduction through part integration and materials cost reduction through the introduction of infusion type processes were common challenges/ issues for the mission hosts.

The unitisation theme had been pioneered at Raytheon with a single shot all co-cured fuselage structure for the Premier and Horizon business jet fuselages. Automated tape placement has replaced hand lay-up. This has been successful, but manufacturing times still have much opportunity for improvement. A similar technology was being taken up by Boeing for the 787 in a simpler form without honeycomb. Raytheon is considering, longer term, to move to RTM with no surface filling and lower labour.

Lower cost materials are playing a back role to metal replacement and unitisation to save weight and assembly time and tooling inventory with an aggressive timescale. Toughened 180°C cure prepreg is used in most Boeing 787 applications.

Spirit AeroSystems is considering RTM and vacuum infusion processes but these are lower priority considerations to fibre placement.



Figure 4.1 Boeing 787 forward fuselage demonstrator (courtesy Spirit AeroSystems Inc)

Successful NASA technology transfer had been achieved for advanced composite technology (ACT) braided frames and resin film infusion (RFI) used by Zodiac for Boeing 787 fuselage frames.

V System Composites preferred vacuum infusion compared to prepreg since it gave fewer parts and lower weight through fastener elimination and adhesives. The company employs an in-house joints analysis module as an aid for composite joint design. The pioneering RTM and VARTM (vacuum-assisted resin transfer moulding) technologies employed by V System Composites have been successful, but the company is setting up for prepreg manufacture to fulfil build-to-print demand. The company's R&D work is supported by \$5 million (~£2.8 million) Small Business Innovation Research (SBIR) Program funding which has

enabled the development of a missile frame with reinforced fuel pipes to withstand 3,000 psi, using infusion manufacture.

V System Composites uses a variety of resin systems including high temperature resins bismaleimide (BMI) and cyanate esters for RTM processing and Hybrid Plastics' resin (a preceramic polymer) that can be RTM processed at a B-stage then at a high temperature to form a metal matrix that can replace carbon-carbon composite. For RTM production of a battery box the mould tool's thermal expansion is used to compression mould.

The VARTM processing that V System Composites specialises in is used to produce Chinook fairings (replacing a four-part component) and non-crimp fabric (NCF) stringers with tackifiers and plain weave skins resulting in a 40% cost reduction. A transmission support, 75 mm thick, which takes a very high loading, made by VARTM gave a 50% weight saving compared to the aluminium design using IM7 fibre and BMI with a local bearing attachment fitting.

V System Composites has produced an unmanned aerial vehicle (UAV) spar concept in which a frame or frame with web can be made in the same tool using a modular tool build. The C-section and I-section flanges are in the same base tool with removable blocks. BMI is used as it is found to be easy to infuse and cure, unlike for prepreg systems.

V System Composites has linked with the University of Delaware to develop an RTM AFI (affordable feature integration) spar concept and has just signed an agreement with Bally Ribbon Mills to develop three-dimensional (3-D) woven shaped reinforced composites.

NIAR's programme for materials data was encouraging, covering recognised proven prepreg systems, but braids and vacuum infusion have also been included.

This programme, organised by NIAR's National Center for Advanced Materials Performance (NCAMP), is an extension of the AGATE (Advanced General Aviation Transport Experiments) programme. The aim is to reduce the cost for the introduction of new materials and use shared data. The liquid resin infusion process was specified, and testing started in 2004.

The intention of NCAMP's programme is to provide publicly available, airworthiness approved, material databases that may be used to design certified components without independent generation of a full proprietary database.

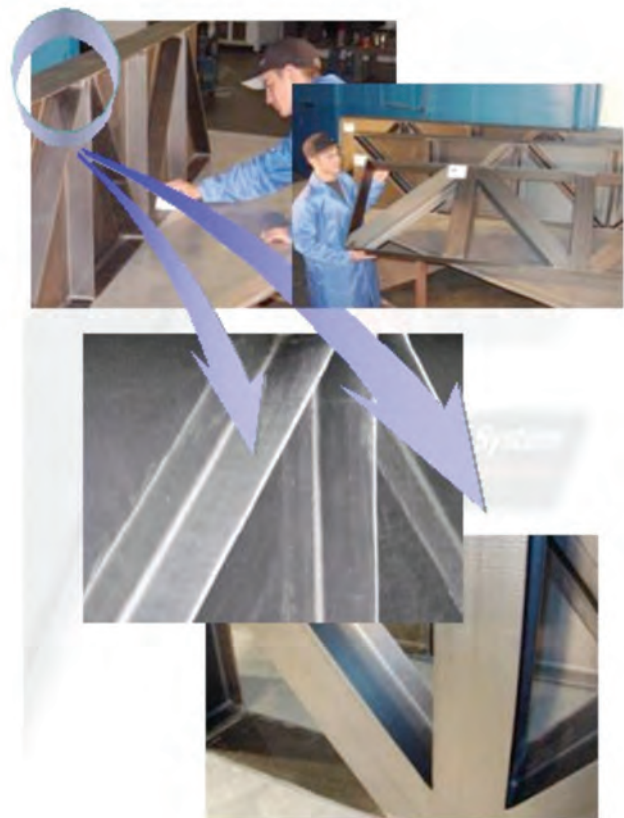


Figure 4.2 V System Composites innovative open and closed reinforced structures, moulded in one step (courtesy V System Composites)

The AGATE programme mapped process development to establish sensitivity of variables. Manufacturing variables such as

wrinkles and voids were studied but not thoroughly. Materials ageing results showed no problems apart from honeycomb.

NIAR would welcome UK industry or university involvement.

Goodrich believes that despite the benefits of part assembly time, RTM is difficult to justify for nacelles business and see the way forward is through fibre placement since the tooling cost with RTM is difficult to justify for low-volume, high-complexity parts. Also the durability of out-of-autoclave materials was questioned since vacuum infusion (VI) and RTM liquid resins are less tough than current prepreg systems.

Boeing has considered RFI but has concerns with its use for large structures – tool costs and process complications and materials properties. After manufacture of a large forward fuselage VI demonstrator, they considered the risks too high for the benefits expected. However, fuselage frames for the 787 are being manufactured using RFI and preforms but cure will be under autoclave rather than vacuum bag pressure. The shape complexity and braiding reinforcement allows curved tows to be used and hence weight reduced. The frame is not highly loaded and so reduced strength from braid reinforcement is not an issue.

Boeing is looking at resin infusion to increase both compression strength and compression after impact (CAI) – tougher resins increase CAI but reduce compression strength.

The 777 composite tail was said to be 25% lighter than aluminium and at equivalent cost. The 787 tail is expected to be at least 30% lighter than aluminium.

Zodiac was selected by Boeing to carry out low-cost manufacturing processes. Projects include Boeing X45 UAV payload doors using 180°C prepreg and C17 VARTM components.

The double vacuum (inlet and outlet) CAPRI (controlled atmospheric pressure resin infusion) process using a Cytec PRIFORM preform and soft tooling was used on a prototype bulkhead.

For the Boeing 787 braided resin infused frames, VI of thick resin film with autoclave compaction is used in place of RTM since lay-up detail was not fixed and RTM cavity size could not be set and a high toughness resin was required. Low-cost soft tooling is utilised.

4.1 Summary

The extremely rapid development of structures for the Boeing 787, combined with the shortage of composite materials and process engineers and concerns over materials performance, process reliability, damage resistance and tooling cost, have diminished the drive towards the replacement of prepregs by lower cost technologies. To realise the replacement of prepreg for highly loaded structure, it is clear that substantial research effort has to be focused on materials performance improvement for preforming and infusion processing technology.

For the 787, the challenge is seen to be successful completion of development, and timely entry into service. The strategy seems to be sticking with what is proven, with later introduction of lower cost technologies. From the comments made, this appears to be a temporary situation with cost reduction seen as a future priority.

5 ASSEMBLY AND AUTOMATION METHODOLOGIES AND IMPLEMENTATION

Roger Duffy – BAE Systems plc

5.1 *Assembly processes*

5.2 *Automation*

5.3 *Future trends*

5.4 *Summary*

5.1 Assembly processes

In many cases the assembly philosophies in the USA are very similar to the industry norm in Europe, with traditional assembly jigs and fixtures. Interfaces are typically liquid or hard shimmed to meet the aerodynamic or other tolerances. Many US companies, like their European counterparts, have embraced a culture of lean initiatives, such as direct line feed (DLF) and Kanban, with some also applying SPC to reduce cost and improve performance and manufacturing flow through their businesses.

Assembly stages still rely on dry-builds or prefitting, and in many cases multi-stage drilling, deburring and cleanup operations, resulting in high levels of manual intervention. Methodologies such as 'determinate assembly' and 'hole to hole' location are used in some applications. Whilst it is possible in some cases to improve these processes during the life of a programme, once established the opportunity to implement major changes can be limited, depending on the savings to be made and the cost of implementation. Frequently issues associated with qualification and/or certification can also restrict these opportunities.

The drive for ever more cost-effective manufacturing processes, led by pressures from the end user for better fuel efficiency of aircraft and vehicles, is also backed by the need to cater more towards environmental considerations.

To meet these requirements, engineers in Europe and the USA have approached these issues in several ways. From a composites point of view, many companies are driving the boundaries of technology and capability by developing and building larger and more complex unitised structures. In the USA the Raytheon approach, for its range of business jet fuselages, combines non-metallic honeycomb core details between fibre-placed and adhesively bonded skins to create two lightweight fuselage sections of sandwich construction. These are then joined to produce a one-piece fuselage assembly. This would traditionally have been thousands of holes and rivets and hundreds of metal-formed details, all of which need to be drawn, planned, manufactured, controlled and factory scheduled. In airframe manufacturing the general view is that assembly accounts for up to 40% of the cost of manufacture. This very labour-intensive process of detail manufacture and assembly is now replaced with a sophisticated two-piece composite moulding that is both light in weight and significantly reduces the manual intervention and work-in-progress (WIP).

This step change in technology has now been taken a significant step further with the development and productionisation of the Boeing 787 fuselage. Though fibre is placed in a similar manner to the Raytheon fuselages, the Boeing composite fuselage approach is more akin in appearance to a conventional looking fuselage but with integrally moulded stiffeners and secondary assembled circumferential frames. Though somewhat similar to its metal counterpart, the technology, scale and investment, and know-how to achieve this should not be underestimated. This is clearly one of the

biggest steps forward in the design, tooling, and manufacture of composite structures. The monolithic skins of the 787 structure allow conventional autoclave pressures, typically 100 psi (~7 bar) to be applied, to ensure the optimum laminate consolidation. This differs from the Raytheon fuselage, where the advantages of the light weight and stiffness of the honeycomb sandwich structure can sometimes be compromised by the limitations of a processing pressure to around 45 psi (~3.5 bar). This reduced pressure can in some cases result in reworks and the need for cosmetic adjustments.

In addition to the reduced cost of assembly, other benefits of these large unitised structures are the far fewer joints required, thus producing a cleaner aerodynamic surface, and improving performance and operational efficiency.

Programmes and businesses with the benefits of advances in tooling technology, automation and the ability to work within a fully integrated digital environment stand to make the biggest gains, especially where these activities are linked with a quality engineering data management (QEDM) philosophy and SPC, where appropriate, thus creating opportunities to control and monitor processes for quality management (QM) and product enhancement.

Opportunities to exploit reductions in assembly cost and product mass for more conventional components and structures, such as flying surfaces, large panels and doors or complex fairings may be available through the introduction of processes such as resin infusion (RI), where dry fabrics and preforms are infused with resin to remove the need for secondary assembly operations such as shimming, drilling and fastening. Typical examples of this technology are some of the complex fairings and products produced by V System Composites for programmes such as the Boeing Chinook helicopter.

5.2 Automation

Within the aerospace and composites industry the automation of processes such as raw material ply profiling, machining and drilling has been established for many years and is used extensively by almost all companies, even those producing relatively low numbers and one-offs. For large scale structures, many of the assembly-type processes have been read across from the automated drilling or fastening methods developed for structures such as metal fuselages and flying surfaces. However, composite materials and structures have significantly different needs in terms of drilling and machining. Cutter costs are significantly higher, with unit cost per length of cut or number of holes drilled being up to ten times that of a metal alternative. Companies such as Raytheon and Boeing make extensive use of abrasive water-jet cutting for a whole range of applications, and to great effect, for both routed edges and in some cases hole cutting, depending on the tolerances required.

The most radical improvements in composites automation have undoubtedly been in the areas of automated tape laying and fibre placement. These machines have revolutionised the manufacture of large and complex components. The fibre placement of the Raytheon business-jet fuselages and the automated tape laying of the detail components for the 777 at Boeing's Frederickson facility are prime examples of the foresight and investment in what were ground-breaking new technologies when those programmes were launched. The Boeing Frederickson facility is also supported by an impressive array of automated forming and mechanical handling systems including AGV (automated guided vehicle) transportation.

The next generation of fibre placement machines being developed is looking towards wider tow widths and increased numbers of tows. These are primarily aimed at the larger

scale and softer contours, typically for civil aircraft applications. Ongoing development in software and machine control systems, with better product repeatability, will improve efficiency and throughput. These advances in conjunction with improvements in raw material control and processing will all aid the drive for better affordability.

5.3 Future trends

Where low mass, stiffness and good fatigue properties are an essential feature of a product, composites are becoming the natural choice, hence the reason for the phenomenal growth in their use in airframe applications. For the near future at least, composite structures will almost certainly contain some level of metallic components, typically titanium for high load concentrations, or where galvanic issues may arise.

The relatively low cost of aluminium alloys and the advent of high-speed machining commonly make this the chosen solution from a cost perspective, although corrosion and fatigue can be an issue.

From an assembly point of view this combination of materials, with their differing processes and capabilities, ie tolerance management, treatments etc, are an open innovation for the introduction of cost-competitive composite preforms, especially for complex components or those that lend themselves to unitisation or matched moulding processes, such as RTM or infusion, as mentioned previously.

To improve process control, composite suppliers are under pressure to reduce features, such as batch to batch variability. Whilst this would aid the assembly process, it is only part of the solution to improving affordability. Ongoing development in software and machine control systems, with better product repeatability, will also improve efficiency and throughput.

In addition, software packages such as those being developed in the UK offer predictive modelling for composite component distortion, thus allowing the automatic biasing of tooling at the point of manufacture. These developments should result in lower recurring and non-recurring cost and improved time to market. Ultimately the goal is 'perfect parts', removing the need to shim or the adjustment of interfaces. Initiatives such as these will aid the drive to achieve better build standards and improve interchangeability (*I&R in the USA*) as well as the overall quality of the aerodynamic surfaces of the product. The end user will also benefit by a reduction in the number and frequency of maintenance cycles leading to better operational efficiency.

5.4 Summary

The mission team found a wide range of manufacturing, assembly and automation methodologies in use, from legacy programmes such as the Boeing 737 fuselage, to the very latest generation Boeing 787 fibre-placed composites fuselage. These two programmes clearly demonstrate the changes and advances in materials, manufacturing and assembly methods, along with the latest that technology has to offer in automation and machine tool control. Other innovative solutions to reduce cost and maximise efficiency were evident in the approaches taken by companies such as Raytheon and V System Composites, with their applications of innovative tooling and component unitisation to reduce the number of detail parts and minimise assembly operations.

Many of the companies visited have implemented the principles and culture of lean manufacturing (LM) and SPC, in common with many companies in Europe.

6 LOWER COST SECONDARY STRUCTURE

John Savage – Smiths Aerospace

With the increase in use of composites for structural aerospace applications driven by new programmes such as the Boeing 787 and Airbus A350 there has been very significant investment, particularly by the primes, in developing and automating manufacturing processes for major structural items such as wing spars, wing skins and fuselage sections. In addition to these major primary structure applications, current and future aircraft designs require considerable numbers of secondary structure composite parts such as wing leading and trailing edge panels, fairings, nacelles and undercarriage doors.

Prime manufacturers tend to view these types of secondary structure as being disproportionately costly for their size, and in the UK there has been a trend to tackle this cost challenge by two routes. Firstly, transfer of existing parts and processes to areas of low cost labour, predominantly in the Far East, and secondly by development of newer, lower cost materials and processes such as 'out-of-autoclave' curing.

A key mission target was to understand how these secondary structure cost challenges were being addressed in the USA.

Secondary structure parts are typically simple monolithic or honeycomb core stiffened sandwich panels produced using woven preregs laid up manually and autoclave cured. Although material costs make up a significant part of the overall component costs, the major segment tends to be labour due to the high manual content of the lay-up process. A further factor driving costs is the high capital value of autoclaves. In Europe there has been a great deal of development in RFI and 'semi-preg' technologies which

allow more rapid lay-up by reducing or eliminating vacuum consolidation and reduce overall processing costs by allowing vacuum oven curing. This technology is now used in production on the A380 lower trailing edge panels produced using Hexcel's M36 resin system and NCFs.

The companies visited during the mission covered the full range from primes through to second tier subcontractors, with examples of secondary structure evident at each company. Strategies to reduce cost varied at each location but the overall impression was of a more conservative approach than in Europe with some movement of very simple structure to the Far East combined with significant investment in improving and automating traditional autoclave cure methods.

At Raytheon there were, in addition to the major fuselage sections produced by automated tow placement, a wide range of secondary structures, all utilising manual lay-up and autoclave cure. The efficiency of hand lay-up had been optimised by use of laser ply positioning for ply and core location with a large number of installations in use. This was a common theme at all plants visited, both large and small. Raytheon had considered off-load of manufacture to areas of lower labour cost but after poor experiences with manufacture of wiring harnesses in Mexico had not progressed this. There was some interest in learning more about the potential of vacuum-only RFI, and RTM processes were in use for control surface manufacture. The general impression given, however, was that manually laid up prepreg combined with autoclave cure was likely to be the process choice for secondary structure for the foreseeable future.

It was a generally similar picture at Spirit AeroSystems where very large investments were being made in automated tow placement for the 787 primary fuselage structure whilst, with assistance from laser ply positioning, nacelle structure lay-up was being done manually. Spirit, however, showed more determination to develop lower cost manufacturing methods for future programmes beyond 787, although with an emphasis on achieving this via automation. The acoustic properties of the component were achieved via perforated skins on a honeycomb core. The perforation holes are formed and cured on a tool with pins, the prepreg forced over/around the pins. There were claimed advantages over the cure and drill alternative. It was said that thinner skins could be used as there was less fibre damage, and co-moulding the hole is less expensive than drilling on a specialist multi-spindle drilling machine.

One of the smallest companies visited was V System Composites, and here a lot of innovative work had been done on development and manufacture of lower cost composites using out-of-autoclave processes including single-side tooling VARTM and closed-mould RTM. A particular success was the forward pylon fairings for the Chinook helicopter, which had been redesigned from prepreg to a monolithic ribbed structure fabricated from dry fabric NCF and resin infused on a single sided tool. Cost savings in the order of 40% over the original prepreg structure were claimed.

Despite this, and other successes in innovative processes, V System Composites stated that, of their rapidly growing turnover, around 75% is currently using standard manually laid up prepreg, autoclave cured. A similar ratio was predicted in the future, which had led to the recent investment in a new large autoclave to support this. One of the reasons stated for the continued use of prepreg and autoclave cure was conservatism



Figure 6.1 Chinook helicopter fairing produced by VARTM (photo: V System Composites)

amongst the bigger primes to accept the newer materials and processes over tried and tested prepreg processes.

Goodrich Aerostructures produces a wide range of composite and metal bonded secondary structures with all composite parts currently being manufactured from prepreg and autoclave cured. Goodrich has already tackled cost reduction by subcontracting the majority of its simpler components to the Far East, notably Malaysia, and seems to have little interest in exploring out-of-autoclave processes such as RFI, having concerns over the structural capability and reliability of this approach. For more complex components its strategy is to move from manual prepreg lay-up to automated tow placement, stating it is investing heavily in this technology to support its engine nacelle work on the Boeing 787.

The majority of the manufacturing at Boeing's very impressive Frederickson plant is of primary structure including a semi-automated process for fabrication of fabric prepreg honeycomb cored ribs is being utilised using lay-up cells, combining laser ply positioning and rubber diaphragm vacuum presses for forming and consolidating plies including those over the honeycomb.

The final company visited on the mission was C&D Zodiac where virtually all of its structures business is being taken over by a very large contract to manufacture fuselage frames and shear ties for the Boeing 787. The shear ties are produced using unidirectional tape, laid up manually to begin with, although automated tape laying is being considered for the future. The ties are then CNC cut from this flat stack lay-up, vacuum heat formed and then autoclave cured.

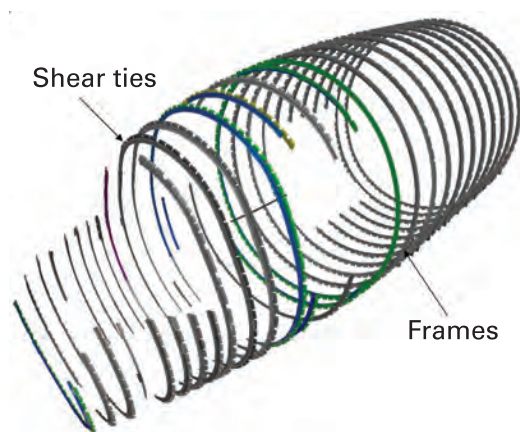


Figure 6.2 Illustration of the shear ties and frame manufactured by C&D Zodiac for Spirit AeroSystems of the Boeing 787, Section 41

A more innovative process is being used for the frames which are fabricated by RFI using a dry carbon braid preform and resin film. Although in theory this process lends itself to out-of-autoclave curing, these parts are being autoclave cured to meet Boeing requirements, and in fact C&D Zodiac is planning to double its autoclave capacity from three to six vessels to provide capacity for this work.

In secondary and tertiary structures, autoclave cured woven prepreg is still prevalent. Processes can be automated as far as computer controlled kit-cutting, pre-machined, pre-assembled lightweight cores, but the established production programmes seen during this mission still involve hand lay-up and autoclave cures. The main cost reduction activity is subcontracting to lower labour-cost countries.

6.1 Summary

Mission objectives were to evaluate progress in the uptake of out-of-autoclave processes such as RFI for secondary structures and the balance between automation and manual processes. Strong evidence was seen of simpler components remaining as prepreg and autoclave cure but being subcontracted to areas of low-cost labour. For more complex structures there was little evidence of any real move to out-of-autoclave processes with the majority of parts still utilising manual lay-up of prepregs, albeit the process being optimised by widespread investment in laser ply positioning equipment. For future programmes the emphasis was very much on major capital investment in facilities and process development to allow manufacture by fully automated processes such as prepreg tow placement and a continued reliance on autoclave curing.

7 AFFORDABLE COMPOSITE MATERIALS TECHNOLOGY

Roger Francombe – Advanced Composites Group Ltd

'Lower weight at an affordable cost' is usually quoted as the main target for development of composite material technology. However, new developments that appear to meet this target are rarely proposed for critical aircraft structure until the technology is considered to be 'mature'. Maturity means confidence that a material will process consistently, within a well-defined processing window, to give a flaw-free structure that will perform well within design requirements. This confidence is gained through extensive coupon testing, process trials, sub-element tests and experience from production of less critical structures, a procedure that can take five to 10 years.

It is not surprising, therefore, that the majority of materials and processes seen in production environments during this mission were originally developed in the late 1980s or early 1990s. The materials used for current primary structure (Boeing 777 empennage, Raytheon Premier 1 and Horizon 600 composite fuselages) and the materials now being proposed for the 'all' composite Boeing 787 aircraft, are mostly prepregs cured at 180°C in an autoclave. The prepregs being used are tough, high glass transition temperature (T_g) epoxies with good damage tolerance, and are produced near the producers of the hardware, in the USA, Europe, and Japan (Toray produces in the USA near Frederickson, but plants are located elsewhere for other producers for the 787).

Cost savings have been achieved mainly by improvements in automated lay-up equipment. Automated tape-laying (ATL) machines, used mainly for large flat or shallow curvature components, are now capable of laying 50-150 mm wide tapes at speeds of 15-20 m/min with minimum wastage. Automated

tow placement (ATP) machines, used for surfaces with complex curvature, are now reaching maturity that can place up to 30 x 3 mm wide tapes in one pass at speeds of 5-10 m/min, with consolidation pressures up to 7 bar. In the production of fuselage sections, ATP machines are programmed to lay material around door and window cut-outs – again minimising wastage.

Such machines represent high capital investment cost but are justified by labour savings approaching 90% and time saving approaching 80% compared to hand lay-up. The material formats required to feed these machines are 5-15% more expensive than hand-lay material. Whilst the basic prepreg system (resin and fibre combination) is considered to be mature technology, the industry believes that material suppliers can do more to develop cost-effective materials for the manufacture formats needed for automated processing.

Invar remains the material of choice for any mould tool used for lay-up. Even very large tools, such as the tool for the Boeing 787 cockpit section, involve Invar sections supported by a frame. Carbon composite is favoured for caul sheets, pressure intensifiers and cure tools that are not used for lay-up (such as the clam-shell outer tool used to cure the Raytheon fuselage sections). As components – and hence mould tools – increase in size, metal tooling has two increasing disadvantages:

- Physical mass, particularly for rotating tools used with ATP machines
- High thermal mass which lengthens process times and curing costs

The challenge for the composite materials industry is to develop either a damage-resistant composite material for tool surfaces, or a highly toughened primary structure resin matrix capable of low-temperature cure. There was no evidence that such developments have yet occurred.

There were some advances. The Boeing 787 fuselage frames and shear stiffeners will include a C-spar produced by RFI of a braided carbon preform. However, the film is the same as used in the primary structure prepregs and the components will be autoclave cured. A proposal to use an out-of-autoclave liquid infusion process was considered but discarded due to tooling costs and lower toughness performance. RFI processing of integrally stiffened 787 wing covers has been proposed by a non-US subcontractor – this is seen as very high risk, and would not be considered by a US subcontractor. Empennage (vertical fin) covers will be made in Frederickson by co-bonding precured prepreg stiffeners to the prepreg skin using a film adhesive in an autoclave process. Front fuselage sections involve co-moulding of prepreg skins with uncured preshaped prepreg stiffeners.

A chopped, carbon-prepreg moulding compound was considered for the large number of small gussets that form a riveted joint between elements of the fuselage frames, but it lacked stiffness and stability and was replaced by press-moulded prepreg.

RTM has been a candidate process for the Boeing 787 main pressure bulkhead, but a number of the Boeing engineers contacted during this mission indicated that the RTM and VARTM resins currently approved to Boeing specifications will not achieve the level of toughness needed to be competitive with prepreg processes in cost and weight. Nevertheless, there is no doubt that many smaller detailed parts will be processed by RTM.

V System Composites is a new company that has specialised in development of liquid resin infusion (LRI) solutions for complex-shaped components, and has patented its own version of VARTM. Its main technology is tooling and processing techniques and it has successfully developed LRI components to replace problem prepreg components in military helicopter, aero-engine, UAV, missile and space applications. Using the widely available epoxy formulations, LRI processing of a single component to replace an assembled complex prepreg has achieved up to 40% cost saving. V System Composites has also developed LRI processes for more exotic high-temperature polymers such as polyimide and phthalonitrile, and inorganic nanostructured polymers for high temperature and fire resistance.

Film adhesive and core materials observed during this mission have been standard for many years. Similarly the reticulation processes used for bonding precured perforated acoustic skins in nacelle applications are well known. It was noted, however, that polyester peel ply is now routinely used in the preparation of composite surfaces for bonding. Once the polyester peel ply is removed there is no further abrasion or cleaning. A study has been carried out at University of Washington showing the vastly improved consistency of adhesive performance resulting from the use of polyester compared to nylon peel plies. Nonetheless, anti-peel rivets are still the norm in any bonded joint.

The prepreg is single sourced, and Boeing is very satisfied with consistency of quality provided by the supplier. The divestment of manufacturing sites such as Boeing Tulsa and Boeing Wichita (to Spirit AeroSystems) and the subcontracting policy for major sub-assemblies will give freedom for other organisations to select other materials for new components. The problem is up-front expense of database generation and material qualification programmes.

Wichita State University is playing an important role in reducing the costs associated with certification of new materials for aerospace use. The National Institute for Aviation Research (NIAR) is part of the university, and they, together with NASA and the FAA, have set up a new organisation known as the National Center for Advanced Materials Performance (NCAMP). This organisation has a governing body consisting of NASA, FAA, the US Air Force (USAF), Naval Air Systems Command (NAVAIR) and industry representatives.

NCAMP is responsible for developing, certifying and publishing design databases for advanced composite materials. It will use advanced analytical tools to reduce the number – and hence the costs – of coupon tests, but the material supplier will still be expected to meet the costs of certifying its material. Any component manufacturer may use the databases to certify components. The only requirement will be a reduced, single batch equivalency test programme to validate the manufacturing site's process conditions. This procedure is gaining support from the large aircraft companies.

7.1 Summary

It would be easy to conclude that US materials technology has not advanced very far during the last 10 years and that the real advances have been in automated lay-up machines, the size of the components now being developed, and the scale of the new factories being built to process them. In North America, however, R&D funding has been directed towards development of out-of-autoclave curing processes, resin infusion processes, and integrated stiffened structures with one-stage cure. It was concluded from this visit that these technologies are not quite mature enough for production of large civil structures and that the overriding priority, for the Boeing 787 at least, has been to fly the first aircraft on time.

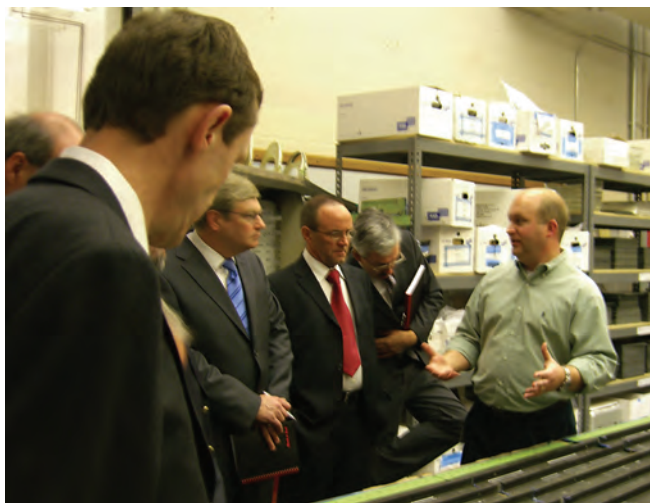
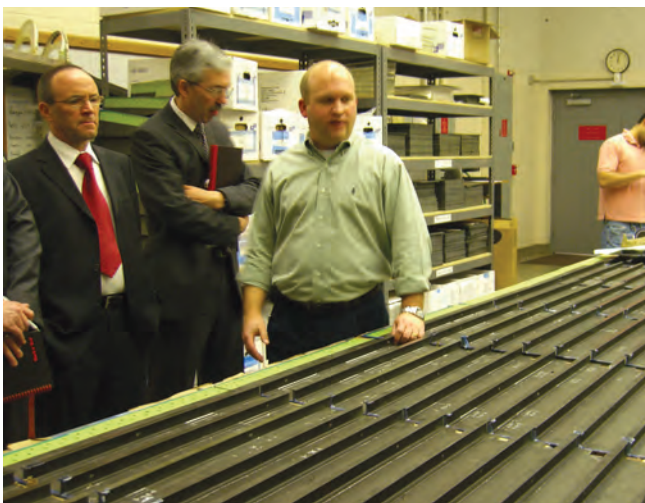


Figure 7.1 John Tomblin (NIAR, Wichita State University) discusses spar analysis

8 MOULD TOOL TECHNOLOGIES

Brian Gilbert – INBIS Ltd

- 8.1 *Single sided, metal tooling*
- 8.2 *Single sided, composite tooling*
 - 8.2.1 *Modular tooling*
 - 8.2.2 *Composite caul plates*
- 8.3 *Closed mould tooling*
- 8.4 *Tooling automation*
- 8.5 *Drivers for change*
- 8.6 *Future technologies*
 - 8.6.1 *Near term*
 - 8.6.2 *Mid term*
 - 8.6.3 *Long term*
- 8.7 *Summary*

The mission delegates were shown a wide range of components being manufactured, including fuselage barrels, frames, tailplane skins, spars, stringers, engine nacelles. The hosts were generous in what the mission delegates were allowed to see, and open in discussion; often proprietary manufacturing methods being shown for component production. To respect this openness, and out of courtesy to the hosts, this chapter focuses more on the technology approach rather than specific production details.

8.1 Single sided, metal tooling

The majority of tooling seen was traditional single sided, metal tooling being used to produce curved or complex-shaped composite components. The unidirectional, pre-impregnated composite plies were laid by hand, as were the structural additions such as honeycomb panels. A typical component was the cockpit window frame for Raytheon's Hawker Business Jet made from a carbon fibre/epoxy resin combination. The tool's surface was machined Invar, selected for its low thermal expansion properties, and had a substantial steel backing structure in order to maintain stability of the profile. For process

control, several thermocouples were attached to the back face of the Invar. On completion of ply lay-up, the tool was vacuum bagged and then sent to the autoclave for heating to 180°C (256°F) following a controlled cure cycle.

An interesting variation of metal tooling was the moulds for the automatic tape laying machines at Boeing (Frederickson) used for making the 777 tailplane skins and spars. The basic configuration of Invar skin and steel backing structure was the same as mentioned above but the tools were very large at 1.22 m (4 ft) wide and 10.98 m (36 ft) long. They were also much more heavily built to allow them to withstand the heavy compaction forces imposed during the tape laying process and to ensure that they did not flex when being picked up and moved by the AGVs.

Boeing (Frederickson) used 9.15 m (30 ft) long Invar mandrels to manufacture tailplane spars in a hot press forming operation. A tape laid, uncured composite sheet, ranging in thickness from 8 mm at the root to 2 mm at the tip, was laid over the mandrel. The mandrel was heated to a temperature just below the epoxy resin gelling temperature to soften the composite material and allow it to conform to the moulding tool. It was then sent to the autoclave for full cure on the mandrel.

8.2 Single sided, composite tooling

Metal tooling is very heavy, and to overcome this Raytheon uses composite mould tools to achieve the smooth outer surface of its Business Jet fuselages. Viper tow placement technology is used to lay up the fuselage

barrel onto an aluminium mandrel. When lay-up is complete, a two part, clamshell, composite mould tool is placed over the aluminium mandrel and the halves bolted together. An inflatable bladder technique is used to transfer the uncured plies to the clamshell mould. The mandrel is then removed and the fuselage autoclave cured.

8.2.1 Modular tooling

Spirit AeroSystems in Wichita will be manufacturing the Boeing 787 front fuselage. This 5.75 m (18.9 ft) diameter composite fuselage barrel has posed some interesting challenges for the company. The main issue has been how to achieve a smooth, well controlled outer profile in a cost-effective manner. The ingenious solution, which was developed jointly with Boeing and the fuselage partners (Spirit, Alenia, KHI and Vought), has been to use a modular support structure to create a mandrel onto which is laid the composite skin. The individual modules seal against each other for vacuum integrity and also provide a tooling location for the precured stringers. Once the process of tow-placing the composite skin is complete, several caul plates are placed around the fuselage to create a smooth outer profile. The assembly is then sent to the autoclave for high-temperature cure.

8.2.2 Composite caul plates

Components made using single-sided tooling have one accurately formed, smooth face. The opposite face is typically overlaid with bagging materials and left free of any constraint to reduce the risk of profile distortion during the cure process. There are many occasions, however, when a smooth surface is required on the 'bagged' surface and this is often done using a caul plate. To produce smooth surfaces for larger areas, composite caul plates are generally used. An excellent example of this was seen at Spirit AeroSystems, and the only example noted during this mission.

8.3 Closed mould tooling

Matched-metal tooling (also referred to as resin transfer moulding – RTM) is used to produce complex-shaped composite components that require accurately positioned, orthogonal mating faces (advantageous during assembly operations). The process is basically a plastic injection moulding technique but with the inclusion of a composite preform placed into the mould prior to injection of a resin matrix. The tools are heated to speed up the production process. V System Composites showed the delegates a highly complex gearbox cover made using RTM in combination with other processes. The component had been formed using silicone mandrels, a salt mandrel and some pre-impregnated composite material. The cover was made as a demonstrator part to show what could be achieved, and the result was very impressive.

8.4 Tooling automation

The composites industry, and particularly high-performance composites, is generally regarded as a manually intensive process, but it was noted that some automation had been implemented. At Frederickson two examples were seen. The first was for rib manufacture with a 'manually assisted' debulking arrangement. This was a silicone bag on guide rails, needing only to be slid into position for use. The arrangement was simple, easy to use and effective. The second was the use of AGVs to move, on demand, the heavy lay-up tools around the factory and into the autoclave. The approach of using 'appropriate' levels of automation was recognised to be a very effective formula.

8.5 Drivers for change

Much time and effort has gone into developing the production environment to make high-quality composite components using single-sided metal mould tools in

conjunction with autoclave cure. Having made such a large investment there is quite naturally a great reluctance to change. Indeed, this production approach has much to commend it, such as tool durability and its adaptability for the newer, lower temperature cure processes. Even so, reduced manufacturing costs will increasingly be a major driver for change. Strategies to achieve this include simplifying the processing operations, using less energy-intensive cure processes, and improved tooling. Process simplification could be achieved by creating preforms through ply stacking, removing the need for tool cleaning, or by introducing automation. The adoption of lower cure-temperature resin systems, lighter weight tooling and out-of-autoclave methods would also help reduce energy costs. Such changes by themselves would not, however, be sufficient to initiate a swing away from single-sided metal tooling for mainstream items. This means it is likely to be the dominant mould technique for some time.

The manufacture of mould tools is a significant part of the production costs for composite components especially when every composite part is different. There are instances when this tooling cost has been the deciding factor when choosing between aluminium and composite parts. The need to reduce the number of tools, and therefore cost, is immense. The cost reduction could be achieved through different mould materials, using common components or features (which may allow the use of modular tooling to make a family of components) or perhaps increasing the functionality of a component, thereby reducing the number of tools required. The modular tooling used by Boeing for the 787 fuselage is therefore a significant technological step towards the acceptability of the modular technique.

There are many drivers to encourage a move towards automated production of composites. In the first instance, rising production rates, combined with improved

consistency of product quality, could well encourage the move. Secondly, shortage of skilled labour is increasingly becoming an issue, and this may be aggravated with ever more stringent health and safety legislation. These factors could well encourage the adoption of automation. Despite the foregoing it is recognised that there are difficulties in automating existing production processes and that any changes would best be implemented during the design stage of future components. By way of example, out-of-autoclave processes would be easier to incorporate into an automated production system, perhaps utilising integrally heated tooling for in-situ curing.

8.6 Future technologies

Based upon discussions with the mission hosts, and some personal reflection, the following comments are put forward with an eye to the future. The comments below relate only to a mould tools perspective and it is recognised that many other influences exist in production scenarios.

8.6.1 Near term

The vast experience gained to date with single-sided metal tooling, combined with the huge investment in materials and autoclaves, means that this processing technology will be around for many years to come. Recently much progress has been made in reduced temperature cure (120°C), out-of-autoclave materials and this could provide one route towards lowering manufacturing costs. However, mainstream aircraft production is unlikely to be an early adopter of the technology, despite being used to make many prototype aircraft. It is more likely that non-aerospace applications will be in the vanguard. Metal tooling is suitable for out-of-autoclave/lower temperature cures, and due to its sheer robustness, single-sided tooling will still be appropriate. Closed mould tooling will be increasingly used to make accurately

formed parts, especially as the capability for making dry, composite 2-D and 3-D preforms improves. The technique of combining several processing techniques to make a component, such as silicone mandrels, greatly enhances the range of applications for this technology.

8.6.2 Mid term

The drive to reduce manufacturing costs is anticipated to lead to the development of a lower tool count than currently required to produce composite components. In the first instance, designers might move towards creating a family of components that have many common features, perhaps a common height but varied in length. This would allow modular 'block' tooling to be utilised, thus requiring fewer tools overall and providing some production flexibility. For the production of 'thin skin' items, reconfigurable tooling may emerge whereby the mould tool surface can be reformed to a new profile. The precedent for this is the 'pogo stick' arrangement used for machining metal skin structures. Such tooling would not be transportable, and the lower processing temperatures of new materials would almost be a prerequisite. Higher performance items would most likely need a freestanding post-cure.

8.6.3 Long term

The logical extension to reducing the cost of mould tools would be to have none at all. Although no technologies to achieve this were noted during the mission, one way to do this could be to use preformed, cured composite beams and sheets, but this would of course impose design restrictions on the range of parts made. For greater structural freedom a rapid-tooling prototype approach is needed. The vision is to 'extrude' a structural composite to form the part, and local heating would ensure the exudate retains its form and allows the part's section to be built up.

8.7 Summary

The majority of applications seen during the mission used the traditional approach of unidirectional carbon fibre, pre-impregnated with epoxy resin, cured at elevated pressure and temperature in an autoclave. The materials were developed for use with single-sided tooling and it became obvious during the tour that over the years many incremental steps have been taken to improve the processes. This experience enables the routine production of high-quality composite components.

The mission delegates noted that their hosts seemed to be poised in readiness for composites technology to move forward – something that was reflected in the 787 modular tooling and the 'RTM plus combination' technique. Technological progress, however, is slow, as it is in the UK, with two of the restraining factors being the high level of investment in current technology and thus a reluctance to change, and the high cost of process certification for the aerospace industry.

Overall it appears from a tooling perspective that the two countries have equivalent composites capabilities.

9 LOWER COST MANUFACTURING IN COMPOSITES

Chris Webborn – St Bernard Composites

- 9.1 *Introduction*
- 9.2 *Use of composites today in civil aircraft manufacture*
- 9.3 *Cost opportunities through process change*
- 9.4 *Observations*
- 9.5 *Summary*

9.1 Introduction

The vast majority of aerospace composite primary and secondary structures in production today are cured using autoclaves. This processing method of temperature and high pressures has been driven by the chemistry of the systems approved for use in aerospace products to produce parts with the required mechanical properties. In the drive for lower cost manufacture, removal of the high-cost autoclave has been one of the goals. This has resulted in the development of new resins and fibre structure and an exploration into lower temperature, lower pressure cures. The application of these materials and processes, however, has not resulted in wide-scale use of the technologies. One of the objectives of the mission was to explore how far these alternative methods had been or was planned to be adopted, how production flows were being managed and whether cost reductions in real terms were being achieved.

9.2 Use of composites today in civil aircraft manufacture

Composites are widely used today in aerospace secondary structure and are gaining use in primary structure for the next generation of civil aircraft. Leading and trailing edge panels, nacelles, thrust reversers,

horizontal and vertical tailplanes, undercarriage doors, flap leading edges and moveable leading edges are some of the major application areas of secondary structure. Both Airbus and Boeing have introduced these components in the drive for lower weight (replacing the centre box structure on the VTP of the B777 saved 1,000 kg). In primary structure the A380 includes a composite wing box, keel beam, wing beams, belly fairing, VTP and HTP. Figure 9.1 attempts to give an indication for the use of composites today.

The next generation of aircraft is being designed with all composite fuselages and main wing spars, wing skins and wing boxes. Despite the attraction of the cost-saving potential of 'out-of-autoclave curing', all these parts and secondary structure are going to be cured in newly procured autoclaves. The reason is clear. The time and cost required to develop and qualify new materials and processes has not yet caught up with the launch programmes of new aircraft. Components need to be produced to meet the current requirements and these cannot be met, with consistent quality and at production rates, with the new techniques. While great strides are being made in the back rooms of the industry, if the next generation of single-aisle aircraft is launched before these processes are proven, then the same technologies as today will be used in the highest volume sector of the aircraft industry.

9.3 Cost opportunities through process change

The processing improvements will come from combinations of:

- 1 Lower cost materials
- 2 Lower cost processes
- 3 Moving production to lower cost economies

Lower cost materials may be delivered in two ways, the epoxy system and the carbon form. These aspects are covered in Chapter 7.

Lower cost processes can be achieved by changing the basis of the process or improving the process itself. The basis of the process

relies on chemistry changes and consolidation to deliver properties equivalent to those seen today from the autoclave. Even when this is achieved, and today it is not in a full production sense, the real cost savings will only be made if the autoclaves are not in the business model in the first place, otherwise their depreciation will continue to feature in the cost. Suppliers without autoclaves will therefore be, almost by definition, new to the composites industry and will have to obtain all the necessary approvals.

Section	Airbus	Boeing	Other
Wingbox	A380 A400M	B787	
Wing beams	A350 A380	B787	
Wing skins	A350 A400M	B787	
Fuselage	A380 tail section	B787	Raytheon
Belly fairing	A380		Hawker 4000
VTP	A320 A340 A380 A350 A400M	B787 B777/h	
Horizontal stabiliser	A340 A350 Spain	B737 Limited Edition B787 B777	
Nacelles	A340, A380	B787	
Reversers	A340 Aircelle A380 Aircelle A350 Goodrich	B787 Spirit	
Reverser details	A320 Reverser doors A380 Gutter fairing A340 Reverser doors A380 Reverser doors		
Flap track fairings	A320 A340 A380		
Wing panels	A320 A340 A380	B777	
Rear pressure bulkhead	A340-600 A380		
Keel beam	A340-600 A380		
J nose – LE and ribs	A340-600 A380		
Floor beams	A340-600		

Figure 9.1 Current applications of composites in aerospace

The other aspect to low-cost processes is the application of LM. Taking cost out of an existing process using the various tools available today is helping manufacturers achieve the cost-down targets set by their customers. In some cases the savings can be large. However, with time it becomes more and more difficult to win substantial savings.

When the process can no longer be changed to deliver the saving, the lower cost economies can save on labour cost but usually at a material cost premium. The cost of transferring work into the lower cost economies has generally been underestimated. The amount of time to achieve the transfer, and the management and technical support needed, are generally far more than originally planned. There is, however, a momentum today that will not be reversed. Even the aircraft manufacturers are being driven to have assembly lines in these countries and put in high-tech production as well as the parts with high labour content.

9.4 Observations

As would be expected at Boeing there had been considerable investment in low-cost production. A good example was seen at Frederickson, where the B777 VTP and HTPs are made, of a well thought out production process and flow. As with all manufacturing this is rarely achieved on day one but has been developed and improved with time. Today the production consists of tape-laid skins, tape-laid panels for the spars, precured 'I' ribs, water jet trimming, automated ultrasonics and various assembly operations.

The composite production moves down the shop in a straight line, moving the bagged skins on AGVs, into the autoclave. The autoclaves open both ends, with one end in the clean room. The part enters the autoclave for the clean room and after the cure leaves at the other end to take it into tool strip and water jet trim. Final assembly is conventional

with all the ribs joined by riveting brackets. The 'black metal' approach is recognised as not ideal, and getting engineering resource to focus on these issues while there are so many new aircraft projects is a problem for the industry at large. To get the best from composites the design needs to reflect the capabilities offered by the process and the materials and include integral functionality wherever possible. Only then will composites begin to deliver the cost benefit to accompany the weight savings. Major composite components were being bought in from as far as Australia and Israel, clearly on a cost-competitive basis, although offset often features in the choice of a chosen supplier.

At Spirit AeroSystems, Wichita, the nearest to single-piece flow was seen: a lean production line for the manufacture of thrust reversers for the B737. The line had been laid out in a classic U with materials entering at one end and finished parts leaving at the other. On entering the factory all materials and components were taken to where they would be used, leading to an efficient process minimising the movement of employees, fork-lifts and trucks. Honeycomb core was all cut on site using five- and seven-axis ultrasonic knives. The cores were preformed before kitting into the lay-up area. The moulding was carried out using laser ply positioning to speed up the process and to provide an assurance that the plies and cores were positioned correctly and in the right order.

The acoustic properties of the component were achieved via perforated skins on a honeycomb core. The perforation holes are formed and cured on a tool with pins, the prepreg forced around the pins. Advantages over the cured laminate and drill alternative were claimed to be the use of thinner skins, as there was less fibre damage, and co-moulding of the hole is less expensive than drilling on a specialist multispindle drilling machine.

At Goodrich Aerostructures, Riverside, the reverser for the A320 V2500 engine variant is produced. The technology is based around metal bonding of aluminium skins, perforates and honeycombs. The treatment is undertaken in-house, with phosphoric and chromic anodise processes being used. The bonding system is via a Henkel Hysol primer/adhesive. The facilities at Riverside are much larger than the current work requires and so it was clearly challenging to rationalise the production into the right-sized area.

Some interesting concepts had been applied to the bottleneck areas of curing and machining. Cures were scheduled to the autoclaves using a bus timetable approach. Specific cures were run on certain days, at set times, to a programme that met customer demand. These were published well in advance.

All other production was geared to delivery to the autoclave of the parts for that cure. This

enabled autoclave capacity to be optimised using the inherent flexibility of the upstream processes – material cutting, treatment, kitting and lay-up. In this way the autoclaves were always run full. The double-sided tools for the larger parts at high production rates improved machine uptime by eliminating set-up time.

In the kitting area even bagging materials were kitted. Goodrich has found two key improvements since introducing this system. Firstly, just the right amount of material is used rather than allowing operators to 'guess' how much material to pull off the roll. Secondly, the skilled lay-up operators are able to spend their time on the tools rather than wandering around cutting bagging kits. The principle was found to work so well in practice that the supplier of the bagging material now supplies the pack in kit form.

Regarding the current thinking on the ideal management structure for manufacturing in



Figure 9.2 Mission delegates with host Paul Oppenheim (3rd from right) and Malcolm McLean (1st left) and Beverly Xu (3rd from left), British Consulate-General Los Angeles, at V System Composites

the US aerospace industry, a recurrent comment concerned the adoption of 'lean leadership' to accompany the other lean principles already accepted. This means the minimising of the layers of hierarchy in an organisation; a 'horizontal' structure is deemed the most efficient. An example was quoted at Goodrich where there are only two layers of management between the General Manager and the shop floor within the facility seen at Riverside.

The drive for cost savings can not be achieved through in-house improvements alone. As with many manufacturers in the developed economies, once the lean manufacture has taken the product as far as the cost base allows, the next cost jump is to lower-cost economies. Goodrich has targeted a number of detail parts to be subcontracted to Malaysia and China.

In the future Goodrich sees greater use of tape laying for smaller parts, through tow placement for cylindrical parts, reversers, nacelles, and tape laying for flat panels to convert to wing components, doors etc.

In the smaller companies visited – V System Composites and C&D Zodiac (Northwest Composites) – technologies had been developed to produce parts via RTM (in fact Hyper-VARTM™). In the case of V systems a very complex rotor-bearing housing saved both cost and weight by changing from aluminium structure to a one-piece RTM moulding. However, to provide meaningful sales for the business the decision was taken to install an autoclave and pursue the more traditional parts required by the market. In Zodiac, the B787 spars were formed using preforms and were to have been RTM cured; however, because of the stage of the process development and the need for integrity and rate of parts production, additional autoclaves were on order for the long-term production curing of the parts.

9.5 Summary

A variety of production processes were seen during the mission. It became clear that the industry is generally at a similar level of technology as in Europe. It is thought that Airbus is more advanced in certain areas (wing box, VTP, HTP) and Boeing in others (fuselage). However, the drivers for the industry are the same and the solutions are similar.

The chemistry of the materials and the processes to cure them cannot be changed without extensive qualification, and a new aircraft programme launched today would use current technology. Any new process must deliver to the industry parts that can be made at rate and consistently to the required quality standards. Conflicting drivers exist where there are 'invested interests' in current technology, and legacy programmes will not change the method of manufacture. This suggests that the industry will generate a new breed of suppliers that will move into the new technologies, either as a spin-off from an existing business or as a start-up, in a low-cost area.

LM is helping companies drive down their costs but this will only take the industry so far. The next cost jump is destined to be in a different geography.

There seems to be an emerging business model that relies on technical development and new product introduction in the developed economies and volume production in low-cost areas.

There is also, however, a move to establish higher technologies in these low-cost areas to satisfy technological requirements in return for aircraft orders. While the industry is buoyant there is sufficient capacity requirement to keep everyone busy. When the downturn comes, as it will, getting the balance of cuts right will be the challenge. Retaining the know-how where it is needed and establishing partnerships for production without losing the foundation of the knowledge base is key.

10 A NON-AEROSPACE PERSPECTIVE

Brian O'Rourke – WilliamsF1

- 10.1 *Processing and qualification*
- 10.2 *Programme and response timescales*
- 10.3 *Design communication*
- 10.4 *Summary*

10.1 Processing and qualification

The primary purpose of the mission was to study reduced-cost composites technologies and their current status in the manufacture of aerospace structures in the USA. A complementary view of these activities, however, can be made from the perspective of the non-aerospace user; out-of-autoclave processes, in particular, having been widely accepted across a range of other industries in recent years. Considering this, the foremost impression gained was that conventional composites processes are still very much the first choice for airframe construction; the majority of the companies visited were seen to be increasing their investment in autoclaves for the processing of prepreg materials, or in one instance, resin film infusion (RFI) of a braided preform.

It is accepted that, for aircraft structural design, optimum mechanical properties are always the primary aim and the manufacturing processes chosen are oriented towards their delivery. Conventional pressure-cured prepreg-based composites are the understood best route to achieving this. In the composites world outside of aerospace, by contrast, lesser – or more variable – mechanical performance is often readily accepted if a manufacturing method chosen will result in a faster rate of production or a reduction in the part-count in an assembly operation. An example of this thinking would be the integration of a number of elements to make up one moulded part.

The reluctance to avoid too much integration for reasons of structural certification – as witnessed on the Boeing 777 co-bonded fin skin/stringer at Frederickson where 'chicken' fasteners are also required in the bonded joint to eliminate any potential for peeling action, although the joint is fully acceptable for primary load transfer – still results in the 'black metal' approach being the preferred one. No examples of paste-adhesive joining were observed for similar reasons. In other industries, where certification is achieved by different means (eg final component performance alone), more adventurous manufacturing methods are often accepted as the norm. A clear conclusion, from these observations, is that bonding by itself is not yet acceptable for primarily-loaded joints. Any change in this situation will be noted with interest over the coming years.

Materials qualification in the aerospace industry is a complex process. The time and expense involved offer a significant deterrent to changes in materials type being made at too frequent an interval. Boeing, the mission learnt, had qualified a new prepreg for the 787 programme in one year which, given the full scope of the testing involved, is regarded as being very fast. This situation was clearly apparent from the mission visits during which very few variations on accepted – and mature – prepreg types were seen (the exception to this would be V System Composites where the nature of the work concerned prototyping and development). By comparison, in other composites industries, there is faster acceptance of new types of materials and the exploitation of what they have to offer. In the motorsport sector it is common for a new prepreg to be used in production after accelerated coupon testing, selected

component checks and manufacturing trials, often within a few months of its release by the supplier.

The work being done at NIAR at Wichita State University on the AGATE programme, which aims to simplify the process of materials qualification and establish a national database primarily for the general aviation industry, should encourage composites use by organisations that currently find the qualifying procedure an obstacle. An initiative within this programme is the concept of a 'super-sourced' material for which a common supply form is agreed (fibre type, matrix proportion, weave style) and a database of performance established together with a 'map' of the influence of processing variables upon it.

10.2 Programme and response timescales

Aerospace programmes, in keeping with their scale and complexity, dictate protracted timescales when compared to those in other industries. Of interest was to understand what response times the host companies considered acceptable for new design requirements. Goodrich Aerostructures (Riverside) stated that, from definition to completion of first component, it would be currently 16-18 months for a new nacelle assembly. The expectations at both Boeing and Spirit, for the 787 programme, are that the planned delivery dates for the major composites assemblies in late 2007 will be met. Given the novelty of the methods described and the complexity of the components witnessed, this will be an impressive achievement, although, clearly, the current status is the result of trial work over several years.

The matching of development activities to intended implementation dates is seen to be of immense importance to the acceptance of composites technologies for the future. A new technique not being ready for a programme start could consign it to 'back-burner' status

for some time thereafter. This was witnessed at C&D Zodiac, where part of the 787 fuselage frame, originally intended for RTM, was using autoclaved RFI laminate due to the progress of events. However, the new processes developed for the fuselage of the 787 programme, using multi-axis CNC tape-placement machines, could – it was confidently predicted at Spirit AeroSystems – easily be applied to any other new programme launch that took place after 2007. The implication was that the initiation of a future generation single-aisle aircraft would see the composites processes carry directly across and be the method of choice from now on.

10.3 Design communication

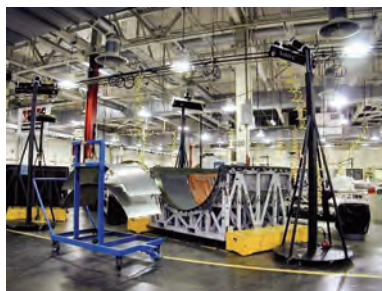


Figure 10.1 Laser guidance equipment for ply placement (courtesy Goodrich Aerostructures Group)

Another interest, from the perspective of non-aerospace industry users, is in the communication of design intent to the manufacturing group and how this is most directly – and efficiently – achieved. Since the activities witnessed were from the production 'end' of the process, it was difficult to judge this completely. It was clear, also, that the companies visited were volume-producers of aerospace parts and that a repeating series of routine production operations was being witnessed. In such circumstances the information provided for the operators was seen to take the form of a written procedure containing lists of detailed instructions; 'drawings', as such, were not seen. The use of laser-projection of ply boundary positions upon mould tools was widespread where hand lay-up laminating techniques remained and, in these instances, the instructions for ply selection and application were given by

the controlling computer. Traceability of the ply stack was seen to be connected to this process by the use of bar-code readers in some examples.

The difference, in these respects, between volume-production aerospace activities and those of an organisation dealing with prototyping – or small-scale production of complex parts such as motorsport – is clear. The link between design and production is, of necessity, much closer within the smaller organisation, and information may have to be conveyed in a more complete form; a separate production-engineering function not existing between them in many cases.

Boeing Frederickson does not currently use FiberSim; however, it was confirmed that software such as FiberSim exists throughout the aerospace industry in the USA and is used for ply flat-pattern development, laser projection and automated tape-laying as well as managing design information. V System Composites makes use of the capability within the laser projector's software to reverse-engineer the ply boundaries into the system's memory.

The choice of materials used for mould tooling, again, reflected the scale and longevity of the components observed. Overwhelmingly, moulds were built from metallic materials – particularly Invar – for reasons of durability, despite long fabrication timescales, weight and energy requirements. Composite tooling – of the prepreg type – was not judged to be suitable in most instances, an obvious exception being the two-part female 'clam-shell' mould for the fuselages built at Raytheon. The contrast to the motorsport industry in this regard was rather stark as, with the latter, the timescales involved and geometric complexity expected mean that no realistic alternatives to composite prepreg tooling are thought to exist; in effect all parts become 'rapid prototypes' when compared to the examples seen.

Similarly, the final operation of non-destructive evaluation (NDE) was simplified as much as possible for the volume-production case. The processes seen all used an ultrasonic technique, mostly through-transmission but with some pulse-echo, the geometry of the parts being simple and, hence, suitable. The approach was, in effect, 'go' or 'no-go' to the detection of defects, with other methods only being employed when questions were raised by a result beyond these options. Components of more severe curvature or complex construction, as encountered elsewhere, would require different – or additional – techniques.

10.4 Summary

Out-of-autoclave composites processes aimed at reducing manufacturing costs have been adopted and readily accepted in industry outside of aerospace. The impression gained through visits on the mission is that, whilst much expenditure has been directed towards the development of these in the USA, the majority of work within aerospace is still reliant on 'conventional' prepreg, metal tooling and autoclave techniques. Considerable investment was witnessed to have been made in these 'known' processes and it is clear that they are, still, regarded as the most reliable and best for structural performance.

Seen in the context of the objectives of the mission – reduced-cost manufacture – it is concluded that efficiency combined with performance has been judged to best come from greater automation of existing methods; the extent to which this had been taken was impressive indeed. The appearance is of a clear divide between aerospace primary structural components in composite materials and those of the automotive and other sectors, particularly in terms of new materials qualification and acceptance. In comparison to the motorsport industry, as an example, the reluctance of aerospace – for respected certification reasons – to embrace primary structural bonded connections limits the scope for component complexity with regard to integration. It would seem that, for commercial airliner construction at least, 'black metal' assemblies will continue for some time to come.

11 EDUCATION AND TRAINING

Sue Panteny – National Composites Network

Education is undertaken in a similar manner to the UK with education that may continue up to degree level and then onto PhD and postgraduate level.

The National Institute for Aviation Research (NIAR) at Wichita State University works very closely with industry undertaking applied research, 70% of which is related to structures and 56% related to composites. No lecturing is given. NIAR is advised by an Industry Advisory Board that consists of the several large American aircraft manufacturers (Raytheon Aircraft Co, Bombardier Aerospace, Cessna Aircraft Co, Spirit AeroSystems and Boeing Co).

R&D at NIAR covers all stages of aircraft life, from concept, development, most certification and use, including ageing aircraft and crashworthiness (becoming more important). Some fuels research is carried out at the institute but no other engine or propulsion work. A significant investment has been made in the Aircraft Structural Testing and Evaluation Center (ASTEC) at NIAR, which has a large facility, including a low-speed wind tunnel with an underfloor balance, for full-scale testing of non-metals as well as metallic structures.

Expertise has been developed in testing, which is undertaken for 70% of US states. Research tends to be reactive such as the study and detection of known problems often hidden under multilayer structures, but proactive research is also carried out, such as studying ageing aircraft, when funds are available for development. Currently there are a number of such projects running, for example studying the composite horizontal stabiliser of the 737, the wings of the T34

trainer and tail cracking of the C5 supporting the FAA. Seventy per cent of the FAA's composite material research is being undertaken at NIAR (involved in FAR – parts 23, 25, 27 and 29). The facilities are continually assessed and upgraded when needed. NIAR's 2 x 3 m low-speed Beech wind tunnel is in the process of an \$8 million (~£4.4 million) upgrade.



Figure 11.1
NIAR full-scale
component test
(courtesy NIAR)

NIAR also recently upgraded its crashworthiness sled, which is used for both analytical and experimental work. There are also facilities, which weren't shown, to undertake virtual aerodynamics. There is a great emphasis in undertaking work to industrial test standards and working very closely with industry. This was also seen at University of Washington where Boeing has a significant influence and at Delaware and North Carolina State Universities during the HYBRIDMAT 4 mission. These institutes' Centers of Excellence are more comparable to the German Fraunhofers, with development close to commercialisation emphasised, rather than the R&D of the UK, which is more research-oriented and guided by the constraints of the funding bodies. Some of the newer UK universities, former technical colleges, are taking up this gap and are successfully interacting with industry on a much smaller scale than these American institutes.

NIAR has set up a Center of Excellence funded by NASA, known as NCAMP (National Center for Advanced Materials Performance). It aims to continuously monitor materials by preparing an initial design database, evaluating process variables, establishing a robust process envelope and validating material and process changes. NCAMP canvassed industry and five prepreg systems were selected for the initial generation of a public database. Although this initial database was government funded, material suppliers will now pay for further databases. It will replace the Mil handbook 17. It has the support of many OEMs including Northrop Grumman, Lockheed Martin, Sikorski, Bell and smaller businesses and general aviation companies. NIAR is keen to extend the use of this materials database, by sharing it worldwide, and is looking for global support, especially from Europe.

Aircraft manufacturers in Wichita define the research areas which are investigated, for Wichita State University, the University of Kansas and Kansas State University (such as LM principles). The Wichita Area Technical College has benefited from Wichita being a centre of excellence for composite manufacture. At the instigation of Raytheon it recognised the difficulty being experienced by aircraft manufacturers in getting a trained workforce and has put on a course that will benefit not only Raytheon but also the other aircraft manufacturers in the Wichita area such as Cessna and Spirit AeroSystems.

At V System Composites 40% of the workforce are degree engineers, many from Northrop Grumman, Lockheed Martin and other major aerospace companies in the USA that were involved in the VARTM and RTM processes. Twenty-five per cent of the engineers are serving in engineering, manufacturing, design and analysis work. V System Composites consciously ensures that there is a balance of young and old staff, with experienced composite workers and

young trainees. It has a close relationship with universities, with a small business grant (a fifth of total turnover) being used for R&D work, with the University of Delaware amongst others. V System Composites has developed an in-house software analysis program that is used in component manufacture design. Companies, as in the UK, have developed a flat organisation structure for composites manufacture.

At Goodrich Aerostructures, as in other companies, an undergraduate will often be employed part time for the last year or two of their course and will normally be employed full time when their course has ended. Currently, Goodrich is finding that there is a shortage of trained staff, with the upturn in aircraft manufacture, but are benefiting with the return of past employees that left when business was not so good a decade ago. With an eye to the future, these employees were helped to find employment in advanced composites manufacture with other manufacturers in the area that did not specialise in aerospace composites. With the downturn in these other markets being experienced at the moment, many of the experienced performance composites processors are returning.

Currently the University of Washington has eight Centres of Excellence in aviation, including the Center of Excellence for Advanced Materials in Transport Aircraft Structures (AMTAS), where there is matched government funding for a consortium of academic institutions, aerospace companies and government agencies. The University of Washington in Seattle serves as the lead academic institution for AMTAS along with three affiliate academic members, including Washington State University, and has eleven main industrial partners including Boeing, Bell Helicopters, Zodiac and materials suppliers such as Cytec, Hexcel and Toray. It is part of the FAA Joint Advanced Materials and Structures Center of Excellence (JAMS)

which comprises AMTAS along with the Center of Excellence for Composites and Advanced Materials (CECAM) led by Wichita State University.



Figure 11.2 In discussion with Alan Prichard (Boeing) at University of Washington

AMTAS will address safety and certification initiatives for existing, near- and long-term applications of composites and advanced materials for large transport commercial aircraft. Funding is helped by the SBIR grant for small businesses. Many of the small companies visited, especially during the HYBRIDMAT 4 mission, work closely with universities and rely on the SBIR funding, which is 100% at the early stage, to enable continued R&D to be viable. This is different from the UK where EU regulations are in force and funding can only be sought up to a maximum of 75% for far-from-market research and 50% for nearer-to-market but not commercially viable development. As in the USA, close-to-market development in the UK is expected to be undertaken using only commercial funding.

11.1 Summary

US universities are noticeably more involved with industry than those in the UK, not only in the R&D undertaken but also in the day-to-day solving of technical issues for a company, as witnessed at NIAR. This is seen in the UK on a much smaller scale with the testing and analysis services that many universities now provide.

As in the UK, there is a shortage of qualified engineers and trained technical staff. The US universities are addressing this issue by working closely with industry to put on courses specific to industrial requirements. This should be considered for the UK. The US Government is aiding its industry significantly with its research programmes and centres of excellence that have been set up in the composites and aerospace sector between universities and industry. The Faraday Partnerships and Technical Centres of Excellence being set up by the UK Government are steps in the same direction and, with the amalgamation into Knowledge Transfer Networks (KTNs), should have enough 'critical mass' to make a difference.

12 CONCLUSIONS AND RECOMMENDATIONS

The companies and academic institutions visited in the USA are justifiably proud of their R&D and the implementation of their innovative solutions developed for composite applications. There is currently under way a marked increase in confidence, and business, in the design and manufacture of carbon fibre composite structures in the USA. The timescale for the development of the Boeing 787 is driving massive investment in manufacturing capability. Whilst many of the processes and practices are similar to those in Europe, programmes such as the Boeing 787 supported by Spirit AeroSystems, Raytheon and others are leading the way in composite applications for the next generation of civil aircraft.

The main drivers for carbon fibre composites include mass reduction, part reduction, complex shape manufacture, reduced scrap, improved fatigue life, design optimisation and improved corrosion resistance. Constraints are material and processing costs, damage tolerance and repair, dimensional tolerance, and conservatism due to uncertainties of a new and sometimes variable material. The drivers and constraints appear little changed from the findings of the last DTI Global Watch Mission on aerospace composites, that took place in 1998, but there is far greater enthusiasm for composites introduction. Composite designs are becoming less conservative with the greater knowledge and understanding that is being gained through further testing, greater experience, more materials data and the ability to model materials, processes and performance that are being developed and continuously improved.

The extremely rapid development of structures for the Boeing 787, combined with

the shortage of composites materials and process engineers and concerns over materials performance, process reliability, damage resistance and tooling cost, have diminished the drive towards the replacement of prepregs by lower cost technologies. To realise the replacement of prepreg for highly loaded structure, it is clear that substantial research effort has to be focused on materials performance improvement for preforming and infusion processing technology.

It would be easy to conclude that US materials technology has not advanced very far during the last 10 years and that the real advances have been in automated lay-up machines, the size of the components now being developed, and the scale of the new factories being built to process them. However, NASA and FAA investment in materials and structural testing at NIAR is removing the barriers of performance and repair uncertainty and reducing the barrier to new materials introduction by smaller companies such as Raytheon.

The mission team found a wide range of manufacturing, assembly and automation methodologies in use, from legacy programmes such as the Boeing 737 fuselage, to the very latest generation Boeing 787 fibre-placed composites fuselage, that clearly demonstrate the changes and advances in materials, manufacturing and assembly methods, along with the latest that technology has to offer in automation and machine tool control.

Many of the companies visited have implemented the principles and culture of lean manufacturing (LM) and statistical process control (SPC), in common with many

European countries. LM is helping companies drive down their costs but with diminishing returns. Innovative solutions to reduce cost and maximise efficiency were evident in the approaches taken by companies such as Raytheon, Boeing and V System Composites with their applications of innovative tooling and component unitisation to reduce the number of detail parts and minimise assembly operations.

Mission objectives were to evaluate progress in the uptake of out-of-autoclave processes such as resin film infusion (RFI) for secondary structures and the balance between automation and manual processes. An emerging business model is one that relies on technical development and new product introduction in the developed economies and volume production in low-cost areas. Strong evidence was seen of simpler components remaining as prepreg and autoclave cure but being sub-contracted to areas of low-cost labour. For more complex structures there was little evidence of any real move to out-of-autoclave processes with the majority of parts still utilising manual lay-up of prepregs albeit with the process being optimised by widespread investment in laser ply positioning equipment. For future programmes the emphasis was very much on major capital investment in facilities and process development to allow manufacture by fully automated processes such as prepreg tow placement and a continued reliance on autoclave curing.

The majority of applications seen during the mission were of composite materials using unidirectional fibre, pre-impregnated with epoxy resin, cured at elevated pressure and temperature in an autoclave. The materials were developed for use with single-sided tooling, and over the last 10 years many incremental steps have been taken to improve the processes. This experience enables routine production of high-quality composite components.

The host organisations seemed poised in readiness for composites technologies to move forward – something that was reflected in the 787 modular tooling and the 'RTM plus combination' technique. Technological progress is slow, as it is in the UK, with two restraining factors being the high level of investment in current technology and the high cost of process certification for the aerospace industry.

A variety of production processes were seen during the mission. It became clear that the industry is generally at a similar level of technology as in Europe, and from a tooling perspective that the two countries have equivalent composites capabilities. It is thought that Airbus is more advanced in certain areas (wing box, VTP, HTP) and Boeing in others (fuselage) but the drivers for the industry are the same and the solutions are similar.

The chemistry of the materials and the processes to cure them cannot be changed without extensive qualification, so that a new programme launched today would use current technology. Any new process must deliver to the industry parts that can be made at a similar or faster rate and consistently to the required quality standards. Conflicting drivers exist where there are 'invested interests' in current technology, and legacy programmes will not change the method of manufacture. This suggests that the industry will generate a new breed of suppliers that will move into the new technologies, either as a spin-off from an existing business or as a start-up, in a low-cost area.

The US universities visited were seen to be heavily involved with industry, not only in the R&D undertaken but also in the day-to-day solving of technical issues for a company, as witnessed at NIAR. This is seen in the UK on a much smaller scale with the materials testing and analysis services that some universities now provide.

As in the UK, there is a shortage of qualified engineers and trained technical staff. The US universities are addressing this issue by working closely with industry to put on courses specific to industrial requirements. This should also be considered for the UK. For example, in the UK there are approximately 25 students training in technical textiles per year, with only a few of those specialising in composite reinforcement. The growing interest and requirements of 3-D woven reinforcements in aerospace composites should be encouraging more courses in this area to sustain the composites textile industry and provide the specialists required.

The EC has funded a number of large well known aerospace composites programmes such as TANGO and ALCAS. In contrast, it was considered surprising, given the ambitious timescales of Boeing's 787 composites development, that there was little information available on US Government funded large structural demonstrator programmes. However, the US Government is aiding its industry significantly with its research programmes and centres of excellence that have been set up jointly between universities and industry in the composites and aerospace sectors.

There are many similarities in the programmes and work being carried out in North America and the UK and, on balance, technology development is similar between the UK and the organisations that were visited.

Non-autoclave processing is generally regarded as the future for composites as aerospace has invested heavily in current technology and so is understandably reluctant to change. Rather than using the new technologies, modifying an existing process, where much experience exists, is seen as preferable before using on an aircraft. Non-aerospace industries would use composites but it is an expensive exercise when

experience is lacking. It is recommended that investment is made in several areas to address this, perhaps through funded programmes to develop low-cost processing technologies with non-aerospace companies.

Investment should be made in automating the composites production process to help retain composites manufacture in the UK, starting with designing composite components for automated assembly, including flexible mould tooling concepts and composites design for component disposal/disassembly.

In collaboration with NIAR, it is recommended that the NCN looks at how a materials performance database can be set up for UK and European manufacturers, using a greater range of materials than covered by AGATE. This will allow smaller companies to enter the aerospace composites supply chain.

Above all it is recommended that research support, courses and training are funded, with guidance from industry, to cater for the current and future workforce needs and provide for the sustainability of a growing advanced structural composites industry.

Appendix A

ACKNOWLEDGMENTS

The delegates found the mission very rewarding and enlightening. Given the fact that some of the UK and US companies are competitors, the openness with which we were received at every venue was very much appreciated. Equally impressive was the knowledge and enthusiasm of our hosts and tour guides and the quality of the products and facilities.

- We would like to extend our deepest thanks to the companies that we visited for their openness and generous hospitality, without which this report would not have been possible.
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Appendix B

HOST ORGANISATIONS

Boeing Co

Frederickson
176th St E
Seattle
WA 98124
USA
T +1 206 655 9921
www.boeing.com

Bill Gerry

Program Manager, Boeing Technology
Ventures, Global R&D Strategy
william.m.gerry@boeing.com

Goodrich Aerostructures Group

8200 Arlington Avenue
Riverside
CA 92503-1499
USA
T +1 951 351 5400
www.aerostructures.goodrich.com

Mike Jacobs

Manager, Research & Development
mike.jacobs@goodrich.com

National Institute for Aviation Research (NIAR), Wichita State University

1845 Fairmount
Wichita
KS 67260-0093
USA
T +1 316 978 3456
www.niar.wichita.edu

Prof John Tomblin

Executive Director, NIAR
john.tomblin@wichita.edu

Raytheon Aircraft Co

PO Box 85
Wichita
KS 67201-0085
USA
T +1 316 676 7111
www.raytheonaircraft.com

Bill Jones

Director, Manufacturing Technology
bill_jones@rac.ray.com

Spirit AeroSystems Inc

PO Box 780008
MC K 12-04
Wichita
KS 67278-0008
USA
T +1 316 526 9000
www.spiritaero.com

Don Blake

Director, Industrial Cooperation,
Office of the Chief Scientist
don.a.blake@spiritaero.com

V System Composites Inc

1015 East Discovery Lane
Anaheim
CA 92801-1147
USA
T +1 714 678 2740
www.vsystemcomposites.com

Paul Oppenheim

VP Programs & Business Development
poppenheim@drtechnologies.com

Center of Excellence for Advanced Materials in Transport Aircraft Structures (AMTAS), University of Washington

FAA Center of Excellence
143F Mechanical Engineering
Box 352600
Seattle
WA 98195-2600
USA
T +1 206 685 6665
www.me.washington.edu/faculty/tuttle

Prof Mark Tuttle

Director, AMTAS
mechair@u.washington.edu

C&D Zodiac Inc (formerly Northwest Composites)

12810 State Avenue
Marysville
WA 98271
USA
T +1 360 653 2211
www.zodiac.com

Jason Scharf

Product Development Manager
scharf@nwcomposites.com

British Consulate-General Los Angeles

11766 Wilshire Boulevard
Suite 1200
Los Angeles
CA 90025-6538
USA
T +1 310 477 3322
www.uktradeinvestusa.com

Brian Conley

Deputy Consul-General and Consul (Trade)
brian.conley@fco.gov.uk

Greater Wichita Economic Development Coalition (GWEDC)

350 W Douglas
Wichita
KS 67202
USA
T +1 316 268 1133
www.gwedc.org

KayLene Haug

Business Retention Specialist
khaug@gwedc.org

Kansas Department of Commerce, Trade Development Division

1000 S W Jackson Street
Suite 100
Topeka
KS 66612-1354
USA
T +1 785 296 3481
www.kansascommerce.com

Randi Tveitaraas Jack

International Development Manager
rjack@kansascommerce.com

Appendix C

MISSION TEAM AND ITP CONTACT DETAILS

Advanced Composites Group Ltd

Composites House
Sinclair Close
Heanor Gate Industrial Estate
Heanor
Derbyshire
DE75 7SP
UK
T +44 (0)1773 763 441
www.acg.co.uk

Roger Francombe

Group Product Manager and European
Aerospace Market Sector Manager
rfrancombe@acg.co.uk

BAE Systems plc

Aerospace and Defence Equipment
Samlesbury
Lancashire
BB2 7LF
UK
T +44 (0)1254 812 371
www.baesystems.com

Roger Duffy

Engineering Manager for Product and
Processes
roger.duffy@baesystems.com

Cranfield University

Building 88
Materials Department
School of Applied Sciences
Cranfield
Bedfordshire
MK43 0AL
UK
T +44 (0)1234 750 111
www.cranfield.ac.uk
www.cranfield.ac.uk/sims/staff/millsa

Andrew Mills

Head of Composites Manufacturing Research
a.r.mills@cranfield.ac.uk

DTI Global Watch Service

Pera
Pera Innovation Park
Melton Mowbray
Leicestershire
LE13 0PB
UK
T +44 (0)1664 501 551
www.globalwatchservice.com/itp

Cliff Young

International Technology Promoter (ITP) –
Manufacturing Industries, North America
cliff.young@pera.com

INBIS Ltd

Club Street
Bamber Bridge
Preston
Lancashire
PR5 6FN
UK
T +44 (0)1772 645 000
www.inbis.com

Brian Gilbert

Senior Consultant and Project Manager
bgilbert@inbis.com

National Composites Network (NCN)

Granta Park
Great Abington
Cambridge
CB1 6AL
UK
T +44 (0)24 1223 891 162
www.ncn-uk.co.uk

Sue Panteny

Technology Specialist
sue.panteny@btinternet.com

Smiths Aerospace

Kings Avenue
Hamble-le-Rice
Hampshire
SO31 4NF
UK
T +44 (0)23 8045 3371
www.smiths-aerospace.com

John Savage

Technical Authority – Composites
john.savage@smiths-aerospace.com

St Bernard Composites

Saberhouse
Lynchford Road
Farnborough
Hampshire
GU14 6JE
UK
T +44 (0)1252 304 000
www.stbernard.co.uk

Chris Webborn

Managing Director
webbornc@stbernard.co.uk

WilliamsF1

Grove
Wantage
Oxfordshire
OX12 0DQ
UK
T +44 (0)1235 777 700
www.williamsf1.com

Brian O'Rourke

Chief Composites Engineer
brian.orourke@williamsf1.com

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Appendix E

GLOSSARY

~	APU
<i>approximately</i>	<i>auxiliary power unit</i>
≈	ASTEC
<i>approximately equal to</i>	<i>Aircraft Structural Testing and Evaluation Center (NIAR, Wichita State University, USA)</i>
<	ATL
<i>less than</i>	<i>automated tape laying</i>
%	ATP
<i>per cent</i>	<i>automated tow placement</i>
£	autoclave
<i>pound sterling ≈ \$1.8 (Jun 06)</i>	A closed vessel for application of pressure and heat, used for processing composite materials
\$	bar
<i>US dollar ≈ £0.54 (Jun 06)</i>	Unit of pressure = 10 ⁵ Pa
3-D	BMI
<i>three-dimensional</i>	<i>bismaleimide</i>
ACG	B-stage
<i>Advanced Composites Group (UK)</i>	Intermediate stage in the polymerisation reaction of thermosets, following which material will soften with heat and is plastic and fusible; also called resistal; the resin of an uncured prepreg or premix is usually in B-stage
ACT	°C
<i>advanced composite technology</i>	<i>degrees Celsius</i>
AFI	CA
<i>affordable feature integration</i>	<i>California (state, USA)</i>
AGATE	CAI
<i>Advanced General Aviation Transport Experiments (programme, NASA, USA)</i>	<i>compression after impact</i>
AGV	
<i>automated guided vehicle</i>	
AMTAS	
<i>Center of Excellence for Advanced Materials in Transport Aircraft Structures (University of Washington, USA) – part of JAMS</i>	

CAPRI

controlled atmospheric pressure resin infusion

carbon fibre

An important reinforcing fibre known for its light weight, high strength and high stiffness that is commonly produced by pyrolysis of an organic precursor fibre (often polyacrylonitrile (PAN) or rayon) in an inert atmosphere

caul plates/sheets

Smooth metal or composite plates, free of surface defects, of the same size and shape as the composite lay-up, which are used in direct contact with the lay-up during the curing process to transmit normal pressure and temperature and provide a smooth surface on the finished laminate

CECAM

Center of Excellence for Composites and Advanced Materials (Wichita State University, USA) – part of JAMS

CFRP

carbon fibre-reinforced plastic/polymer

CMC

Composite Manufacturing Center (Boeing Co, USA)

CNC

computer numerical control – This refers specifically to the computer control of machine tools for the purpose of (repeatedly) manufacturing complex parts in metal as well as other materials, using a program written in a notation conforming to the EIA-274-D standard and commonly called *G-code*; CNC was developed in the late 1940s and early 1950s by the MIT Servomechanisms Laboratory

CO₂

carbon dioxide

composite

A homogeneous material created by the synthetic assembly of two or more materials (a selected filler or reinforcing elements and compatible matrix binder) to obtain specific characteristics and properties

DLF

direct line feed

DTI

Department of Trade and Industry (UK)

EC

European Commission

empennage

The rear part of an aircraft, comprising the fin, rudder and tailplane

epoxy

A thermoset polymer containing one or more epoxide groups and curable by reaction with amines, alcohols, phenols, carboxylic acids, acid anhydrides and mercaptans; an important matrix resin in composites and structural adhesive

EPSRC

Engineering and Physical Sciences Research Council (UK)

EU

European Union

°F

degrees Fahrenheit

F1

Formula One (motor racing)

FAA

Federal Aviation Administration (USA)

fabrication

The process of making a composite part or tool

FAR*Federal Aviation Regulation (USA)***ft***foot = 0.3048 m***GWEDC***Greater Wichita Economic Development Coalition (KS, USA)***HTP***horizontal tailplane***HYBRIDMAT***hybrid materials***I&R***interchangeable and replaceable***injection moulding**

Method of forming a plastic to the desired shape by forcibly injecting the polymer into the mould

Invar

A 36% nickel-iron alloy that has the lowest thermal expansion amongst all metals and alloys from room temperature up to ~230°C; it is ductile, machinable, easily weldable and resists stress corrosion cracking; the average coefficient of thermal expansion of Invar between 20-100°C is $<1.3 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$

ITP*International Technology Promoter (network, DTI)***JAMS***FAA Joint Advanced Materials and Structures Center of Excellence (USA) – comprising AMTAS and CECAM***Kanban**

A just-in-time manufacturing process in which the movements of materials are recorded on specially designed cards

kg*kilogram***KHI***Kawasaki Heavy Industries Ltd (Japan)***KS***Kansas (state, USA)***KTN***Knowledge Transfer Network (UK)***L***left***laminate**

A product made by bonding together two or more layers of material or materials; primarily means a composite material system made with layers of fibre reinforcement in a resin; sometimes used as a general reference for composites, regardless of how made

LM*lean manufacturing***LRI***liquid resin infusion***m***metre***matrix**

The material in which the fibre reinforcements of a composite system are embedded; thermoplastic and thermoset polymer resin systems can be used, as well as metal and ceramic

min*minute = 60 s***MIT***Massachusetts Institute of Technology (USA)***mm***millimetre = 0.001 m*

N

newton – unit of force = kg m/s²

NASA

National Aeronautics and Space Administration (USA)

NAVAIR

Naval Air Systems Command (US Navy)

NCAMP

National Center for Advanced Materials Performance (NIAR, Wichita State University, USA)

NCF

non-crimp fabric

NCN

National Composites Network (UK)

NDE

nondestructive evaluation

NIAR

National Institute for Aviation Research (Wichita State University, USA)

NWAA

North West Aerospace Alliance (UK)

OEM

original equipment manufacturer

Pa

pascal – unit of pressure = N/m²

PAN

polyacrylonitrile

PO

Post Office

polymer

A very large molecule formed by combining a large number of smaller molecules, called monomers, in a regular pattern

polymerisation

A chemical reaction in which the molecules of monomers are linked together to form polymers

preform

A preshaped fibrous reinforcement formed by distribution of chopped fibres by air, water flotation or vacuum over the surface of a perforated screen to the approximate contour and thickness desired in the finished part; also, a preshaped fibrous reinforcement of mat or cloth formed to desired shape on a mandrel or mock-up prior to being placed in a mould press; also, a compact 'pill' formed by compressing premixed material to facilitate handling and control of uniformity of charges for mould loading

prepreg

Ready-to-mould material in roll form comprising a reinforcement (which may be cloth, mat, or paper) pre-impregnated with a specially formulated polymer (resin) and stored for use; the fabricator lays up the finished shape and completes the cure with heat and pressure

psi

pound per square inch – unit of pressure = 6,895 Pa = 0.06895 bar

QA

quality assurance

QEDM

quality engineering data management

QM

quality management

R

right

R&D

research and development

reinforcement

An advanced fibre in unidirectional woven cloth or complex textile format that is used to impart mechanical strength in the polymer matrix

resin

A blend of prepolymers/monomers of mixed molecular weight, with a specific softening point and functionality; used to formulate a prepreg matrix, resin film or liquid infusion resin

RFI

resin film infusion

RI

resin infusion

RTM

resin transfer moulding – a process in which catalysed resin is transferred into an enclosed mould into which the fibre reinforcement has been placed; cure normally is accomplished without external heat; RTM combines relatively low tooling and equipment costs with the ability to mould large structural parts

s

second

SBIR

Small Business Innovation Research – one of the programmes run by the Office of Technology of the US Small Business Administration to strengthen and expand the competitiveness of US small high-technology R&D businesses in the federal marketplace. The Office of Technology also assists in achieving the commercialisation of the results of both the federal R&D programmes mandated by the Small Business Innovation Development Act of 1982, the Small Business Research and Development Enhancement Act of 1992, and the Small Business Innovation Research Program Reauthorisation Act of 2000.

Since its enactment in 1982, as part of the Small Business Innovation Development Act, SBIR has helped thousands of small businesses to compete for federal R&D awards. Their contributions have enhanced US defence, protected the environment, advanced healthcare, and improved the ability to manage information and manipulate data. An American SME, a company of up to 500 employees, can qualify for an SBIR grant provided it is American-owned, independently operated, for-profit and a principal researcher is employed by the business.

The eleven funding federal departments and agencies allocate a percentage of their R&D spend each year to small businesses and designate topics. Following submission of proposals, agencies make SBIR awards based on small business qualification, degree of innovation, technical merit, and future market potential. Small businesses that receive awards or grants then begin a three-phase programme.

Phase I is the start-up phase. Awards of up to \$100,000 (~£56,000) for approximately six months support exploration of the technical merit or feasibility of an idea or technology.

Phase II awards of up to \$750,000 (~£420,000), for as many as two years, expand Phase I results. During this time, the R&D work is performed and the developer evaluates commercialisation potential. Only Phase I award winners are considered for Phase II.

Phase III is the period during which Phase II innovation moves from the laboratory into the marketplace. No SBIR funds support this phase. The small business must find funding in the private sector or other non-SBIR federal agency funding.

SME

small or medium sized enterprise

SPC

statistical process control

WIP

work-in-progress

T

telephone

T_g

glass transition temperature – the temperature at which an amorphous polymer (or the amorphous regions in a partially crystalline polymer) changes from a hard and relatively brittle condition to a viscous or rubbery condition

thermoset

A material that will undergo a chemical reaction caused by heat, catalyst etc, leading to the formation of a solid; once it becomes a solid, it cannot be reformed

UAV

unmanned aerial vehicle

UK

United Kingdom

US(A)

United States (of America)

USAF

United States Air Force

VARTM

vacuum-assisted resin transfer moulding

VI

vacuum infusion

VP

Vice President

VTP

vertical tailplane

WA

Washington (state, USA)

Other DTI products that help UK businesses acquire and exploit new technologies

Grant for Research and Development –

is available through the nine English Regional Development Agencies. The Grant for Research and Development provides funds for individuals and SMEs to research and develop technologically innovative products and processes. The grant is only available in England (the Devolved Administrations have their own initiatives).

www.dti.gov.uk/r-d/

The Small Firms Loan Guarantee – is a UK-wide, Government-backed scheme that provides guarantees on loans for start-ups and young businesses with viable business propositions.

www.dti.gov.uk/sflg/pdfs/sflg_booklet.pdf

Knowledge Transfer Partnerships – enable private and public sector research organisations to apply their research knowledge to important business problems. Specific technology transfer projects are managed, over a period of one to three years, in partnership with a university, college or research organisation that has expertise relevant to your business.

www.ktponline.org.uk/

Knowledge Transfer Networks – aim to improve the UK's innovation performance through a single national over-arching network in a specific field of technology or business application. A KTN aims to encourage active participation of all networks currently operating in the field and to establish connections with networks in other fields that have common interest.

www.dti.gov.uk/ktn/

Collaborative Research and Development –

helps industry and research communities work together on R&D projects in strategically important areas of science, engineering and technology, from which successful new products, processes and services can emerge.

www.dti.gov.uk/crd/

Access to Best Business Practice – is available through the Business Link network. This initiative aims to ensure UK business has access to best business practice information for improved performance.

www.dti.gov.uk/bestpractice/

Support to Implement Best Business Practice

– offers practical, tailored support for small and medium-sized businesses to implement best practice business improvements.

www.dti.gov.uk/implementbestpractice/

Finance to Encourage Investment in Selected Areas of England

– is designed to support businesses looking at the possibility of investing in a designated Assisted Area but needing financial help to realise their plans, normally in the form of a grant or occasionally a loan.

www.dti.gov.uk/regionalinvestment/

The DTI Global Watch Service provides support dedicated to helping UK businesses improve their competitiveness by identifying and accessing innovative technologies and practices from overseas.

Global Watch Information

Global Watch Online – a unique internet-enabled service delivering immediate and innovative support to UK companies in the form of fast-breaking worldwide business and technology information. The website provides unique coverage of UK, European and international research plus business initiatives, collaborative programmes and funding sources.

Visit: www.globalwatchservice.com

Global Watch magazine – distributed free with a circulation of over 50,000, this monthly magazine features news of overseas groundbreaking technology, innovation and management best practice to UK companies and business intermediaries.

Contact:

subscriptions@globalwatchservice.com

UKWatch magazine – a quarterly magazine, published jointly by science and technology groups of the UK Government. Highlighting UK innovation and promoting inward investment opportunities into the UK, the publication is available free of charge to UK and overseas subscribers.

Contact:

subscriptions@ukwatchonline.com

Global Watch Missions – enabling teams of UK experts to investigate innovation and its implementation at first hand. The technology focused missions allow UK sectors and individual organisations to gain international insights to guide their own strategies for success.

Contact:

missions@globalwatchservice.com

Global Watch Technology Partnering – providing free, flexible and direct assistance from international technology specialists to raise awareness of, and provide access to, technology and collaborative opportunities overseas. Delivered to UK companies by a network of 23 International Technology Promoters, with some 8,000 current contacts, providing support ranging from information and referrals to more in-depth assistance with licensing arrangements and technology transfer.

Contact: itp@globalwatchservice.com

For further information on the Global Watch Service please visit

www.globalwatchservice.com

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