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FUTURE DIRECTIONS IN AERONAUTICAL COMPOSITES

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SUMMARY

The use of carbon-fibre polymer matrix composites in civil and military aircraft has been significantly less than originally predicted, despite their excellent attributes. This paper discusses, from an Australian perspective, that of a supplier of many composite parts to the world airframe industry, some of the key issues that could lead to more successful and extensive use of these materials. These include improvements in design, materials, manufacture and supportability.

High costs of procurement and certification of composite components are considered to be the current major inhibitors to more widespread composites use, particularly in civil applications. Thus the major focus of this paper is on improved manufacturing, which is the most significant factor influencing procurement cost. The paper then goes on to discuss two important advanced applications of composites - "Smart" Structures and the High-Speed Civil Transport.

INTRODUCTION

Since they were introduced in the early '70s the use of carbon-fibre polymer-matrix composites (PMCs) for aircraft structures has grown considerably, although not as rapidly as expected. This is largely because of high procurement costs of the PMCs compared with metals - despite the many advantages, including weight saving, fatigue resistance and corrosion immunity, that these materials can provide. Although procurement cost is the key affordability issue, particularly for civil aircraft applications, affordability estimations must also include operational costs (e.g. range or fuel saving, payload) and through-life support costs (cost of ownership). Over the life of the airframe (20 years or more) through-life support costs can be four times the procurement cost; however, through-life support benefits are understandably much harder to sell as they take much longer to be realised.

The high procurement cost is largely due to the high cost of manufacturing and certifying PMC aircraft structures, compared with similar structures made from conventional or even emerging aluminium alloys (such as aluminium lithium). Raw material costs are also significantly higher for carbon fibre PMCs than for aluminium alloys, but this is offset by their lower density and higher "fly to buy" ratio - more of the material is converted into finished component.

Because of high procurement costs and other problems discussed later, composite applications have been slow to grow in civil aircraft and are less than 20% by weight, mostly in secondary applications such as movable surfaces. There are some notable exceptions, such as the empennage of the Boeing 777 and Airbus aircraft, but these, whilst showing reasonable weight saving, have been very costly compared with the metallic equivalent.

For military aircraft the cost of composites compared to metals is not such a major issue, and performance and supportability are the drivers; also airframe costs are usually much smaller than systems and software costs. Nevertheless, even in aircraft such as the F22, which is 25% PMC construction, another 15% of the structure was originally planned to be composite but has been replaced by NC-machined metal to reduce costs.[1] However, where the value of weight saving is very high such as in high-performance helicopters, notably the Eurocopter Tiger, composites have achieved over 50% usage.

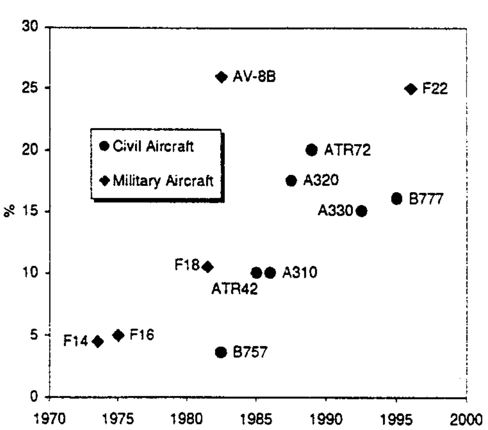

Figure 1: Percentage of fixed-wing aircraft structure made of composite

In addition to concerns with high procurement costs, there are other impediments to the wider use of composites. These include the less-than-anticipated

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weight savings in some applications, often due to overdesign, (designing like black metal) and unanticipated failures in some early development programs. To harness the high specific strength and stiffness and the fatigue resistance that can be obtained from carbon-fibre PMCs, all loading situations which may arise must be fully appreciated and allowed for in design.[2] These include:

- Sensitivity to out-of-plane loading due to lack of fibre reinforcement in the through-thickness direction
- Sensitivity to damage caused by relatively low energy mechanical impacts, particularly when the composite is primarily loaded in compression,
- Sensitivity to mild stress concentrators such as an open hole in tension or compression
- Sensitivity to hot/wet environment in matrix dominated modes, such as shear and compression
- Multiplicity of potential failure modes, some of which are influenced by temperature and absorbed moisture (hot/wet conditions)

Thus although the use of the composites has not acheived the success originally predicted or hoped for, the future should be more promising if good use is made of the lessons learned from past experience.

KEY ISSUES AFFECTING THE FUTURE DIRECTIONS OF COMPOSITES

It is not possible in a paper of this length to consider in detail all of the issues which can affect the future directions of composites, but I have tried to identify the key points as seen from an Australian perspective. Many of the illustrations used here are based on studies in the Cooperative Research Center for Advanced Composite Structures (CRC-ACS); however, these are representative of work in progress around the world. There is no doubt that the major objective world-wide is to reduce component costs, largely through improved manufacturing technology, and this is reflected by the emphasis of this paper.

Table 1 is a summary of some of the key requirements to be met if we are to derive the greatest performance and lowest acquisition and through-life support costs for the of PMCs. Many of these are well known, but others are overlooked or unlikely to be achieved by proposed designs and manufacturing approaches.

The following subsections provide further comments on some of these points, followed by a more detailed review of manufacturing issues. This is the main focus of the CRC-ACS and in our view is the major issue which will determine the future adoption of composites.

Design Issues

A Finite-Element (FE) Analysis can accurately predict complex elastic and elasto-plastic behaviour, providing the external loading is known. The extent and thus the cost of testing depends on the confidence that can be placed in this analysis and on the availability of validated failure criteria. However, there is as yet no general agreement on in-plane failure criteria under complex loading,[3] particularly in the presence of stress concentrations such as fastener holes.[4] This problem has been studied for many years but the approach that provides the best predictive capability has yet to be resolved.

Methods of allowing for typical damage are also empirical; a capability similar to linear-elastic fracture mechanics for metals is a long way off for composites, due to the complexity of typical damage (impact damage), the number of possible failure modes and environmental sensitivity.

There are many design innovations which can improve damage tolerance, reduce sensitivity to stress concentrations and increase structural efficiency. The simplest approach is the so-called soft-skin approach in which the main load bearing 0° fibre layers are shielded by soft ±45° fibre layers. Another approach, discussed by Tsai,[5] is based on iso-grid structures which are similar in concept to the geodetic aluminium alloy construction of the World War 2 Vickers Wellington Bomber fuselage. The primary load bearing elements are tubes or beams largely of 0° fibres, which, if required, can be easily be protected from mechanical damage by soft skins. The grid construction is structurally efficient and has a high level of redundancy, allowing several of the elements to be broken without catastrophic strength loss – a major feature of the Wellington, which had outstanding resistance to battle damage. An experimental composite fuselage barrel using geodetic stiffening is shown in Figure 2.

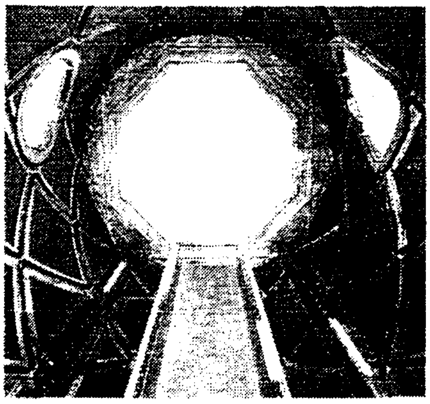


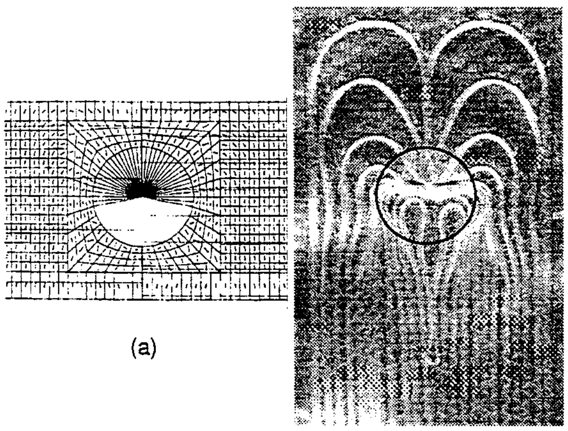
Figure 2: Orthogrid geodesic fuselage barrel formed by filament winding (From Niu[6])

Table 1: Some of the key requirements for successful application of PMCs to aircraft structures

Key Requirements to Realise Potential	
Design, ability to:	• estimate acquisition and support costs and performance value • estimate the service (external) loading and environment • predict failure loads and modes • predict post-buckling and other complex behaviour • predict and minimise out-of-plane loading • allow for degradation due to damage and environment • exploit non-isotropic properties • maximise damage tolerance through design concepts • optimise mechanical or bonded joints • provide for easy inspection and repair
Materials, needs:	• environmental insensitivity for matrix dominated properties • resistance to damage and out-of-plane loading • insensitivity to stress concentrations • wide processing window • improved tolerance to representative damage • reduced scatter in properties
Certification, ability to:	• minimise testing through validated analytical procedures • develop generic data base and methods to prove similarity • derive mechanical properties from limited test specimens • reduce requirements for full-scale environmental and fatigue testing • allow for minor process and materials changes • cope with mixed metal composite structures • cope with environmentally sensitive joints
Through-Life Support, requirements:	• avoid use in areas of high potential mechanical contact • avoid use of easily damaged construction e.g. thin-skinned honeycomb panels • ease of inspection: only visible damage should be significant • ease of repair: minimise requirements for specialised materials or refrigeration • rapid effective, low cost, repair technology • modelling tools for effective design of repairs
Manufacturing, ability to:	• make cost at least comparable with metallic construction • provide high translation of fibre properties • control interface strength to optimise strength and toughness • produce large unitised components with minimum inspection requirements • optimise fibre architecture and maintain fibre alignment • tailor thickness without major cost penalty • model tooling and processes, virtual manufacture • make rapid prototypes to prove concepts

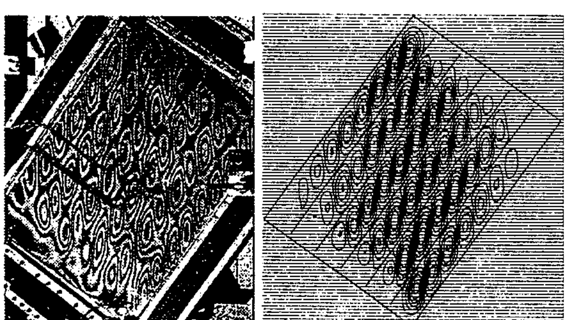
A promising approach being studied in the CRC-ACS is the use of selective reinforcement to reduce the stress concentrations around highly loaded holes – such as in a composite lug. In this approach the principal stress trajectories around the internally loaded hole are determined by FE analysis, Figure 3a. Then to reduce the high stresses, reinforcement tows of unidirectional fibres are located along these trajectories, Figure 3b, in this case by stitching in place with a computer-controlled embroidery machine. The embroidered fabric is added to the fibre preform prior to matrix introduction by liquid resin injection.

Although it is difficult to predict strength, FE analysis can successfully predict buckling behaviour. This is an important design capability for composites since stiffened structures, designed to buckle without damage below ultimate load, are structurally efficient and have many advantages over thin-skinned honeycomb sandwich structure. An extensive program has been conducted in the CRC-ACS on simple stiffened panels and on full-scale components. Figure 4 shows FE predictions and results of corresponding tests on a five-bladed stiffened panel under shear loading.



(a) (b)

Figure 3: Use of directed fibre placement to reduce stress concentrations at a loaded hole: a) shows the FE model used to predict stress trajectories and b) the placement of tows along these trajectories using technical embroidery (from Crothers[7])



(a) (b)

Figure 4: Blade stiffened panel in shear showing a) shadow Moire fringe pattern in actual panel and b) out-of-plane contours from geometric non-linear FE analysis

Joints should be minimised as far as possible, because they add complexity, cost and weight and, in the case of mechanical joints, reduce strength. The ability to produce large unitised components is a major advantage of composites.

Current designs of highly-loaded (thick-skin) mechanical joints require a near quasi-isotropic layup (uniform in plane strength and stiffness, generally based on nearly equal 0°, 90°, ± 45° fibre layers) to minimise stress concentration at the fastener hole. This requirement greatly compromises composite performance; however, more structurally efficient designs based on orthotropic laminates (more load-bearing 0° fibre layers), with local thickening, bonded inserts or reinforcements at holes to reduce stress concentrations and increase bearing strength, are too costly to manufacture and impose limitations on repairability. Thus there is considerable scope for improved design concepts. However, simplicity of repair by mechanically-attached metal patches is a major advantage of using simple quasi-isotropic fibre configurations of uniform thickness.

Designs based on adhesively bonded joints can make more optimum use of PMCs since there is less restriction on fibre configuration. In addition, bonded structure can, if not prone to mechanical damage, operate at much higher strain levels than mechanically fastened joints.[8] Bonding is highly suited to joining of thin-skinned components and can be the lowest cost option; it is of course the only way of producing honeycomb sandwich components. However, highly loaded, thick skin, bonded joints can be complex, as illustrated by the F/A-18 wing attachment joint, Figure 5, and thus very costly to manufacture. Also bonding requires higher skills and quality control than mechanical fastening, so has a higher risk element. Thus bonding is treated with reservation by the aircraft industry, particularly where there is a metal component, due to concerns with environmental degradation at the bond interface. Bonding in an all-composite construction is more reliable, since environmental degradation is not a concern; cocuring (used mainly to make large complex components) is less of a concern since the uncertainties with the pre-bonding processes are largely eliminated. Post-bond inspection is a major concern for all types of bonded structure, since it is not possible to detect weak bonds, only gross voids and disbonds.

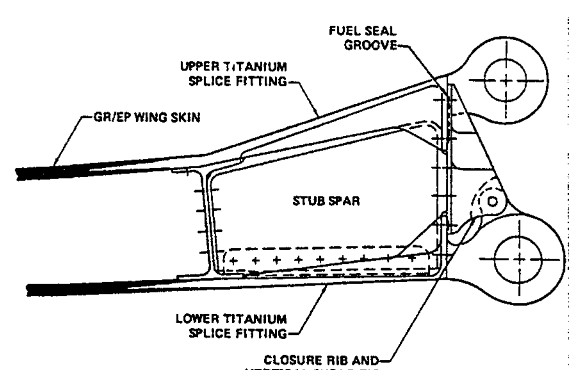


Figure 5: Schematic illustration of the step-lap joint used to attach the carbon/epoxy (gr/ep) wing skin to the titanium alloy fuselage attachment lug of the F/A-18 fighter aircraft (from Mallick[9])

The future increased use of composites requires careful design to optimise properties, predict failure modes and reduce costs. More advantage taken of non-isotropic behaviour, selective reinforcement, post-buckling and co-bonded joints will have a positive effect.

Material Improvements

Epoxies and other thermosets (cross-linked un-meltable polymers), notably bismaleimides (BMIs) for higher temperature applications, are the main matrices used with carbon fibre reinforcement. The early generations of these systems were highly moisture-sensitive and because they were very brittle had low toughness. Many efforts have been made to reduce these limitations as well to improve processability and thus reduce component costs.

Compared to epoxies, use of thermoplastic (meltable) matrices provides significant improvements in toughness, mainly impact damage resistance[10] because of their ductility and much reduced moisture sensitivity compared to thermosets. However, thermoplastics impose considerable cost penalties because of high basic materials cost and the high temperatures (typically over 400°C) and pressures required for processing. Thus there have been successful efforts directed at toughening epoxy resins[11] to make them more comparable with thermoplastics, for example by more innovative use of toughening additions, including their use in discrete resin-rich layers (interleaving). Although moisture sensitivity still remains a concern with most thermosets, less moisture-sensitive systems are being developed.

At present it appears that the use of thermoplastics composites is limited to smaller components requiring very high toughness; for example, resistance to edge damage in small doors and access panels. In military aircraft, where cost is not such a major issue, several large demonstrators have been undertaken, including thermoplastic wings for the F22 and B2; however these major parts were not made from thermoplastic composite in the final airframes. In the future thermoplastic-matrix PMCs could be become more affordable if low-cost manufacturing procedures, as mentioned later, are successful.

Use of carbon fibres with increased failure strains can also provide benefits in some cases, for example by minimising fibre breakage during impact and overload; although the benefits are sometimes hard to translate into improved composite properties.

Without changing the fibres or matrices, considerable benefits should be possible through improved fibre architecture, mainly by increasing through-thickness strength and toughness. The increase in strength occurs simply by having reinforcement in the through-thickness direction and the increase in toughness from the need to fracture and pull out these fibres during delamination. However, there is a penalty from the reduction of the fibre volume fraction of in-plane reinforcement, and the fibre damage and loss of fibre orientation that can arise during the process.

The simplest approach is to apply z-direction reinforcement to a 2-D laminate, for example by stitching. The effectiveness of this in improving impact resistance has been studied by the CRC-ACS, as well as by many others. Stitching is certainly very effective in improving Mode 1 and Mode 2 fracture energy in carbon/epoxy laminates. Improvement in Mode 1 fracture energy[12] is shown in Figure 6 as a function of stitch density and stitch thickness with aramid thread.

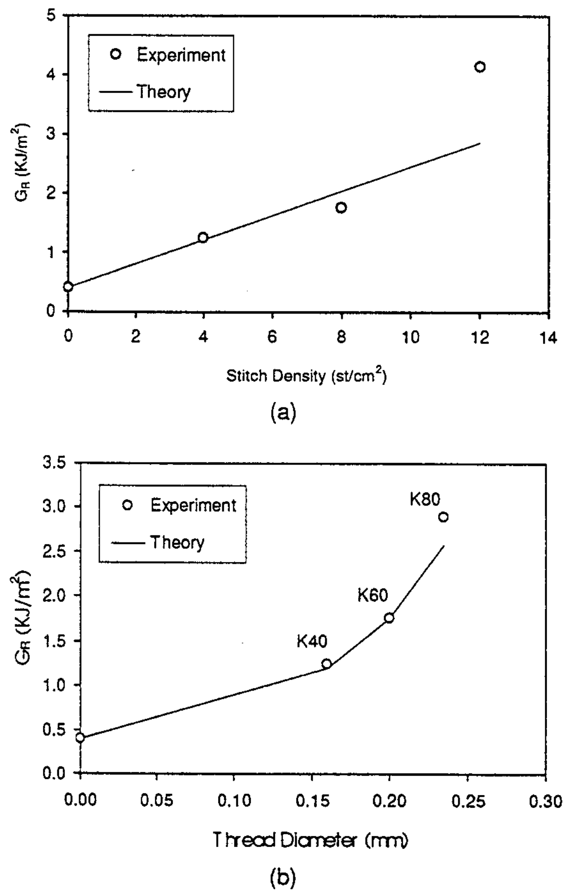


Figure 6: Comparison between theory and test result for stitched specimens: a) different stitch densities with K40 thread and b) different thread diameters at a density of 4st/cm^2 (from Jain[12])

In a major program funded by the NASA Advanced Composite Technology program, Boeing (originally McDonnell-Douglas) has produced large stiffened preforms by stitching of multiaxial fabrics.[13] An impressive facility capable of stitching complete transport aircraft wing skin preforms has been developed. These preforms are subsequently moulded using resin film infusion. Considerable improvement in compression-after-impact strength and defect tolerance has been demonstrated for these thick skins; (Palmer[13] and Kropp[14]) however the cost-effectiveness of this process and the quality and repeatability of manufacture need to be demonstrated.

A research program at the CRC-ACS has investigated the use of stitching for thin composite skins (1-3mm) with woven fabric reinforcement, typical of secondary structure such as control surfaces. As shown in Figure 7, stitching of this type of structure(15) does not provide much benefit. This is because the woven fabrics provide a substantial amount of effective through-thickness reinforcement in their own right. However, stitching can be very effective in improving the damage resistance in thin-skin panel preform joints – such as in blade-stiffened panels.

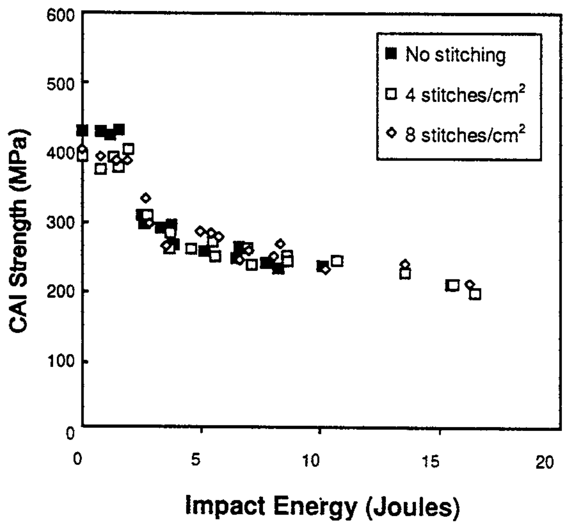


Figure 7: Plot showing the relative ineffectiveness of stitching on the CAI of 3mm plain-weave carbon/epoxy laminates (from Leong et al.(15))

Another approach is the development of composites based on 3D textiles; however, discussion of these composites is left until the discussion on manufacturing.

A steady improvement in material properties and optimisation of fibre architecture to improve toughness will increase the number of applications where composites can be used.

Certification

Certification requirements(2,16) based on the complexities of PMC behaviour have constrained the use of composites. This is particularly apparent for primary structure and bonded joints.

Certification costs can be reduced if the number of composite systems used is minimised, since each system must be characterised by a comprehensive testing database. However, even with the same fibres and matrices there can be a need for extensive testing, if relatively minor process or material changes are made. Testing requirements could be reduced greatly if a simple method of proving similarity with a generic data base for a given fibre/matrix system could be developed, based on a few simple tests at the coupon level.

The need for hot/wet testing of large elements is a significant cost issue in aircraft certification. This is because of the time required for moisturisation, which can be many months, and the cost and complexity of procuring and running the test equipment – this is a significant issue for full-scale testing. The cost of the testing can determine the choice of PMCs or metals for some applications.

To minimise the need for hot/wet testing, work is in progress in the CRC-ACS to see if it is possible to use hotter dry conditions to simulate hot/wet. This study is based on some promising work by Collings et al,(17) illustrated in Figure 8. The premise is that hot/wet and hot/dry properties will be similar at the same percentage of the glass transition temperature, which, from Figure 8, appears to be the case. If this approach can be validated it could allow a huge saving in large-scale testing cost. Of course there are complexities in components containing more than one resin system, such as those containing adhesive bonds. Also this approach does not address environmental durability issues for example where there are metallic components.

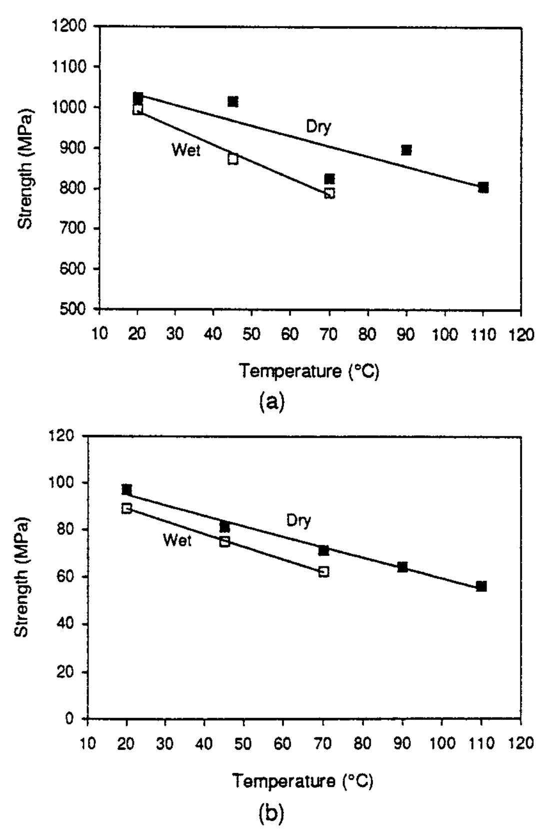


Figure 8: Comparison between hot/wet and hot/dry test results for a) compression strength and b) interlaminar shear for a carbon fibre/epoxy system (after Collings et al(17))

The issue of the need for full-scale fatigue testing for structural certification is a contentious one for composites. Because of fatigue insensitivity such tests are only really required to probe for unexpected through-thickness stresses, where fatigue may be a problem and where fatigue-sensitive metallic structure is present.

Certification testing for composites, in the absence of fatigue issues, reduces to the confirmation of adequate static strength in the presence of representative damage in the most adverse environment. It seems possible that much of this may be achieved computationally when sufficient confidence is gained in the design/analysis procedures and failure criteria. However the ability to ensure that damaging out-of-plane stresses are not present, and to assess strength for all possible failure modes, with or without damage, is a long way off.

The cost of certification can be reduced if material standards are developed which are not proprietary to individual companies. Alternative approaches to hot-wet testing may help to reduce fatigue testing. Improved monitoring and control of manufacturing processes should reduce the variability in material properties. In the long term certification largely by analysis may be possible.

Through-Life Support

A very important requirement for successful exploitation of composites is to ensure that through-life support costs are less than for similar metallic components. Fatigue and corrosion, which are high-cost problems with metals are not an issue with composites. Most through-life support costs with composites arise from mechanical damage and water penetration into honeycomb panels. Design guidelines to minimise these costs are provided in a recent SAE document.[18]

Water penetration into honeycomb, common to metal or composite-skinned honeycomb structures, is a very high-cost issue which is best avoided by the use of integrally-stiffened structure. Thin-skinned composites may be more prone to this problem than metals, since moisture can pass through microcracks and damaged regions (this has proven to be a very costly problem with some composite engine cowlings, leading to them being replaced with metallic components). Entrapped moisture can cause severe corrosion and disbonding of the metal core and significant weight gain, and is very difficult to remove for repairs.

With major damage the damaged region will usually need to be removed and the lost load path restored by a patch or reinforcement. Mechanically-fastened structure which has uniform-thickness, near quasi-isotropic skins is relatively easy to repair[19] by bolted-on titanium, aluminium or composite patches. Several computer programs are available to aid the design of this type of repair. Unlike metals, even poorly drilled fastener holes will not pose a fatigue problem in composites although they can reduce static strength. However, complex structure with local thickening or inserts will be costly to repair.

Repairs to damaged, high-strain, orthotropic composite components are more challenging since these must generally be bonded[8] to restore the original strength. Bonded repairs are also essential for honeycomb panels to ensure sealing and maintain strength. However, bonded repairs whilst highly feasible and successful require higher technical and design skill levels than mechanical repairs and often require materials with limited storage. Bonded repairs will be greatly aided by the use of generic (non-system specific) composites and adhesives that can be stored at ambient temperature.

Repairs to stiffened, post-buckling structure can be highly challenging and may limit this, otherwise, highly effective structural concept. Work at the CRC-ACS (Zhang et al[20]), see Figure 9, has demonstrated that bonded repairs can restore almost all the load capability of such structures. The repairs can be simple to install, although the design requires greater analysis effort due to the need to restore strength without adding substantially to the stiffness of the repaired area. The long-term durability of such repairs also needs to be demonstrated.

Repairs to composites must be simplified and use standardised materials and systems. Impact damage sensitivity and water ingress into honeycomb cores must be reduced. Ideally the use of thin-skin honeycomb structures should be minimised. Airline operators need to be assured that repairs to composites are no more likely, nor no more difficult, than for metal structures. Repairs for advanced structures containing 3D-woven or stitched preforms require further development.

MANUFACTURING ISSUES

Most composite parts for commercial transport aircraft are made by hand layup of pre-impregnated cloth or unidirectional tape (prepreg), followed by autoclave curing, which has been the standard manufacturing technology for aircraft since it was first used with glass-fibre PMCs thirty years ago. This method has definite advantages—it is well known and very versatile. In addition, the infrastructure (especially autoclaves), although moderately costly, is already installed in many factories around the world. However the high cost of manual labour, coupled with the resulting variability in quality, imposes a heavy penalty on hand layup, as does the comprehensive non-destructive inspection (NDI) program usually necessary for these parts. Thus great efforts are being made to lower the cost of autoclaved prepreg construction, and to develop alternative cheaper production methods for aircraft parts. The former will be briefly outlined below, while alternative production methods will be discussed more fully in the following sections.

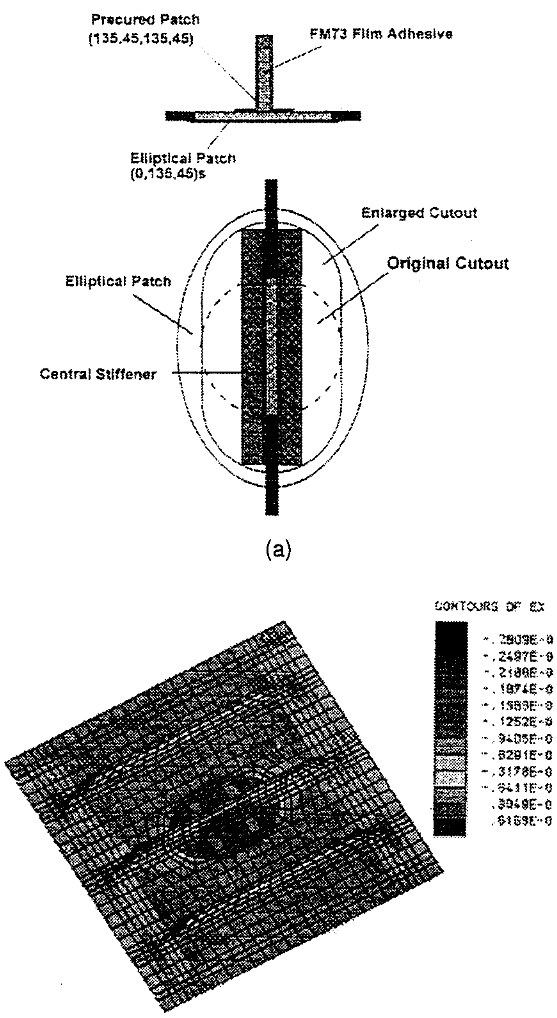


Figure 9: Repair to a damaged three-bladed post-buckling panel: a) repair concept and b) FE analysis of repaired panel (from Zhang et al.[20])

Improved Prepreg Manufacture

Efforts continue to reduce the number of parts, and thereby the overall cost, by integration of many sub-elements into larger "co-cured" parts. This will continue in future, but co-curing has limits imposed by NDI capabilities, additional tooling and process development costs, workforce skill and the increased cost of scrapped parts. Co-curing has progressed furthest in countries with highly-skilled workforces, such as Japan but in some cases (e.g. Airbus vertical tail skins) has proved costly.

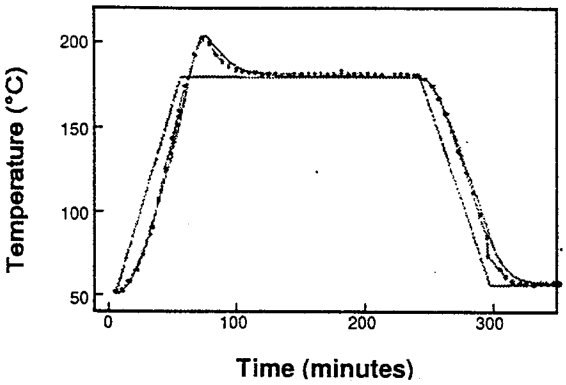
Secondary bonding, (adhesive bonding of cured subcomponents), has several benefits over cocuring for producing large unitised parts, since this approach allows optimum manufacture and inspection of each subcomponent prior to final assembly.[21] However, costs may be higher than co-curing because of extra manufacturing steps, including pre-bonding surface treatment, and the need for expensive adhesive. Perhaps the optimum is a mixture of the two approaches in which particularly critical elements are cured and inspected, then the rest of the structure "co-bonded" with the pre-cured parts located on the layup.

Tooling remains a major cost. The industry is constantly seeking less expensive materials and processes, and is attempting to harness the benefits of rapid prototyping systems (at present more suited to smaller, 3D shapes) to the fabrication of advanced composites tooling.[22]

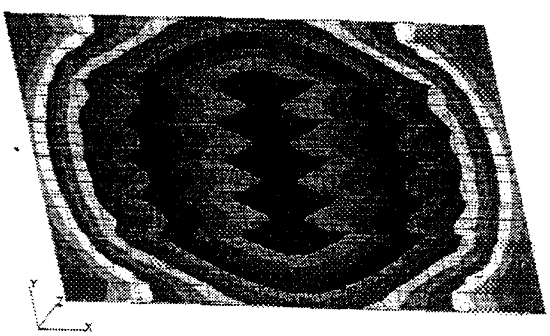
Computer Process Simulation, often based on FE analysis, is being introduced in many aspects of design and tooling to aid concurrent engineering, and help ensure that expensive mistakes do not appear only after the tooling has been manufactured and the schedule committed. At present these tools include simulation of heat transfer and resin cure, fabric forming, resin injection, and part "spring-in", as well as manufacturing cost. Additional simulation tools can be expected, to further reduce the cost and risk of bringing new parts to the factory floor.

A major area of progress in manufacture of composites is the introduction of Computer-Aided Manufacturing (CAM) systems. These systems, which normally use digital design data from a CAD package, can also be "taught" by the operator, include the now ubiquitous ply cutting devices such as Gerber™ Cutters, and laser outlining systems to replace templates in hand layup and assembly. A new development is the conformable jig or fixture for holding parts for inspection or trimming. Such CAM devices, which provide repeatability and precision while allowing labour to concentrate on the tasks for which it is best suited (such as manual dexterity), may provide more efficiencies for many parts than fully automated manufacturing. Other developments of this type can be expected. However many companies have had practical difficulties with the translation of CAD data to CAM formats. Software integration and compatibility remains a challenge particularly for subcontractors dealing with several different CAD formats.

Co-curing of large parts and co-bonding of cured and uncured parts offer cost advantages. Low-cost tooling methods need to be developed and process simulation *introduced for all important manufacturing processes. Reliable translation of CAD/CAM data and some software standardisation will further reduce costs.*



(a)



(b)

Figure 10: Process simulation: a) One-dimensional simulation of temperature in a thick prepreg laminate; b) Simulation of resin flow in a five-blade stiffened panel

Automated Fibre and Fabric Handling

Development of automated layup systems for aircraft composite parts dates from the 1960's and two different concepts emerged: "pick-and-place" systems, and automated tape layup. Pick and place systems, using fabric prepreg or broadgoods, broadly imitate the manual layup method, with ply cutting, transfer, layup and compaction performed by mechanical devices or robots. This concept attracted considerable support at first, but was found to be difficult to develop. However there has been a resurgence of interest in this approach lately, following considerable effort to develop efficient methods for the fabrication and shaping of liquid moulding preforms. An experimental system developed by a team at Brunel University is illustrated below. Development is also taking place on the automated placement of thick non-crimp fabrics laminated with a layer of resin film, for subsequent RFI processing. Layup rates of 200m^2 per hour for heavy non-crimp fabrics are claimed for this system.[23]

Automated (prepreg) Tape Layup (ATL), which uses a CNC-controlled head to lay down and compact thin strips of unidirectional prepreg tape, has been more successful and attracted the bulk of the development effort. This is largely because this approach uses prepreg tape, the preferred form of reinforcement for composites in military applications, and has therefore benefited from the considerable spending on military technology. The process has much in common with CNC machining. In the USA great advances have been made in the capabilities of these machines, which can now handle complex curvature and are in routine use for the production of large parts for military aircraft. However, the considerable cost of current ATL machines, and the practicalities of their operation, have delayed their introduction to the manufacture of price-sensitive commercial aircraft components. Only on such large, mildly curved parts as the skins of the Boeing 777 horizontal and vertical tail have commercial aircraft manufacturers been willing to introduce ATL machines to commercial aircraft production.

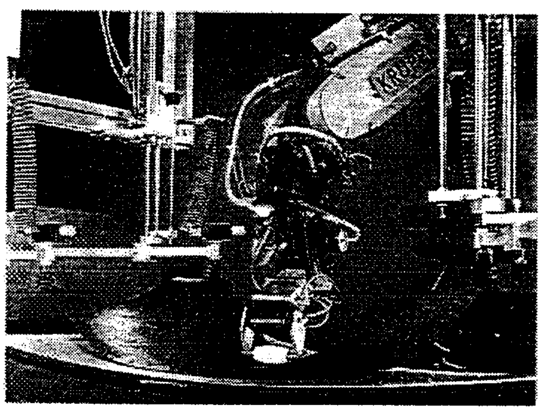


Figure 11: Multi-arm Robotic Pick-and-Place system (from Buckingham et al.[24])

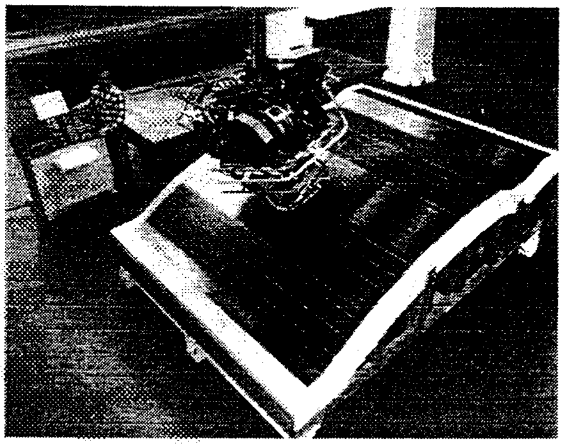


Figure 12: A Cincinnati Milacron contoured automatic tape laying machine (from Niu[6])

Natural limitations to the capability of ATL machines to manufacture more complex shapes has led to the development of Automated Tow Placement (ATP) systems, which lay down multiple prepreg tows and are able to stop and re-start individual fibre tows. This allows more complex shapes to be fabricated, including layup on complex curves and the steering of tows into curved trajectories. These machines, therefore, offer the potential for greater structural optimisation by locating fibre where it is most effective. However, ATP systems, which are usually combined with a spindle to allow layup of closed shapes such as ducts, are so far even more expensive to purchase and operate, and have not yet been used on commercial aircraft programs.

Figure 13: ATP system in use at Bell Helicopter (from Automated Dynamics Corporation[25])

ATL and ATP machines, already commonly used by major airframe manufacturers on military programs, seem likely to spread to commercial programs in parallel with the introduction of composite primary structure. Their use on secondary structure, which is smaller, thinner, and more curved, or by smaller subcontractors, will not be competitive until acquisition costs are substantially reduced and operating economics improved.

Automated tape, tow and ply handling machines will reduce costs of larger parts and enable greater optimisation of the lay-up, particularly for large-volume production. They are most likely to be used by large companies with large workloads. Reduced costs for smaller components will have to come from other technologies.

Pultrusion

Pultrusion is a continuous process for producing composite sections which, as the name suggests, is the composites equivalent of extrusion for metals or thermoplastics. In its simplest form, reinforcement in the form of unidirectional tows (rovings), mats or fabrics is pulled through a bath of resin and then through a heated die to compact the section, cure the resin and fix the shape. It is the cheapest method for manufacturing structural composite shapes, and the production of pultruded parts is growing steadily worldwide especially for civil engineering applications. Despite this, pultrusion has not been used much for aircraft parts. One reason is that the pursuit of structural optimisation does not favour the design of the long, constant-section shapes that can be produced by pultrusion. Nevertheless all aircraft include parts such as stringers and floor beams where pultrusion could be applied, although no large-scale applications of pultrusion to structural aircraft parts is known at present.

Pultrusion has excellent potential to produce high-quality, low-cost parts but designers will need to re-think their design and manufacturing philosophies to take advantage of this. They will need to compromise on structural performance, and employ constant section parts. It will also be necessary to develop or modify aerospace grade epoxy resins that can be pultruded without excessive pull forces. There is usually a need to introduce ±45° fibres in such parts; an economic form of such fabric suited for the manufacturing demands of pultrusion and the structural demands of aerospace parts is desirable. These challenges appear solvable and it is predicted that pultrusion will help lower the costs of aerospace composites in future. An example of a wing stringer made at the CRC-ACS by a process based upon pultrusion is shown below.

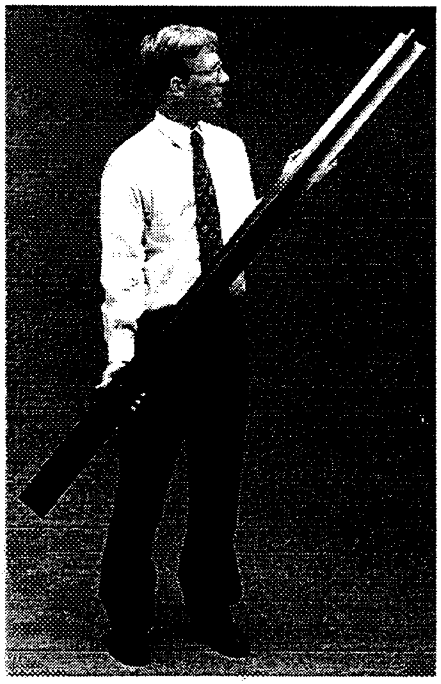


Figure 14: Developmental wing stringer section (from CRC-ACS)

Pultrusion offers great potential to manufacture constant-section parts, such as wing stringers, at low cost. Designers will need to revise their design approach to claim the benefits of this process. There is *a need for specialised reinforcement, optimised for pultrusion.*

Filament Winding

This technique has also been in use since the 1950s and is well suited to the manufacture of shapes of revolution, such as pressure vessels, cylinders, pipes and tubes, and has also been used to make rotor blades. The method can make parts quickly and is highly developed, including sophisticated computer control, which allows winding with non-geodesic fibres and manufacture of non-solids of revolution. Filament winding has been the standard method of making large rocket motor cases for some years; large machines are big enough to wind whole railway hoppers in one operation. There is great interest in the potential use of filament winding or similar processes such as tow placement to produce aircraft fuselages, and some experimental or prototype fuselages, such as an experimental Beech Starship fuselage section (shown in Figure 2), have been made this way. It seems possible that the fuselage of a smaller transport aircraft will be made by filament winding or a related process in the near future. The winding process appears to be a strong contender for the manufacture of larger transport aircraft fuselages in composites.

Filament winding can lay-up large quantities of material quickly. The process seems well-suited for the production of composite fuselages. Small fuselage sections can be produced economically.

Liquid Moulding

Liquid moulding is the generic term describing a family of processes where the "dry" reinforcement is shaped, placed into a closed mould, and injected with resin which is then cured. The most common version is Resin Transfer Moulding (RTM), where liquid resin is injected into a stiff, closed mould. Resin Film Infusion (RFI) resembles autoclave prepreg moulding, and uses a vacuum bagged layup in an autoclave, but the partly-cured resin and the reinforcement preform begin the autoclave cycle as separate layers held in contact by the vacuum bag. The critical advantages of liquid moulding over the prepreg layup process are that the shaping and compaction of the reinforcement can be much simpler; the closed mould process delivers improved surface finish, dimensional tolerances and repeatability; and the introduction of the resin to the fibre at the last minute can save substantially on material shippage and storage costs, especially those due to scrap. This last advantage is important for the Australian aircraft industry, which imports all prepreg from Europe or USA in refrigerated shipping containers.

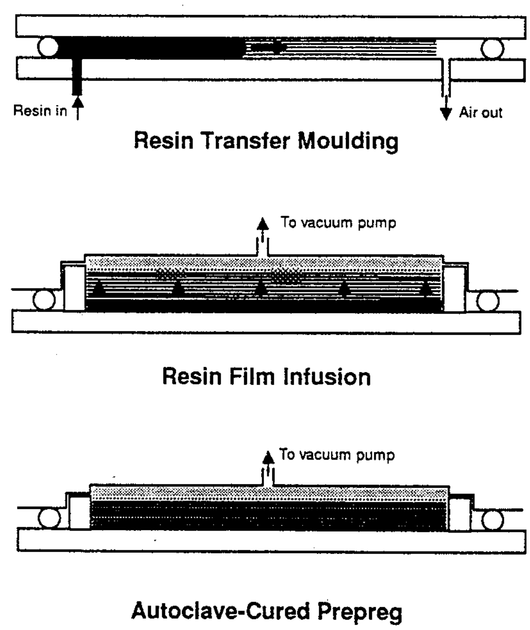


Figure 15: Schematic diagram illustrating resin flow in: a) the RTM, b) the RFI processes, compared to c) a prepreg layup

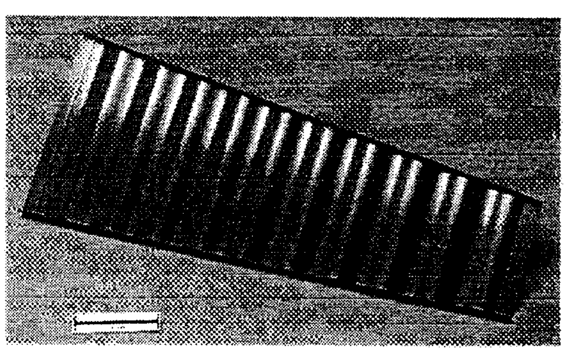


Figure 16: Sine-wave rib made by RTM (from CRC-ACS)

A further advantage of the liquid moulding processes is that the reinforcement preform can be made of any type of fibre material, without the cost of pre-impregnating specialist reinforcement fabrics. Indeed many types of preform that can be easily moulded by liquid moulding processes cannot be practically made from prepreg at all. Such preforms include those made up from Multi-Axial Warp Knit (also called Non-Crimp or Stitched) fabrics, and so-called 3-Directional fabrics or preforms, which include fibre in the through-thickness direction, such as the stitched wing skin preforms mentioned previously.

Stitching of woven or multi-axial fabrics can be used for manufacturing reasons (to hold the preform stack together) or, as discussed previously, to improve mechanical properties of the composite.

Liquid moulding processes offer better process control, with excellent quality and dimensional accuracy. Near-

net-shape parts can be produced. These methods permit both inexpensive fabric reinforcements and sophisticated preforms such as three-dimensional fabrics to be used. These processes can be introduced by smaller subcontractors and their use should grow steadily.

Three-Dimensional Fabrics

Three-dimensional weaving can produce complex preforms with controlled amounts of fibre in each of the three orthogonal directions. Such preforms are routinely used to make carbon-carbon composites for ablative applications, such as rocket motor nozzles and nose cones. Three-dimensional braiding can also produce similar structures, but at present is not a mature process.

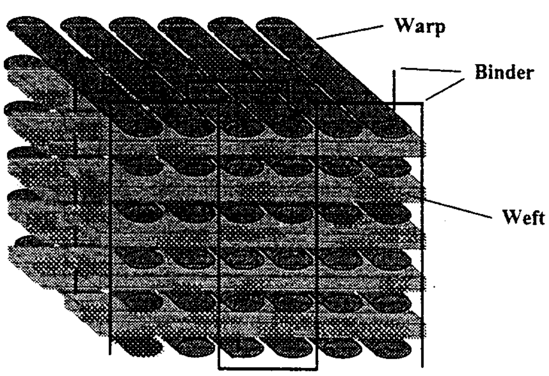


Figure 17: Example of a 3D-woven preform with an orthogonal fibre architecture (from Bannister et al.[26])

Composites made using such preforms have excellent "through-thickness" properties resulting in good impact resistance and damage tolerance but with significant loss of "in-plane" properties, due to crimping and reduction in volume fraction of the in-plane reinforcement. Complex shapes, such as stiffened panel preforms with intersecting ribs, can be produced in one shot. Weaving can be a highly-automated process, and the prospect of net-shape preforms with good control of fibre placement justifies considerable development in this area. 3D-weaving and stitching processes are being used to develop composite fan blades,[27] an application which defeated earlier attempts to use composites because of the very high damage tolerance requirements. In the CRC-ACS, where several development programs based on simpler 3D-woven preforms are under way, reduced recurring preform production costs have been demonstrated compared to existing or alternate methods.

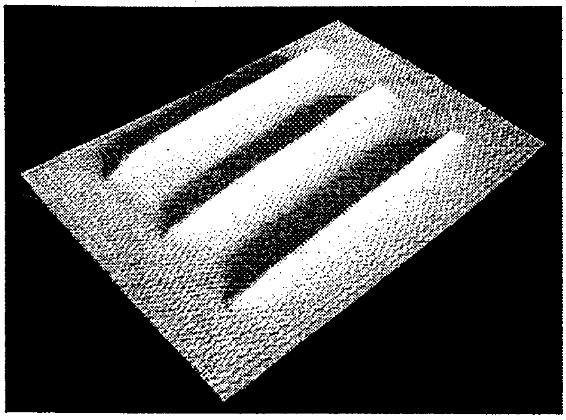


Figure 18: 3D-woven blade-stiffened panel preform (from CRC-ACS)

Despite these advantages it is likely that application of 3D weaving will need to be highly selective. While recurring costs may be low, aerospace production runs are short, and non-recurring costs such as setup costs for the loom may be considerable. There are few tools for the analysis and modelling of the mechanical properties of such preforms, or for their inspection. One disadvantage of all types of weaving is the great difficulty of including fibres at ±45°. For 3D fabrics or preforms it is also difficult to guarantee the desired fibre volume and keep the through-thickness fibres straight due to the clamping forces in the mould. Therefore the certification of such parts will be expensive since it may need to be based on extensive testing rather than analysis. It would also seem to be difficult to repair parts made from such preforms to re-gain full strength capability except by the use of bolted metal plates.

Three-dimensional fabrics have great potential to make complex, net-shape parts with unique properties at low cost. More development is needed of the capability to predict material properties and control of the weaving process. Certification and repair of parts made from these materials needs careful consideration. Non-destructive inspection methods need development

Knitting

Useful knitted fabrics can be made using glass and carbon yarns, and despite the generally low mechanical properties of the resulting composites, there are good arguments for their use in certain applications. The mechanical properties are not so low compared to woven glass composites: see Figure 19 below. Since the resulting composites have high strain-to-failure and good impact resistance they can achieve high-energy absorption during fracture. The main advantage of knitted fabrics is, however, that they have very high formability (drapability) or can be knitted to shape. The preform for the non-structural cover shown below is formed in one piece from a flat knitted glass fabric. If necessary knitted preforms can be locally reinforced with non-crimp material.

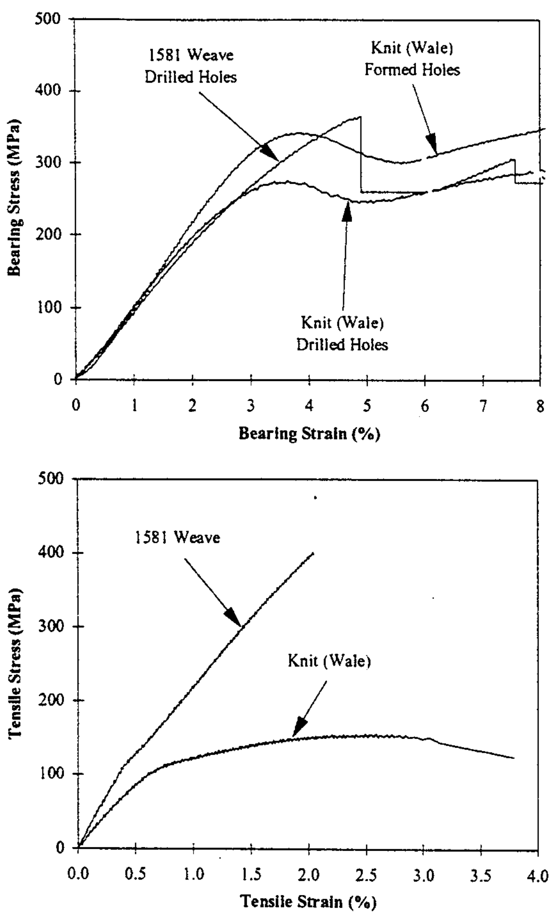


Figure 19: Tensile and bearing properties of panels made from knitted and woven glass fabrics (from Herszberg et al.[28])

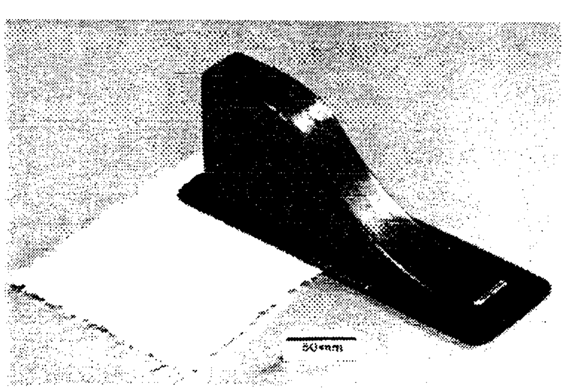


Figure 20: Experimental helicopter door track cover made by RTM with a knitted preform (from CRC-ACS)

Knitted materials offer great drapability and impact resistance. Selective reinforcement of knitted parts can improve properties at low cost.

Alternative curing methods

Almost all composite aircraft structure uses heat to activate the cure mechanism in the thermoset polymer matrix. It is also quite possible to use other forms of radiation such as ultraviolet light, X-rays and electron beams to initiate the curing process. Ultraviolet light cannot penetrate carbon fibre and X-Rays pose significant safety problems, but electron beam curing is being developed in France, Italy and the USA for application to aerospace structures. Key advantages of the process are that it is much faster than thermal curing; curing proceeds at ambient temperature; and prepreg does not degrade or cure during storage at room temperature. E-Beam curing installations capable of curing thicker parts (10MeV, 10 kW accelerators) are very expensive and must be shielded by thick concrete walls during use. It is unlikely that smaller manufacturers could afford to install such equipment. Smaller, cheaper, and safer systems (less than 500keV) are being developed for curing filament-wound or tow-placed structures immediately after layup during the winding phase.[29,30]

When developed this process offers considerable advantages in curing speed and dimensional control. There is the potential to combine E-beam curing with filament winding of thermoset materials to produce low-cost structures rapidly. The technology may be beyond the reach of smaller companies in the near term.

Automated Forming

Standard prepreg layup practice involves the positioning, forming and consolidation by hand of individual plies. Despite the use of various technologies such as drape simulation and laser outlining to assist this process, it remains slow and costly. There is considerable effort to develop mechanised methods to assemble flat ply stacks, and particularly to shape this stack in one operation. Continuous roll forming, stamping, and diaphragm forming are amongst the methods being introduced. These methods are particularly appropriate for liquid moulding preforms and thermoplastic composite parts, but may also be used with thermoset prepreg preforms. A robotic ply layup and folding system has been used for some years with modest success in the manufacture of vertical tail skins on Airbus A320 by Daimler Benz Aerospace, who also make small ribs using diaphragm forming. Diaphragm forming of prepreg stacks is used for skin stringers on the Boeing 777 empennage. A schematic of the diaphragm forming system, and a part made using this system are shown below.

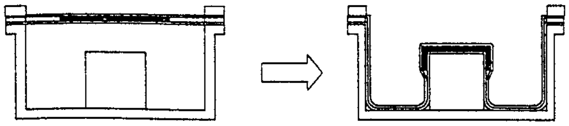


Figure 21: Schematic of the diaphragm forming process

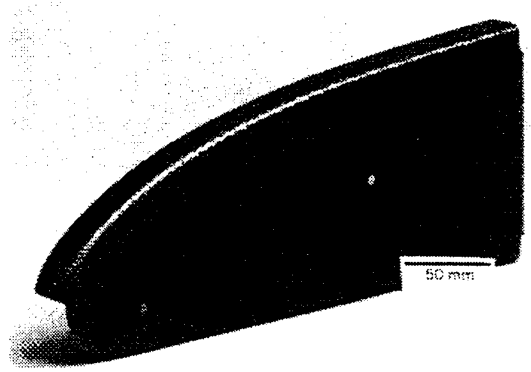


Figure 22: Flap rib shaped by diaphragm forming (from CRC-ACS)

Diaphragm forming already offers low-cost manufacture of smaller complex parts. Process modelling and development should provide opportunities to extend the process to form thick sections into complex shapes.

Thermoplastic Composites

Large funds were spent on the development of thermoplastic composites, particularly carbon-PEEK, and on the development of manufacturing methods for parts made from such materials, during the 1980s and early 1990s. Unfortunately the return from this effort has been very modest. High material prices, and high processing temperatures and pressures forcing the use of expensive tooling and plant, more than offset the benefits of greatly reduced production times for typical aerospace production rates. In some cases the higher toughness and environmental resistance of thermoplastic composites were able to ensure their application in some areas, especially on military aircraft, but improved thermoset resins have reduced the advantages of thermoplastic composites in those properties as well.

Success for thermoplastic composites in aerospace, however, may be in sight. There is renewed interest in the use of thermoplastic composites with automated production methods like filament winding and automated tow placement, where thermoplastic unidirectional tow can be rapidly laid down and welded to make parts like fuselage skins, without the need for a subsequent curing or consolidation operation.[31] In addition, structure such as stringers or frames, which could be formed by automated stamping operations, can be welded to the skins by diffusion bonding without the need for additional adhesive or manufacturing steps. There are considerable challenges, for example in the control of residual and transitory stresses caused by in-situ compaction.[32] However it seems likely that in fuselages, where damage tolerance is very important, and automated manufacture a requirement to compete with aluminium, thermoplastic composites may best meet the requirements.

Thermoplastic composite materials, although currently expensive compared to thermosets, are well-suited because of their toughness to fuselage and door construction. Further development and demonstration of automated processes and welding methods are needed.

Quality Assurance

The non-destructive inspection of composite parts is a major part of the manufacturing cost. As well, many designs or manufacturing techniques which could produce structurally-efficient and inexpensive components cannot be used because current NDI techniques cannot easily demonstrate that important design features, such as internal structure, are sound. With composites, where the material is produced at the same time as the part is made, quality assurance is a major driver of design and manufacturing cost.

At present the industry mainly uses ultrasonic and X-ray imaging to inspect parts. The laminated morphology of current prepreg construction makes ultrasonic inspection, which is well suited to detect the typical interlaminar flaws, the most important tool. To reduce significantly the cost of NDI, there are several possibilities. The first is to design and manufacture structures that are quite insensitive to possible flaws - the stitched preform wing skins fall into this category. The second is the hope that new NDI methods now being introduced such as Acoustical Interferometry or Laser Ultrasonics will lead to faster scanning or improved resolution,[33] or that improved signal processing technology will bring the kind of imaging advance by which CT scanning transformed X-ray imaging. A third way is to demonstrate to certification authorities that with new manufacturing methods such as RTM, increased process control at earlier stages, or increased experience with composite parts in service justify significant reductions in post-manufacturing inspection cost. It should be remembered however, that the introduction of a new technology such as RTM or 3D preforms, which promises reduced inspection, may initially bring with it different or increased inspection requirements because of the proper caution which must be shown for new processes or materials.

Increased monitoring and control of aspects of the production process, such as resin injection in liquid moulding or resin curing, will also play a part in reducing non-destructive inspection of finished parts, by demonstrating that the production process is under tight control. This approach is already evident in the introduction of new manufacturing processes such as RTM,[34] however the existence of proven Process Specifications for the existing autoclave-cured prepreg process has meant that improved cure monitoring for example has not been widely introduced.

Improved methods of inspection and image processing are being developed; however introduction of tighter control of manufacturing processes to reduce the need for inspection after manufacturing stage may be more effective in reducing costs. In-service inspection should only be required to detect structurally-significant damage, which needs to be readily visible.

TWO NEW DIRECTIONS IN COMPOSITES

Smart Materials and Structures

Smart materials can be defined as materials with the ability to respond to changes in the operating environment or to other stimuli in an controllable way.[35] This ability may be achieved by processing information from sensors and driving actuators or more simply from a "built in" response mechanism. This capability is a major feature of most biological structures.

Smart behaviour of structures could include:

- Adaptive Shape
  - e.g. for aerodynamic control (muscle, biological equivalent)
- Adaptive Stiffness
  - to optimise for loading conditions
- Adaptive damping
  - to minimise damaging vibrations
- Health Monitoring
  - indication of damage or overstress (nerve system biological equivalent)
- Multifunctional Skins
  - e.g. built-in antenna/sensors to maximise stealth

Most current approaches are based on individual **sensors** and **actuators** embedded in the material or bonded to its surface with an external processor and, if required, power source. The current approaches for "smart" functions are:

- **Sensor**
  - strain: optical fibres; resistance strain gauges; piezoelectric film transducers,
    - *interrogated by a light beam or electric current, in the case of passive elements or by voltage output in the case of piezoelectric transducers*
  - chemical: e.g. optical fibres and various ceramics
- **Actuator**
  - piezoceramic transducers; memory alloys; magnetostrictive alloys; electrorheological fluids
    - *actuated by an electric or magnetic field or temperature (electric current) to change shape or produce a force from a power source generally an amplifier*
- **Processor**
  - microcomputer or a "built-in" response which may simply be included in the sensor or actuator

PMCs lend themselves very well to the embedded approach since sensor and actuator elements can be incorporated during manufacture of the component and the mechanical properties tailored to provide the desired mechanical response to actuator forces. Embedding is possible since the relatively low temperatures and pressures required to produce PMCs will not damage the sensors or actuators. Thus composites are well suited to the formation of adaptive structures (for example, structures able to change geometry) described later. However, these technologies are likely to be very costly, so are mostly limited to military applications.

Least risky, and probably the most promising approach, is the application of smart technology to health monitoring. This is an important application for composites since mechanical impact, which can occur at random anywhere in the structure, is the most critical form of damage. In metals fatigue cracking, which often develops from known stress raisers ("hot spots"), is usually the critical problem.

The most common structural health monitoring approach for composites being investigated is the use of embedded orthogonal networks of optical fibres.[36] In the crudest use of these materials, mechanical damage is detected by the local fracture of the fibres, breaking the light path. However, a more sophisticated (and potentially relatively inexpensive) use of use of optical fibres is to measure stress at various points by the use of Bragg diffraction gratings. The main problem at present (other than cost) is in the miniaturisation and ruggedisation of the associated connections and instrumentation. The possible degradation of composite properties due to the presence of the optical fibres is also an important issue.

An example of the (retrofit) use of smart structure technology in Australia is the approach being trialed to reduce high-frequency buffet in the vertical tail of Australian F/A-18 Aircraft. This study is being conducted under the TTCP Cooperative Program by a team from the USA, Canada and Australia. Vortex-induced buffeting is an aero-elastic phenomenon that plagues high performance aircraft, especially those with twin vertical tails. Buffet loads and severe vertical tail response can dramatically reduce the fatigue life of the metallic substructure of the tail. The smart approach is to bond piezoceramic transducers on the carbon/epoxy skins, to act as sensors to detect vibration, and as actuators to provide an out-of-phase damping response. Using this approach it has been found possible to reduce vibration levels by over 25%.

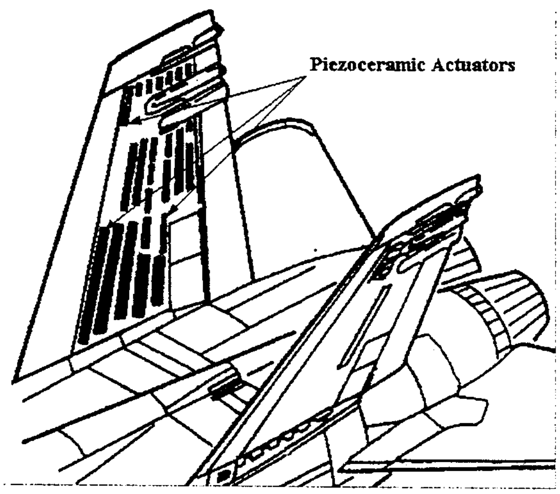


Figure 23: Diagram showing piezoelectric actuators bonded to the carbon fibre/epoxy vertical tail of a F/A-18 fatigue test article.

Composite materials have great potential to include smart sensors and actuators which detect damage, change shape or provide stealth capabilities. The effect of the imbedded sensors on the structure needs to be investigated extensively, and a benefit established, before they will be used in civil aircraft.

High-Temperature Applications - The High Speed Civil Transport

Carbon fibre composites with epoxy matrices are limited to applications below about 150°C. Other polymer matrices, including bismaleimide (BMI) and polyimide (PMI), allow increases to about 200°C and 300°C respectively, for short to medium terms but, in the case of PMI, with the penalty of much more difficult processing. BMI and PMI systems have been used successfully in some military applications, for example, BMI in the lower wing skin and other regions of the AV8B exposed to engine efflux and PMI in the outer engine casing of the F/A-18.

The proposed new supersonic transport (SST) is the most challenging future civil application of PMCs. For the Mach 2.05 design of Concord, supersonic transport peak (stagnation) skin temperatures of over just over 100°C allow use of conventional aluminium alloys. A similar SST developed now could thus make extensive use of epoxy-matrix composites which have similar temperature limitations to aluminium alloys. Unfortunately, the Mach 2.05 limitation will not satisfy the US economic requirements which are for a much larger (300 passenger, in various classes) and faster Mach 2.4 aircraft; this aircraft is called the High Speed Civil Transport (HSCT). The forecast Los Angeles-to-Sydney time of 7.3 hours (with a one-hour refuelling stop in Honolulu) would be very popular in Australia.

The HSCT in supersonic cruise will have most of its structure around 140°C with leading-edge regions (wing, nose and tail) around 180°C; even the 140°C requirement is well outside the range of carbon/epoxy composites and conventional aluminium alloys. Further, the HSCT must have the design life of 60,000 to 80,000 flying hours, over four times the design life of Concord.

To carry an economic payload, extensive composite construction is essential, particularly since, at these temperatures, metallic regions will have to be made of titanium alloys which are nearly twice as dense as aluminium. Figure 24 shows the construction proposed by Boeing.[37] While some of the promising currently available composites (BMIs and PMI-based thermoplastics) are at least close to making the temperature requirement, the problem is how to prove that they will last the required lifetime; accelerated tests are very unreliable, particularly if large extrapolations are needed.

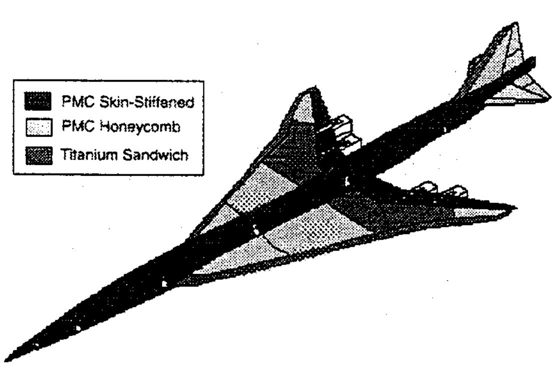


Figure 24: Materials proposed for the HSCT (from Hatakeyama[37])

Problems with composites at elevated temperature include weight and strength loss due to oxidation at prolonged temperatures and microcracking (which further enhances oxidation) caused by thermal cycling. Recent Japanese work,[38] Figure V, has shown that carbon/thermoplastic PMI can retain acceptable levels of notched tensile and short beam shear strength after 15,000 hours aging at 180°C. However, because of the huge investment required, some very convincing science will be needed to develop confidence in accelerated tests. Testing will also have to include representative loading and environmental exposure.

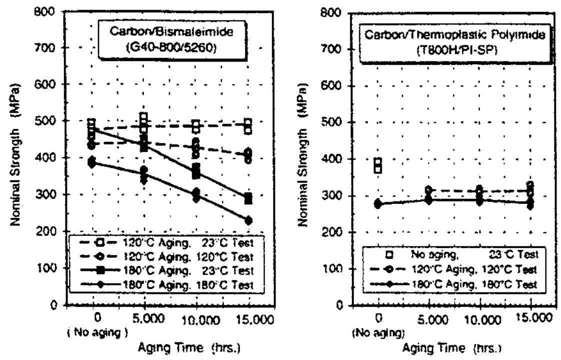


Figure 25: Strength of high-temperature composite systems after aging at 180°C: a) Carbon/BMI and b) Carbon/PMI (from Shimokawa et al.[38])

Another problem is the inherent brittleness (very poor impact resistance) of the viable high-temperature composite systems, particularly those based on PMI. However, Boeing is developing an approach that may overcome both problems. This is based on the use of a hybrid material consisting of interleaved layers of titanium alloy foil and composite. The face sheets of titanium will improve impact resistance and, importantly, also provide a barrier against oxidation. Titanium and carbon fibre composites (with a quasi-isotropic fibre construction) have similar expansion coefficients, so thermal fatigue should not be a problem. However, the development of suitable bonding surface treatments for the titanium, and proving bond durability over the required lifetime, will pose considerable challenges.

The development of the high speed civil transport will be greatly aided by composite materials. Material development and qualification for sustained high temperature operation is challenging.

CONCLUSIONS

We have seen the introduction of composites in both civil and military aircraft, from a few specialised components in the late 1940s, to major portions of the airframe today. Military helicopters are now being produced with over 50% of the airframe by weight of composite: a "typical" fixed wing military aircraft now has around 25% of composite; and the latest large civil aircraft have about 15%.

Many of us have been disappointed by the slow growth in composite use: it would appear that a ceiling has been reached which will only be raised if costs can be reduced. Only in military helicopters, where the complex shapes, stealth considerations, and the high value of weight saved favour composites, has their use reached the forecast potential. Composites have the performance, but the cost of replacing further metal structure with composites is just too high, and some structure originally planned to be composite has been made in aluminium instead.

Without doubt, the major issue facing the composites industry is affordability. In this paper I have concentrated largely on the use of composite materials for applications in civil aircraft. I have reviewed the key challenges for design, manufacturing, certification, quality assurance, smart structures and the supersonic transport. In all of these areas much is being done to reduce costs, so as to compete more favourably with metals. Many innovative cost-effective processes are being developed which will enable major advances in manufacturing and design to be made. Most of the barriers to progress have been identified and are being worked upon vigorously on a broad front.

Automatic tape laying machines are being introduced more rapidly although only large companies can afford them and only large parts can justify their use. Non-crimp materials are achieving wider acceptance, as a low-cost, high performance option. Resin transfer moulding and resin film infusion are being used more extensively to improve quality and reduce cost. Filament winding and pultrusion will play a greater role if we can design for manufacture by these processes. Three-dimensional woven and stitched fabrics offer greater potential to tailor properties more precisely and lessen the sensitivity to defects.

New design approaches, such as grid structures offer more efficient use of materials and greater damage tolerance. There is a greater awareness of applications where composites have natural advantages beyond weight saving, such as aeroelastic tailoring, corrosion and fatigue resistance and the ability to implant sensors and activators. Standardised, low-cost, simple repair schemes are receiving greater attention as airline operators demand reduced maintenance costs. Composites, especially stitched materials, offer the potential to reduce inspection and improve damage resistance and durability. Composite properties and benefits are now better understood.

While the advance of composites into airframe applications traditionally held by aluminium has slowed, other sections of the composites industry are forging ahead, in many instances making use of research and development from the aerospace industry. Composites technology is spreading into other areas such as land and marine transport, industrial machinery, civil engineering and sporting equipment. The large reductions in military spending worldwide in the early 1990s, which at first seemed a setback for the expanding use of composites in aircraft, may turn out to be a boon for commercial applications as thousands of skilled engineers turn their attention to cost-effective use of composites in other fields, and the larger volumes of materials required should reduce material costs. The reduction in the number of suppliers triggered by the same causes may also lead to a smaller number of "standard" specifications for composite materials, reducing materials and certification costs.

These developments should make composites more affordable enabling them to be used in a greater proportion of the airframe, thus lifting the current ceiling imposed by cost. The future for còmposites in aircraft is bright: reduced manufacturing cost should soon see the a resumption of the upward trend in the use of composites in aircraft.

ACKNOWLEDGEMENTS

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