

THE RESEARCH REQUIREMENTS OF THE TRANSPORT SECTORS TO FACILITATE AN INCREASED USAGE OF COMPOSITE MATERIALS

Part I: The Composite Material Research Requirements of the Aerospace Industry

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SUMMARY

Composites are, besides aluminium, the most important materials for aerospace applications. Due to the opportunities they present for weight saving, their share has reached more than 15 % of the structural weight of civil aircraft, and more than 50% of the structural weight of helicopters and fighter aircraft over the last 40 years. In addition to their high mass specific stiffness and strength, the high potential of composites for additional functionality is another reason for their success. Defined anisotropic behaviour, the possibility to integrate sensors or actuators, high structural damping, and superior fatigue performance are typical advantages.

Nevertheless, there are still some drawbacks that are preventing composites from being used more extensively. Material costs can be prohibitively high, processing is time consuming and involves a lot of manual work, and the behaviour of the inhomogeneous and anisotropic materials is still not fully understood.

In order to discuss the most critical issues relating to the use of composites with experts from other transport sectors, ten workshops were organised within the framework of the COMPOSIT thematic network on "The Future Use of Composites in Transport". These ten workshops addressed the issues of composite repair, design and structural simulation, crashworthiness, manufacturing, lightweighting, joining, recycling, modelling, fire safety and new material concepts. The objective was to exchange knowledge in order to identify solutions or define common research directions. As an output from each workshop, priorities for future research activities to meet the needs of the transport sectors were identified.

This report presents the findings of COMPOSIT in terms of the aerospace industry. Key recommendations for future research priorities include:

- Cost effective, automated manufacturing technologies, e.g. the

development and application of textile preforming technologies in combination with non-autoclave impregnation and curing processes.

- Improved design methodologies and analytical tools for simulating processing and performance (especially non-linear behaviour and long-term behaviour).
- Improvement of material systems (fibres, matrix systems, binders) with respect to cost, processing and performance, e.g. through the application of nanotechnologies.
- Advanced (adhesion) joining techniques for improving performance and simplifying processing.

Further information on COMPOSIT can be found at www.compositn.net.

INTRODUCTION

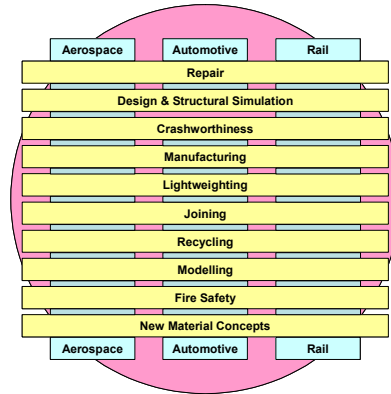
This report summarises the findings of the COMPOSIT thematic network on “The Future Use of Composites in Transport” in relation to the aerospace sector.

The COMPOSIT Thematic Network

The aim of the COMPOSIT thematic network was to bring together researchers, designers, manufacturers and end-users of composite materials across the aerospace, automotive and rail industries. This was achieved through a series of ten workshops that were held throughout 2002 and 2003. Each workshop addressed a specific theme or issue relating to the use of composites in transport by providing a forum for comparison, collaboration and cross-fertilisation between the different sectors. The intention was to encourage knowledge transfer and promote best practice in the use of composites within the transport system.

As an output from each workshop, issues of common interest were highlighted and future research needs were identified and prioritised. Centres of excellence that could act as focal points to address these research needs were also identified. In this way, research “clusters” were developed for each workshop theme, thus providing a roadmap for future research direction. The full details of the clusters can be found at www.compositn.net.

The COMPOSIT consortium was headed by four partners, each representing one of the industrial sectors with a vested interest in the project: NewRail for the rail industry, EADS Deutschland for the aerospace industry, Centro Ricerche Fiat for the automotive industry, and SICOMP for the composites industry. Six additional members provided further specialist technical input: D’Appolonia, IKV, INEGI and the Universities of Leuven, Newcastle and Zaragoza.



Summary of the COMPOSIT thematic network - research clusters have been developed for each of the ten horizontal workshop themes

In identifying and ultimately addressing the composite material research needs of the transport sectors, it is anticipated that the legacy of COMPOSIT will be:

- New and improved concepts for composite material transport applications, leading to an increased usage of composites and better vehicle solutions.
- Improved competitiveness for the composites industry by reducing development costs and time-to-market for new transportation products.
- The creation of an infrastructure for sustainable inter-industry co-operation.

The Scope of this Report

This report summarises the findings of the COMPOSIT thematic network in relation to the aerospace sector. It provides an overview of the applications in which composite materials are currently employed. It then considers the various technical issues associated with the use of composites in aircraft as identified by the research clusters. These issues provide the basis for a list of future research priorities. Furthermore, centres of excellence capable of leading this future activity are identified.

Finally, assuming that the research deficiencies can be addressed, potential future applications for composites within the aerospace industry are suggested.



Airbus A380

This report constitutes Part I of the collated published output from the COMPOSIT thematic network. The companion volumes are:

- Part II: The Composite Material Research Requirements of the Automotive Industry.
- Part III: The Composite Material Research Requirements of the Rail Industry.

CURRENT APPLICATIONS OF COMPOSITES IN AEROSPACE

Starting with projects such as the first fully-composite glider “Phönix”, a development at Stuttgart University in 1959, fibre reinforced polymers have gained an important role as structural materials in the aerospace industry. High specific stiffness and strength, superior fatigue performance, corrosion resistance and high energy absorption capabilities are the main properties that have led to a steady growth in the use of composites in all fields of aircraft and space application. Figure 1 presents a comparison between the mechanical properties of composites and light metals, whilst Figure 2 illustrates the growth of composites in civil aircraft structures over the last 40 years.

Market studies estimate that 2000 tons of finished composite parts, with a value of \$760 million, were produced for the European aerospace industry in the year 2000.

The application of composites in place of metals requires different approaches to the design and service of structural components. Labour intensive manufacturing, expensive raw materials, damage tolerance aspects, and the need for new inspection and repair philosophies are all issues that need to be addressed. Furthermore, the differing requirements of civil and military aerospace applications need to be considered.

Here we review the current status of composite use in the various aerospace fields.

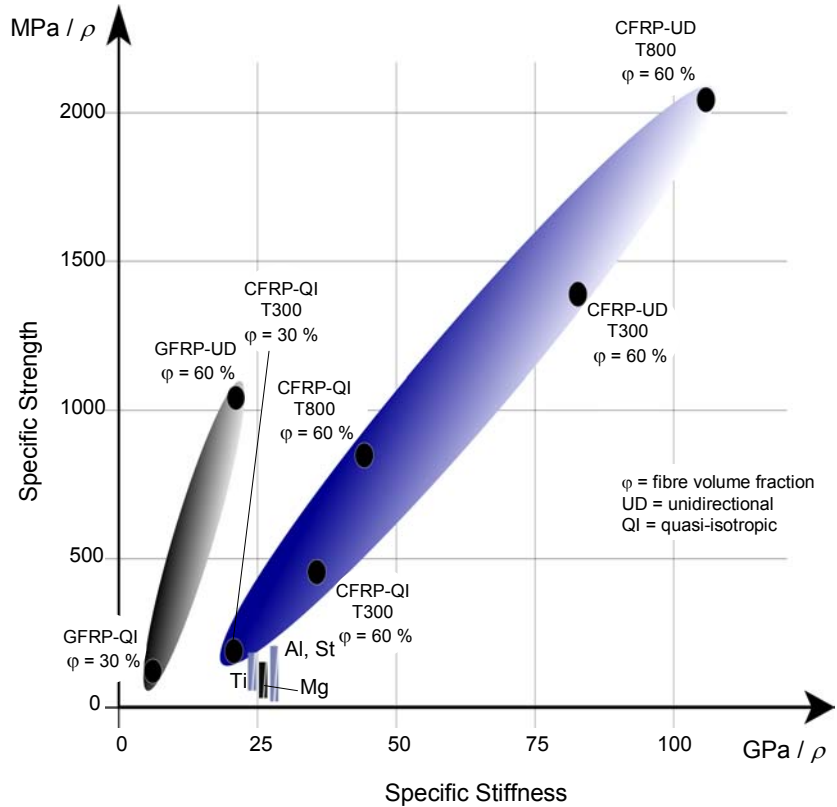


Figure 1 – comparison of the mechanical performance of composites and light metals

Share of Composite Components

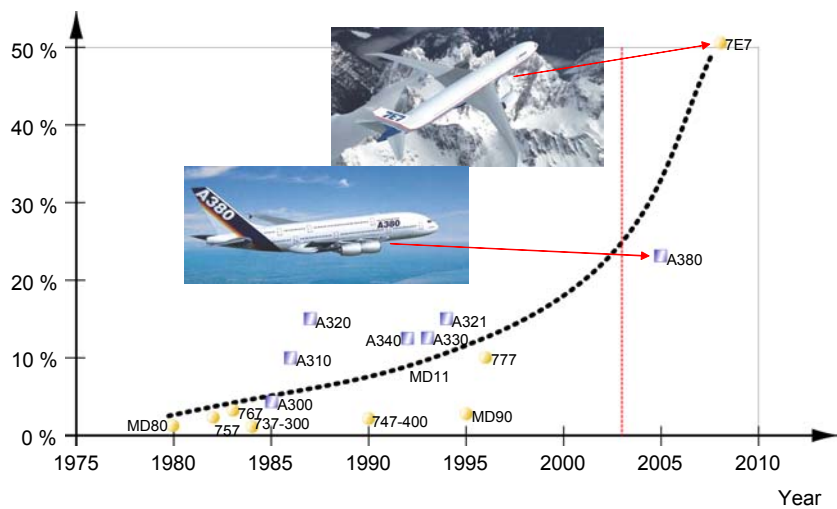


Figure 2 – the development of composite aerospace applications over the last 40 years (source: DLR Braunschweig)

Civil Aircraft

Figure 3 illustrates the breakdown of direct operating costs (DOCs) for a typical civil aircraft. Due to the high impact of material selection on (i) the aircraft price (material and processing costs), (ii) the fuel consumption (lightweighting), and (iii) the maintenance costs (inspection and repair), a significant proportion of the DOCs can be influenced by the application of composites.

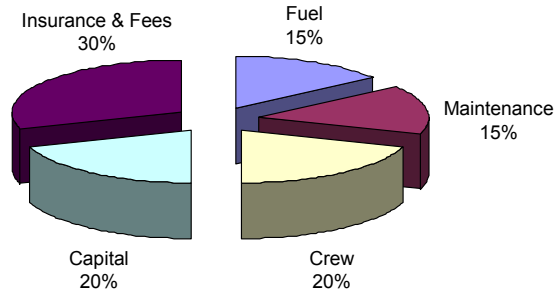


Figure 3 – breakdown of the direct operating costs (DOCs) for a typical civil aircraft (source: Airbus)

Although it is difficult to give precise figures, it can be estimated that the value of lightweighting is around €100 to €1,000 (for specific applications) per kilogram of weight saved.

In addition to the cost issues, safety aspects also have to be considered in the material selection and design definition phases. Consequently, the implementation of any new material system such as composites is both time consuming and expensive because of the extensive qualification requirements. The absolute requirement for safety also leads the industry to adopt an evolutionary approach to the uptake of composites. This is in order to progressively gain confidence and experience in manufacturing technologies, operation and long-term behaviour. Indeed, Airbus has followed this route very closely. Starting with the movables and the vertical stabiliser of the A310 in 1983, an increasing number of structural components have been developed using composite materials. Figure 4 shows the development of composite applications from the A300 to the A380.

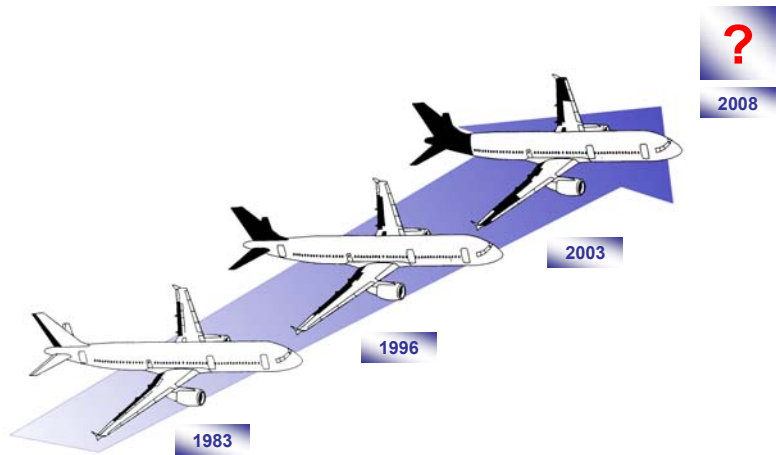


Figure 4 – development of composite applications (highlighted in black) from the A300 to the A380

Figure 5 shows the actual composite parts of the A340-600. Approximately 15 % of the structural weight consists of carbon fibre reinforced plastics. This number, as well as the share of composite parts, is now typical for modern civil aircraft. Figures 6 and 7 show the composite applications of the Boeing 777 and the Dornier 328 for comparison.

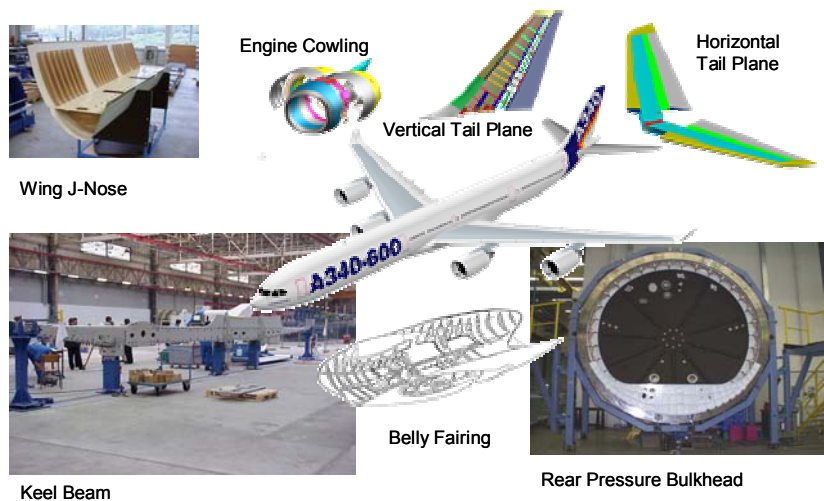


Figure 5 – composite parts of the A340-600 (source: Airbus)

It has been demonstrated by the structural composite components in the above applications that typical weight savings of 15-20% can be achieved compared to equivalent aluminium designs. However, in some cases, the application of composites has led to a significant increase in part cost. To improve affordability, composite technology selection should ideally be optimised according to the geometry and loading of each part. This results in the use of a wide range of different composite materials and processing technologies for different applications. For example, whereas the A310 used only relatively expensive and labour intensive prepreg technologies, the A380 will employ a mixture of technologies including textile preforming, resin injection and thermoplastics. Figure 8 shows the planned composite parts for the A380.

Today, there is still no carbon fibre fuselage or wing in series application, but many current technology programs are developing the basic understanding for the design, manufacture and operation of fully composite aircraft. The next big step forward will be the A400 M military transport plane, for which major parts of the wing are foreseen in composites. Within Airbus, there are visions of using composites for more than 60% of the airframe structure by 2025. Boeing is also working intensively on the wider use of composites. For the 7E7, with a planned market introduction of around 2008, the use of composite wing and fuselage technology has been announced. This would lead to a composite share on this aircraft of more than 50% of the structural materials.



Figure 6 – composite parts of the Boeing 777 (source: Boeing)

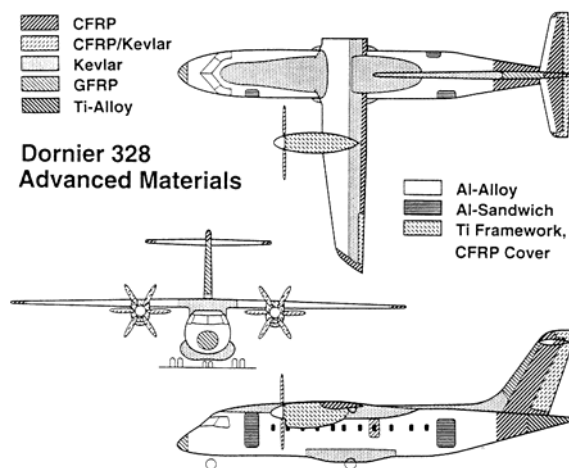


Figure 7 – composite parts of the Dornier 328 (source: Dornier GmbH)

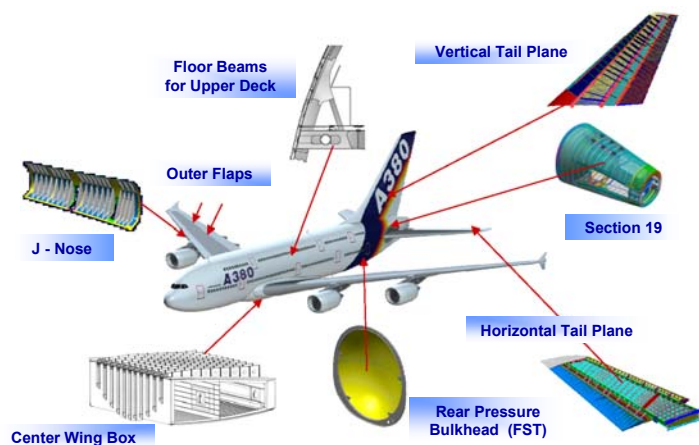


Figure 8 – planned composite applications for the A380 (source: Airbus)

Military Aircraft

Fighter aircraft often drive new technologies because of their special requirements. For example, lightweight structures are necessary for improved payload, improved agility, and short take-off and landing capabilities. Therefore, it is not surprising that many of the early composite technology programs in the 1970s were part of fighter aircraft development projects such as the F15, Alphajet, Tornado and Mirage. Figure 9 illustrates some typical composite parts on military aircraft, including fins, undercarriage covers and fuselage components. These were developed by MBB within the framework of the Tornado, X31 and Eurofighter projects. A significant proportion of the existing composite knowledge with respect to design, damage tolerance, manufacturing technologies, and in-service behaviour (e.g. moisture pick-up and crack sensitivity) was generated within such programs.

Whilst European companies such as Airbus and Dornier were quicker to implement composites in civil aircraft, the US has led for military aerospace applications. This development is compared in Figure 10.

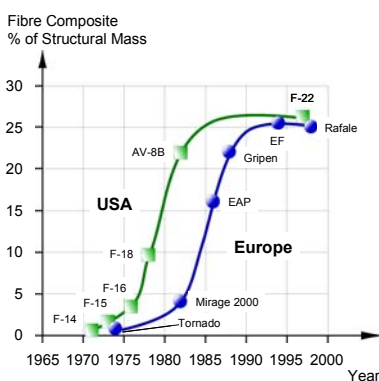


Figure 10 – development of composite share in military aircraft structures in the US and Europe

Nowadays, all modern fighter aircraft make extensive use of composite materials throughout the airframe structure. A typical example is the Eurofighter, which has a 70% (surface area) share of composite materials.

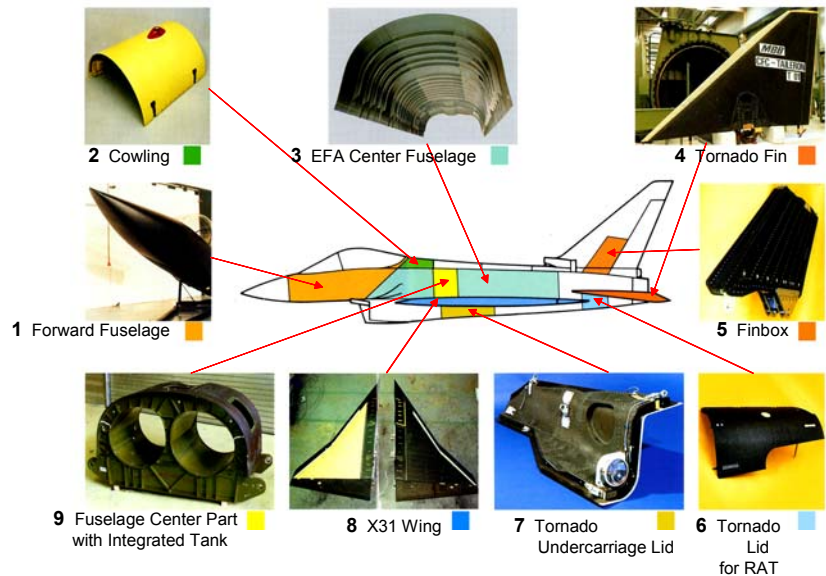


Figure 9 – typical composite components for military aircraft (source EADS)

The material selection for this airframe is shown in Figure 11.

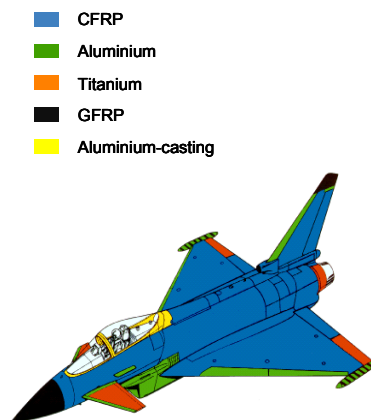


Figure 11 – composite parts of the Eurofighter

Intensive research on new materials and processes has also been conducted in the joint strike fighter program in the US. Thermoplastic wing skins and braided horizontal stabilisers are just two examples. However, it is not known which of these technologies will finally enter series production.

In general, it is remarkable that the variety of materials and technologies in military aircraft is much smaller than that of civil aircraft. Prepreg technology still dominates for military applications. There may be two reasons for this. Firstly, prepreg materials offer the highest mass specific stiffness and strength compared to other composite technologies (such as liquid moulded textile preforms). They therefore provide the highest weight saving potential. Secondly, fighter aircraft programs normally run for more than thirty years from the definition phase to the start of series production, and the number of such projects within a given company at any time is very limited (normally only one). Therefore, it is not possible to use the strategy followed by Airbus (for example) of implementing new technologies in a stepwise fashion across a whole family of planes.

Helicopters

Helicopters have employed composite materials in the rotor blades for about 40 years. Compared to aluminium blades, the adoption of glass fibre reinforced plastic blades increased the service life by a factor of up to 200. Nowadays, all helicopters use composite blades because of their superior fatigue properties and their potential for multifunctional design. The rotor blades and the rotor blade head are typical examples in which composites are used not only for their high specific stiffness and strength, but also for their additional functionality. Tuned anisotropy and integrated hinges are just two examples of how composites can be used to improve both performance and cost. In Figure 12, a conventional rotor blade head is compared with that of the EC 135, a highly optimised composite design. The part reduction and integration of the latter leads to a significant reduction of the assembly and maintenance costs, as well as improved reliability.

The helicopter industry also makes extensive use of composites as structural passenger cell materials. Following several technology projects such as the BK117 "Composite-Cell" (a joint development between MBB and Kawasaki in the 1970s), an increasing number of composite parts have entered series application. Nowadays, nearly all military and civil helicopters use composite materials for the passenger cell. Two examples, the EC 135 and the Tiger, are shown in Figure 13. Due to the specific requirement for lightweight structures in helicopter applications, extensive use is also made of sandwich structures.

Another specific requirement for helicopters is the energy absorption capability of the underfloor. Extensive research has been conducted into the development of energy absorbing structures. Due to their high mass specific energy absorption capability, composites are also employed for this purpose. One of the most interesting concepts is the composite sine wave beam.

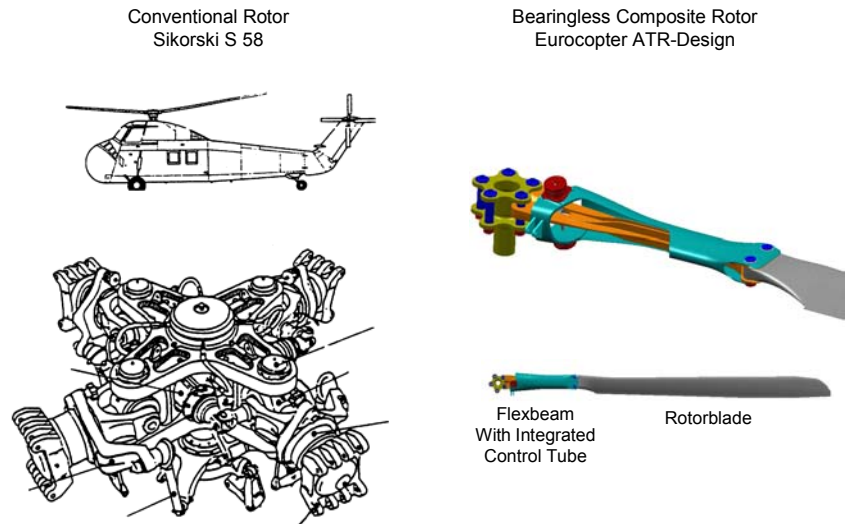


Figure 12 – comparison of a conventional and optimised rotor blade head (source: Eurocopter)

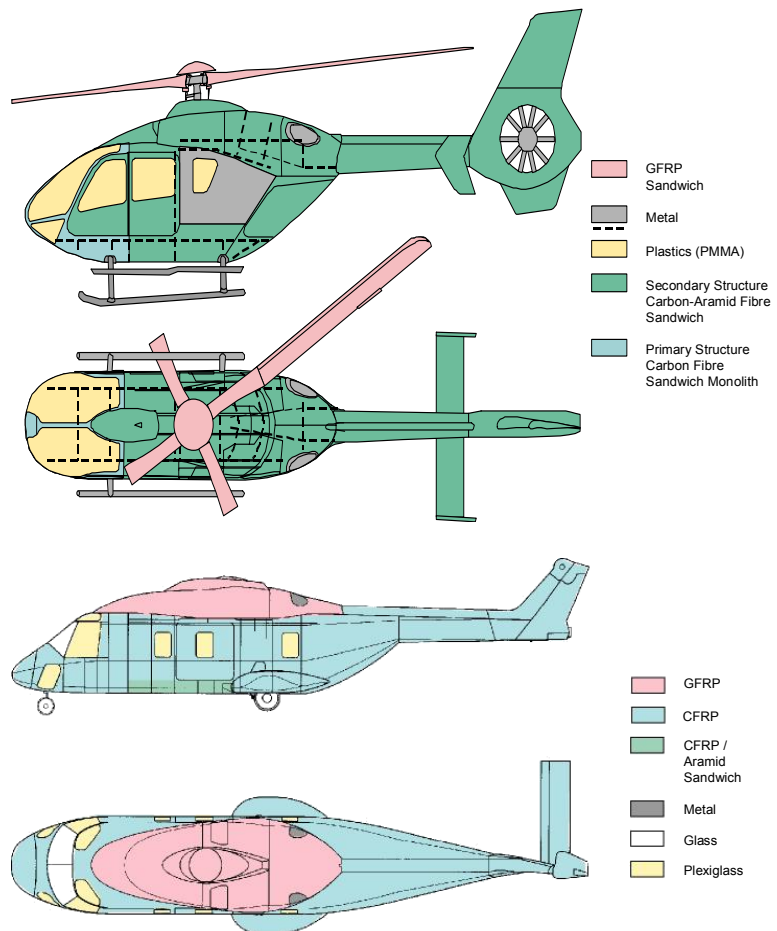


Figure 13 – composite parts of the Eurocopter EC 135 and Tiger (source: Eurocopter)

Space Applications

The aerospace sector with the highest interest in lightweight design is of course the space industry. A kilogram saved can have a value of more than €10,000. Therefore, high modulus carbon fibres are the most important candidates for structural space materials. In addition to their mechanical performance, the low coefficient of thermal expansion of carbon fibre reinforced plastics is highly relevant for satellite applications.

A typical structure, a sandwich for solar panels, is shown in Figure 14. The skin consists of high modulus carbon fibres produced by a special filament winding technique. The core is extremely light aluminium honeycomb.

Another use of composites in space applications is the carbon/carbon technology employed, for example, as the heat shielding material of re-entry structures or rocket nozzles.



Figure 14 – ultra-lightweight design of a solar panel (source: Eurocopter)

TECHNICAL ISSUES ASSOCIATED WITH THE USE OF COMPOSITES IN AEROSPACE APPLICATIONS

The COMPOSIT thematic network focussed on ten key issues relating to the use of composites in transport. During the course of the project, a workshop was dedicated to each of these ten issues. Leading international experts in the relevant fields were invited to present and participate at the workshops. Here, the findings are presented in terms of their relation to the aerospace industry.

Repair

Repair topics are very important for the aerospace industry. They have an influence on design philosophies, maintenance procedures and material selection.

Several approaches to repair have been developed and these are applied for different cases:

- If the damage is small and does not affect the structural behaviour of the aircraft (e.g. because of damage tolerant design), then no structural repair is necessary. The damage is simply filled for aesthetic or aerodynamic reasons.
- If the damage is sufficiently significant to affect the load carrying function, and the part can be removed from the plane (often possible in civil aircraft; not applicable for very big, highly integrated structures), then the repair can be performed in an autoclave using the original material and process parameters. The procedure is described precisely in handbooks and leads to a performance close to the original part.
- If the damage is significant and the part cannot be removed from the aircraft (typical for military aircraft structures with high integration), then an in-situ repair method has to be employed. Two processes have been developed. The first involves working with a repair patch that has been specially developed for use in conjunction with relatively low

temperatures (up to 130°C) and pressures (1 bar). This results in the repaired structure having a lower glass transition temperature than the original and reduced mechanical performance compared to autoclave-repaired parts. A further complication is that moisture in the structure can lead to voids in the bond-line area during cure. The second option is to manufacture a separate replacement part in an autoclave using the original material and process parameters, and to integrate it within the damaged structure by adhesive bonding. In this case the structural performance of the repaired part is equivalent to the original structure, but the bonding can again suffer from moisture leading to weakness in the bond-line.

In summary, it can be stated that repair-methods for composite structures are available and established within the aerospace industry. Nevertheless, further improvements are necessary to simplify the processes and come closer to the performance of non-damaged structures.

Design and Structural Simulation

The industry's capabilities with respect to the design and simulation of composite structures has a major influence on: (i) performance (utilisation of material properties and reduction of safety factors), (ii) time to market and development costs (the number of experimental tests that must be performed), and (iii) development risk (identification of problems at an early stage).

Historically, it can be seen that advances in composite design capability have tracked the development of computer hardware and software. Before the widespread availability of computers, the effort associated with laminate calculations involving more than six plies was considerable. However, as calculation programs running under Assembler or FORTRAN became available,

so global laminate calculations became increasingly feasible.

Nevertheless, in the early days, the reserve factors associated with composite structures were rather high and the maximum permitted stresses were rather low. Consequently, the full potential of composite materials was not being realised. The next major breakthrough was the advent of finite element analysis (FEA) programs with the capability to perform analyses using laminated shell elements. The design and calculation of local phenomena now became feasible, and it was possible to reduce the reserve factors for composite parts. This allowed a big push towards lightweight design.

Nowadays, composite FEA is a common structural design tool within the aerospace industry. Almost every software package offers sophisticated linear or quadratic elements with laminate capabilities, often with a selection of different failure criteria. The ability to visualise local effects and stress concentrations makes FEA an essential tool in the early and middle design phases.

The widespread use of FEA for composites has reduced time to market enormously. For example, parametric FEA models can provide a broad range of stress evaluations under different conditions within a short time. FEA models also deliver more results than experimental techniques because "conditions" can be determined at all element integration points and not only at specific (e.g. strain-gauged) test locations. Furthermore, FEA analysis is much cheaper than performing experimental tests. It therefore facilitates a more extensive study of structural behaviour, thus reducing the risk of poor design.

Still, the maturity of FEA codes for composite design is insufficient at present. As the drive towards lightweighting produces increasingly complex structures, so the standard laminated shell elements become increasingly restrictive. New calculation capabilities are required by the aerospace

industry, including the ability to accommodate dynamic behaviour (crash and impact), post-buckling, sandwich materials with anisotropic cores, and multi-ply or last-ply failure.

Often, user subroutines for advanced failure criteria evaluation are implemented within FEA codes. Recently, considerable effort has been directed towards the development of new delamination behaviour laws for FEA, both in implicit static and explicit dynamic software codes.

In summary, it can be stated that the design and simulation of composite structures has improved dramatically over the last decades. This is largely due to the improvement of hardware, software, and fundamental material understanding. Nevertheless, a lot of research work is still required, with some of the most important topics being:

- Advanced material models for stiffness, strength and failure mechanisms (especially for three-dimensionally reinforced composites and new sandwich materials).
- Integrated tools covering design, manufacturing (e.g. draping or injection), and mechanical performance.
- Advanced design concepts (e.g. those based on bionic approaches).
- Adapted certification methods for new design philosophies (e.g. highly integrated structures).
- Improved design tools and methods for adaptive composites (e.g. with integrated actuators).
- Improved simulation of highly dynamic failure (e.g. crash and impact).
- Improved understanding of in-service and long-term behaviour.

Crashworthiness

With the assumed wider use of composites (e.g. CFRP fuselages), crashworthiness is becoming an increasingly important topic for aerospace applications. This is because of concerns over passenger safety and the associated legal requirements.

Composite materials are of particular interest for use in energy absorbing structures because of their high mass specific energy absorption capability. Energy absorption capacities of more than a 100 kJ/kg can be achieved with careful design. This is realised by the complex failure mechanisms of composites, involving fibre breakage, matrix cracking, and fibre-matrix interface cracking.

To realise composite structures with high energy absorption capabilities, special designs are required. Stable, progressive failure must be initiated by appropriate trigger mechanisms. Furthermore, careful consideration needs to be given to the design of the fibre reinforcement and the structural geometry.

The first successful aerospace applications to employ energy absorbing composites have been helicopter sub-floors. Recently, a complete passenger cell of the NH90 helicopter was successfully crash tested. It was demonstrated that all the requirements relating to passenger decelerations and structural integrity could be fulfilled by a composite structure.

In the future, civil aircraft will also be designed to meet more stringent crash requirements. New design concepts are needed to allow, for example, the sub-floor to absorb energy. One interesting approach is the "Gondel-Concept" of DLR Braunschweig.

Most importantly, a good compromise needs to be found between composite material energy absorption and wider requirements such as packaging, structural performance and aerodynamics.

Intensive research is also needed in the field of crash simulation. Material damage models and approaches to the simulation of structural failure need to be developed to facilitate design optimisation.

Manufacturing

Important issues relating to the research and development of new manufacturing methods for aerospace applications include:

- Improved affordability (e.g. automation, tooling costs).
- Improved part performance (e.g. light-weighting, damage tolerance).
- Quality assurance.
- Concurrent engineering.

The most interesting technologies with a high potential to fulfil these needs are:

- Textile preforming.
- Automated tape laying / fibre placement.
- Liquid moulding technologies (especially non-autoclave).
- Advanced curing technologies.
- Thermoplastic technologies.
- New sandwich technologies.

Textile preforming is particularly relevant to the automated manufacturing of structural composites with a high degree of integration and optimisation, and in which three-dimensional fibre reinforcement is required. Important technologies are non-crimp fabrics, braiding, textile fibre placement (embroidery) and stitching. These technologies have been developed for composite applications over the last ten years and their potential has been demonstrated in many development programs. First series applications are

planned for the A380 and the A400 M (pressure bulkhead, ribs, flap-track, etc).

Some examples showing complex preforms (based on non-crimp fabrics, braids and textile fibre placement) that have been stitched together by robot-controlled single-sided stitching are shown in Figure 15. Nevertheless, there is still the need for further improvement. The stiffness and strength properties of components based on such preforms are currently significantly below prepreg levels. Furthermore, design guidelines and calculation methods are still only on an academic (rather than industrial) level.

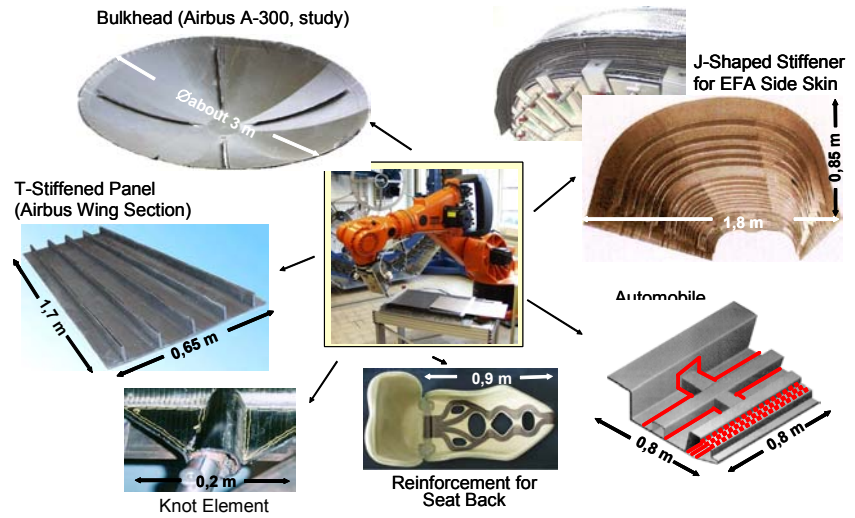


Figure 15 – examples of complex stitched fibre preforms

Liquid moulding techniques are, when used in combination with textile preforming, an interesting alternative to prepreg technology. Many different approaches to liquid moulding have been developed for different purposes (e.g. resin transfer moulding - RTM, Seeman Composites Resin Infusion Moulding Process - SCRIMP, vacuum assisted resin infusion - VARI, differential pressure resin transfer moulding – DP-RTM, etc.). In all cases the dry fibre preform is placed in a mould and a low viscosity liquid resin is injected with or without pressure. Of special interest is the opportunity for low cost tooling. For some liquid moulding technologies, only one stiff tool side is necessary, the other side being realised with film. This is especially relevant for big, highly integrated structures which are typical for wing or fuselage applications. An additional benefit is the possibility for non-autoclave curing because, even with only one bar consolidation pressure, high quality impregnation and fibre volume fractions of close to 60% can be realised.

In parallel with the thermosetting technologies described above, thermoplastics have now been developed to a stage where the first significant structural applications are starting to emerge. An example is the A380 J-nose, a sheet-formed and welded structure that exploits the benefits of thermoplastics. Of particular importance for this application is the good damage tolerance of thermoplastics. It can

be expected that this development will lead to new advances in thermoplastic technology.

For the affordable manufacturing of sandwich structures, newly developed folded cores offer some interesting opportunities. They can be produced automatically into near net shapes, and they offer much more flexibility in their performance compared to honeycombs. Their functionality with respect to drainage, acoustic damping and signature is also higher. Nevertheless, the technology is still relatively new and only small-scale lab samples have been manufactured up until now.

Lightweighting

Lightweighting is still one of the most important driving forces in aerospace development programs. However, in attempting to reduce weight, many other aspects also have to be taken into consideration. These include:

- Affordability.
- Quality assurance.

- Durability.
- Comfort.
- Maintenance.
- Repair.

Therefore, the real challenge with lightweighting is to find the optimum compromise through a multidisciplinary approach. Starting from the basic design concept and ending with in-service aspects such as maintenance and repair, optimised lightweight design requires trained and experienced engineers.

In terms of conceptual lightweight design, many new ideas or approaches can be found in other areas. The COMPOSIT workshop on lightweighting included two fascinating presentations – one on lightweight structures in nature, and another on architectural approaches to lightweighting.

The perceived cost benefits of lightweighting are very different for the various aerospace fields. Whilst civil aircraft applications can normally justify an additional cost of €100 per kilogram of weight saved, space applications are sometimes prepared to

accept costs of more than €10,000 per kilogram of weight saved.

It has been demonstrated in many aerospace applications that the use of composites can yield weight savings of around 20% compared to aluminium.

Joining

The dominant joining technique in the manufacturing of civil aircraft has been, and still is, riveting. However, structural adhesive bonding also has a long tradition in the aerospace industry for some aluminium applications and nowadays also for composite structures.

One approach for the joining of composites is adhesive film bonding. This requires high temperatures and pressures and consequently has to be performed in an autoclave. It is also limited in its design freedom as only constant bond line thicknesses can be achieved. Therefore, it is not possible to compensate for large tolerances.

Recent research efforts have focused on the development of adhesives and processes requiring low temperatures and pressures for non-autoclave curing. An interesting candidate technology is two component paste adhesives. Their application would simplify processing and allow a compensation of tolerances due to the high flexibility in bond line thickness.

An additional development goal is the lowering of curing temperature to below 100°C to prevent the out-gassing of moisture causing voids in the bond line

Another important topic is the preparation of the composite parts for adhesive bonding. The state of the art is to use a peel ply with additional mechanical treatment after removing the ply to ensure no residual material is left. This procedure is both time consuming and expensive in terms of quality assurance. New developments in bond preparation are examining the use of grit

blasting, or atmospheric plasma or laser treatments.

Other research and development topics relating to the joining of composites for aerospace applications include:

- Nano-fillers for improved performance.
- Advanced adhesive curing based on laser or microwave heating.
- Debonding on demand for repair purposes.
- Adhesives with improved fire, smoke and toxicity properties.

A final issue relating to adhesive technologies is GLARE, in which aluminium sheets are bonded to unidirectional glass prepregs with an adhesive film. GLARE panels will be used in the upper fuselage of the A380.

Recycling

The recycling of composites is currently not a primary topic in the aerospace industry due to the long life cycle of aircraft. Because of this, there are no legal requirements as in the automotive sector.

Presently, the principle possibilities for the "recycling" of carbon fibre composites are burning (energy recovery) or grinding. The resulting particles can then be used as filler in secondary structures.

A bigger aerospace interest surrounds the recycling of production scrap. The first priority is of course to avoid scrap by, for example, using optimised nesting or prepreg tapes with reduced width. The remaining prepreg scrap is then usually hardened in an autoclave, hot press or oven and then deposited, burned or milled.

Significant advantages with regard to the recycling of production scrap are offered by manufacturing technologies based on textile preforms and resin injection processes. By

using near net shaped preform technologies (e.g. braiding), together with optimised resin injection processes, waste fibres and resin can be reduced to a minimum. Another advantage of preform technologies is that the scrap is already separated into fibres and resin, and not mixed as with prepregs.

Modelling

Modelling is, in combination with design and simulation (see page 11), an important factor for improving the performance, affordability, safety and development costs of composite aerospace structures.

The modelling of composites is a highly sophisticated and complex task due to the inhomogeneity and anisotropy of the materials. Models for layered two-dimensional reinforced structures have been developed successfully over recent decades. Stiffness, strength and fracture properties are generally understood and are applied in finite element programs and analytical models.

Much more challenging is the modelling of new material and manufacturing concepts based on textile preforms and liquid moulding technologies. The fibre structure can be very complex, the degree of integration is much higher, and the performance is significantly influenced by the manufacturing process. Issues such as three-dimensional fibre reinforcement, fibre distortion caused by draping, and the variation of resin content due to local permeability changes all have to be addressed. In particular, the following influential factors have to be taken into consideration:

- Fibre and matrix material.
- Fibre architecture (two-dimensional or three-dimensional, fibre curvature, etc.).
- Fibre-matrix interface.
- Fibre volume fraction.

Consequently, the following manufacturing processes have to be understood and modelled:

- Textile technologies (non-crimp fabrics, braiding, embroidery, weaving).
- Resin processing technologies (resin transfer moulding - RTM, resin film infusion - RFI, vacuum assisted non-autoclave processes).
- Integration / bonding process (e.g. stitching).

Clearly, therefore, the modelling of mechanical performance must be combined with the modelling of the manufacturing process. Integrated tools are required taking all influential factors into account.

Furthermore, these models must be accessible for development engineers. If input data is required that is very difficult to determine, or deeply specialist processing knowledge is necessary (e.g. of advanced textile processes), then the models will never make the transfer from academia to the aerospace industry. It is therefore necessary to integrate the fundamental understanding within professional software packages and to prepare associated design guidelines.

Further research is also required into the modelling of new material and design principles such as advanced sandwich structures (e.g. employing folded cores), or adaptive structures with integrated actuators.

Fire Safety

The requirements regarding fire, smoke and toxicity are defined by the Federal Aviation Administration (FAA). They are dominated by a post-crash scenario that dictates that passengers must be able to leave a crashed aircraft within five minutes without being injured by toxic gases or heat, or hindered by smoke. This scenario is quite different from the approaches of the rail, marine or bus industries. Furthermore, the technical

regulations relating to aerospace fire safety are very different from other transport sectors.

There is a goal of the FAA to further improve fire safety by cutting the allowable peak heat release rate of interior component materials by a factor of two. For composites, this goal cannot be reached by current phenolic resin technologies. However, up until now, no other resin material has been able to fulfil these requirements either.

Current development work is largely concentrating on the development of new fire-safe core materials to replace Nomex honeycombs. For example, phenolic foams or folded honeycombs could improve processing and affordability.

Other recent requirements and research topics that have arisen in the field are hidden fires (e.g. due to cable burning or short circuits with low energy / long exposure times), and the burn-through behaviour of structural materials following accidents.

New Material Concepts

The most important material for composites in aerospace is of course the carbon fibre.

Today, the primary focus for new carbon fibre developments is not the improvement of fibre performance. Instead, it is the reduction of costs and the improvement of processability (e.g. through textile preforming). 24k fibres are now, more or less, established and new approaches using flat bands instead of "round" rovings look promising for further improvements in performance and affordability.

In the long term, significant performance improvements can also be anticipated through the development and application of carbon nanotubes (CNTs). These have considerable potential for enhancing mechanical performance and functionality. In Figure 16, the performance of CNTs is compared to current state of the art materials. It shows that as well stiffness and strength increases, improvements in thermal conductivity and heat transfer open-up new worlds of opportunity.

Several companies in Europe, the US and Japan are working on CNTs. Today, only a limited amount of CNTs are available, and it may take another five years to produce CNTs on an industrial scale with high quality and acceptable costs.

The initial applications for CNTs are likely to be as a filler material for improving the

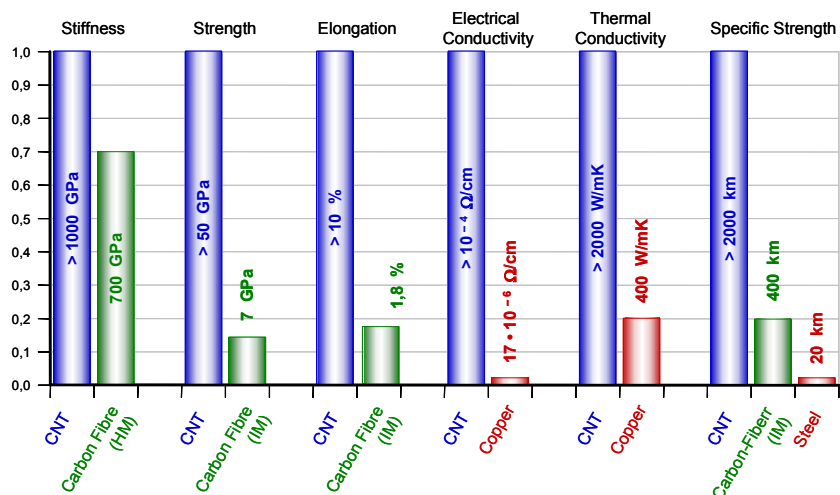


Figure 16 – comparison of the performance of carbon nanotubes and conventional materials

performance of conventional composites (e.g. with respect to electrical conductivity), as well as in niche applications such as reinforced stitching yarns.

In the development of new resin systems, the main focus is in the field of liquid resin infusion. Improved processability (low viscosity, wide processing window) as well as improved toughness are amongst the

goals. Nevertheless, there are still the general goals of cost reduction and obtaining a good balance between high temperature capability and toughness. Increasing attention is also being given to specific topics like fire, smoke and toxicity (FST).

Interesting developments are on the way in the field of sandwich structures. Two

examples are new foam core materials adapted to resin infusion processes through the use of smaller surface cells, and new folded structures allowing the automated and affordable manufacturing of contoured cores with special features like drainability.

FUTURE RESEARCH PRIORITIES FOR COMPOSITES IN AEROSPACE

The challenge for all developments in aerospace is always to find a good compromise between performance and cost. Depending on the nature of the mission and the market, one or the other will dominate. Figure 17 shows the goals for the next generation of Airbus planes. Clearly a 40% cost saving and a 30% weight saving compared to the state of the art cannot be reached by small steps. An integrated approach that takes all disciplines into account is necessary. With this in mind, recommendations for future research priorities are presented here.

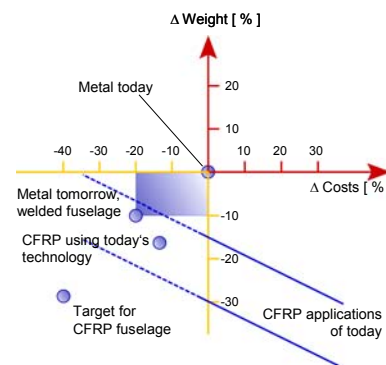


Figure 17 – the goals for weight and cost reduction on future Airbus planes

Primary Research Priority – Manufacturing Technologies

Improved manufacturing technologies are the primary key to better affordability and quality. Higher degrees of automation, better quality control, reduced tooling costs and

shorter cycle times have to be consistently attained.

When optimising manufacturing technologies, a multi-disciplinary approach involving the views and technologies from across the transport sectors (automotive,

rail, marine and aerospace) can be very useful.

The following topics have been identified as the most promising:

- Textile preforming and fibre placement technologies.
- Non-autoclave injection technologies.
- Advanced curing technologies (e.g. microwave curing).
- Overall quality concepts.
- Thermoplastic technologies.
- Automated sandwich core material manufacturing technologies (e.g. folded cores).

Primary Research Priority – Design, Analytical Tools and Simulation

Only a good basic understanding of materials and processes allows an optimised application of new concepts. Otherwise, high safety factors have to be applied, preventing the optimum exploitation of any lightweighting potential and generating additional costs.

Three-dimensional fibre reinforcement and high degrees of integration are just two future challenges for the development of design and simulation tools with improved performance, short development time and high reliability.

Integrated design tools are required that take both materials and processing aspects into account. Basic fibre architecture, draping, impregnation, curing and bonding, as well as fibre and matrix properties, are the main factors that influence structural performance. It is necessary to optimise and integrate current isolated approaches to the simulation of complex fibre architectures, draping processes, mould filling, curing and joining, into one design tool.

Finally, these tools have to be integrated within professional computer aided design packages such as CATIA. In parallel, user-friendly guidelines have to be developed to assist designers in realising cost effective, high performance structures.

Primary Research Priority – Material Systems

Continuous improvement is necessary in the fields of carbon fibres (e.g. cost reduction, improved textile processability), binders, and matrix systems (e.g. fast curing, high temperature capability, high toughness). Significant advances can be expected in nanotechnologies. Nanoparticles can improve functionality and nanotubes (and even nanoyarns in the very distant future) have the potential to provide structural properties far superior to those of carbon fibre composites. However, availability and costs are a long way from being relevant to

real applications, and much more research is required regarding basic understanding and processing.

Primary Research Priority – Joining

Research has to be focused upon improved joint performance and simplified processing. This will lead to higher reliability and reduced costs.

The most important research areas are:

- Low temperature paste adhesives.
- Advanced curing based on laser or microwave heating.
- De-bonding on demand for repair purposes.
- Adhesives with improved fire, smoke and toxicity properties.
- Assembly technologies.

Secondary Research Priority – Multifunctional Structures

Composites are the most promising materials for realising multifunctional structures with active damping, shape control and health monitoring. This is due to the possibility of integrating actuators (e.g. piezo fibres or shape memory alloys) or sensors e.g. (piezos or optical fibre sensors) within a composite. The basic principles and concepts are known, but intensive research is required in topics such as sensor and actuator material optimisation, integration technologies, and sensor signal processing.

Secondary Research Priority – Recycling

It is possible that the recycling of aircraft will assume a much higher priority in the future because of political pressure and regulations.

Technologies that allow the re-use of recycled “valuable” materials in high performance products are the most interesting. For example, employing ground composites as fillers in injection moulding or other processes, where the properties of the filler can be used for improving mechanical performance or functionality (e.g. electrical conductivity or thermal expansion), is very interesting. These developments would require close cooperation between processing partners and potential end-users.

In production, the focus must be to avoid scrap by developing near-net shape processes.

FUTURE OPPORTUNITIES FOR COMPOSITES IN AEROSPACE

As described on pages 5-10, composite materials are well established in all aerospace fields. Nevertheless, there are big opportunities to further intensify the use of composites for improving the performance and affordability of aerospace structures.

From the expected achievements of ongoing research and development programs, further improvements in mechanical performance, cost reduction and improved fundamental understanding can be anticipated. This will lead to composites becoming the number one candidate material for more and more components.

In civil aircraft, the next big steps could be the composite wing and the composite fuselage (Boeing 7E7). Current demonstration projects show promising results and the decision to employ a composite wing for the A400 military transport aircraft demonstrates the confidence in this application.

Technologically, many interesting topics are under continuous and successful development. Textile preforming, non-autoclave injection technologies, microwave-heating and health monitoring are only a few examples. In the longer term, further progress could also be realised through the

use of nanotechnologies. In particular, carbon nanotubes look very promising as potential reinforcements to produce composites with unique performance.

A very important task is the development of integrated design tools that allow the simulation of the manufacturing process as well as the structural performance (short-term and long-term). This will reduce the development effort by limiting the number of experimental tests required. It will also further improve the utilisation of materials in the ongoing quest for optimised weight reduction.

CENTRES OF EXCELLENCE FOR COMPOSITES IN AEROSPACE

Centres of excellence for composites in aerospace can be divided into:

- Material suppliers.
- Part manufacturers.
- Aircraft manufacturers.
- National research centres.
- Universities.

With respect to material suppliers, there has been an extensive consolidation of the industry in recent years. Toray and Tenax / Toho should be mentioned as carbon fibre manufacturers, whilst Hexcel and Cytec Fiberite are the biggest producers of prepregs. However, several other companies are well established with their own individual products.

Independent part manufacturers include, for example, Fischer FACC (Austria), Composite Aquitaine (France), MAN (Germany), Fokker Special Products (The Netherlands), Sonaca (Belgium) and Gamesa (Spain). These organisations all run their own development projects and have specific expertise and fields of application.

The largest aircraft manufacturers with competence in composite development and manufacturing are EADS (Airbus, Military Aircraft, Eurocopter, Astrium), Dassault (France), SAAB (Sweden), Alenia, Agusta Westland, Pilatus and Diamond Aircraft (Austria).

An interesting approach is being followed by Airbus with the establishment of the Composite Technology Centre (CTC) in Stade. Several suppliers are working in close cooperation with Airbus in the vicinity

of the Stade composite manufacturing plant on the development of new production technologies for composite materials.

The EREA (European Research Establishment in Aeronautics) is a cross-border organisation that links the most important national research centres: DLR (Germany), ONERA (France), NLR (The Netherlands), DERA (United Kingdom), CIRA (Italy), INTA (Spain), and FFA (Sweden). These all have their own specific competencies, but work together in the EREA to share resources and avoid duplication of effort.

Of course, many Universities all over Europe play an important role in the research and development of composites for the aerospace industry, but it is beyond the scope of this document to mention them all here.

CONCLUSIONS

Composite materials and structures have proven their potential for use in high performance aerospace applications over the last fifty years. High mass specific stiffness, strength and energy absorption, high functionality (e.g. through tailored anisotropy), and optimised structural concepts (e.g. due to high levels of design integration) are the main reasons for specifying composites.

The materials share for composites has reached 15 % in civil aircraft and more than 50% in military aircraft and helicopters. Furthermore, there is considerable potential for further increases in these figures through applications such as the composite wing and composite fuselage, both of which are being investigated by Boeing and Airbus.

New developments such as textile preforming, liquid moulding technologies, advanced thermoplastic technologies, new material systems and optimised design methodologies will support this tendency. Nevertheless, there is still a lot of research and development work to do. For many applications, costs are still too high compared to aluminium structures, even when life cycle costs are taken into account. Development times are still very long and the qualification of a new materials and processes is very expensive. Therefore, basic understanding of design, manufacturing processes, and in-service behaviour must be improved.

The unique feature of composites compared to metals is that the material and structure

are produced in one step, and that there are many more factors influencing performance. On the one hand this is the reason for the success of composites. On the other, it is a challenge for future developments. Integrated approaches are required that take the material, process, structure and in-service conditions into account. The necessary tools must be developed to assist engineers in both the design and manufacturing phases.

Interdisciplinary views that take the knowledge and experience of other transport sectors (e.g. automotive, marine, rail) into account are also important.

