Avalon Consultancy Services Ltd

The Use of Composites in Aerospace: Past, Present and Future Challenges.

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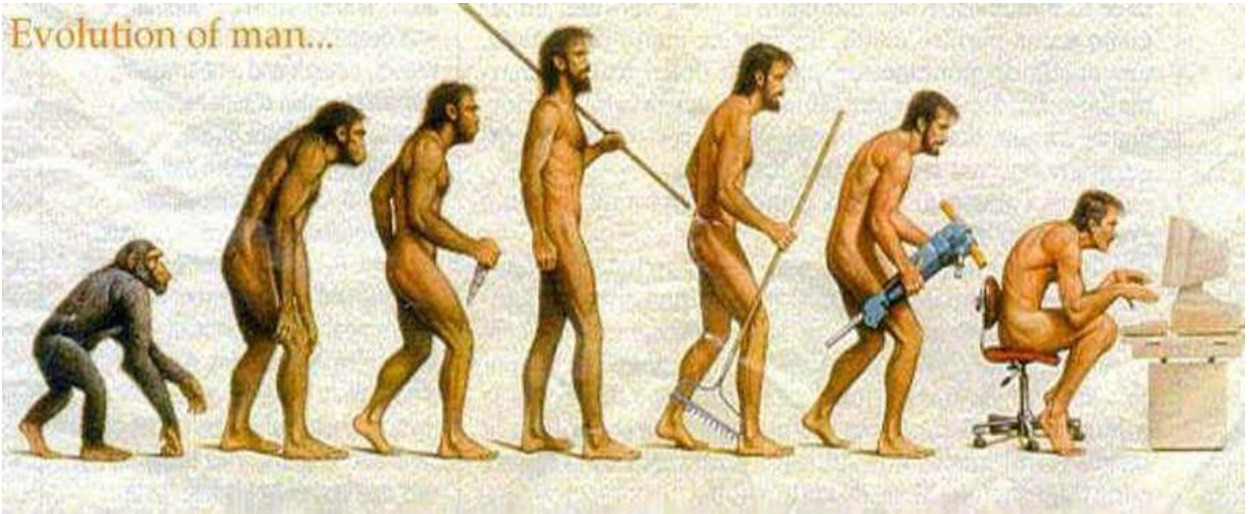
Contents

Introduction to Composites

Material Evolution

- Evolution is driven by economics, logistics and the expectations of society.
- Evolution is facilitated by developments in materials, processing methods and design tools (understanding of materials).

Material Evolution



Stone age

Bronze age

Iron age

Steel age

Plastics age

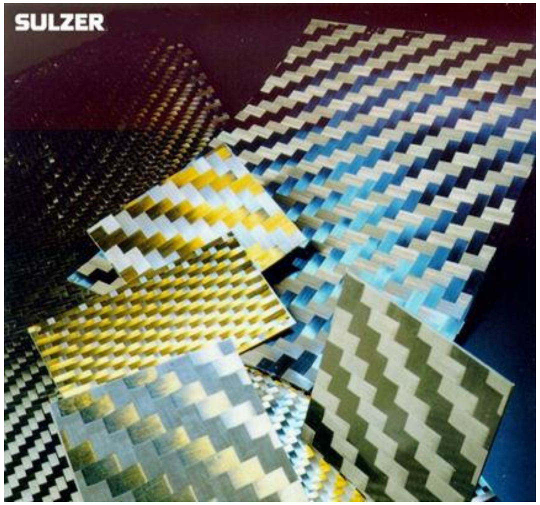
Silicon Age

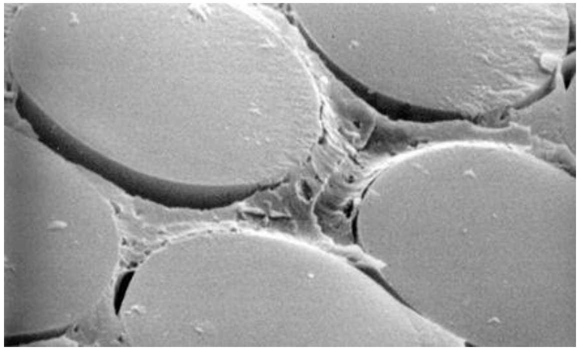
Designer materials age

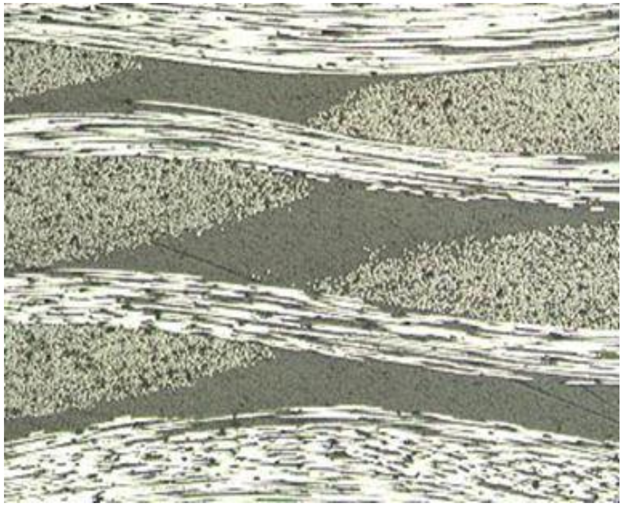
Material Ages of Man

What Are Composites?

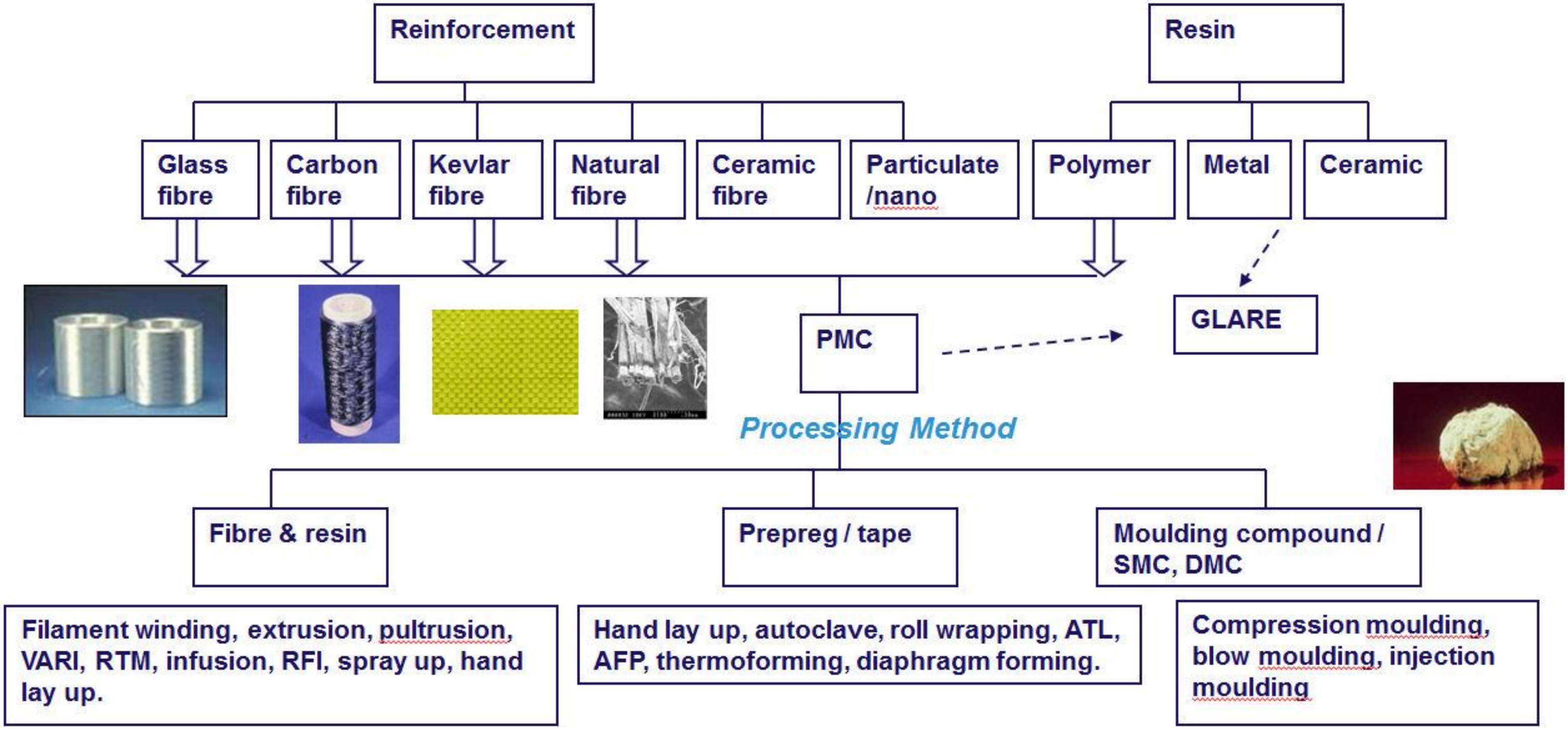
- A composite material is one which is composed of at least two elements working together to produce material properties that are different to the properties of those elements on their own.
- Typically reinforcing fibres in a matrix.
- The ultimate ‘designer material’!







A Wealth of Design Options



Reinforcement

- Glass fibre
- Carbon fibre
- Kevlar fibre
- Natural fibre
- Ceramic fibre
- Particulate /nano

Resin

- Polymer
- Metal
- Ceramic

PMC

GLARE

Processing Method

Fibre & resin

Filament winding, extrusion, pultrusion, VARI, RTM, infusion, RFI, spray up, hand lay up.

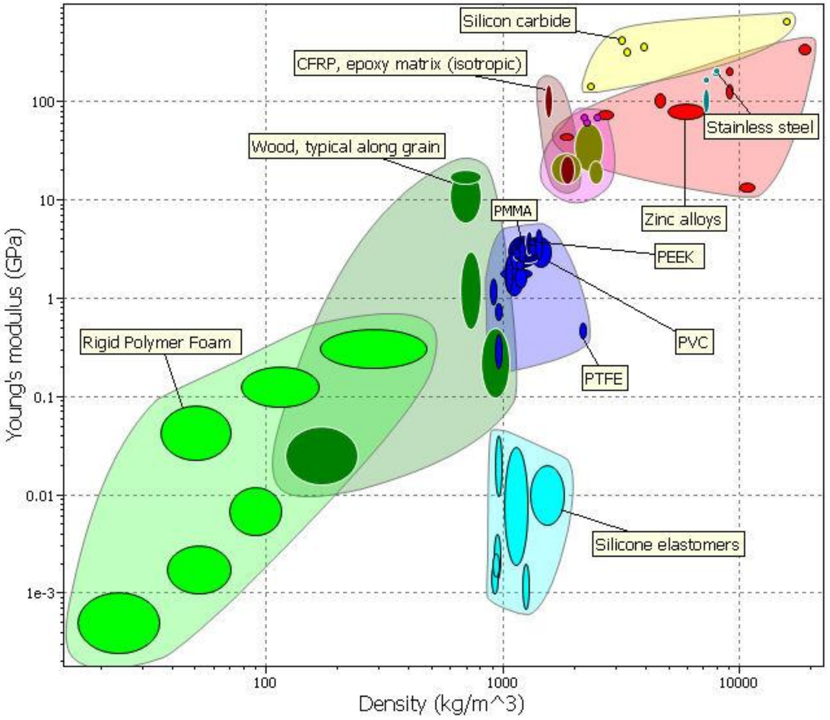
Prepreg / tape

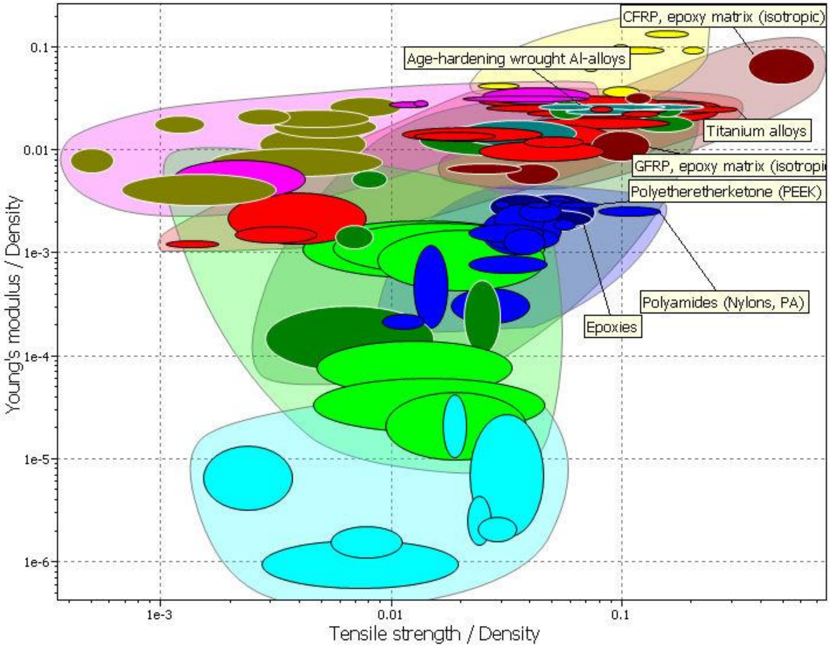
Hand lay up, autoclave, roll wrapping, ATL, AFP, thermoforming, diaphragm forming.

Moulding compound / SMC, DMC

Compression moulding, blow moulding, injection moulding

Composite Properties

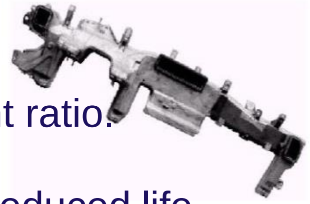




For a given stiffness, composites have low density.

Composites have excellent specific strength and stiffness.

Swot Analysis

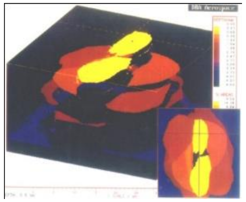


Strengths

- Properties.
- High strength to weight ratio.
- Fatigue resistance.
- Corrosion resistant – reduced life cost.
- Tailor properties within a part.
- Complex shapes possible.
- Lower pressure tooling.
- Reduced part and fastener count.
- Reduced materials waste.

Opportunities

- Innovative manufacturing (automation, ALM, OOA).
- New recycling technologies.
- Legislation.
- Smart/functional materials (self healing, heating, morphing, SHM, integrated electronics).



Weaknesses

- High cost.
- Damage tolerance.
- NDT requirements.
- Lack of design data and tools (improving).
- Uncertainties in failure prediction (improving).
- Need specialised repair techniques.

Threats

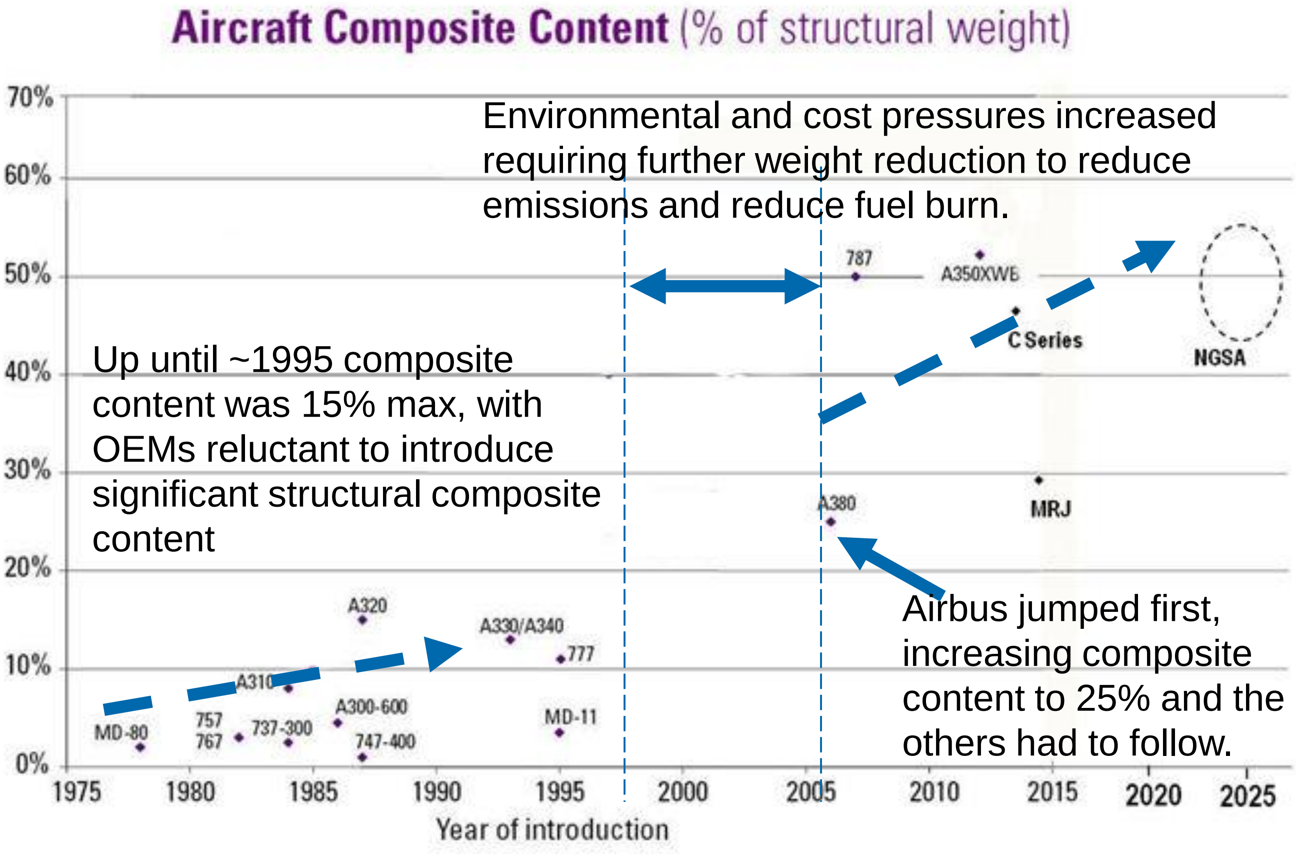
- Innovation in metals (machining/ ALM/ super plastic forming).
- Recycling Issues.
- High profile failures.
- Material shortages.
- Legislation (REACH).
- Cost of oil.

Use of Composites in Aerospace Applications

Aircraft Composite Content

Graph shows:

- Since 2005, civil aircraft have dramatically increased the composite content.
- Airbus has relatively steadily increased its usage of composites over the years.
- Boeing has jumped from 12% composite by weight in the 777, to 50% composite by weight in the 787.
- Next generation single aisle – percentage composite and launch date still unknown.



Aircraft Composite Content (% of structural weight)

Environmental and cost pressures increased requiring further weight reduction to reduce emissions and reduce fuel burn.

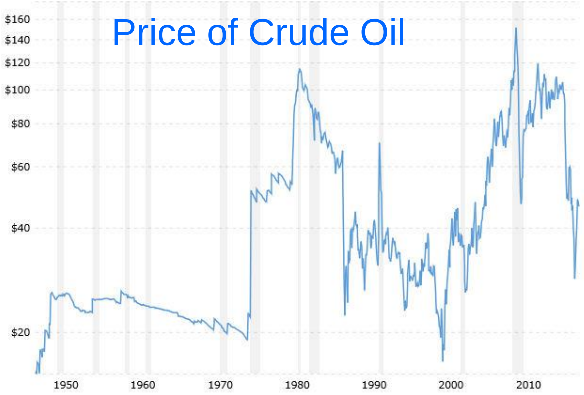
Up until ~1995 composite content was 15% max, with OEMs reluctant to introduce significant structural composite content

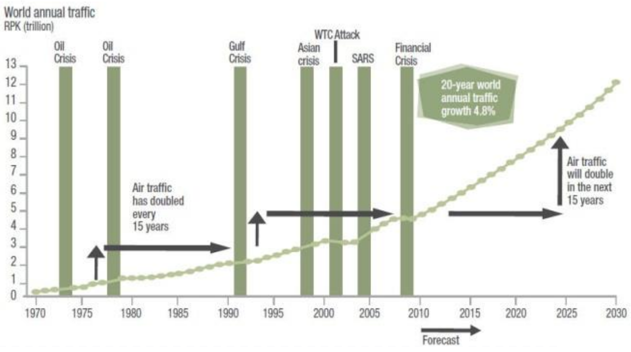
Airbus jumped first, increasing composite content to 25% and the others had to follow.

Source: Teal Group, Boeing, Airbus, Composite Market Reports

Explanation

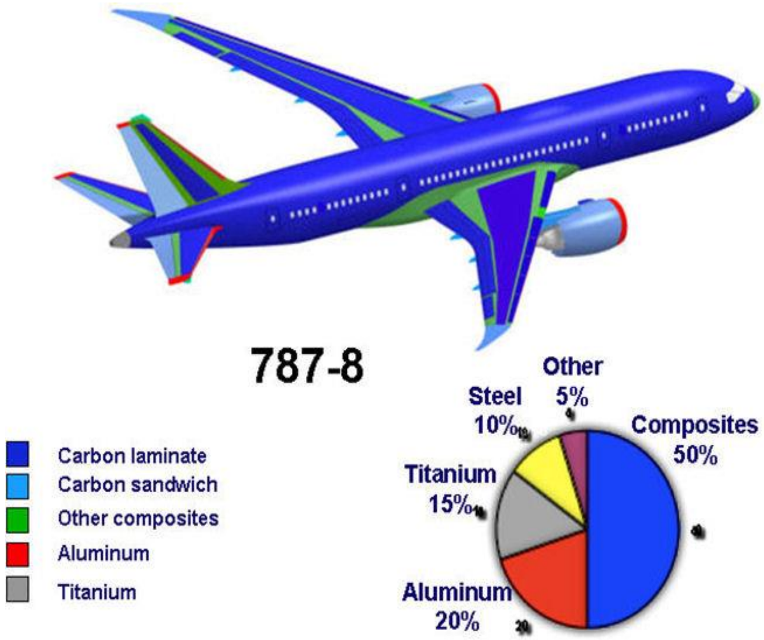
- Development of composites for aerospace use was both costly and potentially risky, therefore initial development was performed by military who had relatively large development budgets and are not so risk averse as the civil side.
- On the civil side, composite development was restricted to non-structural applications.
- However, the drivers to produce light-weight structures were provided by:
  - Price of oil
  - Change in attitude towards environmental issues (e.g. the ACARE targets of 50% reduction in $C0_2$, a 50% reduction in perceived noise and an 80% Reduction in NO_x by 2020).
  - Predicted increase in airline traffic.

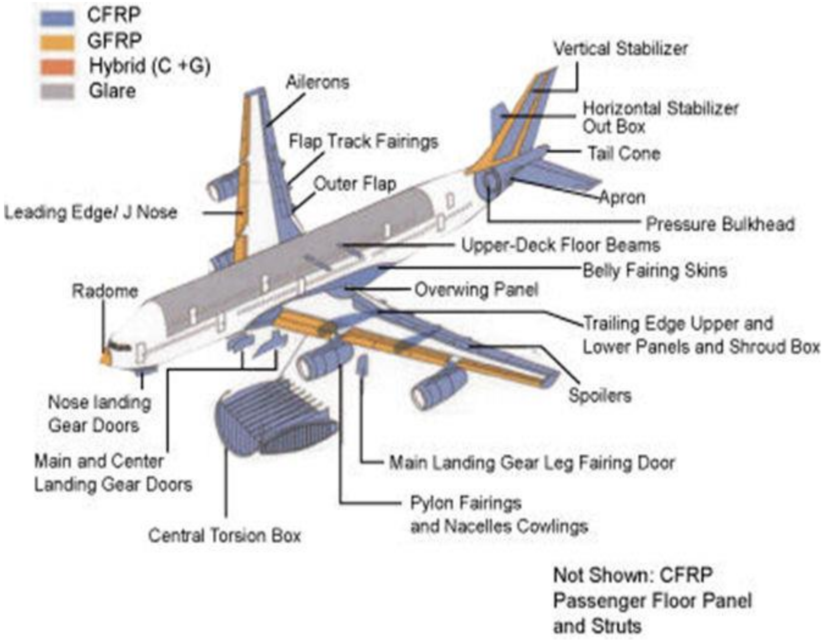

Price of Crude Oil



Explanation

- Composites give the OEMs the opportunity to produce lightweight structures thereby reducing fuel bills and reducing emissions.
- The cost of development and introduction of these new structures is now offset by the gains.
- Hence the increase in the usage of composites in aerostructures.





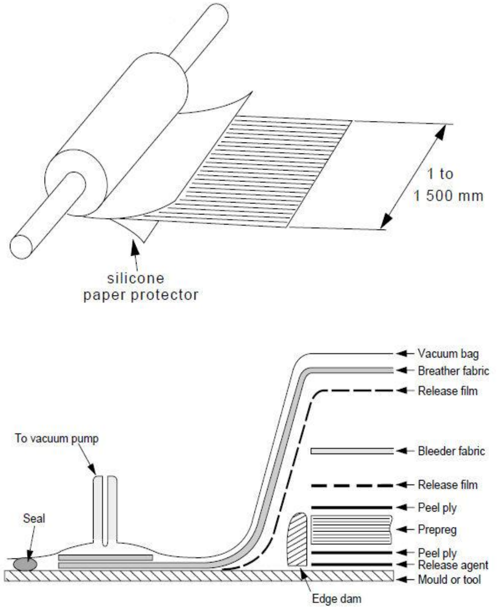
Current Challenges and Opportunities:

1. Manufacturing
2. MRO
3. Functional composites
4. Reputational damage

1.Manufacturing

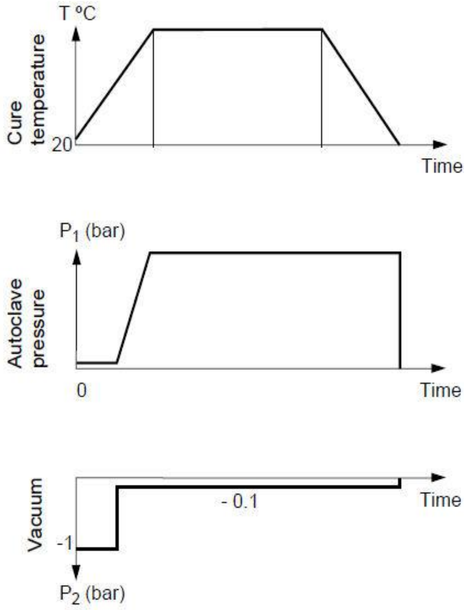
- Prepreg and autoclave cure has traditionally been the standard for aerospace - necessary to guarantee ultimate quality (high V_f).
- Not appropriate for very large scale structures and preparation and cycle times are long.

Lay-up process



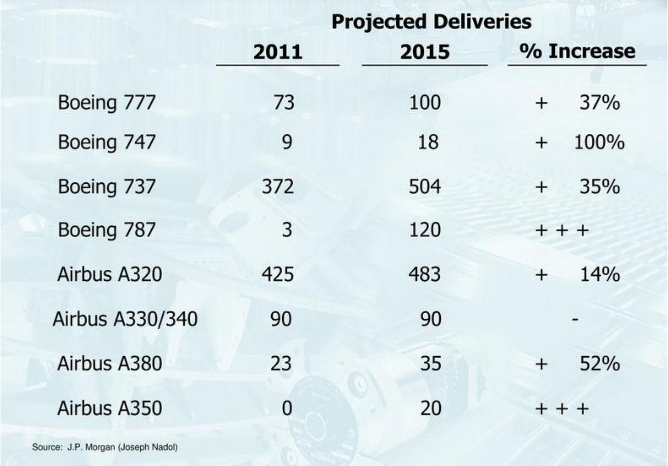
Autoclave

Cure process



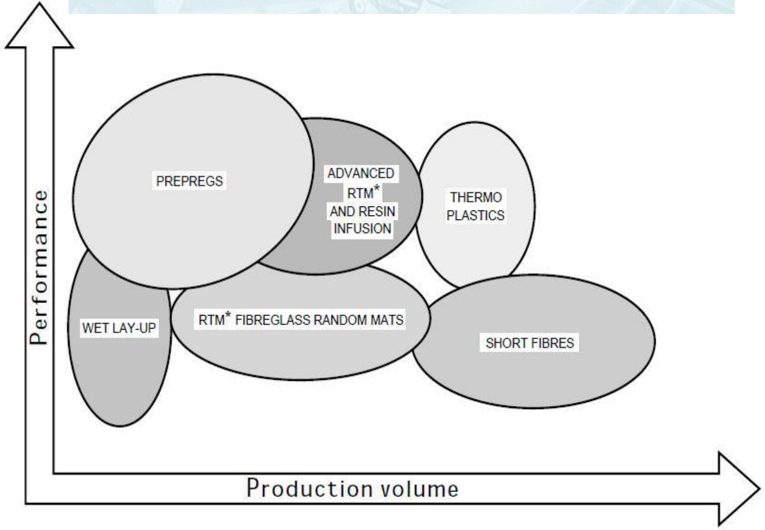
Manufacturing

- With build rates rising to satisfy demand, the OEMs needed to find a way, without compromising quality, to:
  - Increase production rate.
  - Eliminate autoclave.
- This has produced two trends:
  - Automated production.
    e.g. Automated tape laying (ATL), automated fibre placement (AFP).
  - Out of autoclave processing.
    e.g. Infusion, RFI, RTM.



	Projected Deliveries		
	2011	**2015**	**% Increase**
Boeing 777	73	100	+ 37%
Boeing 747	9	18	+ 100%
Boeing 737	372	504	+ 35%
Boeing 787	3	120	+ + +
Airbus A320	425	483	+ 14%
Airbus A330/340	90	90	-
Airbus A380	23	35	+ 52%
Airbus A350	0	20	+ + +

Source: J.P. Morgan (Joseph Nadol)

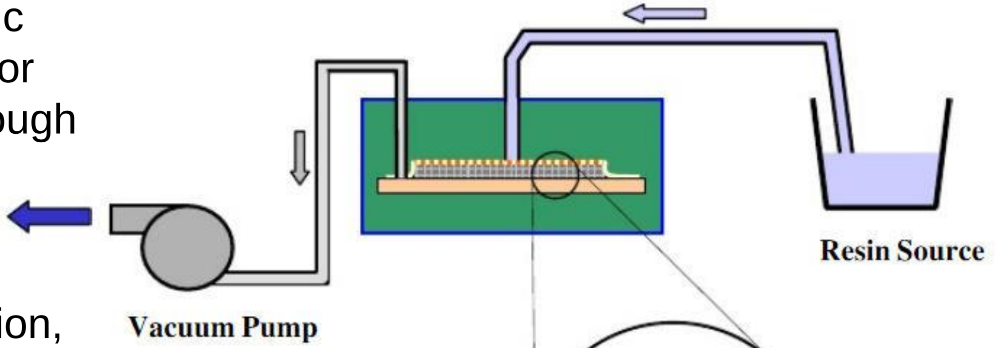


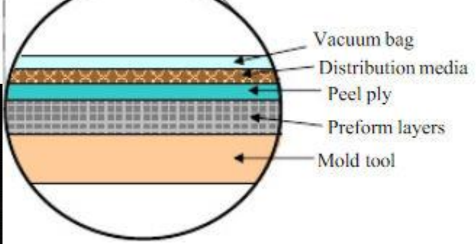
AFP/ATL

- AFP (automated fibre placement) and ATL (automated tape laying) provide rapid automated placement of strips of prepreg material onto a mould.
- AFP can be used with much more complex geometries because it lays narrow tows, which can be steered over sharply curved surfaces whereas wider tapes cannot be so placed without buckling some of the fibres and potentially weakening the laminate.
- Cure can either be done in or out of an autoclave as long as an appropriate material is used.
- Examples of usage are 787 nose and A350 fuselage panels.

Out of autoclave processing

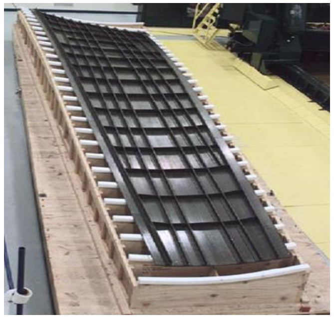
- Process involves laying up of dry fabric and introduction of resin either in wet or film form using a vacuum to pull it through the fabric.
- There are many variations on the technique and therefore a wealth of names and acronyms – vacuum infusion, resin film infusion (RFI), vacuum assisted resin transfer moulding (VARTM) etc.
- This technique allows the use of technical textiles, which provides more design freedom and enhanced through thickness properties.
- However, the resin usually has to have a relatively low viscosity to allow it to flow through the fabric, which can mean compromising on toughness of the final part.
- Example – A380 rear bulkhead and A400M cargo door.

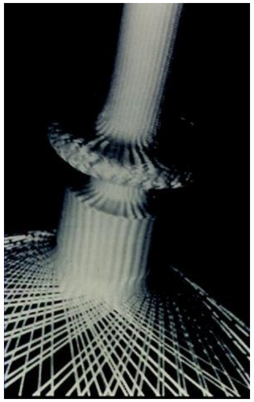


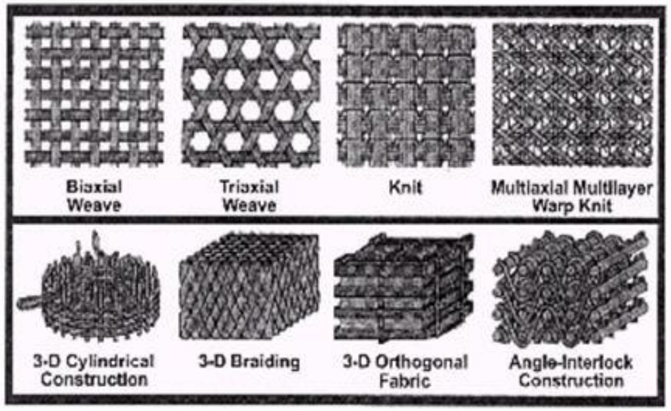


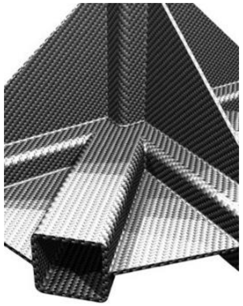
Textiles

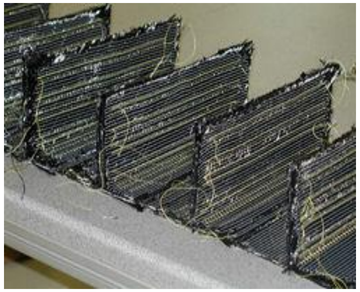
- 2D and 3D textiles and other methods of producing through-thickness reinforcement allow greater design freedom and potential for reduction in joining steps.
- However to optimise production technology, automated preform handling techniques are required.
- To optimise final part properties, modelling of preform movement during infusion is also required.







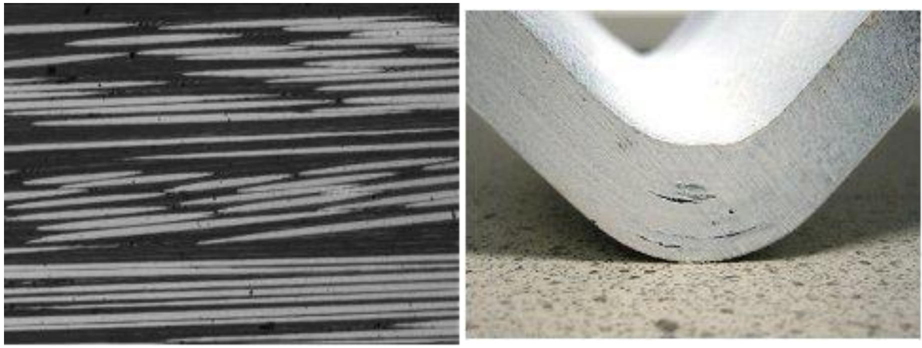




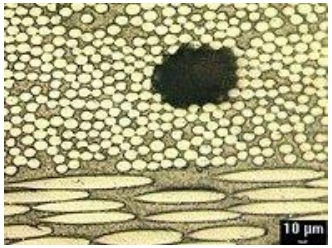
2. MRO - Maintenance

- Maintenance, repair and overhaul (MRO) requirements of composites are very different from those of metals.
- Shorter track record of use than metallic structures, many MRO companies therefore do not have much experience of maintaining composite structures.
- Parts are designed to cope with typical defects/damage (although given variations in microstructure in composites, even this can be difficult) but non-destructive testing is required to pick up damage/growth beyond these limits.
- Specific challenges with maintenance:
  - Defects are initiated during manufacturing as well as in-service.
  - Inspection regime usually involves use of several NDT techniques.
  - New and developments in existing techniques offer improvements in current state of the art, but these need to be validated and certified.

Manufacturing Defect Types

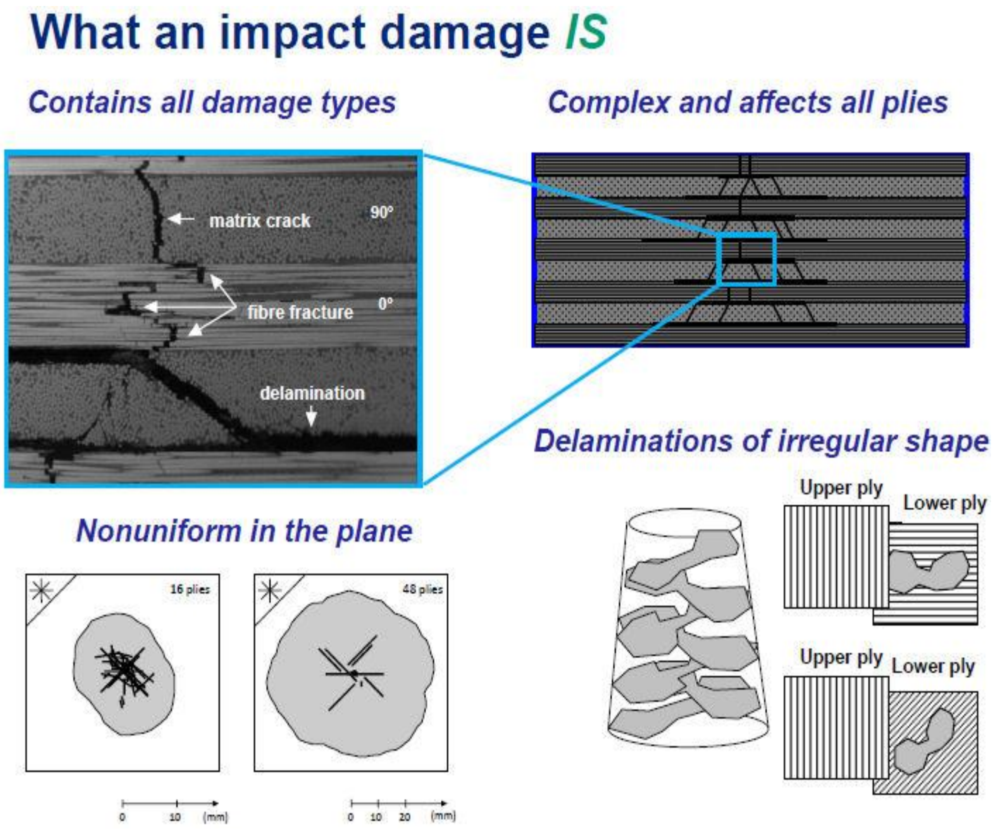


- Fibre misalignment.
- Inappropriate fibre volume fraction.
- Overlap or gap between fibre bundles.
- Knots or missing roving.
- Inclusions and contamination.
- Uneven, insufficient or over curing.
- Non-uniform hardener content.
- Cure shrinkage (Delamination, broken & buckled fibres and matrix cracking).
- Excessive porosity or voids.
- Poor wet-out and/or dry spots.



In-Service Defect Types

- Impact damage
- Ballistic damage
- Moisture ingression
- Chemical attack.
- UV damage & weathering
- Erosion or abrasion
- Fatigue



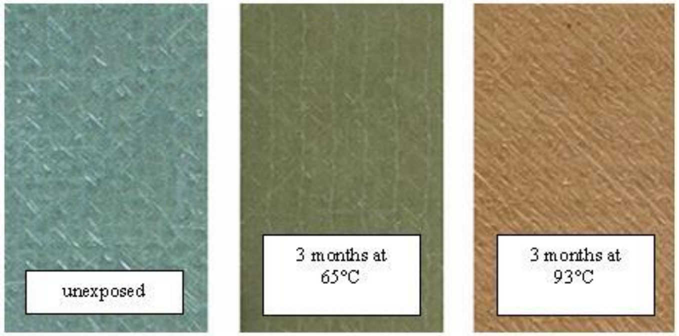
What an impact damage *IS*

Contains all damage types

Complex and affects all plies

Delaminations of irregular shape

Nonuniform in the plane



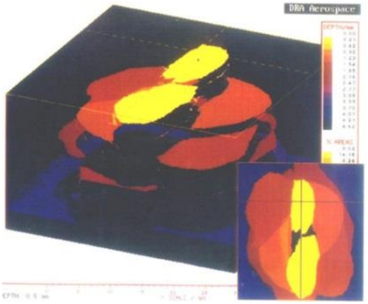
unexposed

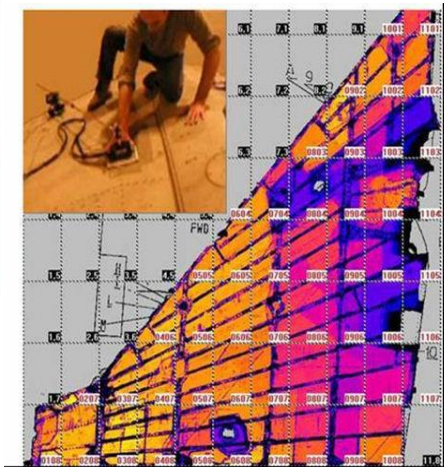
3 months at 65°C

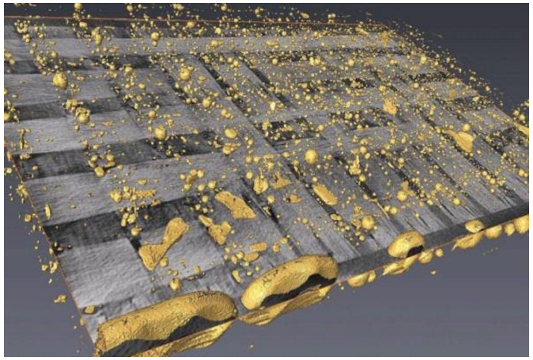
3 months at 93°C

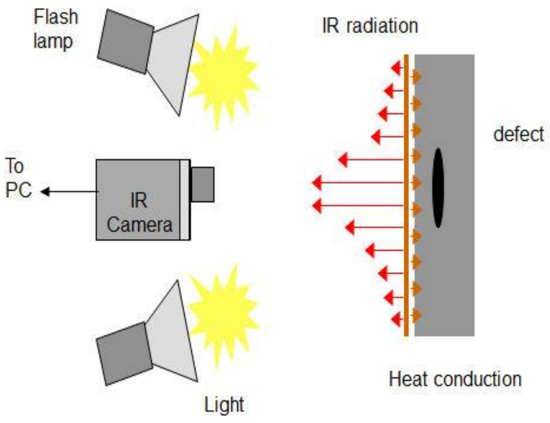
NDT Methods

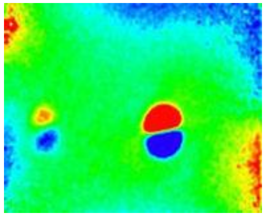
- Visual.
- Ultrasonics.
- Radiography.
- Thermography.
- Laser shearography.
- Coin and tap testing.
- Microwave.
- Acoustic.





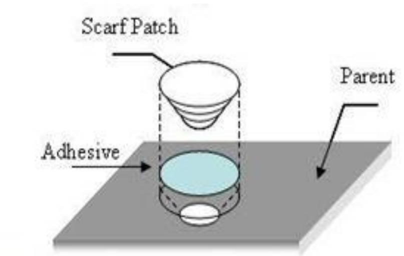


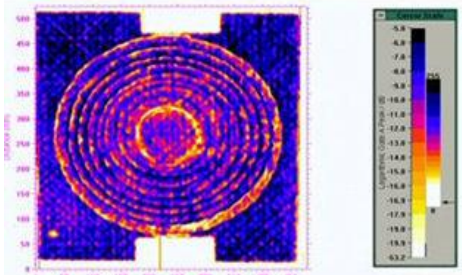




MRO - Repair

- Damage to composites or repair of damage to composites involves cutting of fibres, therefore strength and stiffness of a repaired composite will always be compromised.
- Repair of composites usually uses one of 2 techniques; bolting a patch (potentially metal) over the damaged area or scarf repair.
- A bolted patch increases weight.
- Scarf repair techniques require clean conditions, are time consuming and have traditionally utilised expensive, and difficult to store, prepregs.
- In-field repair techniques based on dry fabric preforms and infusion are being investigated. Possible problems centre around the use of brittle resins for infusion and the likelihood of poor fatigue life and shock resistance.





3. Functional Composites

By virtue of the fact that composite materials consist of more than one material, and the material is formed at the same time as the part, it is possible to incorporate other materials or structures during processing to provide integrated functionality to the part.

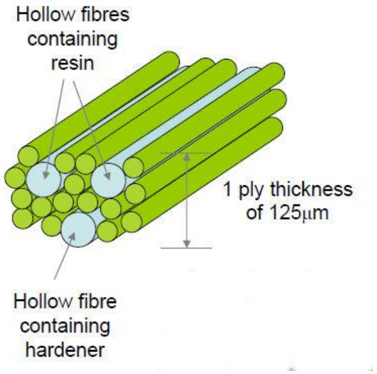
The following slides provide examples of research being done to provide additional functionality to composite structures in the areas of:

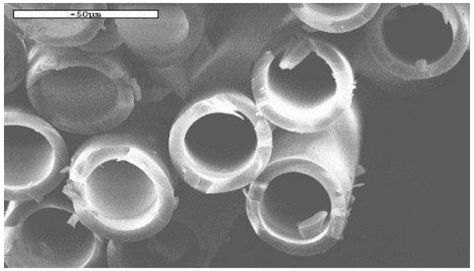
- Self-healing
- Sensing
- Morphing
- Lightning protection
- Energy storage

Self-Healing Composites

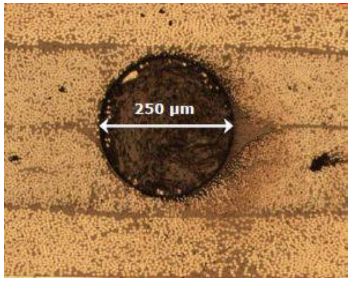
Examples:

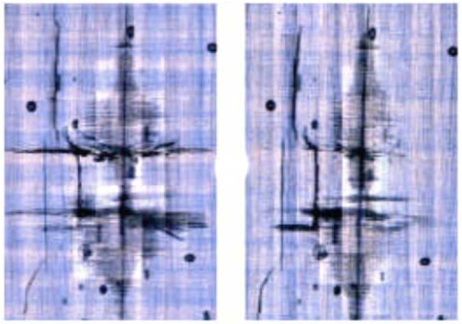
- Hollow fibres. (I. Bond, et al. Bristol University)
- ‘Lost wax’ process. R. Trask et al. Bristol University.
- Sheffield Solid State Healing. S. Hayes et al. Sheffield University

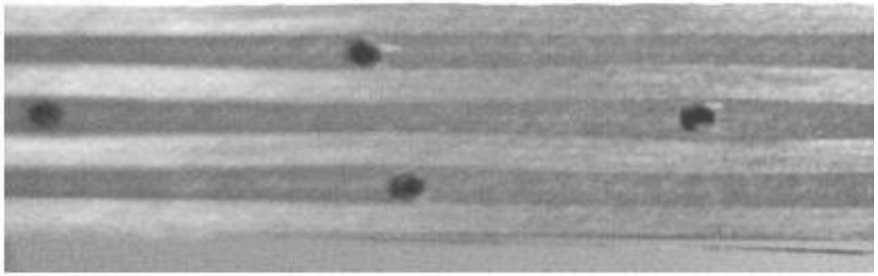




Courtesy of Bristol University







Courtesy of Sheffield University

Sensing

In order to trigger self-healing, composites needs to be able to detect damage, i.e. contain a health monitoring system. There are many approaches under development including:

- Fibre Optic/Bragg Gratings (e.g. Aston Uni, Birmingham Uni, Insensys, Ulster (woven structures)).
- Carbon nanotubes/graphene (Reading Uni, Imperial, Bristol Uni, Cambridge Uni etc.)
- Ferromagnetic microwires (Bristol Uni)
- Acoustic Emission (Airbus)

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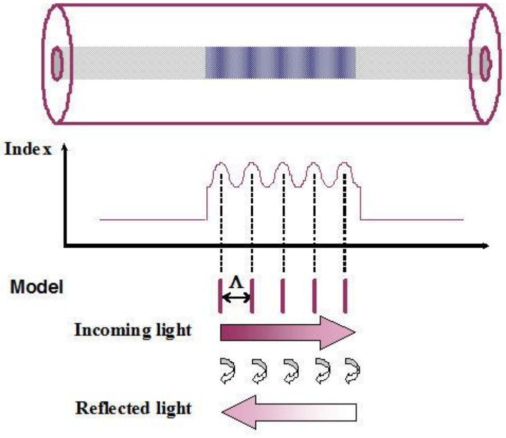
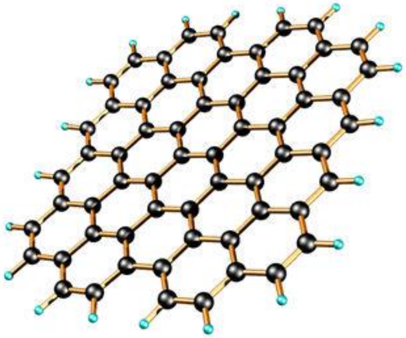
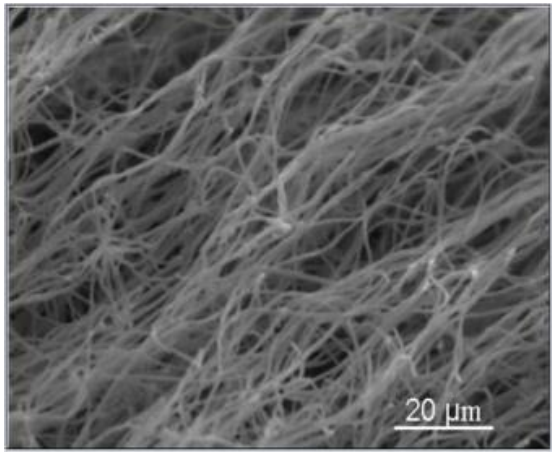


Constructive interference when $2n_{eff}\Lambda = m\lambda$

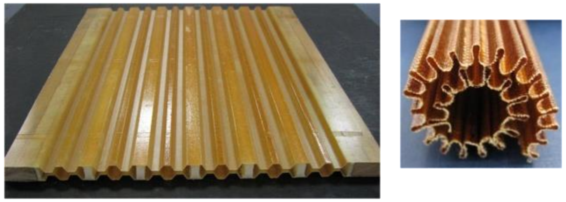


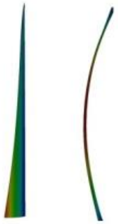


Morphing

Structures that can change shape negate the need for motors and other weight adding mechanisms.
Examples from Bristol University:

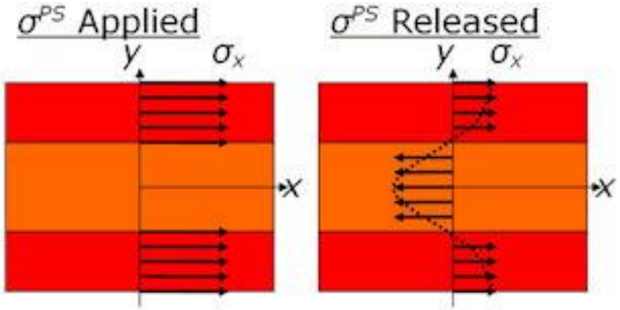
- Morphing corrugated structures, C.Thill et al.

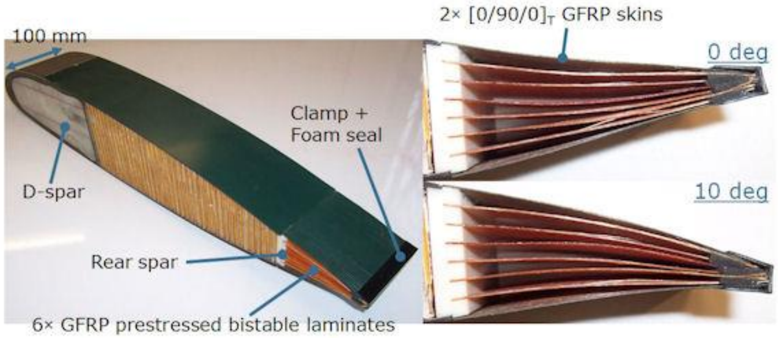




Finite Element modelling assists in identifying the deformed shapes of the multi-stable states.

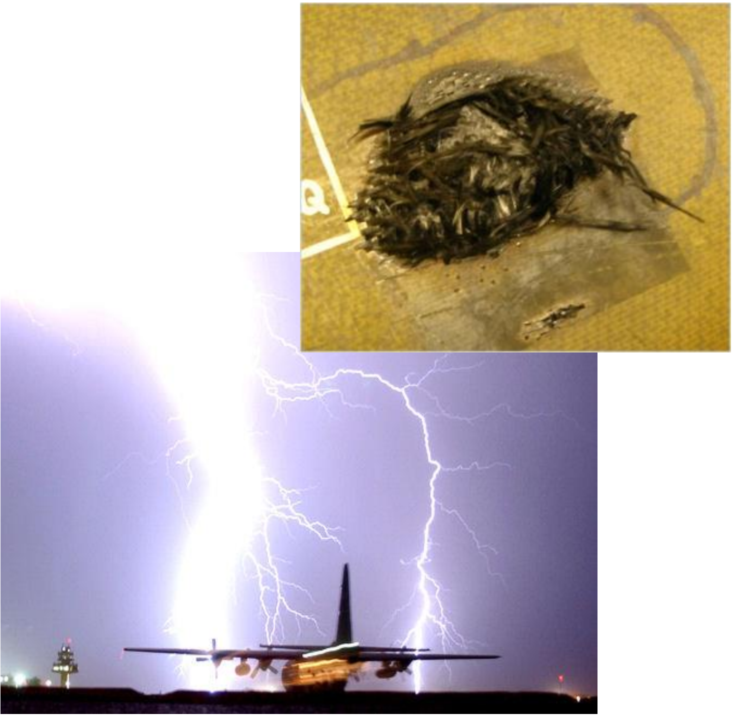
- Prestressed, bistable composites.
  Daynes, S., Weaver, P., Potter, K., and Hardick, M., U.K. Patent Application





Lightning Protection

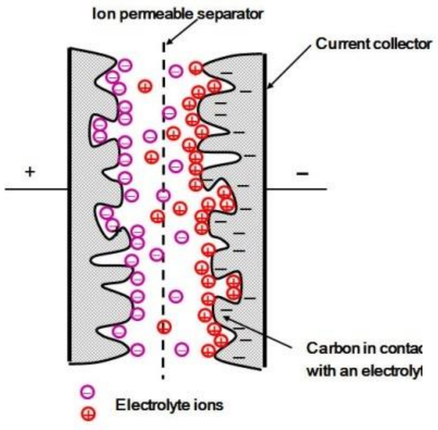
- Two types of effect caused by lightning strike:
  - Physical damage at attachment locations.
  - Indirect effects from induced voltage and current.
- Prevention methods in composite structures:
  - Cu foils & meshes in the outer plies.
  - Co-bonding Cu strips to the inside skins of panels.
  - Insulation caps on collars, nuts and fasteners.
  - Conductive paints (sprayed metal).
  - Al foil strips for shielding.
  - Nickel-coated carbon fibres.
- Examples of new innovations:
  - MAST Consortium (UK MoD programme) developed an integral woven SMA/carbon fibre preform. Improved damage tolerance AND lightning protection.
  - Bristol, M. Russ et al – CNT coatings for lightning protection.
  - Polyaniline (PANI)-based conductive thermosetting resin.

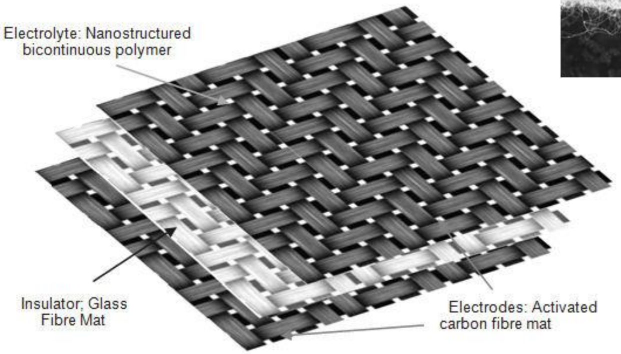


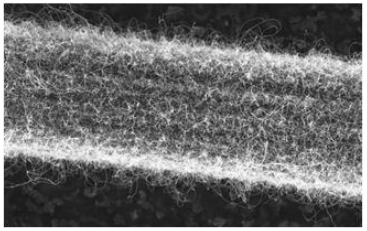
sigmatex material innovation

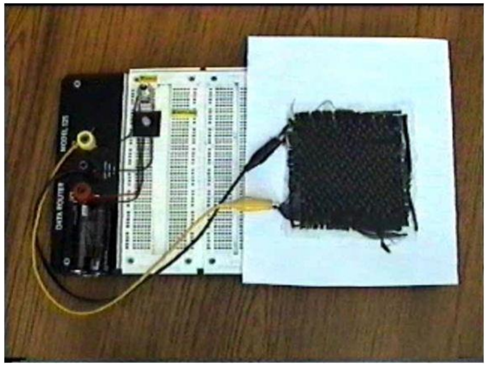
Energy Storage

- Giving a composite structure the added functionality of being able to store energy could allow further reductions in weight through elimination of heavy batteries.
- Work at Imperial College has produced a composite supercapacitor.
- Prototypes being developed for aircraft tertiary structures and automotive application.









Courtesy of Imperial College

4. Reputational damage

- It is a dangerous time for the reputation of composite structures. Increase in their use in aerostructures has been widely reported and is being closely monitored by the press.
- The Airbus A300 crash in Queens in Nov 2001 and the Team Phillips catamaran were classic examples of how confidence in composites can be damaged despite neither failure being due to deficiencies in the composite material itself.
- Delays in the production of the 787, which were primarily due to lessons being learnt by Boeing on outsourcing of part production, were immediately assumed to be due to problems in composites part production.
- It is a shame that the press is not congratulating the aerospace industry more for innovation and development of the use of new materials.
- The fact that the sector has very strict regulations and procedures has facilitated the safe implementation of these new structures and all industry sectors can learn from this.

Future Challenges and Opportunities

1. Carbon fibre availability
2. Recycling
3. Materials development

1. Carbon fibre availability

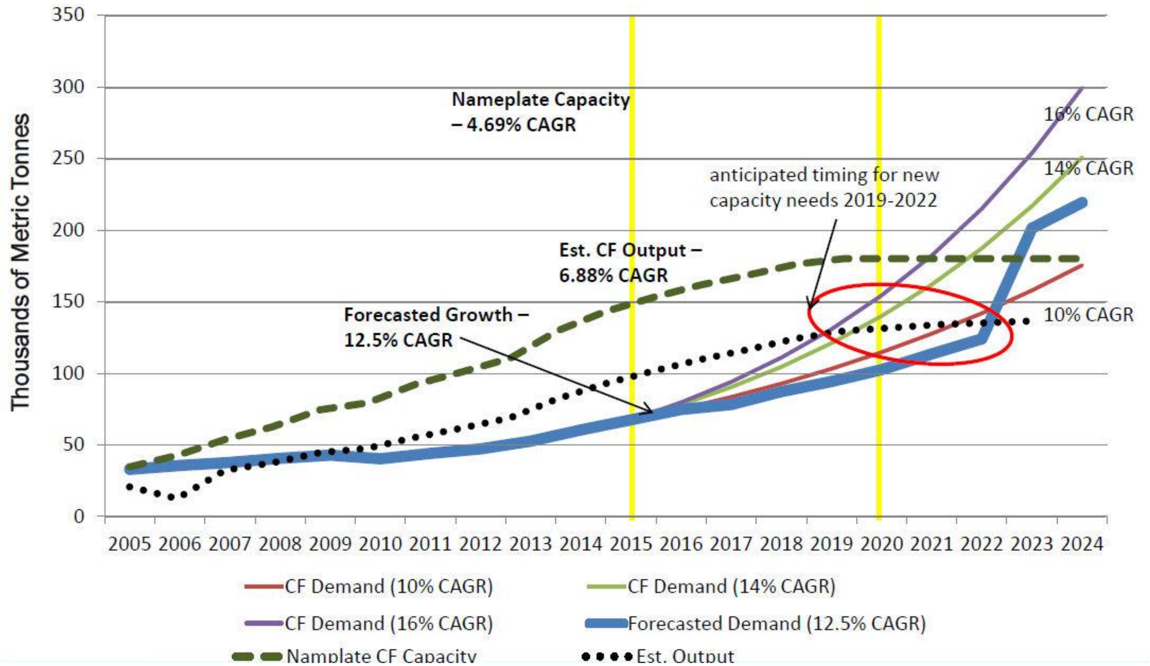
- Global usage of carbon fibre is growing and the growth rate is accelerating.
- The aerospace sector is not the only sector increasing use of carbon fibre. There is greater uptake in the 'industrial sector' (includes wind and automotive sectors) too.

Market Sector	2005 (kTa)	2010 (kTa)	2015 (kTa)	2020 (kTa)	2024 (kTa)	2015-2024 (kTa)	Forecasted % CAGR
Consumer and Rec.	13.24	12.68	14.83	16.74	18.62	166	2.30%
Aerospace	6.67	10.06	15.46	22.10	21.65	302	3.42%
Industrial	13.01	25.66	52.80	118.49	178.92	1,117	12.98%
Total	32.92	48.41	83.09	157.32	219.20	1,489	10.19%

Source: Chris Red, Composites Forecasts and Consulting LLC

Carbon fibre availability

- Carbon fibre demand will exceed output by 2022. New production capacity (on top of already planned) needs to be considered now.
- Aerospace grade fibres are the most expensive to produce and need to be certified before use therefore increase production may be limited in comparison to industrial.
- Shortages in supply of suitable fibres would drive prices up and make metal again seem like a viable option for future designs.



Source: Chris Red, Composites Forecasts and Consulting LLC

2. Recycling

- End-of-life waste for CFRP is still small, though production waste can be 30 to 50% of production volumes where prepreg processes are used, resulting in an estimated 2000 to 3000t p.a. CFRP waste in the UK.
- Neither landfill nor incineration disposal of CFRP scrap is optimal, and environmental regulations may eventually lead to a ban on both.
- End of life waste will build - 6000 to 8000 commercial planes expected to reach end-of-life dismantlement globally by 2030.
- Therefore work has been done to develop methods that can be used to recycle carbon fibres out of CFRP.
- This process has only recently been commercialised by:
  - ELG Carbon Fibre, UK
  - CFK Valley Stade Recycling, Germany
  - Carbon Conversions (formerly MIT-RCF),
  - South Carolina, USA
  - Karborek, Italy
  - Carbon Fiber Recycle Industry Co. Japan
- There is currently no real market for the recycled product that is produced.
- Work needs to be done to demonstrate the properties of the recyclate, create a market and give it a value.

New recycling report available at:
https://compositesuk.co.uk/system/files/documents/Recycling%20Report%202016.pdf

3. Materials development

- The recent increase in the use of composites has involved the development of new/improved manufacturing methods.
- These manufacturing techniques are now allowing us to develop parts that are testing the limitations of the materials used.
- Future applications will require developments in material properties.

Examples:

- Scaling down to produce a NGSA with a CFRP fuselage, could allow hail stones penetration. Increasing the thickness (weight) of the fuselage not an option – investigate a tougher composite material.
- Current carbon fibres are based on 30 year old technology. Work for industrial applications is investigating new variants. This will also bring new applications for aerospace.

UK Strategy

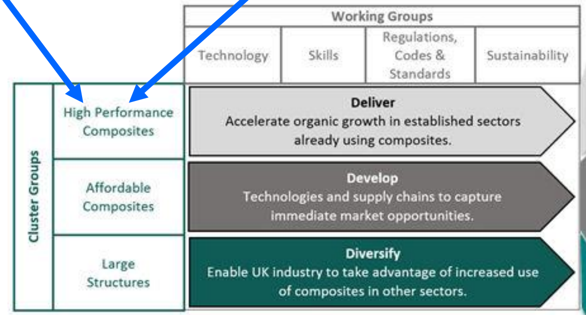
Aerospace

- UK Strategy led by Aerospace Growth Partnership http://www.theagp.aero/
- Technology led by Aerospace Technology Institute http://www.ati.org.uk/
- Have Specialist Advisory Groups
- Refreshing roadmaps.

Composites

- UK Strategy led by Composites Leadership Forum http://www.compositesleadershipforum.com/
- New strategy 2016: https://compositesuk.co.uk/system/files/documents/Strategy%20final%20version_1.pdf

Working together

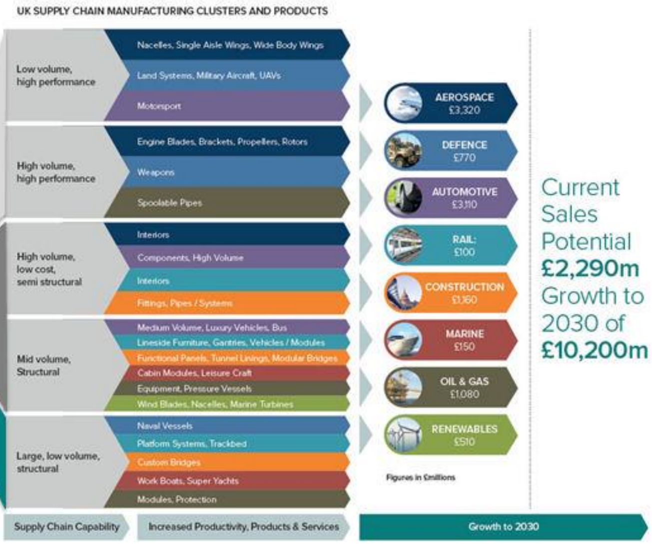


Working Groups

	Technology	Skills	Regulations, Codes & Standards	Sustainability

Cluster Groups

High Performance Composites	**Deliver** Accelerate organic growth in established sectors already using composites.
Affordable Composites	**Develop** Technologies and supply chains to capture immediate market opportunities.
Large Structures	**Diversify** Enable UK industry to take advantage of increased use of composites in other sectors.



UK SUPPLY CHAIN MANUFACTURING CLUSTERS AND PRODUCTS

Cluster	Products
Low volume, high performance	Nacelles, Single Aisle Wings, Wide Body Wings Land Systems, Military Aircraft, UAVs Motorsport
High volume, high performance	Engine Blades, Brackets, Propellers, Rotors Weapons Spoolable Pipes
High volume, low cost, semi structural	Interiors Components, High Volume Interiors Fittings, Pipes / Systems
Mid volume, Structural	Medium Volume, Luxury Vehicles, Bus Lineside Furniture, Gantries, Vehicles / Modules Functional Panels, Tunnel Linings, Modular Bridges Cabin Modules, Leisure Craft Equipment, Pressure Vessels Wind Blades, Nacelles, Marine Turbines
Large, low volume, structural	Naval Vessels Platform Systems, Trackbed Custom Bridges Work Boats, Super Yachts Modules, Protection

Sector	Current sales
AEROSPACE	£3,320
DEFENCE	£770
AUTOMOTIVE	£3,110
RAIL:	£100
CONSTRUCTION	£1,160
MARINE	£150
OIL & GAS	£1,080
RENEWABLES	£510

Figures in £millions

Current Sales Potential **£2,290m** Growth to 2030 of **£10,200m**

Supply Chain Capability → Increased Productivity, Products & Services → Growth to 2030

Summary

Summary

- Environmental regulations have meant that the cost of introduction of lightweight composite structures is now often offset by the gains and has led to a significant increase in the use of aerospace composite structures.
- Current challenges include:
  - Development of rapid rate manufacturing processes.
  - Coping with MRO requirements very different to metallic structures.
  - Avoiding reputational damage while composites are so high profile.
- Current opportunities include the ability of composite structures to include functionality such as morphing, energy storage, damage sensing, self repair etc.
- Future challenges include:
  - Supply of carbon fibre may struggle to match the increase in demand.
  - Developing applications for recycled carbon fibre.
  - Developing new materials to optimise output from new production methods.
- The UK has a strategy to remain world-leading in this area.

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Avalon

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