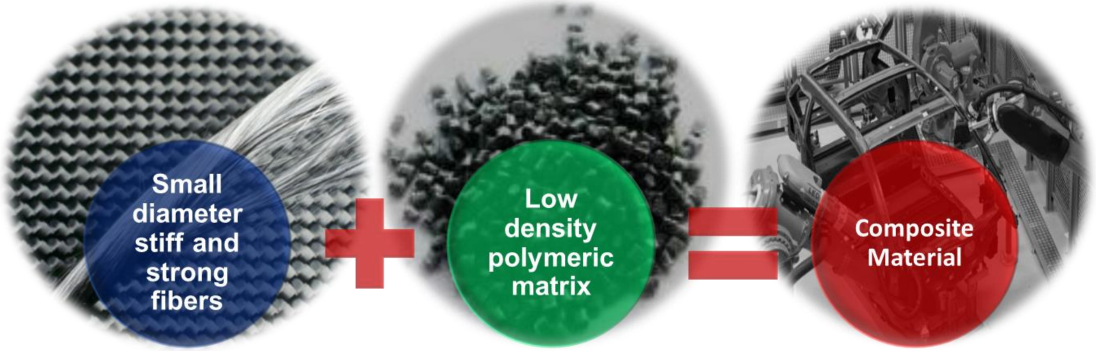
Composite applications

Composite materials combine complementary substances



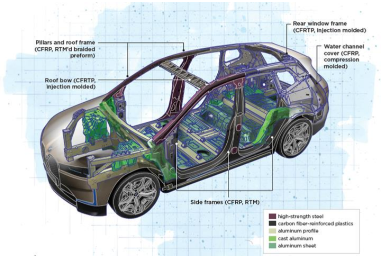
For properties not present in the individual components

Dr. Martyn D. Wakeman

martyn.wakeman@epfl.ch

Composites will see rapid growth as enablers towards 2050 SSPs

Main sectors	Aerospace	Wind	Automotive	Hydrogen	Infrastructure	Consumer
Sub sectors	☐ Civil wide body	☐ Wind on-shore	☐ Super cars	☐ CNG tanks	☐ Concrete rebar	☐ Bicycles
	☐ Civil narrow body	☐ Wind off-shore	☐ Premium	☐ Auto Hydrogen	☐ Buildings	☐ Marine
	☐ Evtol/drones	☐ Tidal	☐ EVs	☐ Aero Hydrogen	☐ Train	☐ Consumer
	☐ Military	☐ Fuel cells	☐ Other	☐ Ground Hydrogen	☐ Other	☐ Other
	☐ Other	☐ Other		☐ Rail Hydrogen		
				☐ Other		



EPFL industrial sector segmentation 1980-2050

Overview

Current usage of advanced composites

- Aerospace use of composites: high performance
- Automotive use of composites: mass-production
- Wind Energy and composites: mass-adoption

Mass adoption … & Mass production

usage in large parts, lower no. parts/yr

usage in small parts, high no. parts/yr

Mass adoption is high overall tonnage:

Aerospace, e.g. Civil

2013 $ 626 MM in CF raw mat.
CAGR 2014-2019 = 12% (lbs)

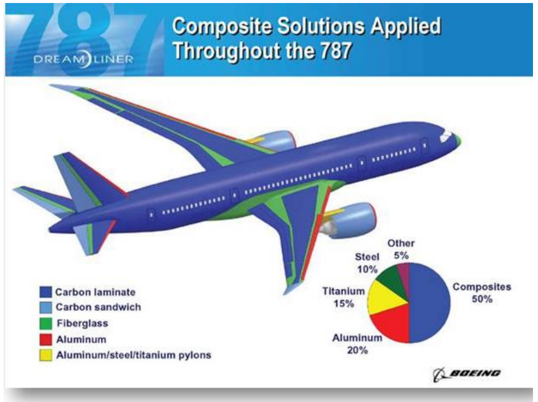
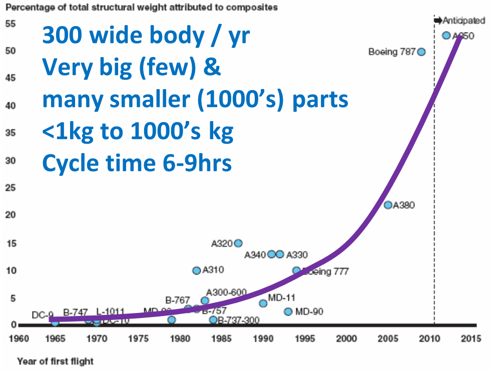


Figure 1: Commercial Airplane Models over Time by Percentage of Composites



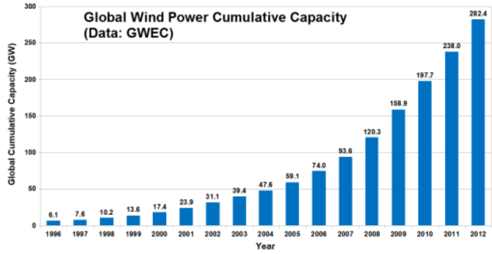
300 wide body / yr
Very big (few) &
many smaller (1000's) parts
<1kg to 1000's kg
Cycle time 6-9hrs

Sources: GAO analysis of information from FAA, NASA, Boeing Company, Jane's All the World's Aircraft, and Jane's Aircraft Upgrades.

Industrial, e.g. wind

2013 $ 156 MM in CF raw mat.
CAGR 2014-2019=13% (lbs)

3 MW Blades are 50 T
~ 60'000 blades/yr
Cycle time 24-38hrs



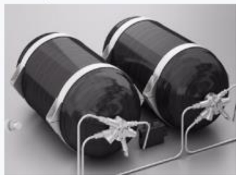
Automotive / transportation

2013 $ 129 MM in CF raw mat.
CAGR 2014-2019 = 19% (lbs)

Super cars
(100's kg,
<1'000/yr)
- Cycle time
10-30min

Niche / Premium
(200-300 kg
<50'000/yr)
- Cycle time 4min
& getting faster

Bus tanks
Source | Plastic Omnium



ICE, e.g. chassis

also, short fiber CF

Consumer electronic
chassis
(<1kg, 1 MM/yr)
Cycle time 10-30s

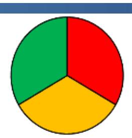
Consumer cars
(2-10kg,
50-300'000/yr)
- Cycle time 1min

Mass production is high overall tonnage:

EPFL

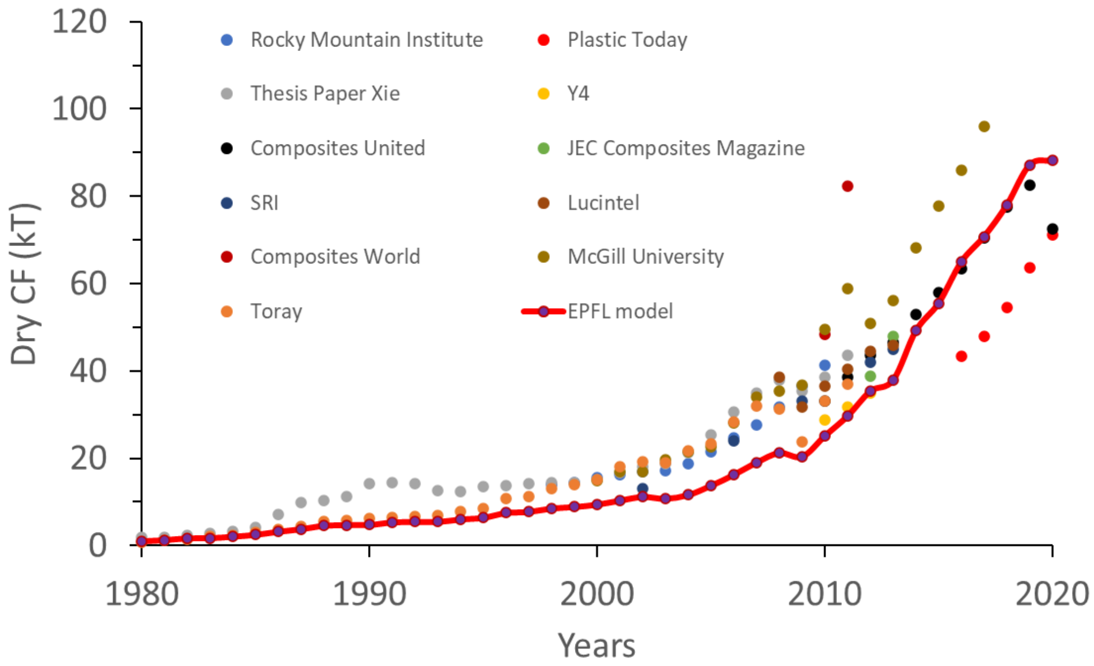
LPAC
Laboratory for Processing of Advanced Composites

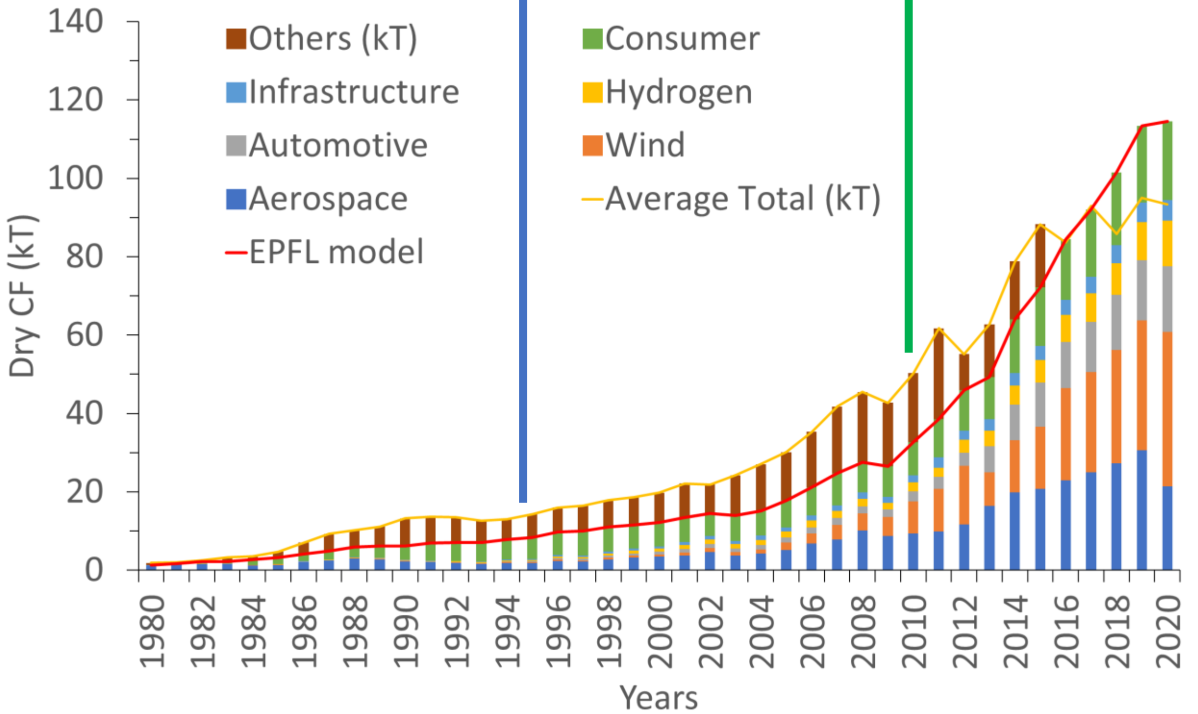
EPFL model of dry carbon fiber historical demand 1980-2020



Durability by sector and sub-sector

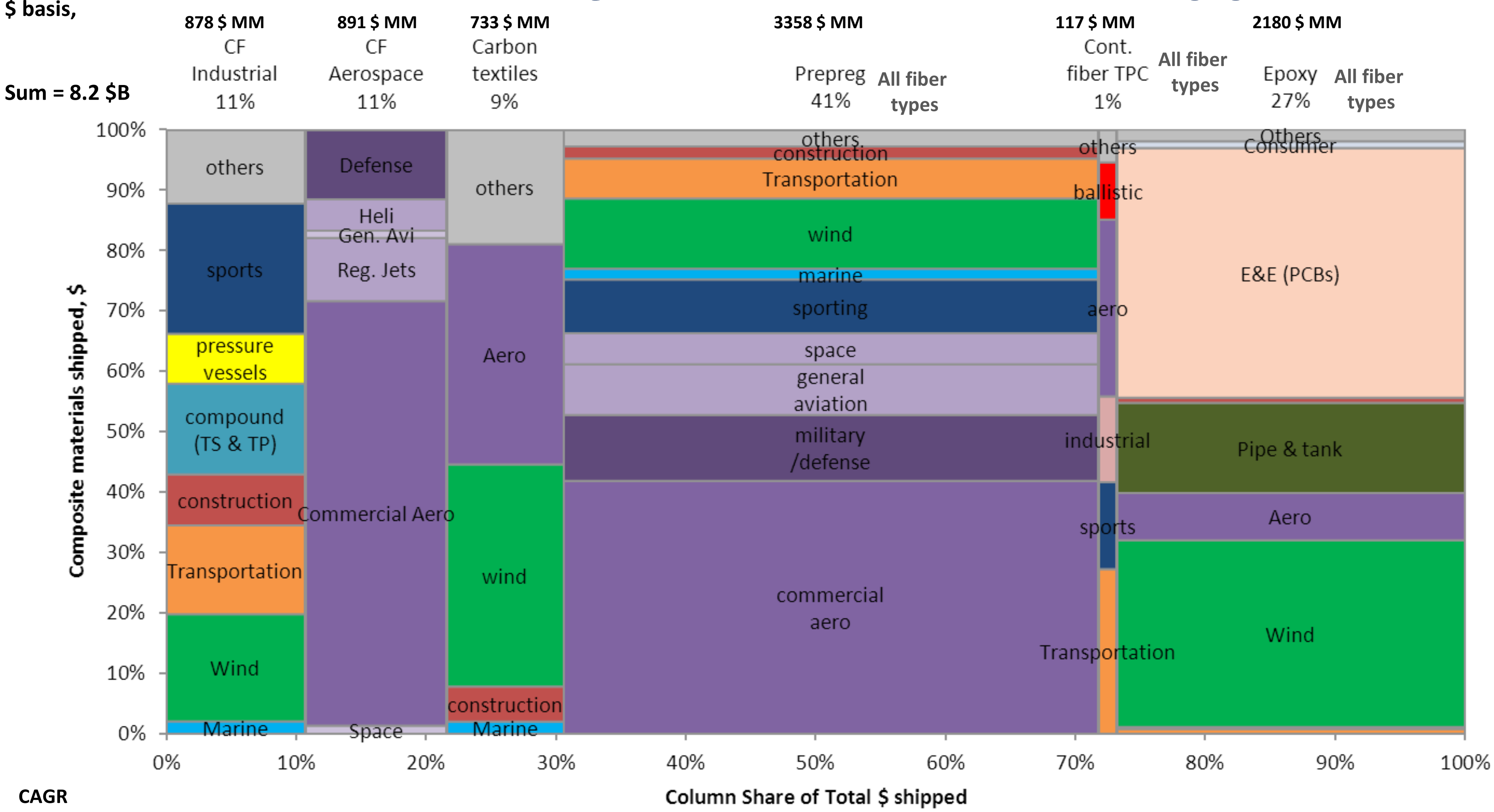
Durability is the delay to reach end of life and enter recycling / disposal scenarios





Data used in MFA (circularity versus time)

Mekko chart of $ basis by value chain and application sector



CAGR
($ basis)

		Carbon industrial	Carbon aerospace	Carbon textiles	Composite prepreg (all fiber types)	Continuous fiber TPC	Epoxy (all fiber types)
a)	Last 5yrs	%	%	9.5%	7.3%	4.6%	5%
b)	Next 5yrs	14.4%	10%	13.9%	10.4%	8.6%	6.6%

Revenue Growth
< 3% 3 to 5% > 5%

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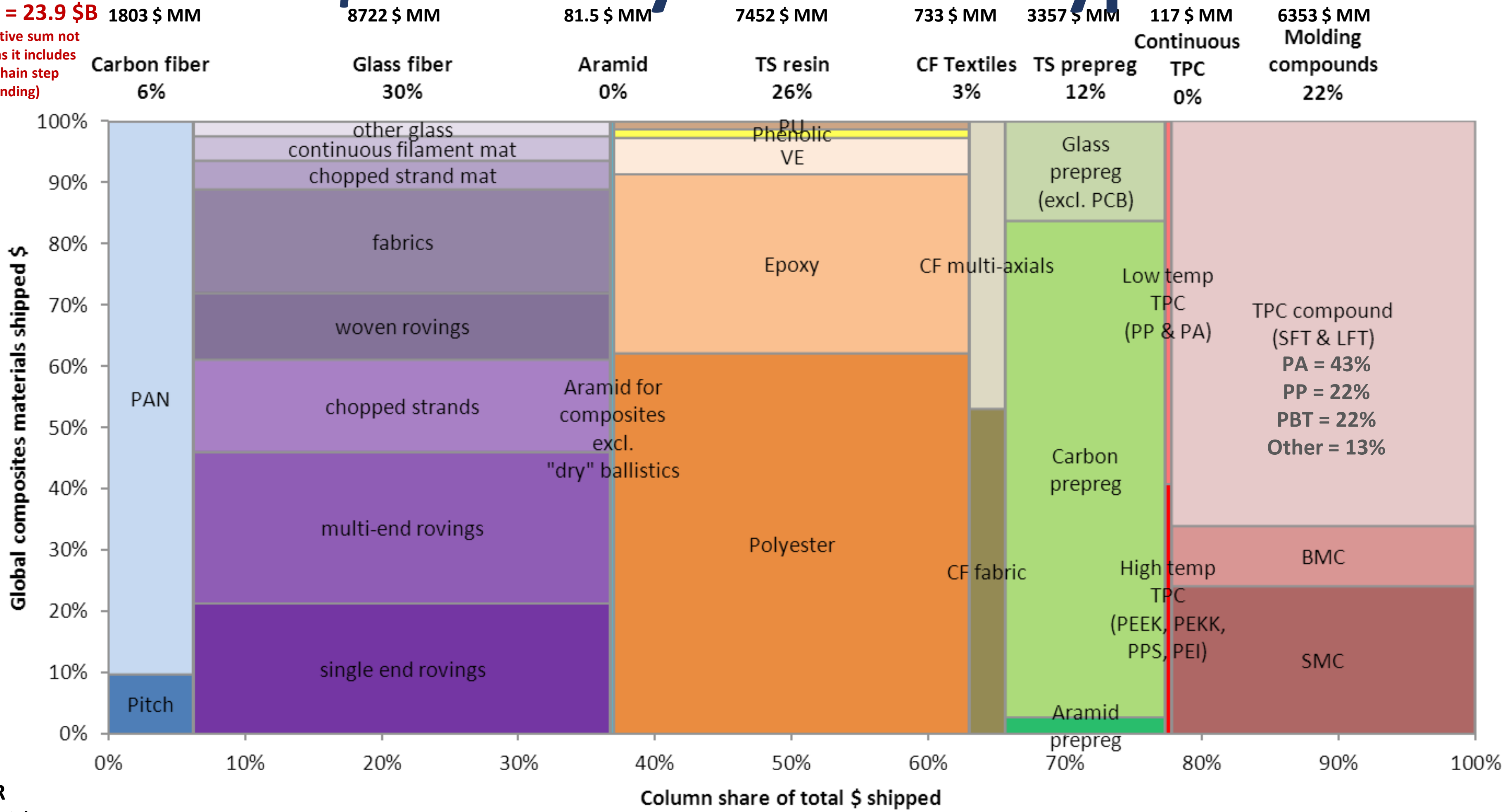
of Advanced Composites

Mekko chart of $ basis by material type and form

Total = 23.9 $B (cumulative sum not shown as it includes supply chain step compounding)



CAGR ($ basis)

	Carbon fiber	Glass fiber	Thermoset resin	Fabrics/ Multi-axials	Thermoset prepreg	Continuous TPC	Molding compounds
a) Last 5yrs	4.6%	-0.4%	4.7% (epoxy)	9.5%	7.3%	4.6%	6.5% (SFT)
b) Next 5yrs	11.3%	5.8%	6.6% (epoxy)	13.9%	10.4%	8.6%	4.3% (SFT)

Revenue Growth
< 3% 3 to 5% > 5%

Gross profit average across total landscape 23% for materials, 21% end product

Aerospace

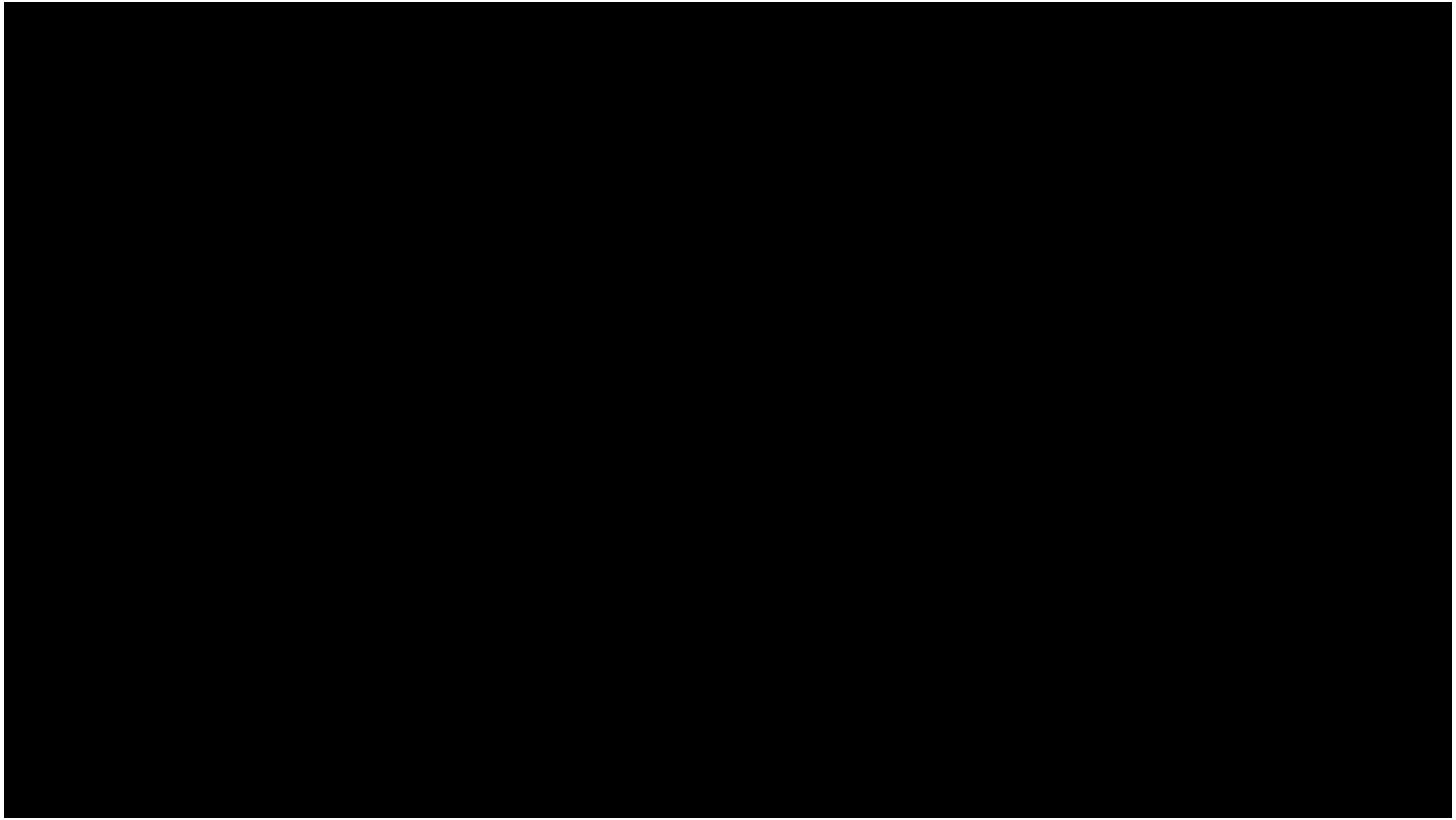
Aerospace driving forces for composites

- Composites evolution: niche military to intensive use in civil aviation primary structure
- Aviation, 4% towards global warming but increases predicted to consume 1/6th remaining temperature budget to limit warming to 1.5 deg C

Economic	• Light weighting, reduce life cycle fuel costs • Change in material costs (lower) • Improved and automated manufacturing technology *(latest generation of advanced fiber placement machines, out of autoclave processing),* moving beyond black aluminum • Composites reduce the parts count in an aircraft, reducing assembly and maintenance costs • Increased service intervals *(A350XWB increased from 6 to 12 years, better fatigue, better corrosion resistance)*
Environmental	• Reduced fuel burn per passenger kilometer • Light weighting reduces CO_2 emissions • Changing legislation for aero industry emissions & penalties

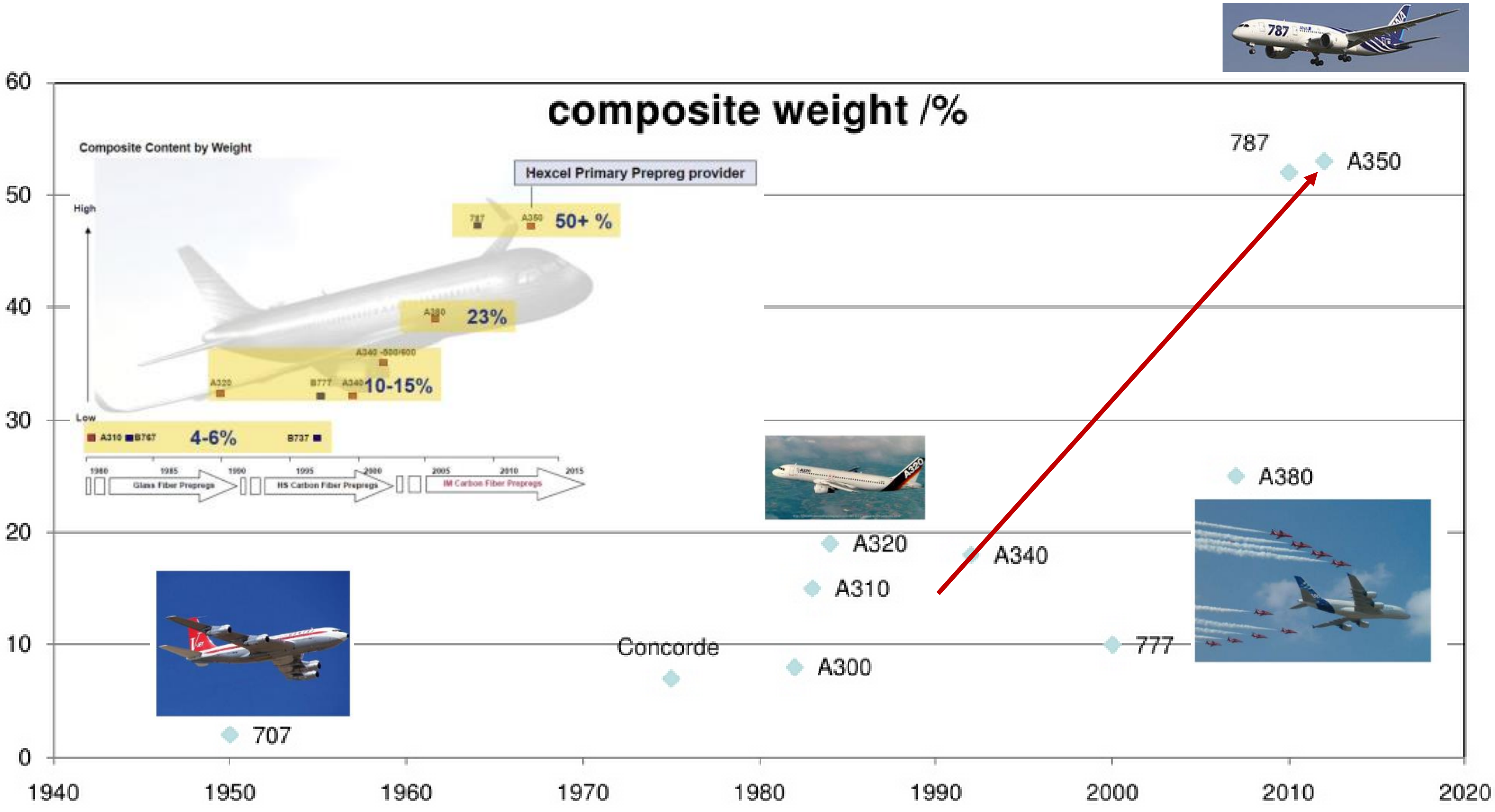
Aerospace

[25 years of carbon fiber production at Airbus Illescas plant - YouTube]



4min

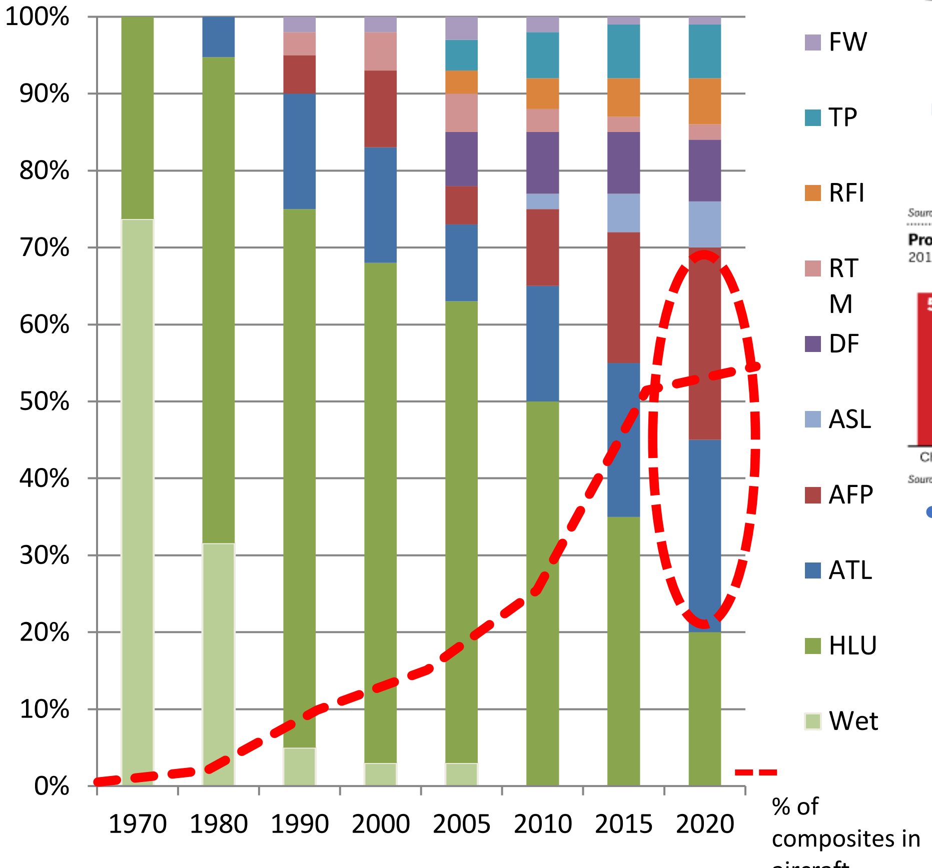
% aircraft composites weight vs. time



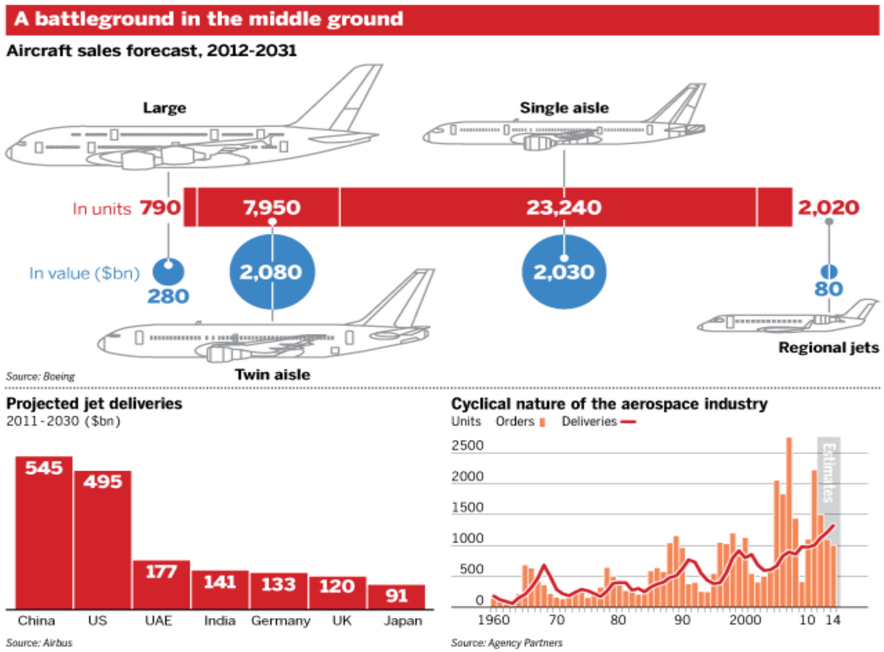
Evolution of Commercial Aircraft Use of Composite Processes

- 1970s-80s
  Shift from wet lay up to prepreg
- 90s-00s
  Shift from hand lay up to automation
- 2014, OOA ~ 10% composite aerostructures volumes
- By 2023, OOA 15% of total
- Increases in AFP and ATL
- 40'000 new aircraft 2041

Change in Manufacturing Process v. Percent Airframe Content



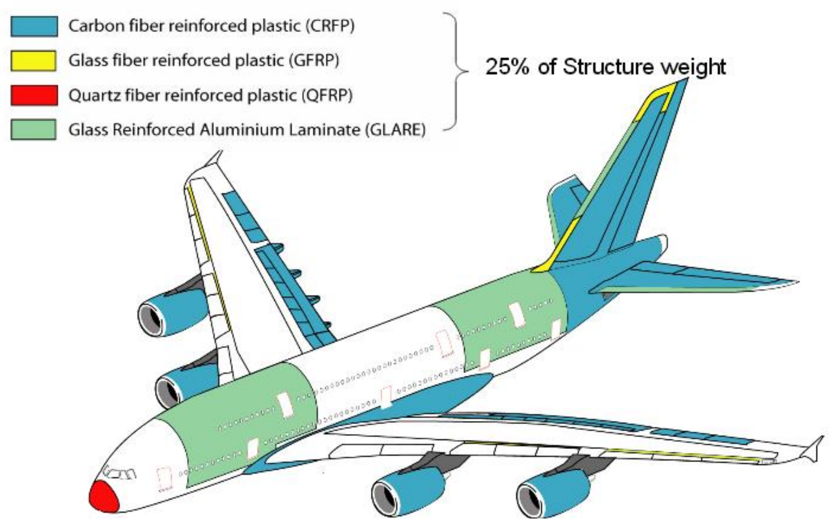
Source: Composites Forecasts and Consulting, LLC and ICF SH&E



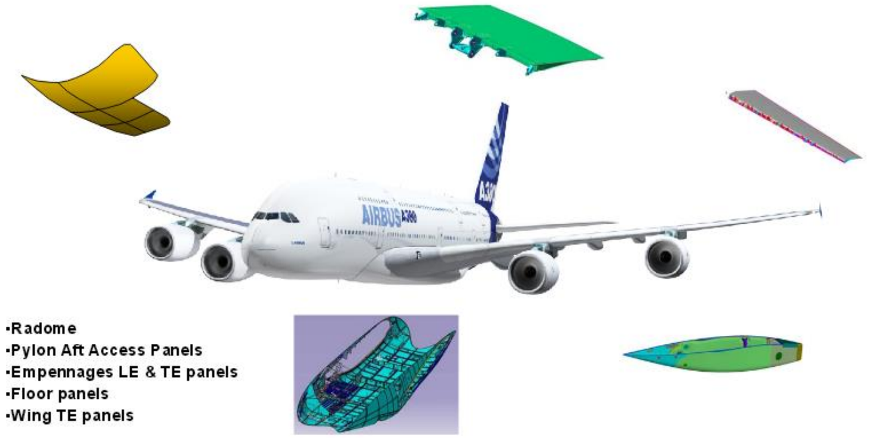
- To capture single-aisle replacement work, appropriate OOA and NDI tech needs to be ready for commercialization around 2022-2025
  - Could enable CFRP fuselages at 400-600 units/year
  - could drive CFRP volumes up 25% (2030-2033)

A380 composites use

A380 Composite applications



Sandwich structures



A380 Composite applications

Monolithic structures

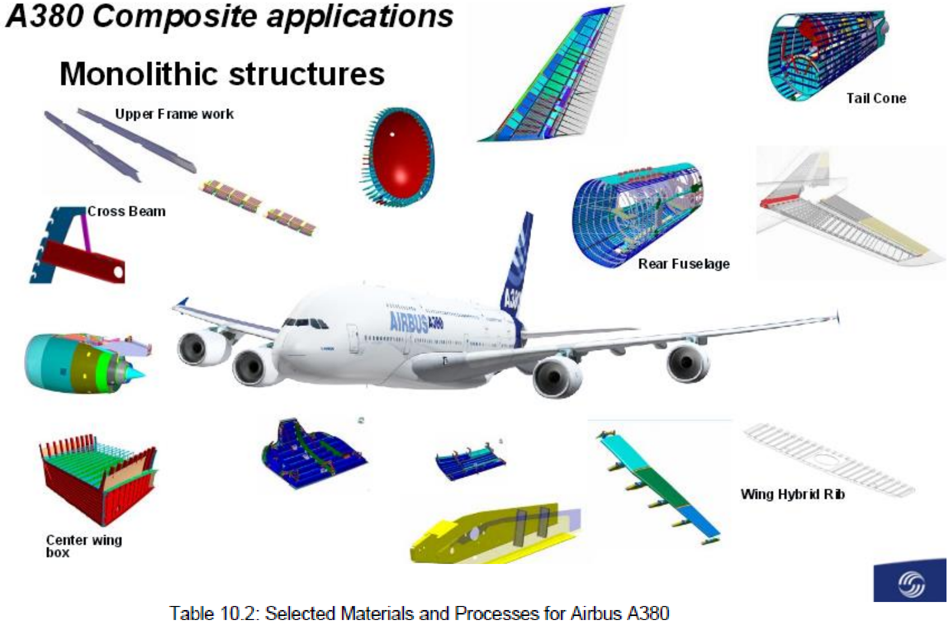
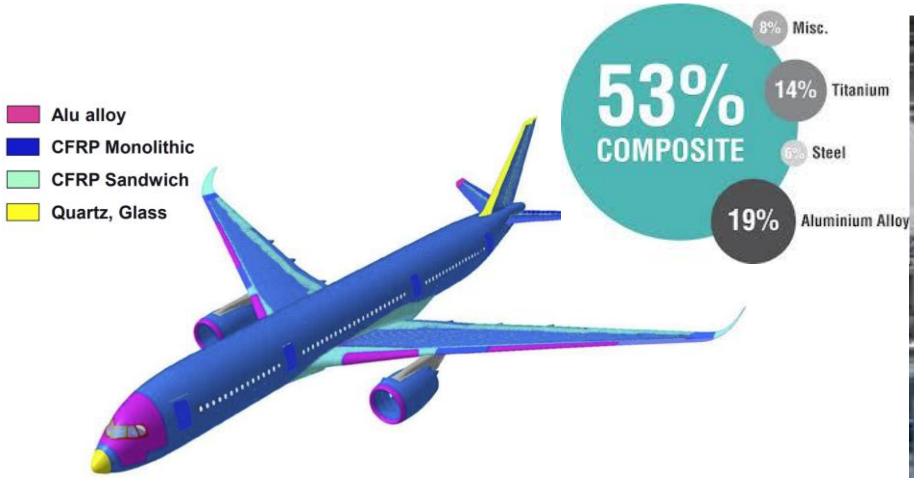
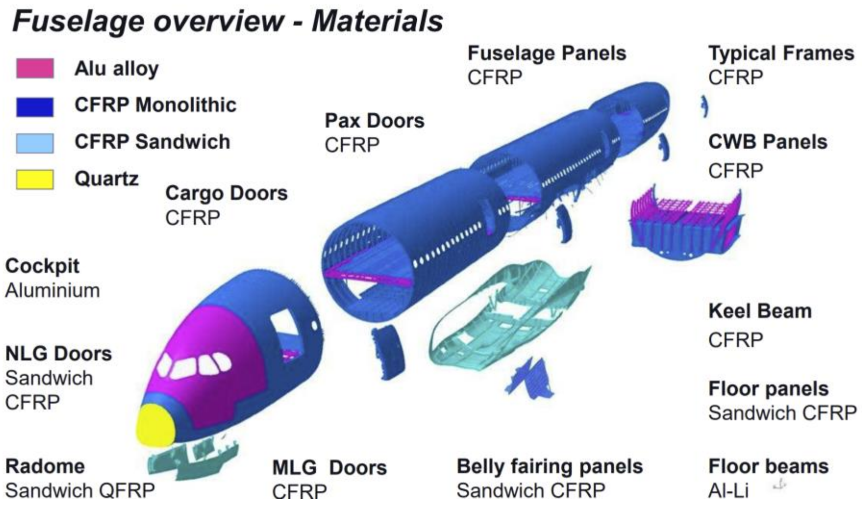


Table 10.2: Selected Materials and Processes for Airbus A380

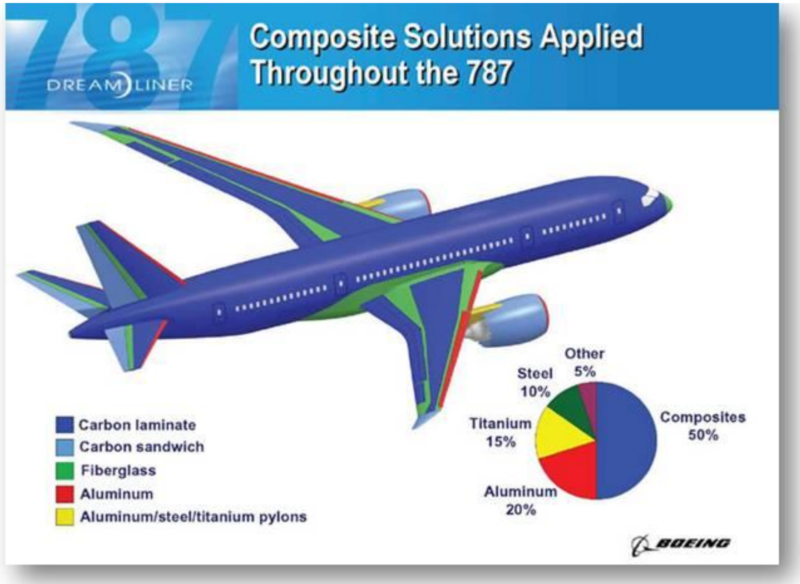
Parts	Materials Used	Manufacturing Processes
Wing J-nose	Thermoplastic, PPS	Thermoplastic forming, thermo welding for assembly
Belly fairings and flap track fairing	Fabrics and prepregs, low-density honeycomb	Hand lay-up
Fittings	NCF and RTM6	RTM
Torsion boxes	HT or IM Tapes	ATL
Pultrusion-Stringers	HTA, tapes and fabrics	Continuous process
Fuselage skins, gear doors, cowlings	Slit-Tape (Tows)	AFP
Rear bulk head	Non-crimped fibers (NCF) and RTM6	RFI
Torsion box spars and ribs	NCF and RTM6	Resin infusion under vacuum

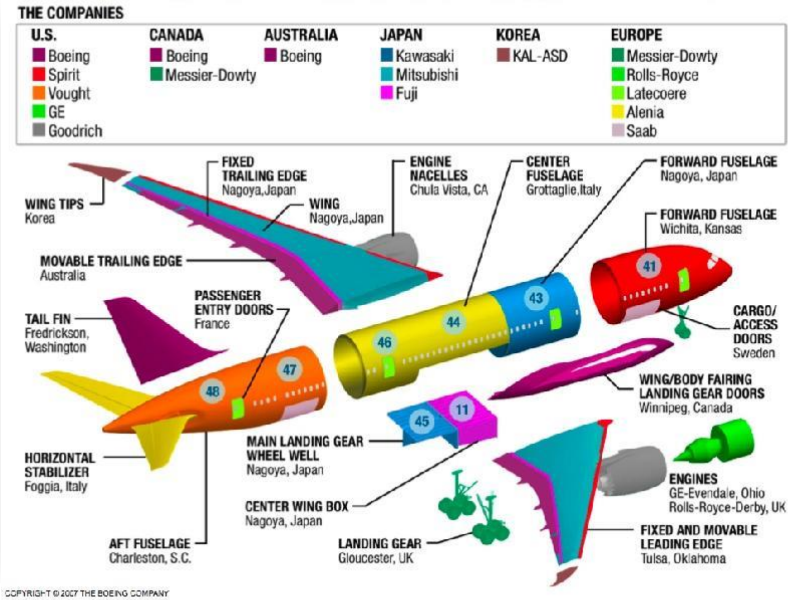
A350XWB composites use



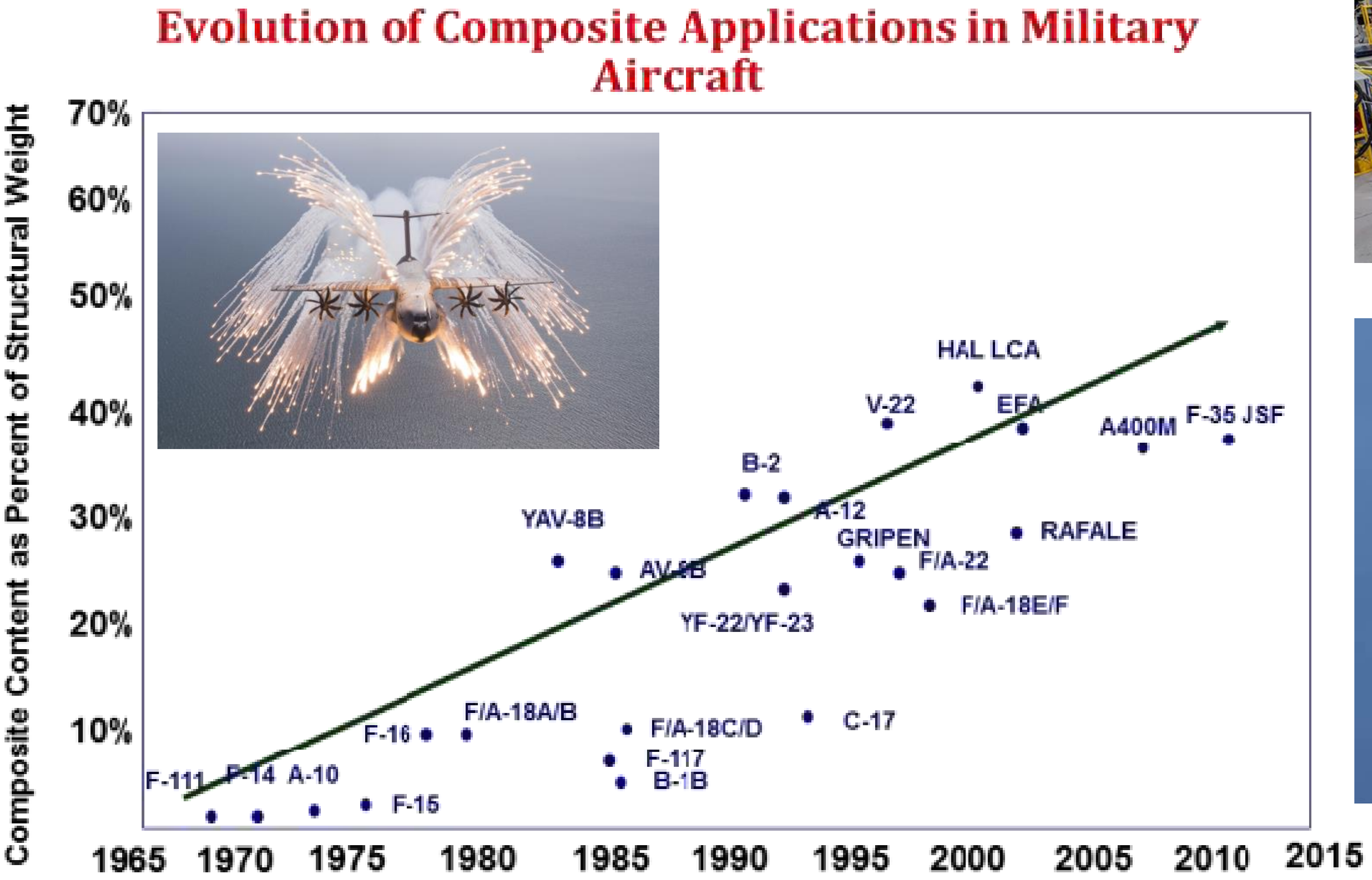


B787 Composites usage



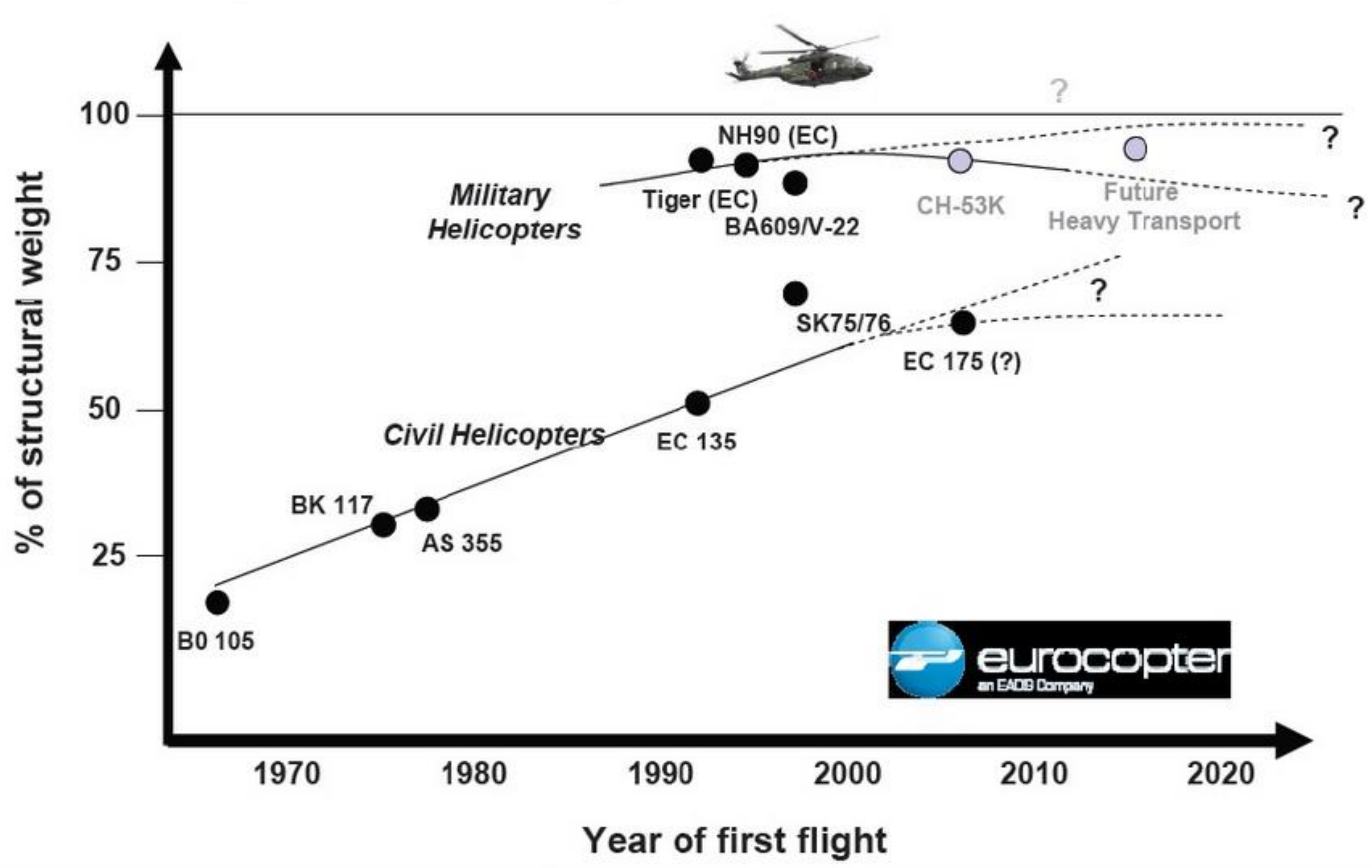


Military use of composites



[Skinning the F-35 fighter | CompositesWorld]()

Helicopter composite content by year

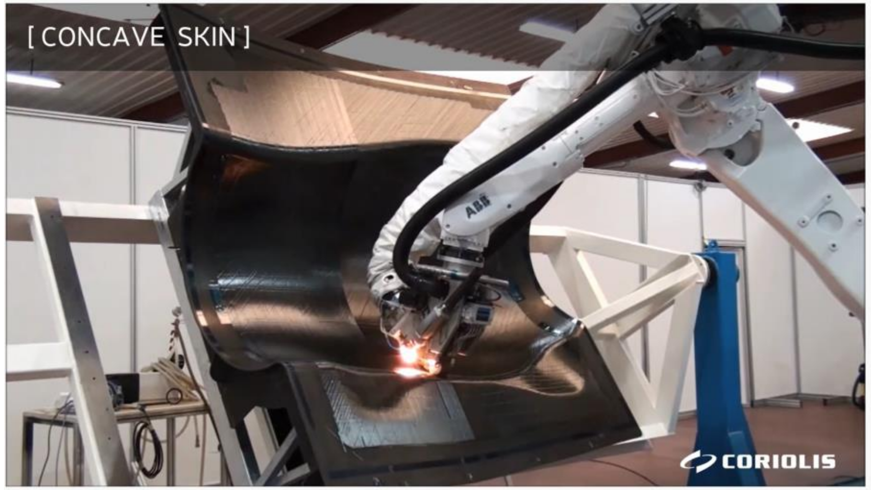


80% carbon fiber

AFP (automated fiber placement)

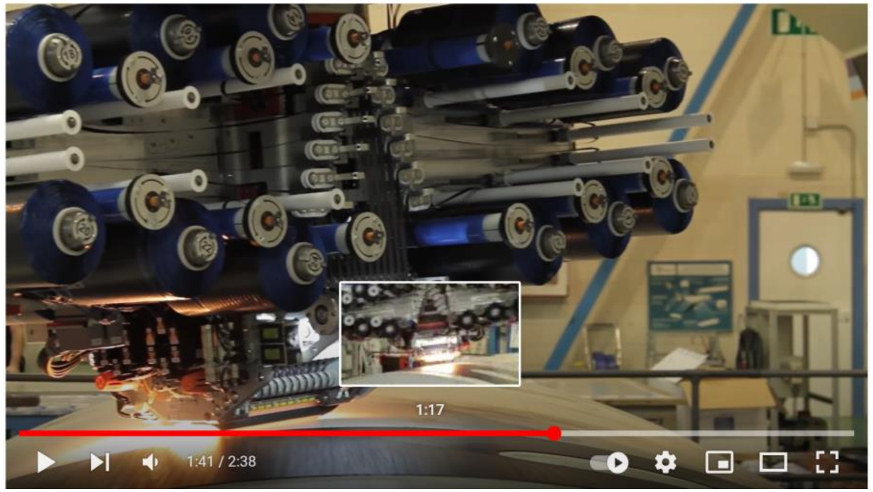
1min

Automated Fiber Placement Machines | TORRESFIBERLAYUP | MTorres - YouTube



30s

Coriolis Composites - CONCAVE SKIN (25) - YouTube



2.5min

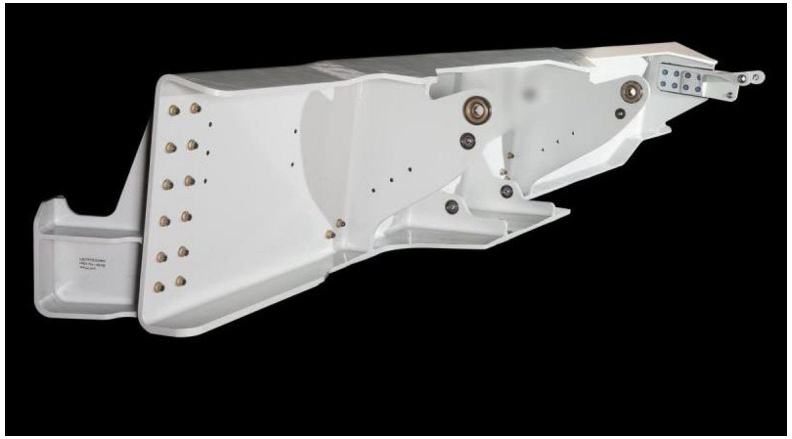
MTORRES AFP A350XWB - YouTube

Airbus A380 - Wing Construction - HD - YouTube

C1.2 : New AFP Coriolis Composites machine - YouTube 1:44min

Out of autoclave (OOA)

- Spar structure, developed by Daher for Airbus Wing of Tomorrow (WOT) program
  - Hexcel's M56 epoxy prepregged into AS4 CF fabric and IM7 UD CF tapes
  - Layup with Coriolis automated fiber placement (AFP) system, applies material over a male mold.
  - Cure performed out of autoclave (OOA) under vacuum bag in oven, 0.1% void content
- Prepreg chosen vs. liquid resin molding (prepreg a staple of aerospace manufacturing over the last 30 years, providing a consistent and dependable Vf and consistent and dependable dimensions and mass).



Out-of-autoclave VBO rear spar| CompositesWorld

Out of autoclave (OOA) with resin infusion

- Airbus evaluating liquid resin infusion (dry reinforcement) of lower wing skin as part of WOT program (as ATL requires autoclave cure)
- Benefits are OOA cure, ability to co-cure skins and stringers, near net shape fabrication, potential for economical manufacture at high rate (60-100 shipsets per month, e.g. A320 narrow body replacement). Main challenge is long on-tool time.
- Single-aisle Irkut (Moscow, Russia) *MC-21* aircraft features wing skins fabricated via liquid resin infusion.
- Other aircraft that feature an infused wing skin is the Airbus A220 (but autoclave consolidation).

Bombardier.pdf (ingenia.org.uk)

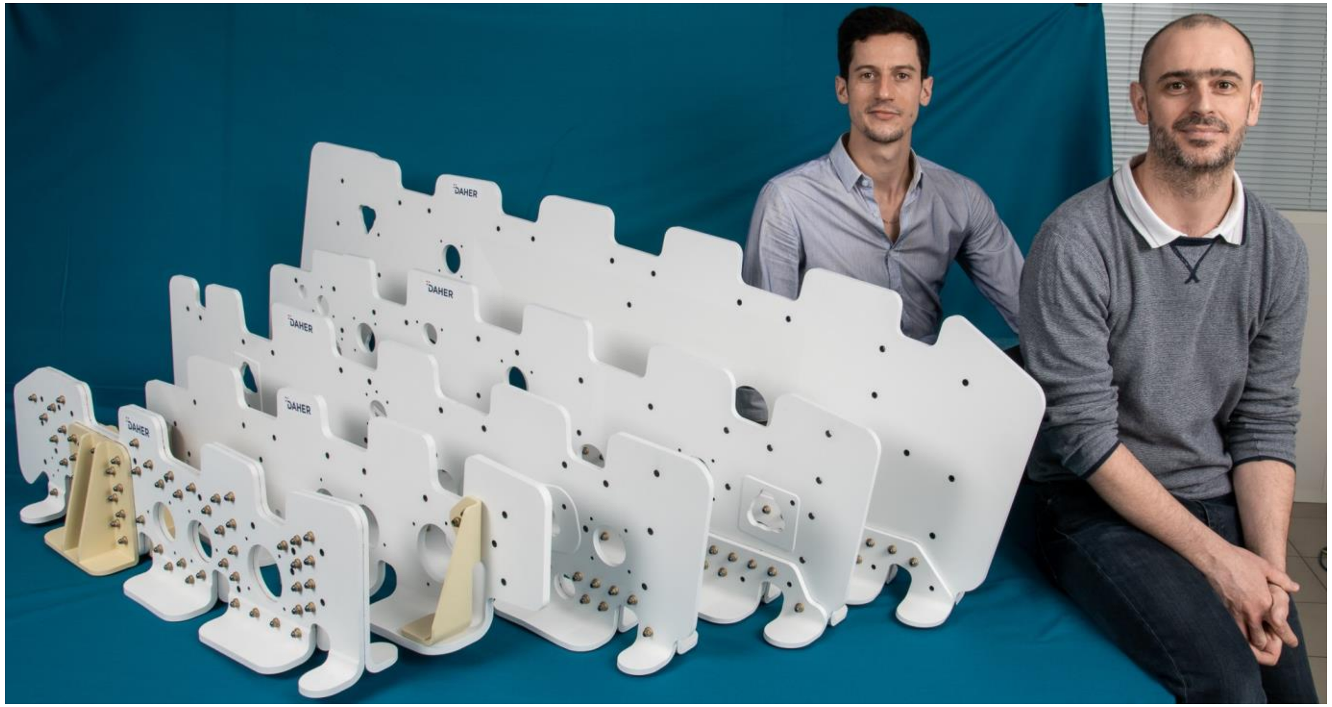
Update: Lower wing skin, Wing of Tomorrow | CompositesWorld

Making the aircraft wings of the future - YouTube

Infused wing sheds light on aerocomposites future | CompositesWorld

Aerospace thermoplastic composites

- UD carbon fiber/low-melt polyaryletherketone (PAEK) tapes (Toray using Victrex resin)
- Extreme toughness, 5x increase in ILSS, 2x fatigue increase , 2x compression after impact (vs. toughened epoxy)
- Rib manufacture: flat blanks made using AFP followed by oven consolidation — in some cases, materials are pre-consolidated prior to stamp forming

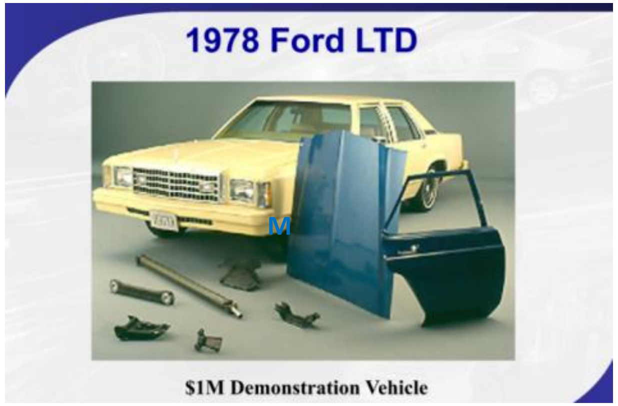


five ribs in the Daher Wing of Tomorrow lineup. Material is carbon fiber/PAEK supplied by Victrex and Toray Advanced Composites. Each rib is press-formed and then trimmed to final size and dimension. Flanges are either “L” or “T” shaped.

Automotive

Automotive use of carbon fiber

Historical:
- Technically possible
- Material cost too high
- Manufacturing techniques not available for high volume



Super cars:
- Technically possible
- Material cost not important
- Manufacturing techniques suitable

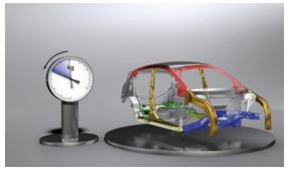
Towards high volume use:
- Significant investment (3 billion) by OEMs in the supply chain & technology
- Technically possible
- Material cost important
- Manufacturing techniques developed
- Automation in-place
- High speed resins
- Large scale equipment developed for molding parts

Options for light-weighting in Automotive

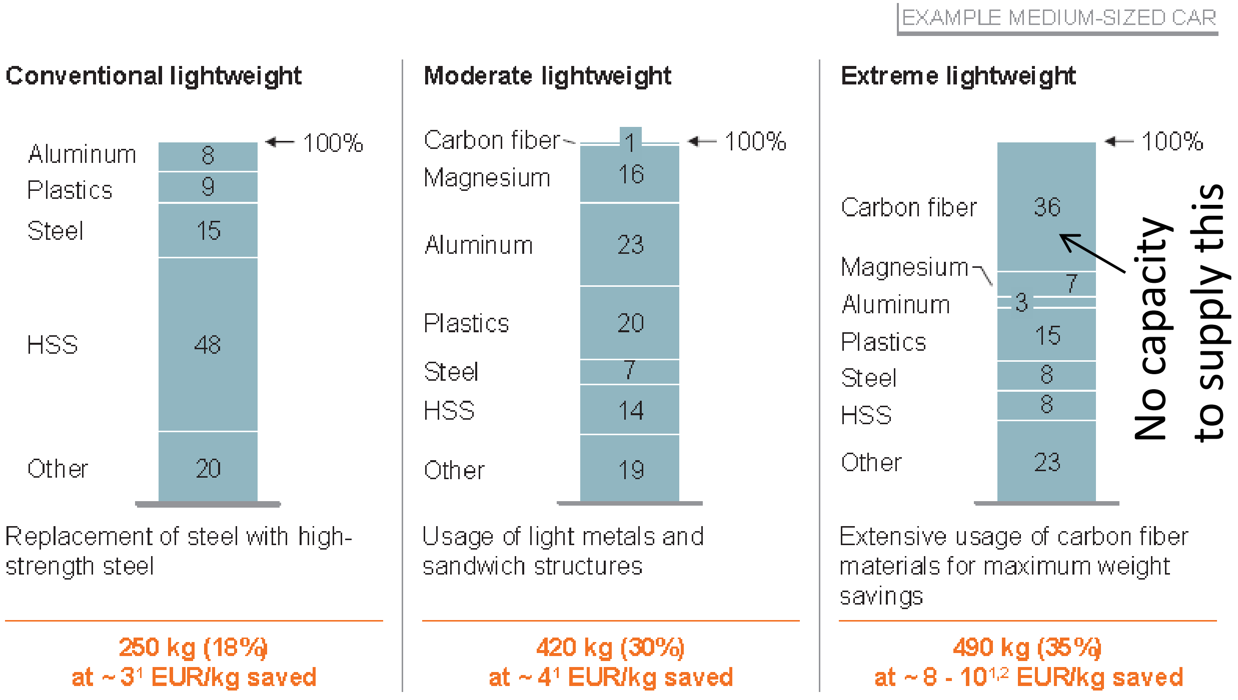
- Multiple material solutions
- Different OEM strategies, platform specific needs
- OEMs choose materials to meet part functionality and cost targets
- One OEM will choose steel, another aluminum, and other composite:
  ALL are correct: they all sell cars and they have different approaches

- Easy / lowest invest weight saving
  - Bolt on random fiber composites
  - HSS
  - Selected parts in Alu
- Medium invest
  - Extensive use of Alu / very local use of composites
- High invest
  - CFRP BIW (i3 approach)

Multi-material systems to save weight



Lightweight packages apply different lightweight material mixes with different weight and cost impact



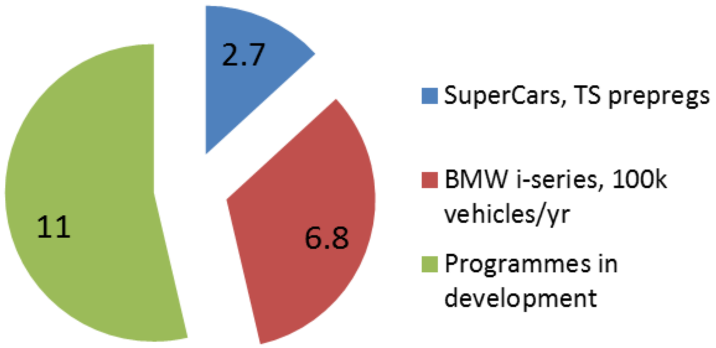
1 Numbers in 2030 2 Low range: aggressive scenario, high range: moderate scenario

SOURCE: McKinsey

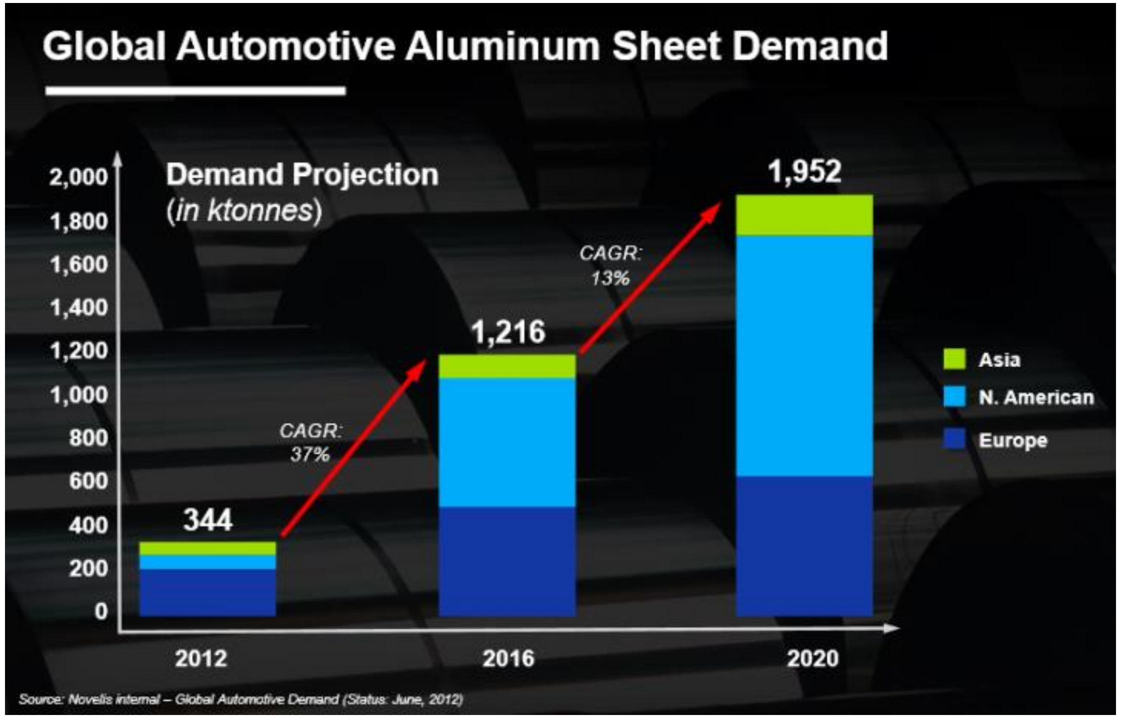
Supply chain perspective

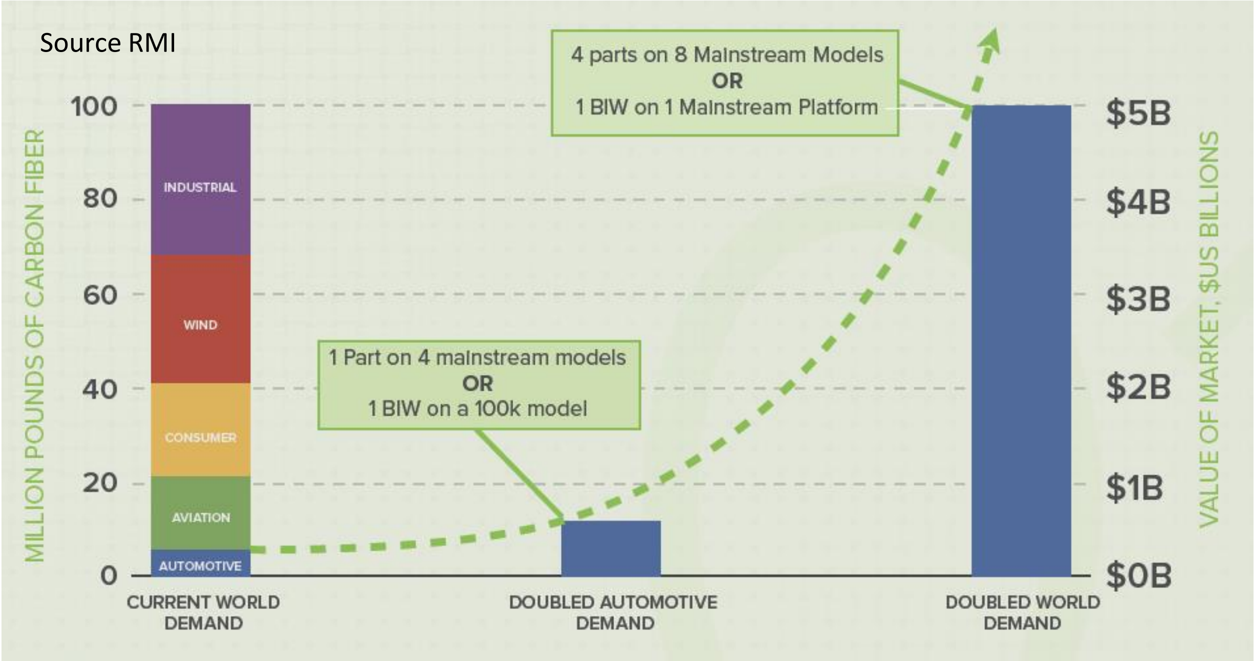
110kT of CF made world wide in 2022

- Ignoring die castings and extrusions … for simplicity:
  1kT Al sheet = 1kT composites
- 1952kT of Al sheet in 2020 vs. 20kT CF composites
  - To displace Al would need 10x HMD capacity … or >200 DBP lines
- limited inroads but significant growth and revenue



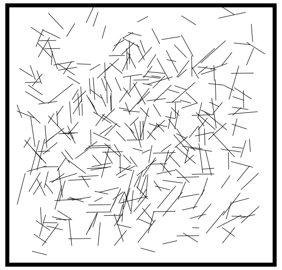
20kT of CF in automotive in 2020



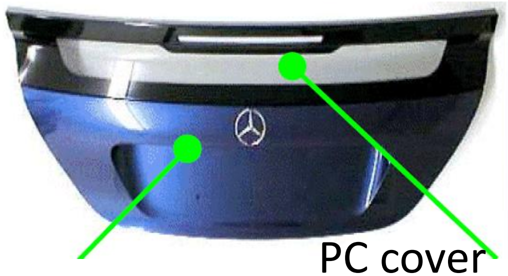


SMC: High volume thermoset composites

- Material
  - *chopped glass fibre*
  - *thermosetting resin*
  - *filler*
- Random fiber material, low V_f
- Net shape part
- Cycle time = 30 –150s
- OK for electro coat bake oven temperature (200°C)
- Class “A” automotive surface



Mercedes CL tailgate



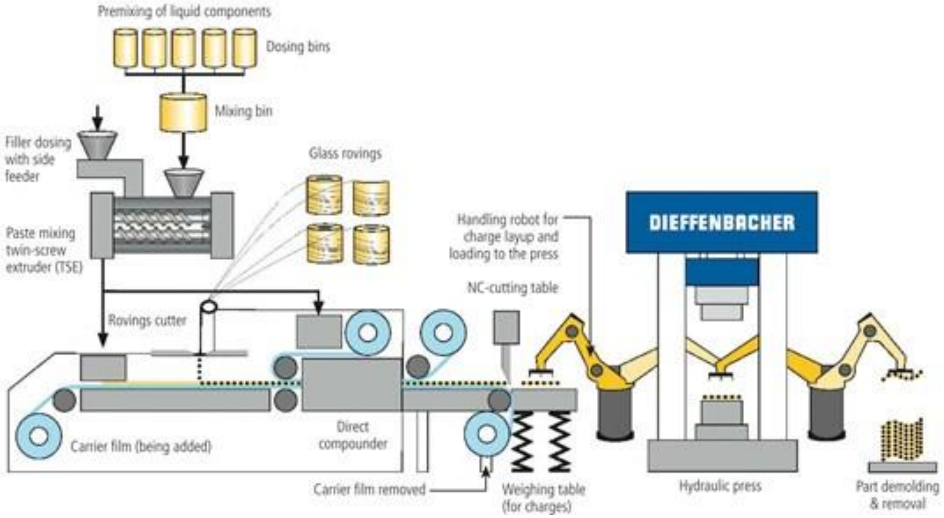
SMC panel geometry

PC cover geometry

F-350 Crewcab

SMC manufacturing is the most mature of automotive composite manufacturing processes

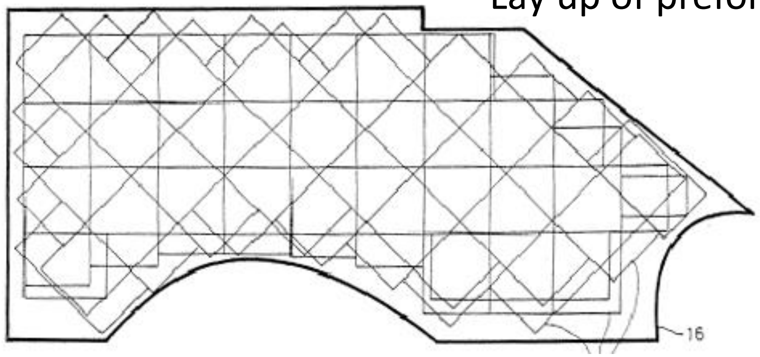
Ford Transit (MY2000), 850 /day, cost & weight saving

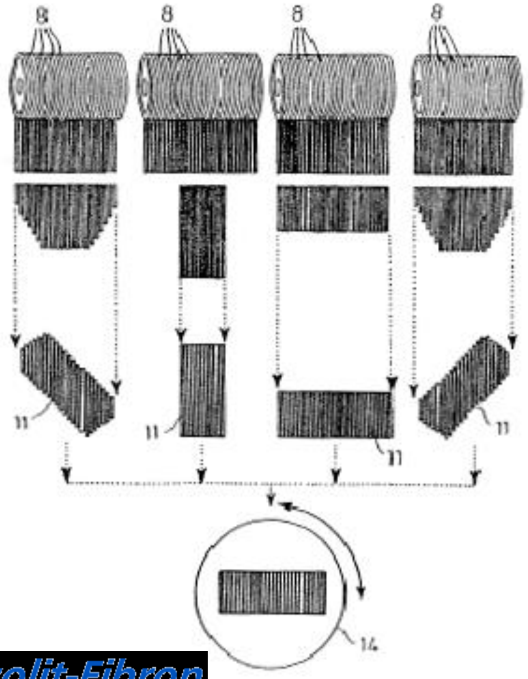


[Formulation flexibility: Direct-SMC | CompositesWorld]

SMC - Netshape thermoset preforming technologies

Lay up of preform





- Reduced scrap
- No textile processing
- Aligned fibre preforms
- Pseudo-global SMC flow

Menzolit-Fibron

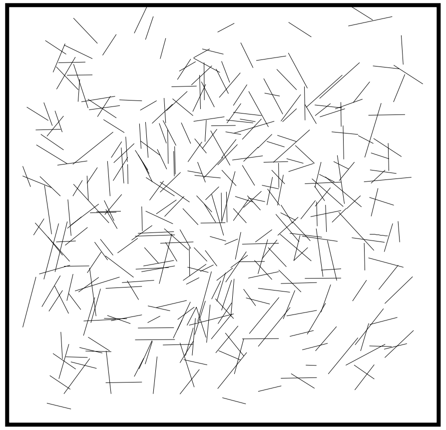
Mercedes SLR

GMT: High volume thermoplastic composites

e.g. Mercedes C-Class

- 200’000/yr, cycle time = 50s
- PP and 30% random glass fibre, low V_f, flow moulding
- weight = 4.2 kg
- high strength and crash resistance

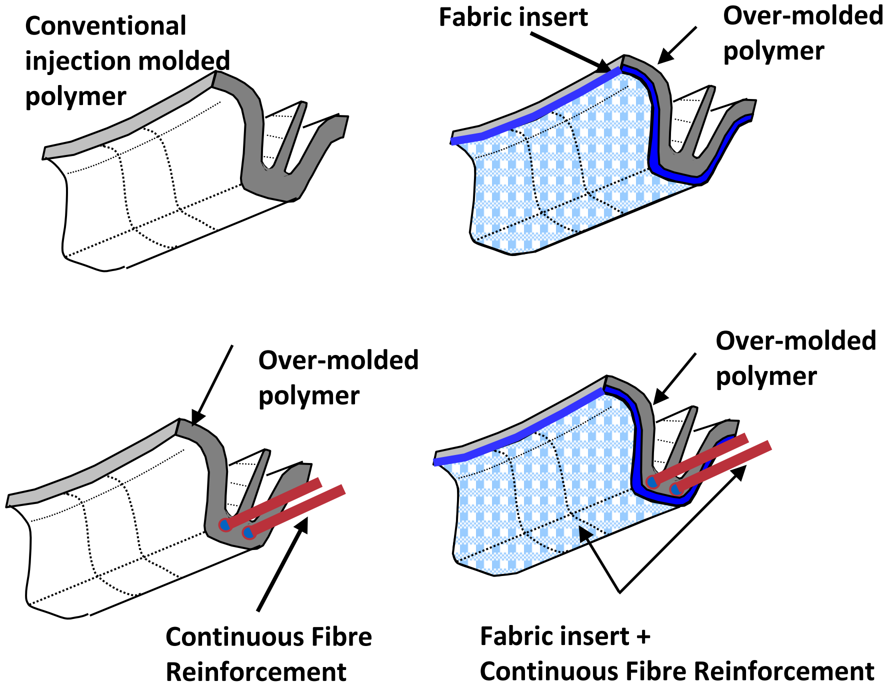
- weight and cost reduction
- design freedom and integration of functions
- noise dampening, corrosion resistance
- assembly after painting
- recyclability



Hybrid molding of thermoplastic composites

- Continuous fiber reinforcement
  - Fabrics and/or unidirectional fiber
  - High mechanical properties (stiffness, strength, impact, creep and fatigue resistance)
  - Used locally to maintain attractive cost structure

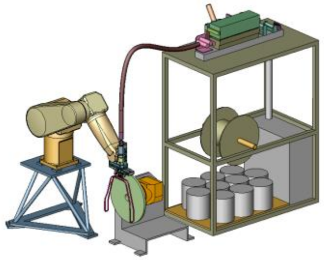
- Over-molding
  - High design freedom
  - Functional integration
  - Global part stiffness
  - Net shape parts
  - Used for the bulk of the part to maintain attractive cost structure



Stiffness at temperature, compression strength, higher fiber loadings

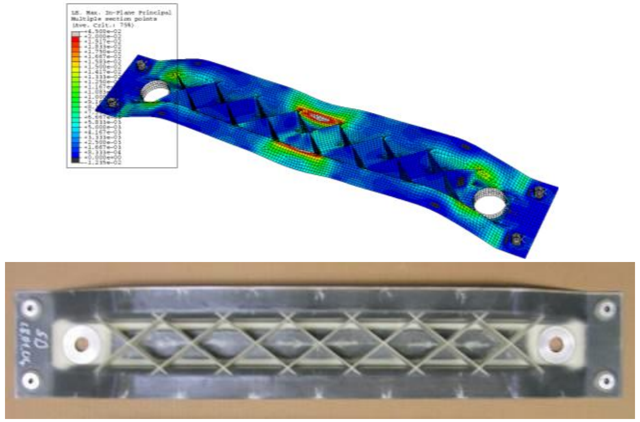
Integrated processing of polymers and composites

Cost modelling & business case evaluation



Development of facilities

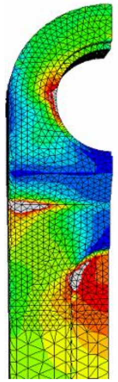
Generic insert trials



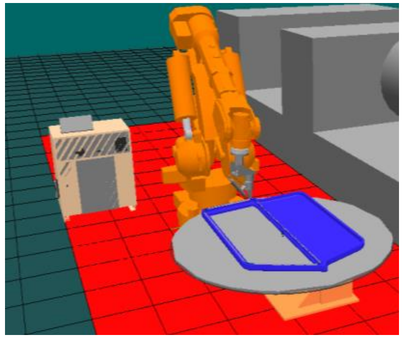
Generic demonstrator over-molding trials, test, FEA

Focus on

- PP and PET
  GMT, GMTex, IM, commingled
- Interfacial healing
- Void content evolution
- Process optimization



FEA and design



Scale-up of facilities

Rapid scaling – trials with existing tooling

Design specific demonstrator trials

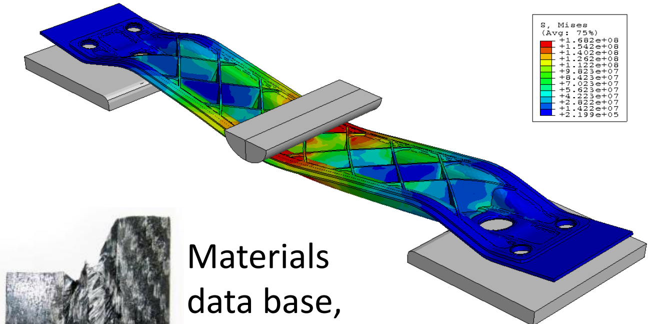
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
DAIMLERCHRYSLER
LTC LABORATOIRE DE TECHNOLOGIE DES COMPOSITES ET POLYMERES
JOHNSON CONTROLS
QUADRANT
fortafil
DU PONT
SAINT-GOBAIN VETROTEX
ABB

Total consortium effort € 2.9 million

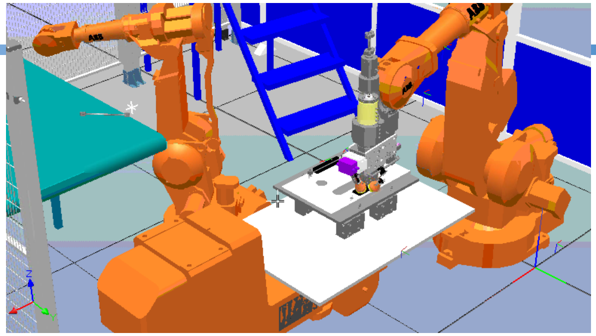
Vinnova

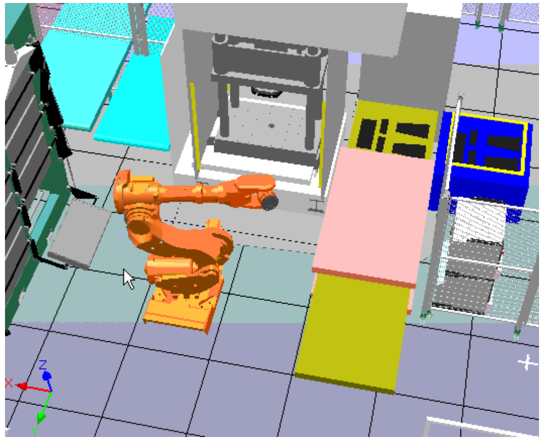
UD tow insert

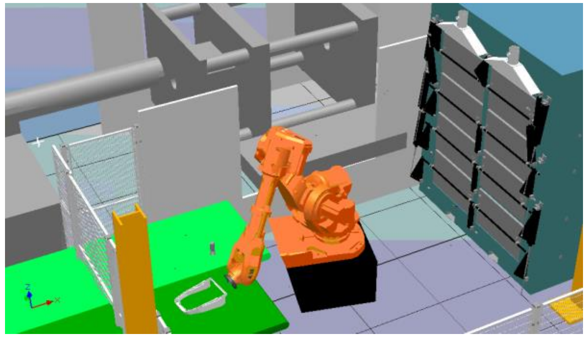
Over-molded generic beam

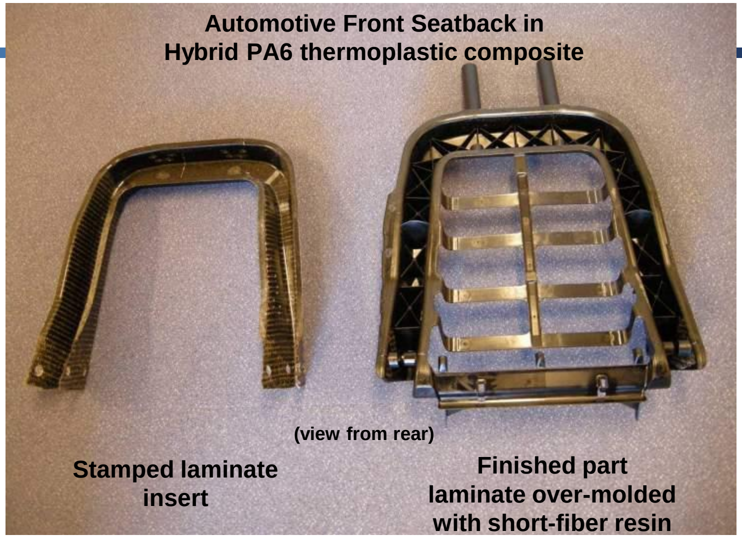


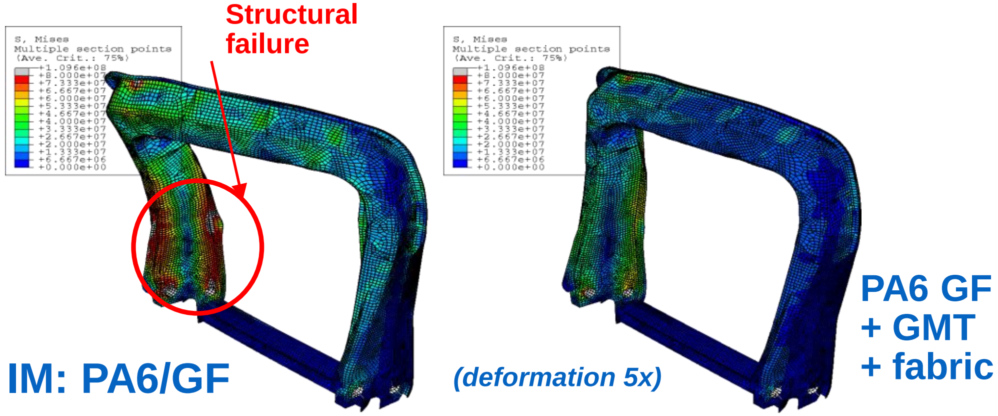
Materials
data base,
Tension, compression, shear
temperature, moisture









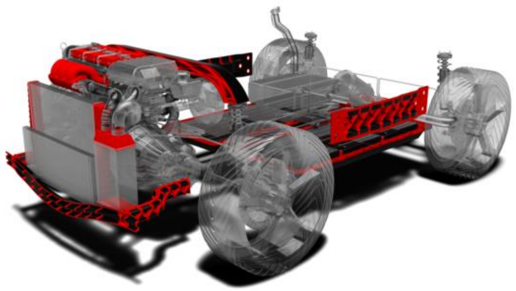


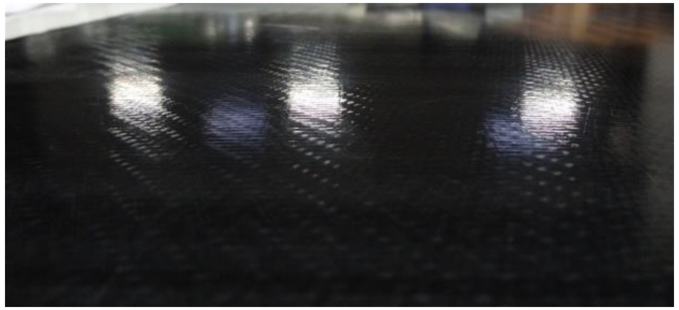
- Weight save 25-30% vs. steel
- Systems cost reduction 15-20%

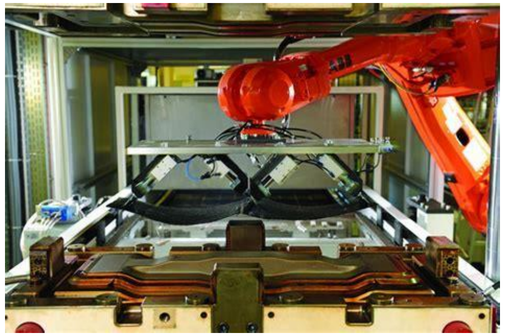
Total consortium effort
€ 2.7 million

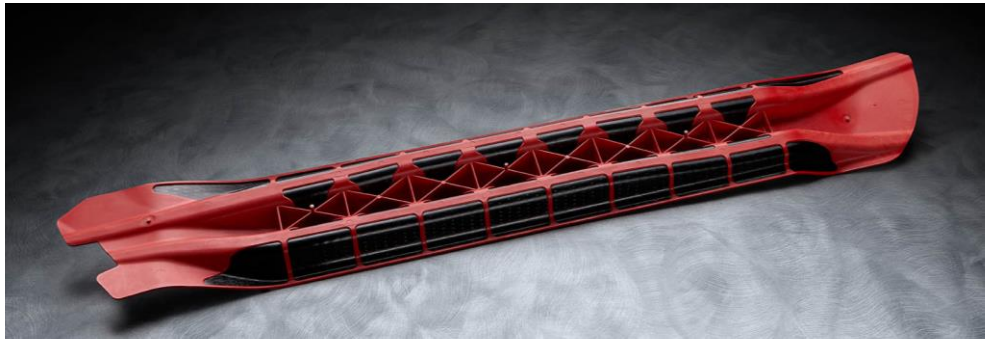
DuPont: Thermoplastic composite sheet development

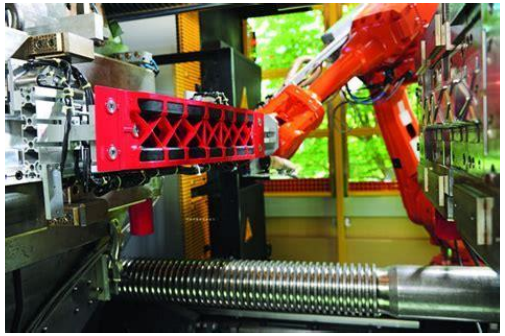
- Developed TPC sheet and over-molding resins
- Full data set, FEA, design methodology & costing
- Processing support









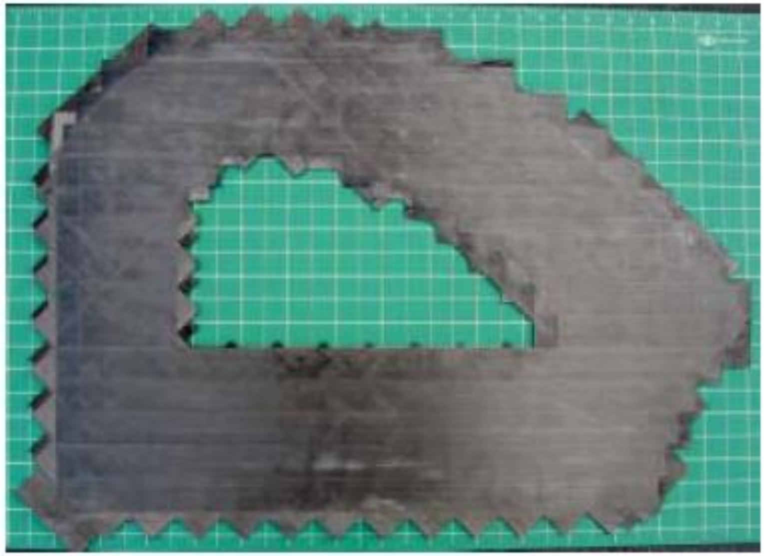


PSA Side Intrusion Beam development with overmolded DuPont Vizilon™ TPC sheet, JEC Paris, March 2013

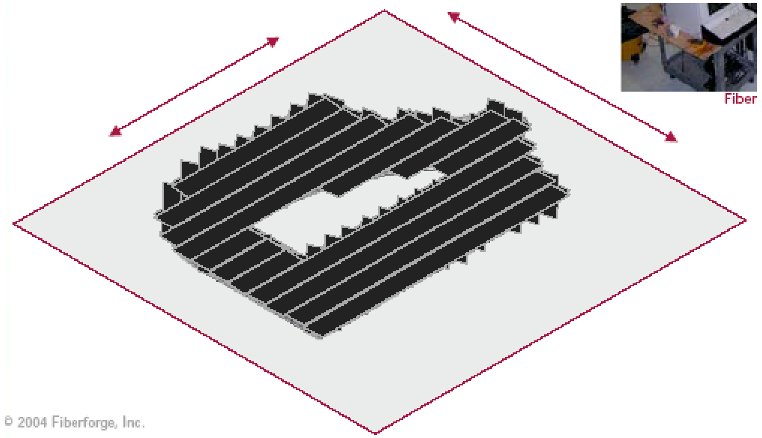
Thermoplastic composite sheet over-molding

Trim reduction for HP-RTM and TPC

- Reduce cost of waste textiles, CF systems and semi-finishe
- Flat plaque to demonstrator scale



Cost	• Reduce waste of carbon fiber materials
Performance	• Use of UD tape for maximum mechanical properties
Supply chain	• Reduce reliance on use of CF weaves (waste costs highest where impregnated CF woven sheet is used)
Automation	• Lower cost and faster automation than full aerospace AFP
Design freedom	• Make TPC parts of varying thickness



Netshape preforming, Engel / Fiberforge

- UD tape preforming, optimized fiber orientations, low waste
- No need for investment in DBP technology

[I-PDF_ENGEL_Kunststoffe-international_2020_06_.pdf (engelglobal.com)]

[ENGEL Tapelegezelle - YouTube]

[DIEFFENBACHER Tailored Blank Line - Large series production of lightweight components. - YouTube]

Netshape preforming, Engel / Fiberforge

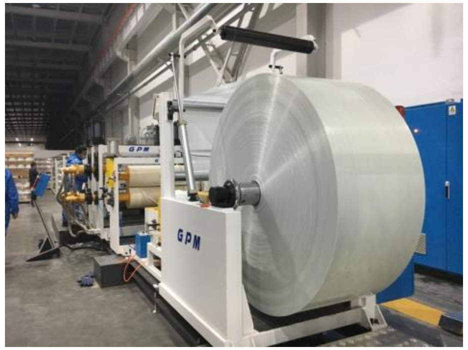
ENGEL Tapelegezelle - YouTube

DIEFFENBACHER Tailored Blank Line - Large series production of lightweight components. - YouTube

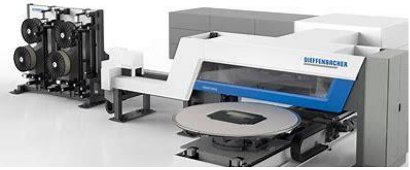
Now a process emerging into supply chain

- Machine suppliers in place
  - Engel organo-melt
  - Krauss Maffei Fiberform
  - Fiberforge / Dieffenbacher
- Multiple material suppliers
  - Laminate
  - UD tape
- FEA approaches developed
  - BASF
  - Lanxess
  - DuPont
- Early niche OEM developments







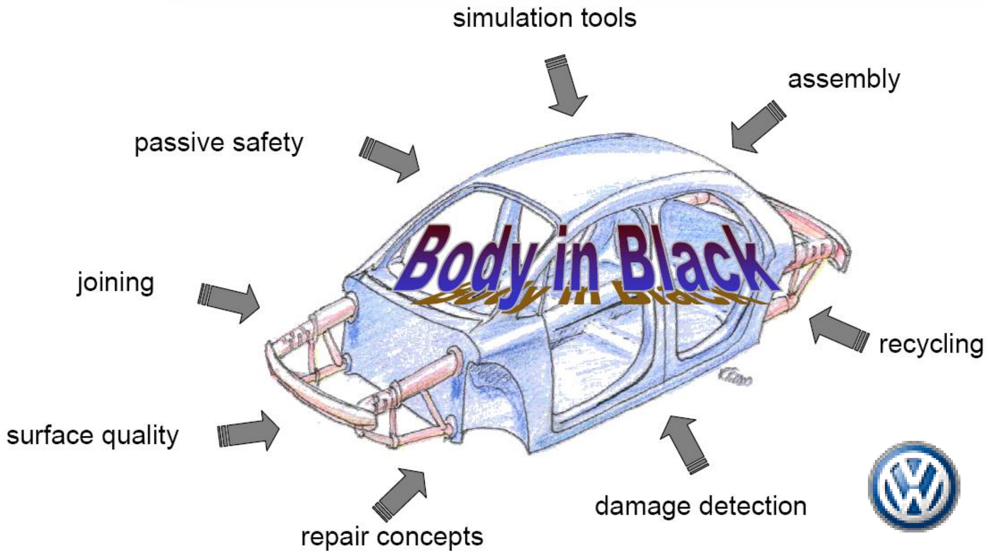




Fully structural parts : Demands on BIW applications

- sufficient torsional- and bending stiffness
- sufficient denting stiffness and strength
- sufficient fatigue strength during operation time
- defined eigenfrequencies
- defined fracture behaviour (splinter-proof)
- defined energy absorption ability
- Class A finish after painting

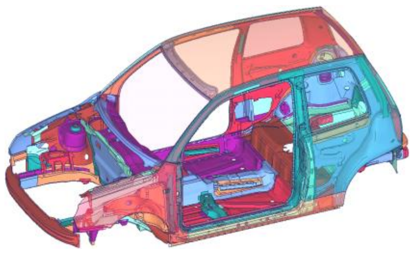
- **High degree of part integration**
- **Dimensional stability**
- **Little variation in part stiffness from -40°C to 90°C (120°C)**
- **Withstand temperatures during e-coating, 200 °C +**
- **Environmental resistant (chemicals)**
- **High damping coefficient, improved NVH**
- **Recyclable in production and at end of life**

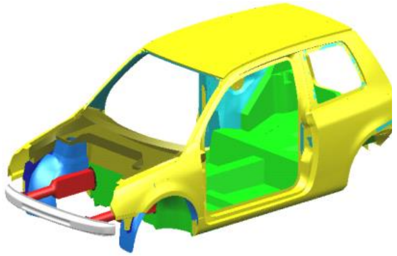


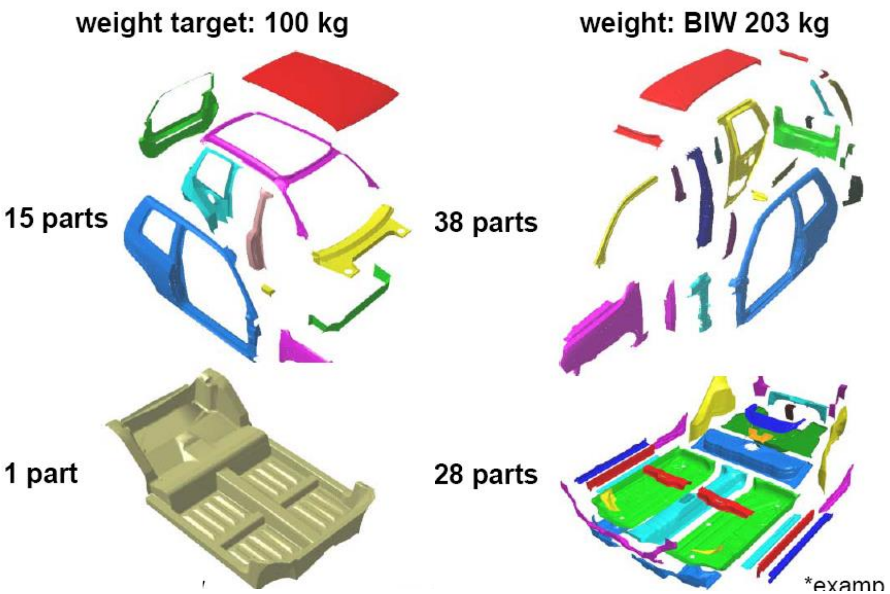
Carbon Fiber :
focus on STIFFNESS driven parts where GF is too bulky & heavy plus crash applications

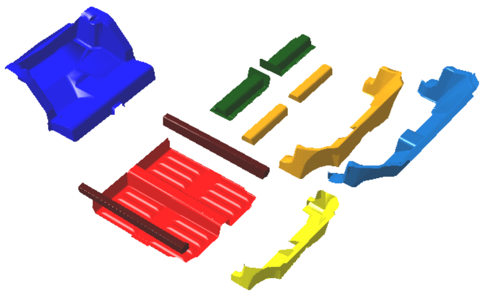
Current steel vs. advanced composite BIW

- composite BIW for existing A00 car
- 50% weight & 70% parts count reduction
- CF textile preforms processed by RTM at 50 units/day

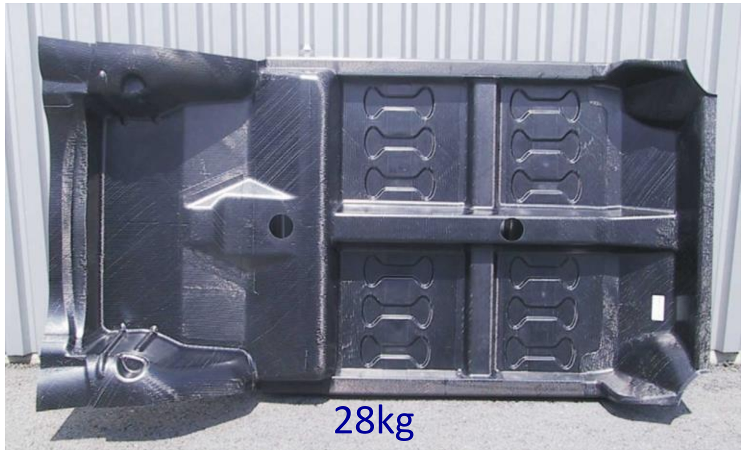




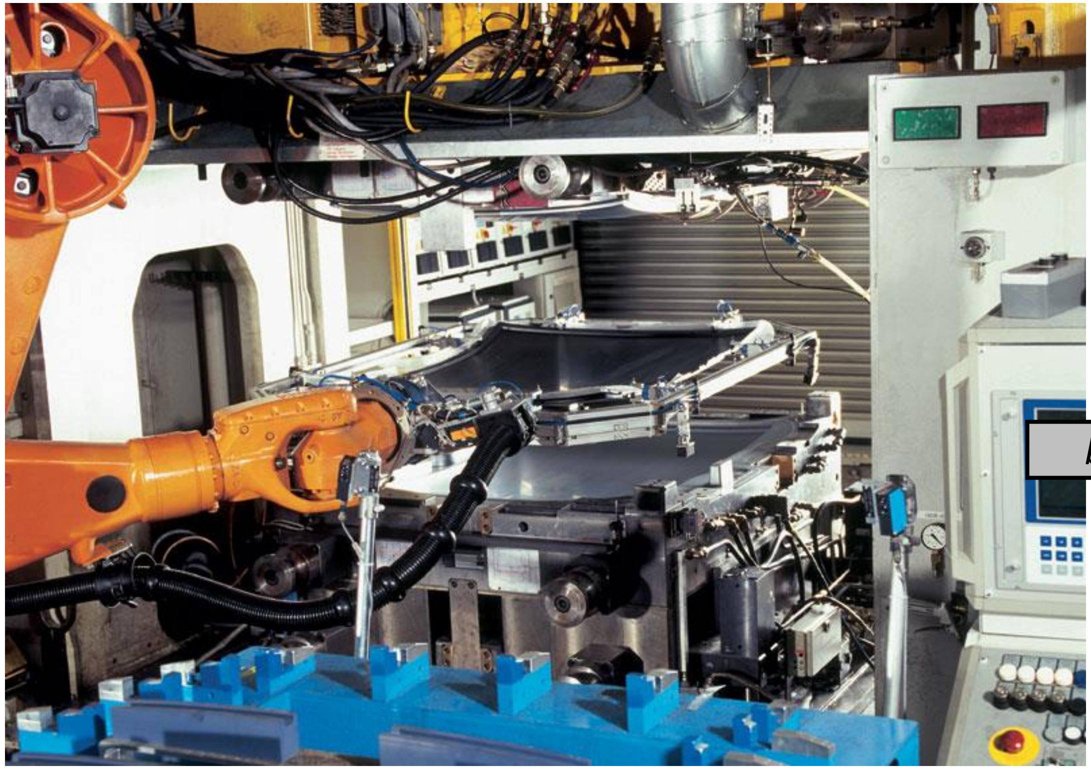




8 preforms + 5 cores



Automated manufacturing – HP-RTM



but also

reduce preform trim (waste) and use of expensive NCF (lowest cost precursors)

BMW's Landshut Plant
50% lighter than steel,
RTM of CF/epoxy, 1800 T press

How to reduce the cost of textile structures for <u>high manufacturing volumes</u>?
Invest in fixed costs, for quality, reduced labour, …

Fast cure (snap cure) resin systems

thermoset resins

How fast does it set?

Even more than cost reduction, reducing the time of manufacture for composite parts is a key factor in getting composites to penetrate industrial sectors, notably the automotive sector. Manufacturers of thermoplastic materials for injection moulding processes are used to fast cycle times and high production rates. SMCs and BMCs have paved the way for thermosets, but in recent years new ultra-fast curing formulations have made their appearance.

MARKET

For large parts (in terms of size and thickness), solutions comparable to thermoplastics are now in use with practically all the major manufacturers of thermoset resins (see Table 1).

RTM leading the way...

Most resin manufacturers are focusing on RTM. This process makes it possible to obtain parts that require very little post-fabrication machining and offers greater

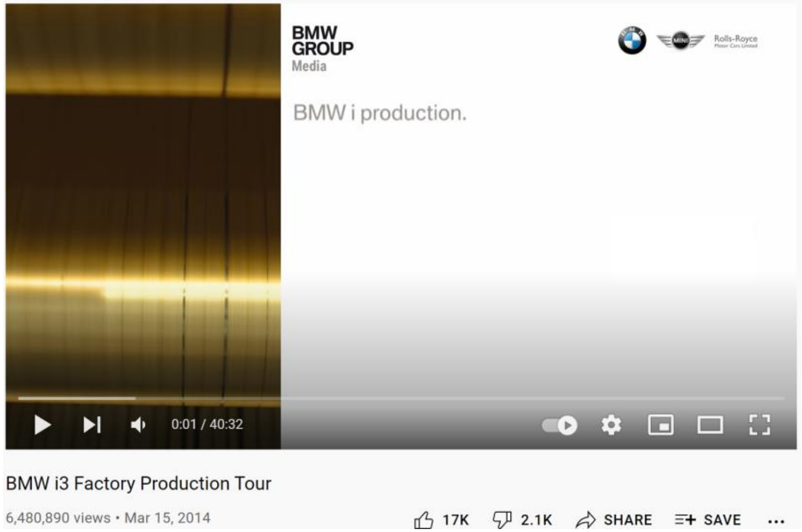
Tab. 1: A few examples of the latest fast-curing resins

Company	Resin Chemistry	Brand / Commercial Name	Process	Comment
BASF	Epoxy	Baxxodur	RTM	demolding time of only 2.5 minutes at 120°C
Cytec	Epoxy	XMTR50	HP-RTM	3 minutes at 120° C for a 135° C Tg
Dow	Epoxy	Voraforce 5300	HP-RTM	90-second cycle times
DSM	Epoxy	Daron	RTM	Fast cure (less than two minutes)
Henkel	Polyurethane	Loctite MAX 2	RTM	curing time can be reduced to one minute
Hexcel	Epoxy	HexPly M77	Prepreg	curing in two minutes at 150°C,long shelf life of six weeks at 23°C, Tg of 125°C
Huntsman	Epoxy	Araldite LY 3585/ Aradur 3475	HP-RTM	5-minute "part-to-part" production cycle
Huntsman	Epoxy	Araldite expandable epoxy systems (EES)	Wet compression moulding	45-60 seconds at 145 -160°C
Lonza	Cyanate Ester	Primaset CE-320	RTM and Infusion	Tg up to 320 °C
Momentive	Epoxy	Epikote Resin 05475 / Epikure Curing Agent 05500	High- or low-pressure RTM	long injection window of about one minute, very fast cure at 115–120°C
Swancor	Epoxy	Swancor	RTM	-

BMW 7 series 150s M77

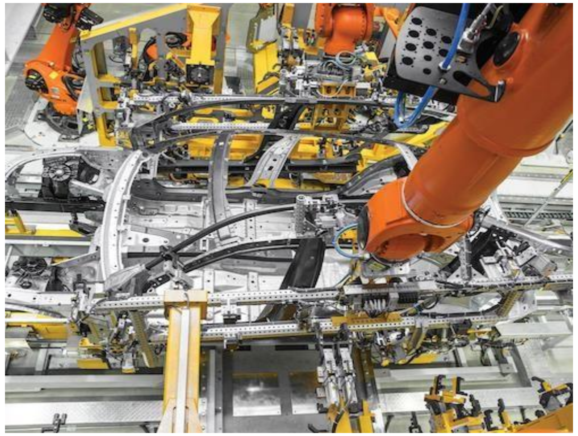
BMWi3, 5 min

BMW i3 and 7 series



[BMW i3 Factory Production Tour - YouTube]

3min30s



[BMW 7 Series Carbon Fibre Technology - YouTube]

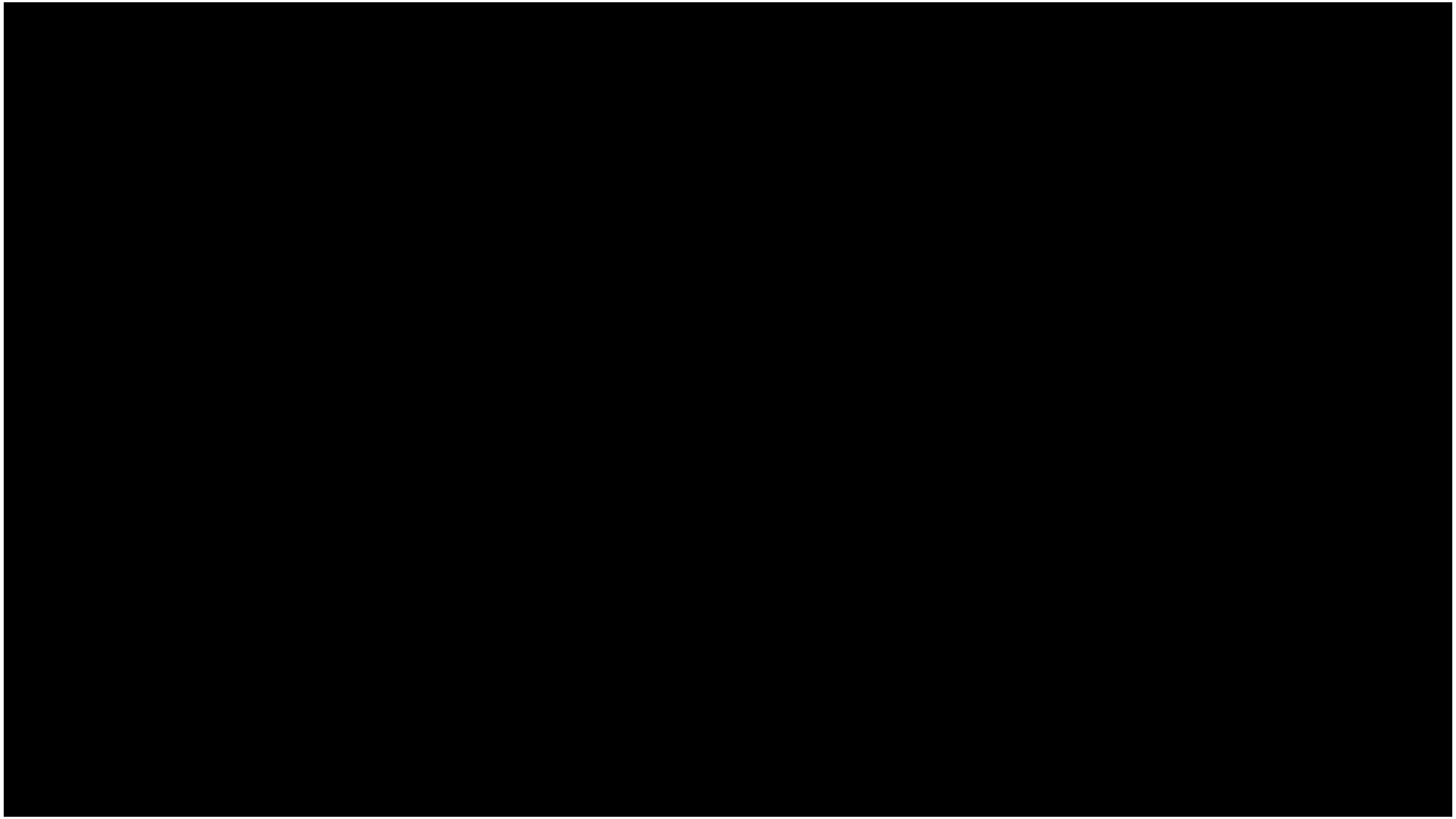
Hexcel's HexPly M77 resin, snap cures in 1.5 min at 160°C

[Snapcure HexM77 and HexMC® on Vimeo] 1min30s

BMW I3 AND BMW 7SERIES IN COMPARISON BY ASPECTS OF CFRP

	 BMW i3	 BMW 7 Series
Production volume	100 cars/day	> 300 cars/day; > 4000 CFRP p/d
CFRP technologies	Wet Compression Pressing; HP-RTM	Wet Compression Pressing; HP-RTM ; Steel Hybrid; CF SMC
Design concept	LifeDrive == > CFRP dominant in Life-Module	Carbon Core == > Multi-Material (Steel, ALU, CFRP)
Painting concept	CFRP none Exterior thermoplastic parts (painted and mounted)	Classic also for CFRP (temperature of about 180 °C in EDP)

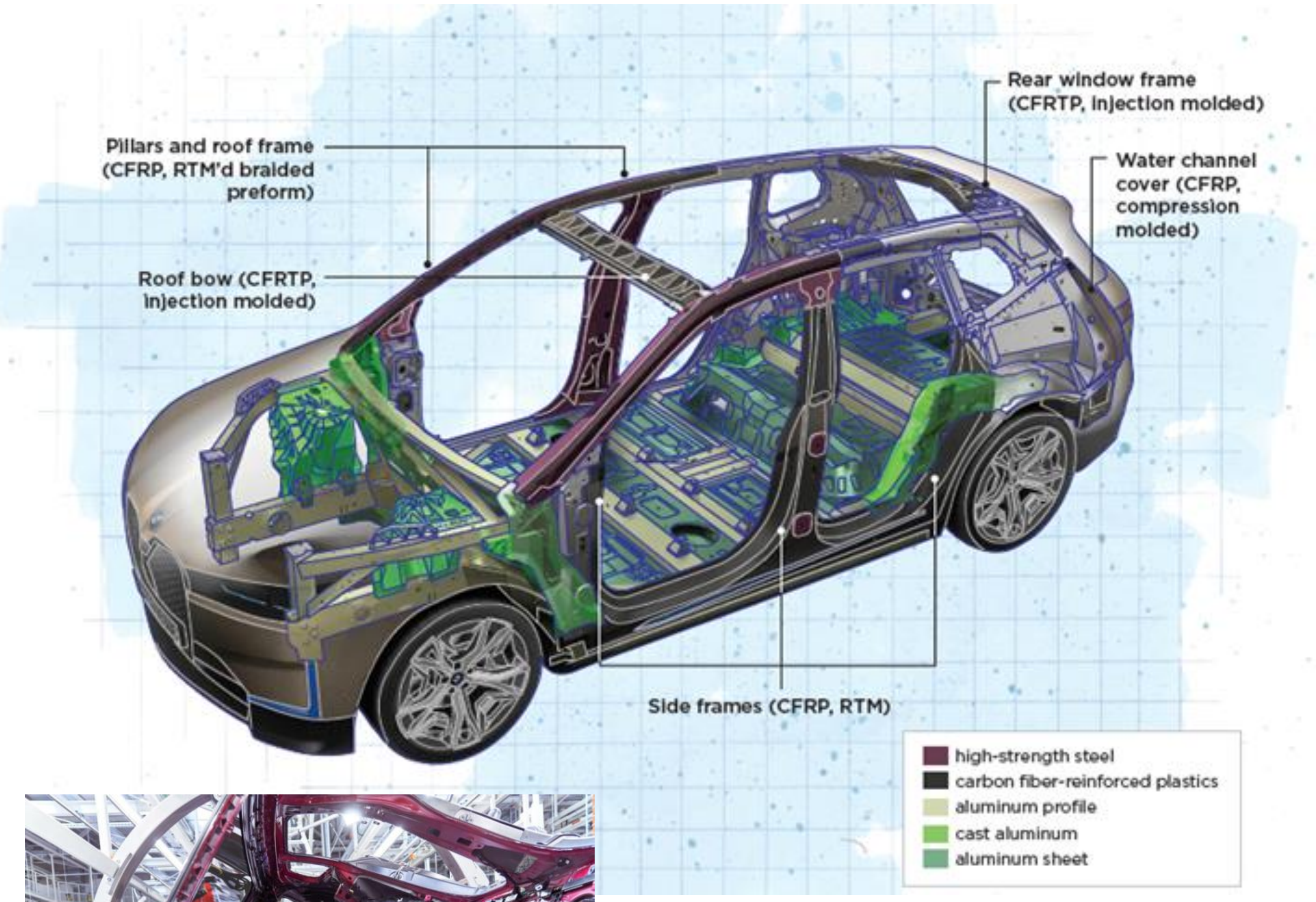
BMW i3 series



[BMW i3 Factory Production Tour - YouTube]

3min30s

BMW iX, CFRP

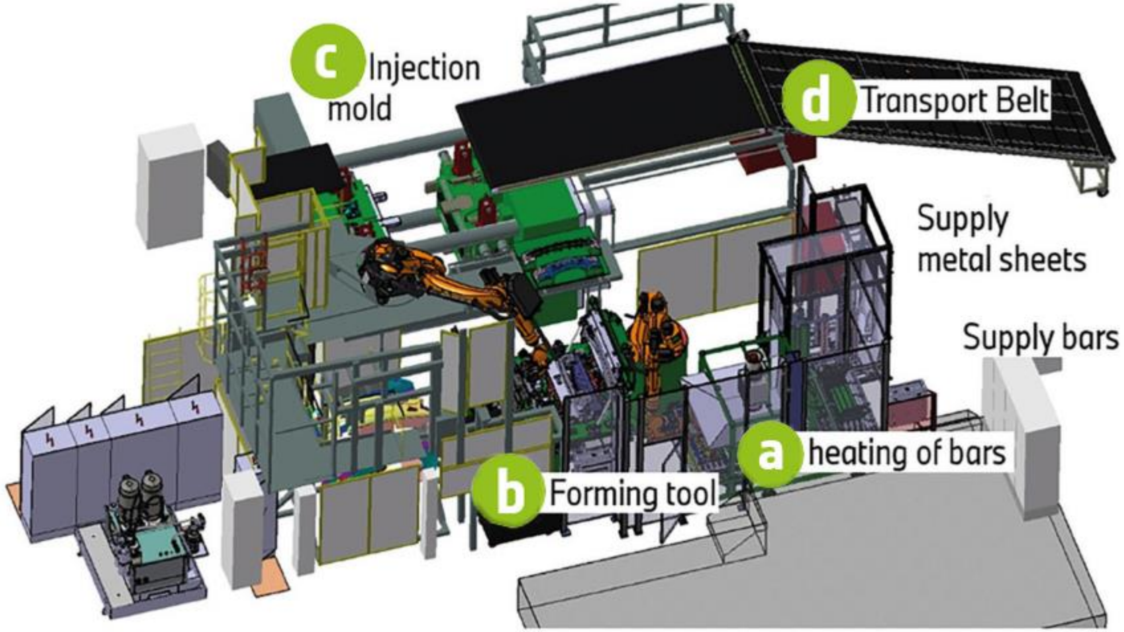


The cowl panel and rear window frame components are manufactured from continuous fibre reinforced thermoplastics (CFRTP) using an all-new method (Production at Plant Dingolfing)

[The first ever BMW iX - JEC (jeccomposites.com)]

BMW iX roof bow

Skeleton roofbow vs. Sheet metal	
weightreduction of at least 40%	45%
minimal use of continuous carbon fibres	415g
no production waste	0%
Net shape process	✓
Second use of carbon fibres	✓
fully automated process	✓
reduced number of parts	4 → 1
cycle time less than 90 seconds	85 s
Part costs	✓
CO2 equivalent	✓



[Serial CFRTP structural part for BMW Group body-in-white application - JEC (jeccomposites.com)]

Fig. 6: Results of the BMW iX's CFRTP windscreen using the skeleton design

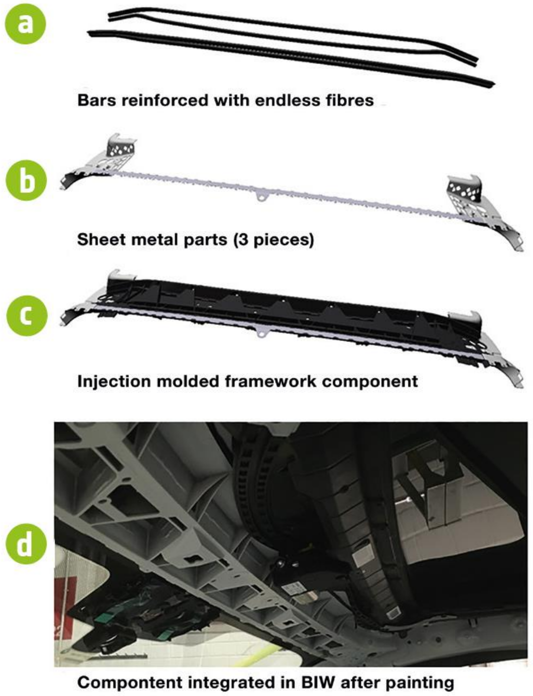


Fig. 3: Components of the BMW iX's series front roof bow

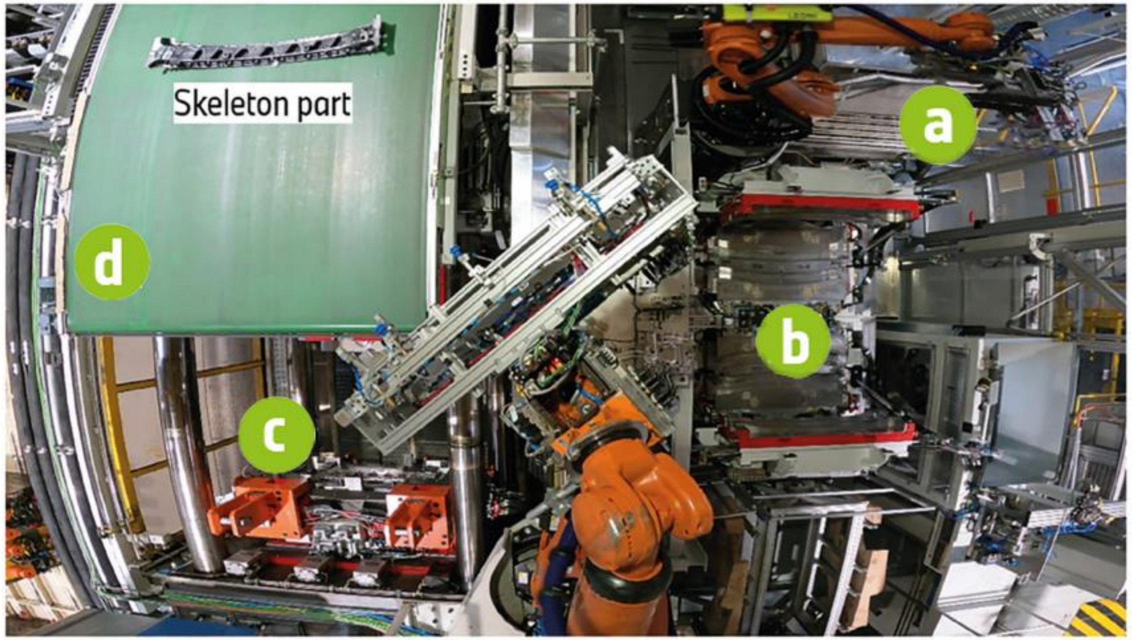
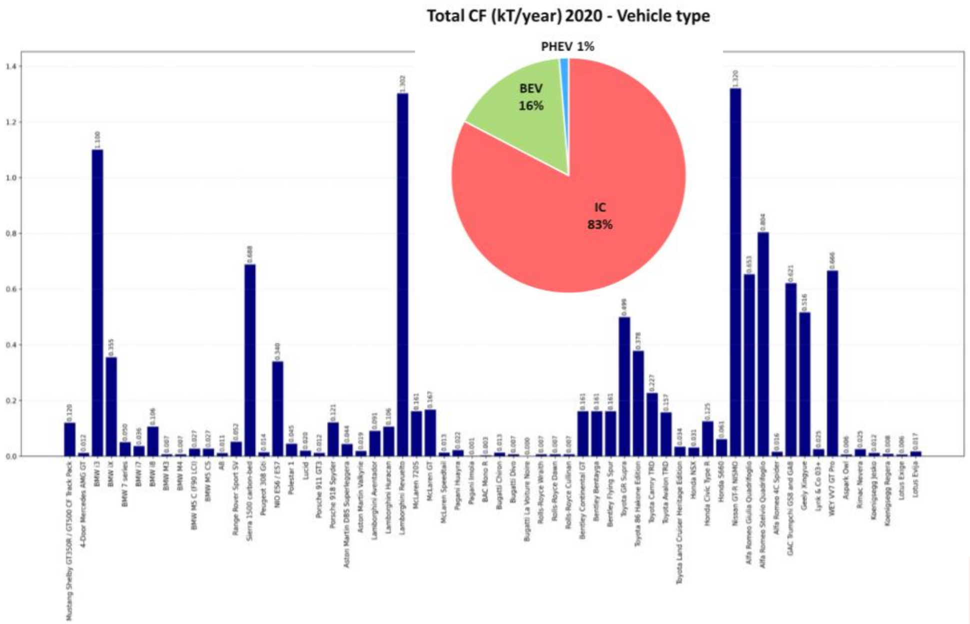
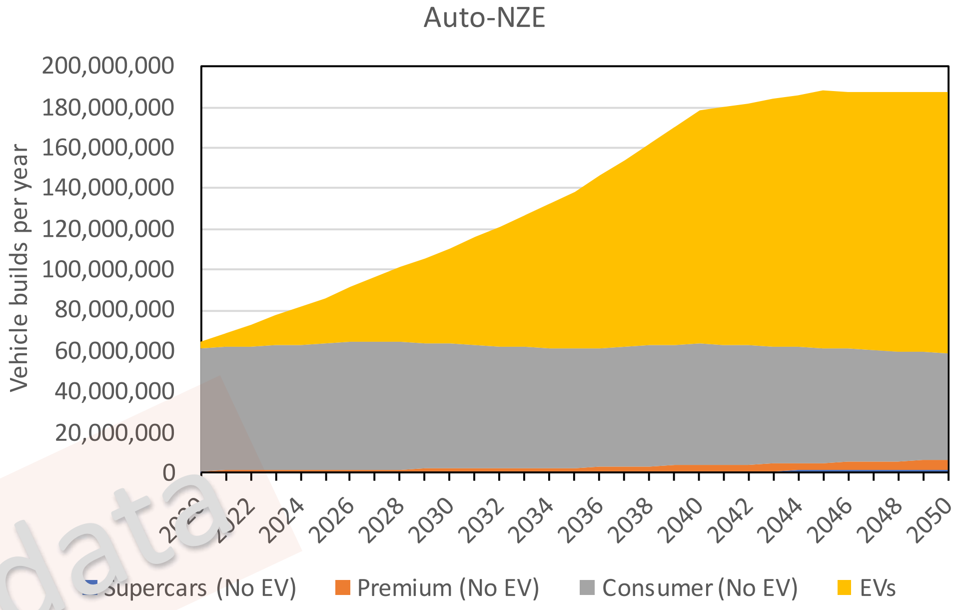


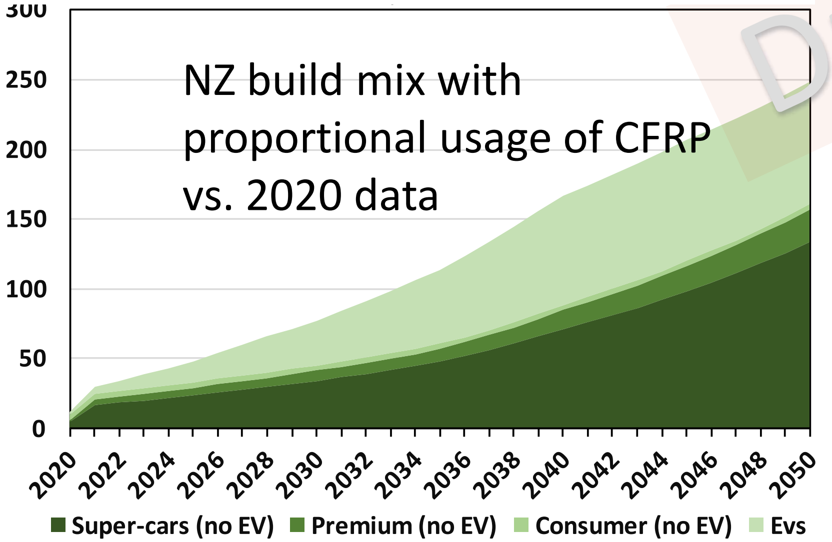
Fig. 5: BMW Group's plant in Landshut that produces the BMW iX's skeleton components

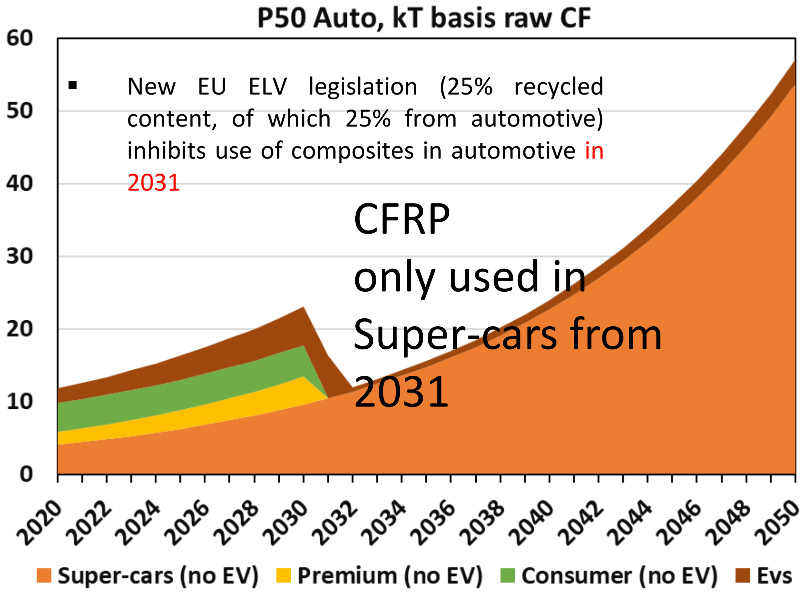
EPFL

Example for automotive (from IEA and McKinsey models)









Preliminary data subject to revision

Wind

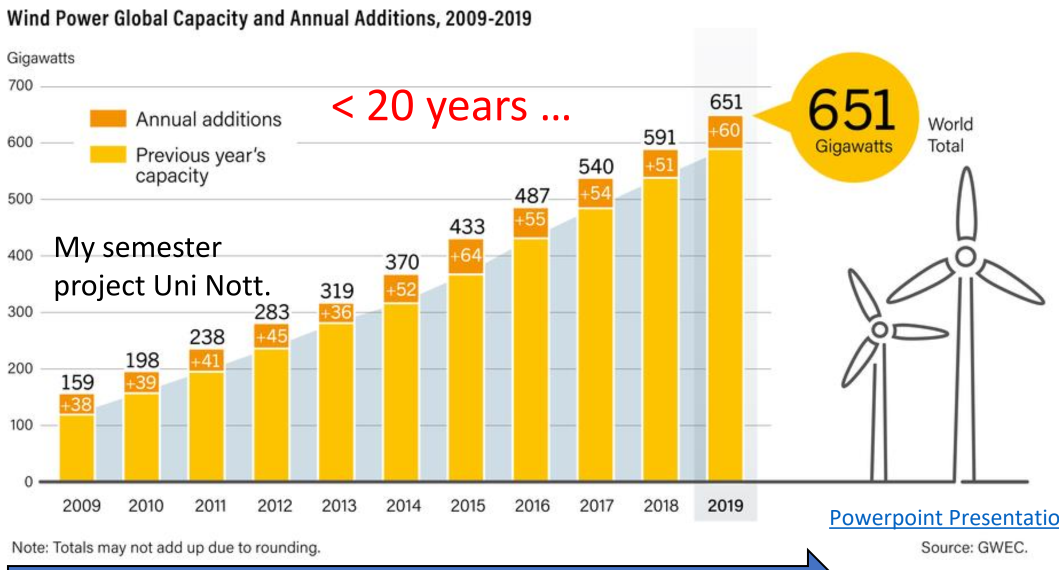
Scale of wind turbine blades …

A close up view of the rotor as it awaits installation of its third 61.5m blade. Source: LM Glasfiber

5MW rotor blade

These are seriously large composite structures

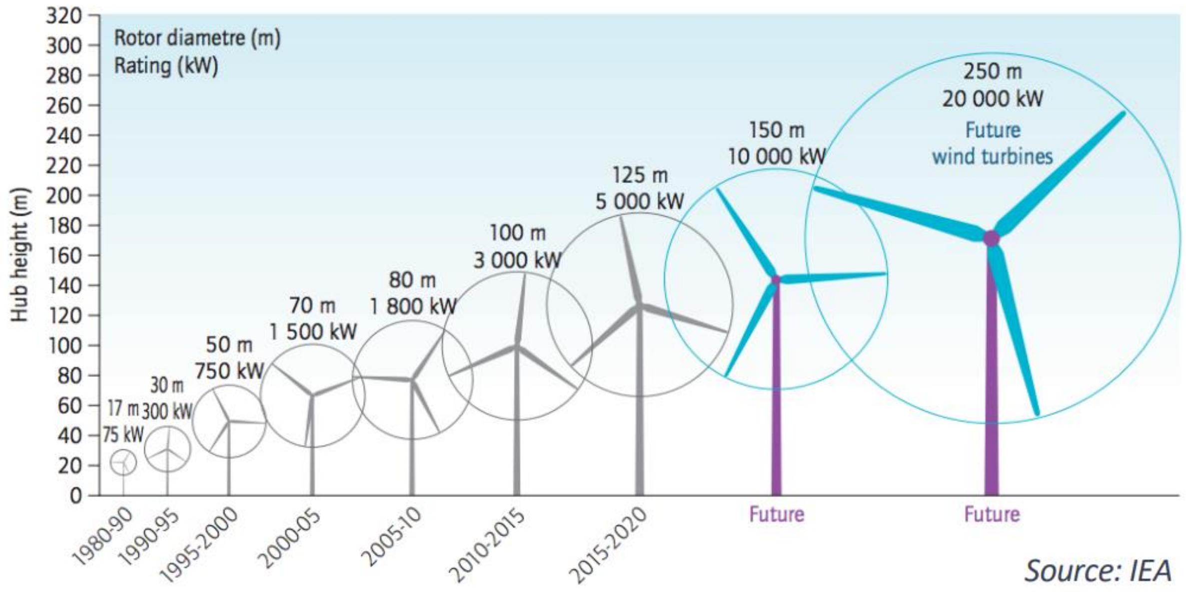
Wind turbine size and capacity with time

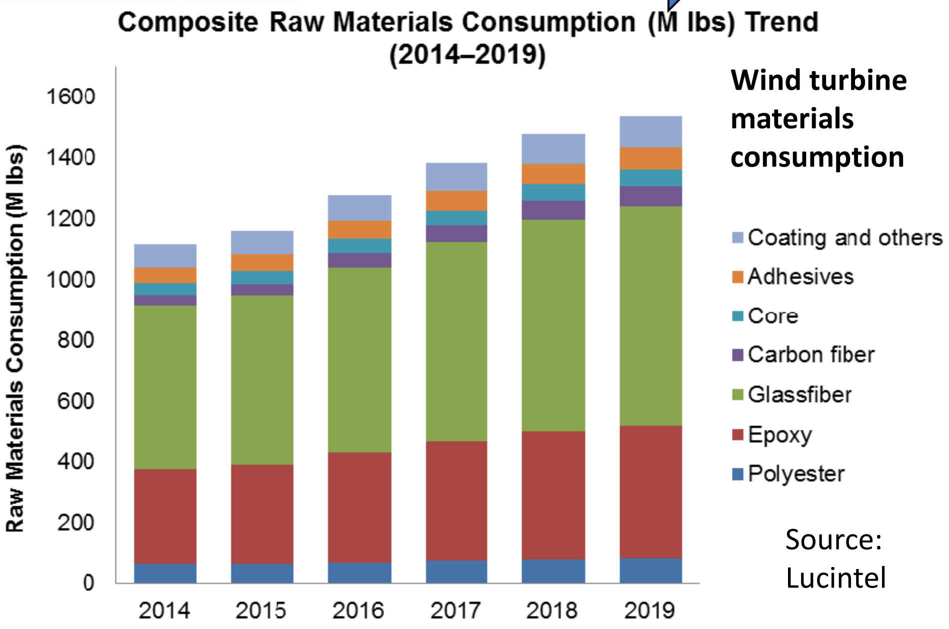


< 20 years …

My semester project Uni Nott.

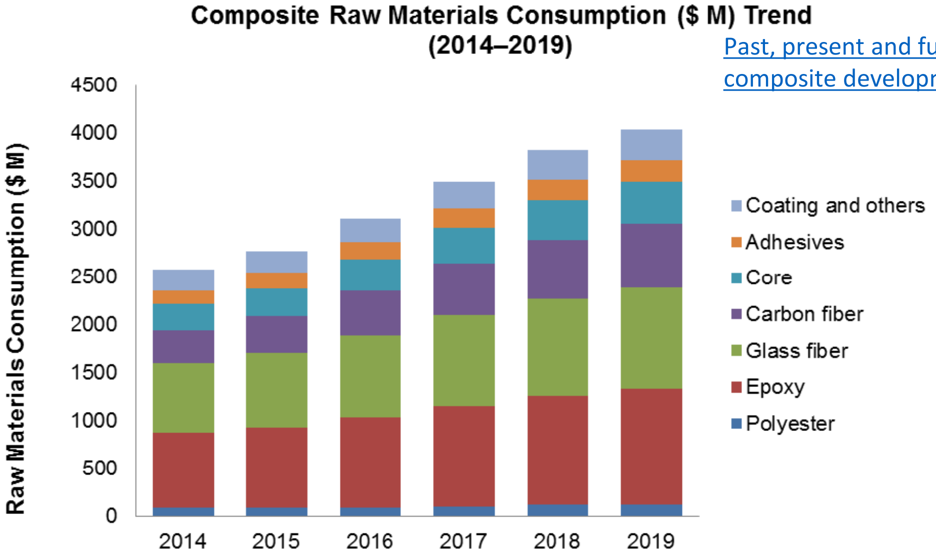
[Powerpoint Presentation (ren21.net)]



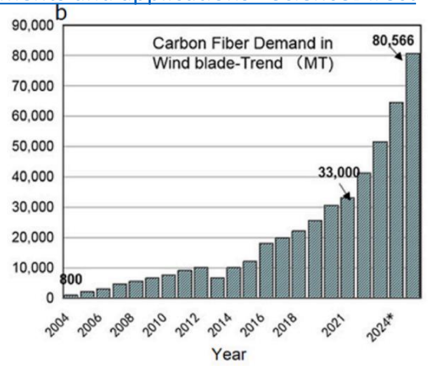


Wind turbine materials consumption

Source: Lucintel



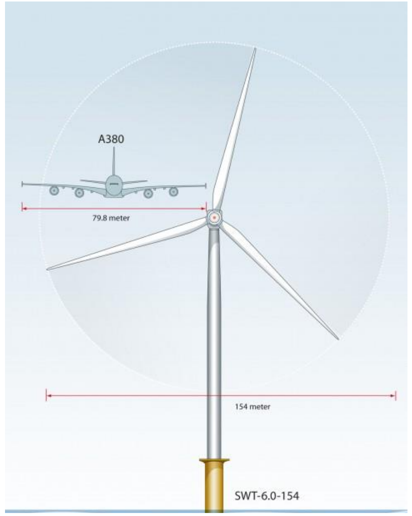
[Past, present and future prospective of global carbon fibre composite developments and applications - ScienceDirect]



EPFL

LPAC Laboratory for Processing of Advanced Composites

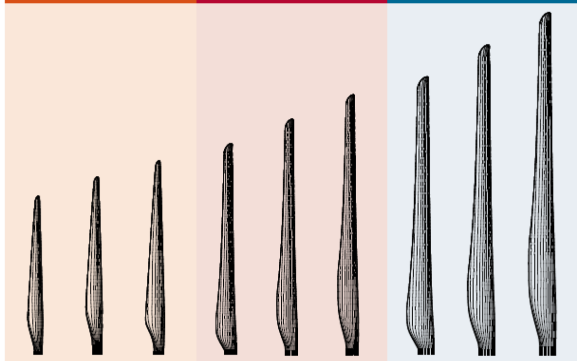
Wind energy: bigger blades, more composite



75-meter-long blades

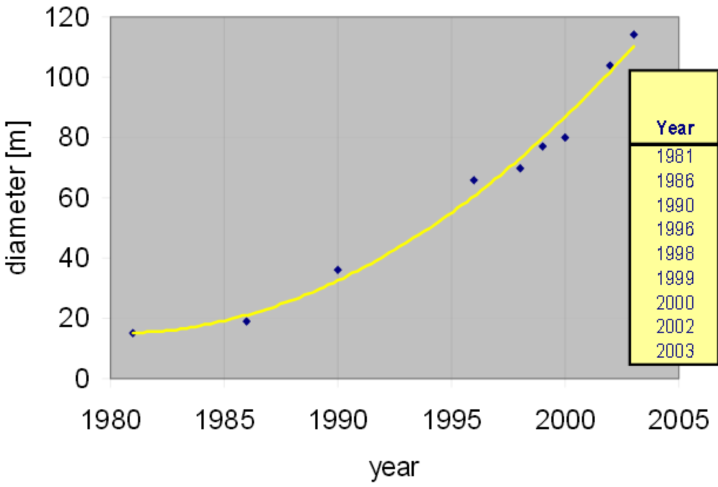
Range of products

Blade family EU51 I 55 I 59	Blade family EU70 I 77 I 80	Blade family EU90 I 100 I 120



	EU48–52	EU56	EU60 I 64	EU70	EU77	EU80	EU90	EU100	EU120
Bl[1]	23.5–25.5 m	27–27.5 m	29–31 m	33.5–35.5 m	36.5–37.5 m	39.0 m	44.0 m	48.8 m	58.6 m
Bs[2]	40 × M24	44 × M27	44 × M27	54 × M30	54 × M30	54 × M30	64 × M36	64 × M36	72 × M36
Bcd[3]	1200/1250 mm	1400 mm	1400 mm	1800 mm	1800 mm	2000 mm	2300 mm	2300 mm	3200 mm

[1] Blade length [2] Bolt size [3] Bolt circle diameter



Year	Turbine	Power Rating [kW]	Diameter [m]
1981	Vestas V15	55	15
1986	Vestas V19	90	19
1990	Vestas V36	500	36
1996	Enercon E66	1500	66
1998	Jacobs MD70	1500	70
1999	Tacke 1.5sl	1500	77
2000	Vestas V80	2000	80
2002	GEWind 3.6MW	3600	104
2003	Enercon E112	4500	114

Why composites? … Giga cycle fatigue

IEA R&D Wind Annex XI
Symposium on Wind Turbine Fatigue
DLR, Stuttgart
February 1-2, 1996

DAMAGE ESTIMATES FOR EUROPEAN AND U.S. SITES USING THE U.S. HIGH-CYCLE FATIGUE DATA BASE

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Wind Energy Technology
Sandia National Laboratories
Albuquerque, NM 87185-0708
Phone: (505)844-2037
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E-Mail: hjsuthe@sandia.gov

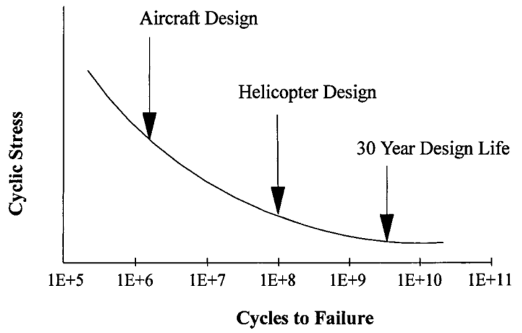
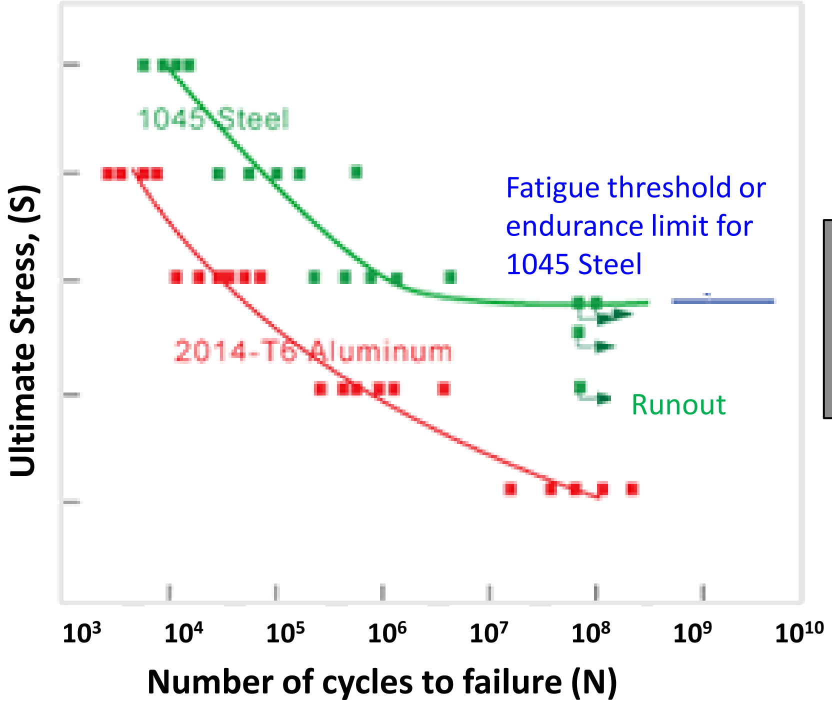


Figure 1. Schematic S–N diagram for various fatigue-critical structures



Aluminum alloys do not have a defined fatigue limit whereas steel alloys often do

Composites are widely used in "high cycle" fatigue, e.g. wind turbine blades

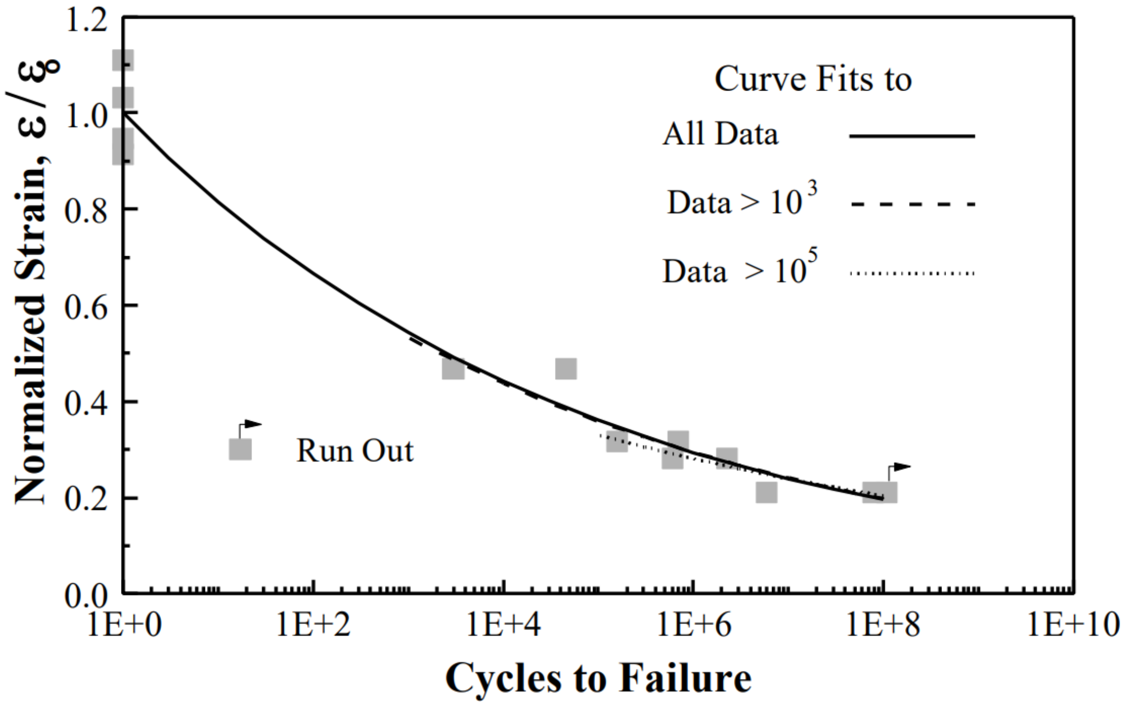
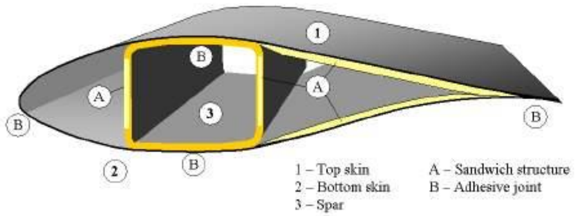


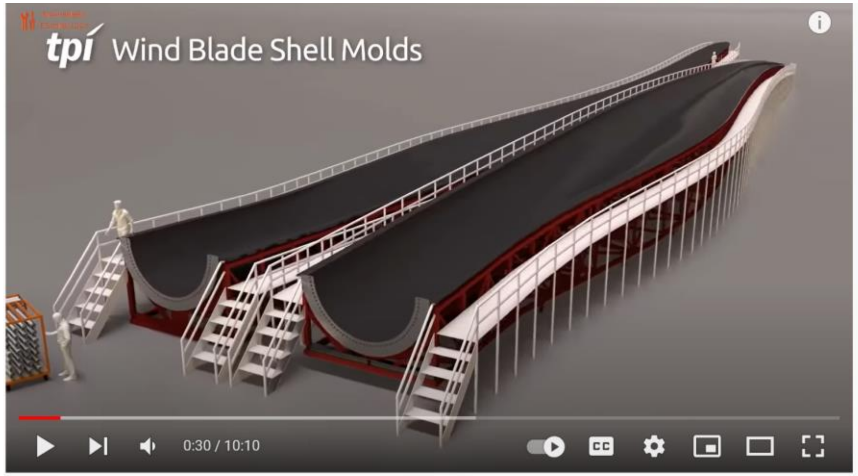
Figure 1. High cycle S-N data for R=0.1 with selected curve fits to the data.

Manufacture of a wind turbine blade

- Thermoset composites
- 2 skins and 1 spar assembled through structural bonding
- Vacuum infusion or pre-pregging of individual parts

WindEurope-Accelerating-wind-turbine-blade-circularity.pdf





This is How Wind Turbine Blades Work, Modern Technology Wind Turbine Production

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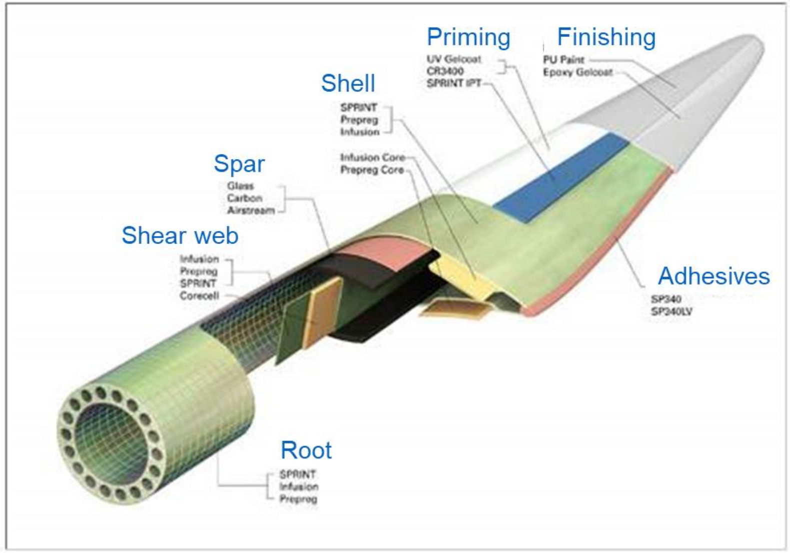
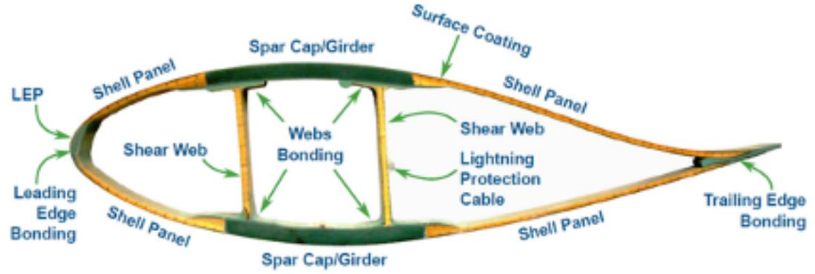


A diagram from a Gurit presentation on "Materials Technology for the Wind Energy Market" shows where Gurit materials may be applied within wind blades, as well as Gurit's definition of four key areas for materials development: root section; structural spar/ spar cap; aerodynamic fairing/shell; and surfacing system. Source: Gurit

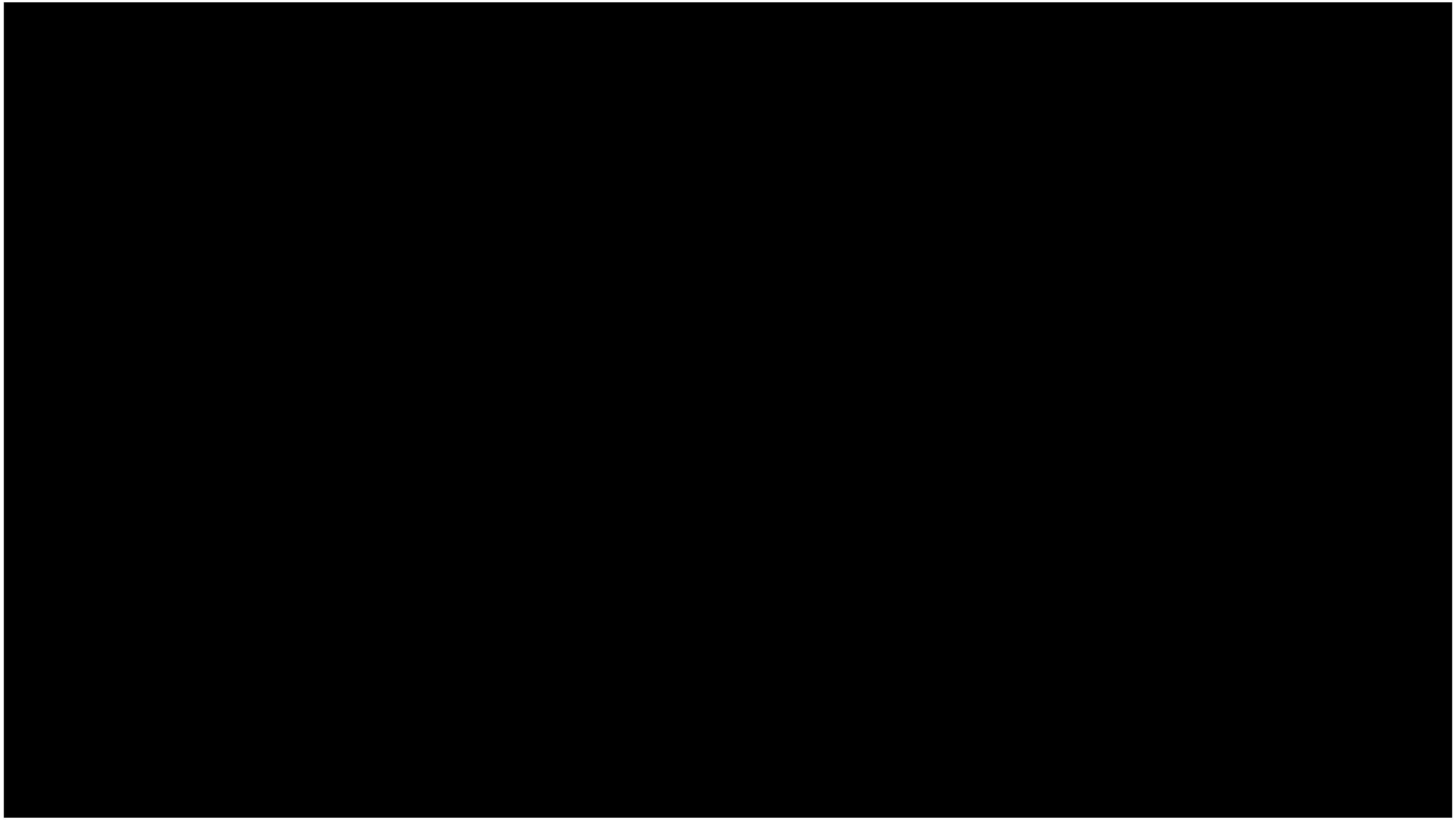
Generic cross-section of rotor blade



Spar Caps/Girders: Unidirectional (UD) Glass/Carbonfibre, supported by Epoxy, Polyester, Polyutherane or Vinylester matrix
Shear Webs and Shell Panels: Multiaxial GFRP Sandwich laminates using Balsa/PVC/PET as core material and Epoxy, Polyester, Polyutherane or Vinylester as matrix systems
Leading/Trailing Edge and Webs Bonding: Epoy/Polyutherane based structural adhesive
Lightning Protetion Cable: Aluminium or Copper
Surface Coating: Polyutherane based lacquer
LEP (Leading Edge Protection): Polyutherane based lacquer/tape

Source: TPI Composites

Manufacture of a wind turbine blade



[This is How Wind Turbine Blades Work, Modern Technology Wind Turbine Production - YouTube]

3min

Advanced blade designs

- Zoltek: manufacture of CF pultruded spar caps for turbine blades 55m in length and longer

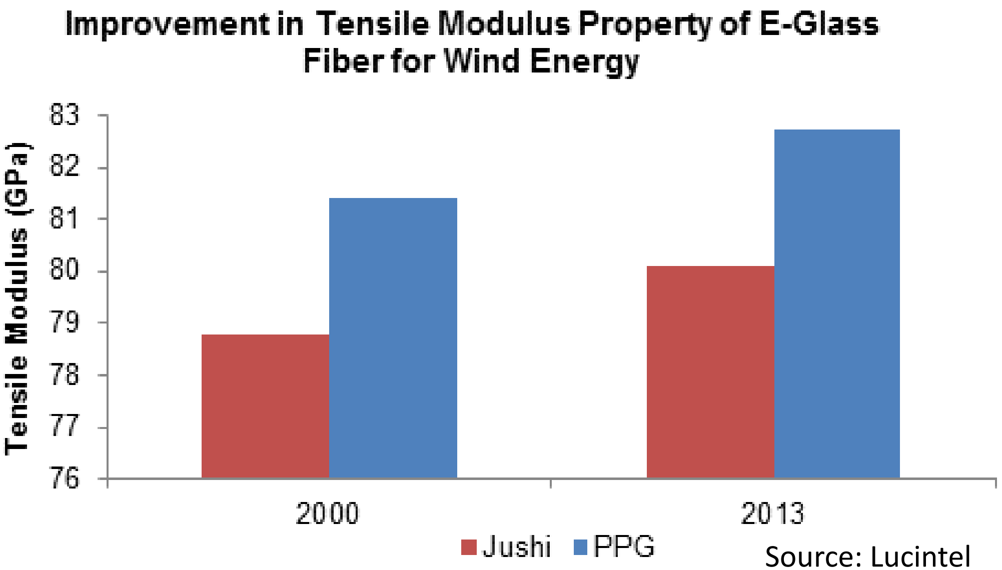
COMPETITIVE HIGH PERFORMANCE

HiPer-tex® high performance fibre is the result of a groundbreaking development in manufacturing technology that enables **high performance fibreglass** to be **produced at an attractive cost**:

- new glass formulation
- specific melting, fiberizing and sizing technologies
- high capacity production platform for scale economy.

Compared with traditional E-glass, HiPer-tex® high performance fibre typically provides:

- + 25% in strength
- + 45% in strain energy
- 10 x in fatigue resistance. [High performance glass | 3B Fibreglass (3b-fibreglass.com)]



Source: Lucintel

Summary

- Composite materials are an established material class
- Widely used in aerospace and performance automotive
- Early adoption in automotive (TPCs and TS systems)
- Significant use in wind applications
- Hydrogen storage applications covered in 3rd lecture

LPAC

Laboratory for Processing of Advanced Composites