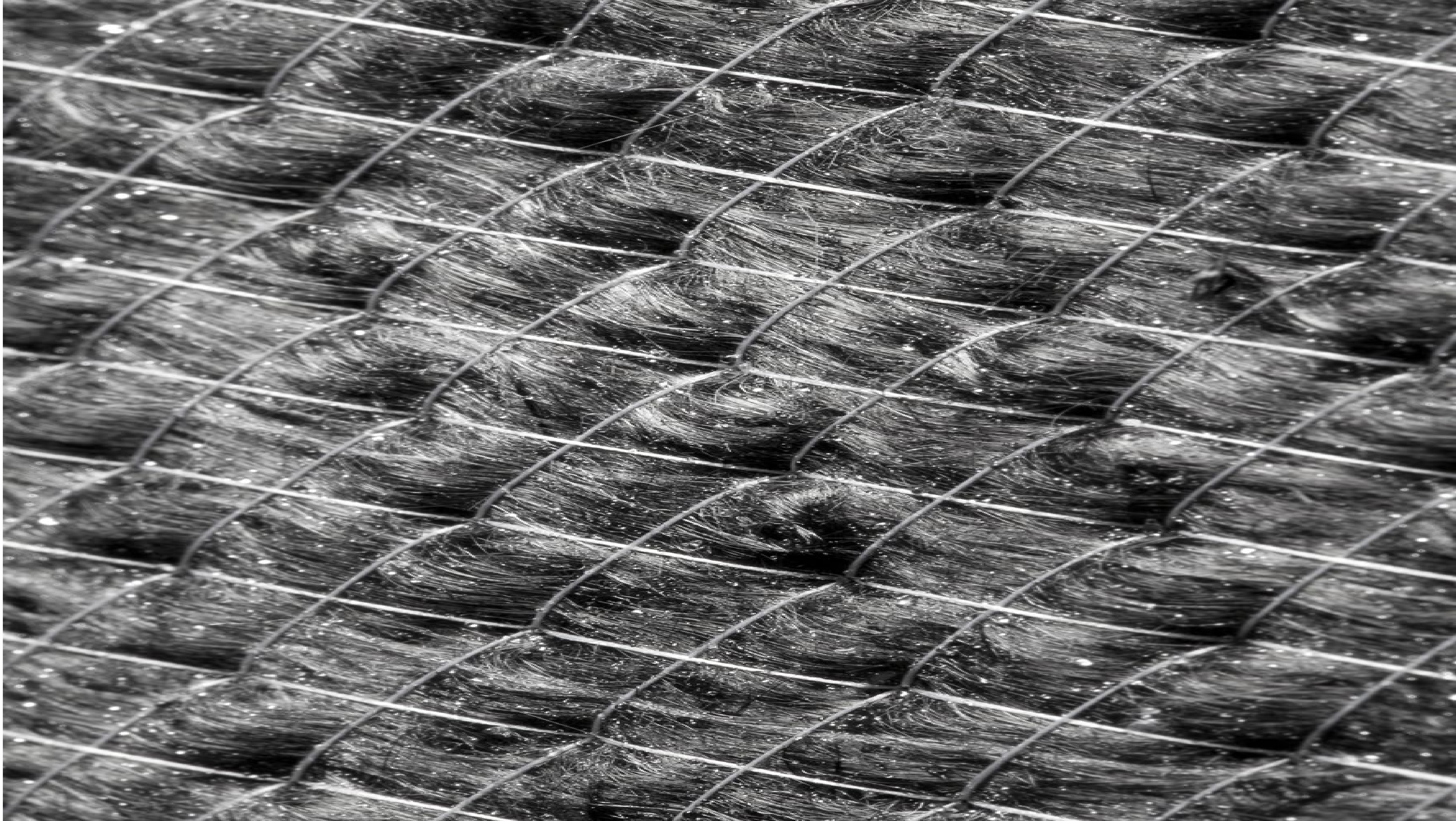
EPFL

Prof. Anastasios P. Vassilopoulos

Advanced composites in engineering structures

GRoMeC
Composite Mechanics Group

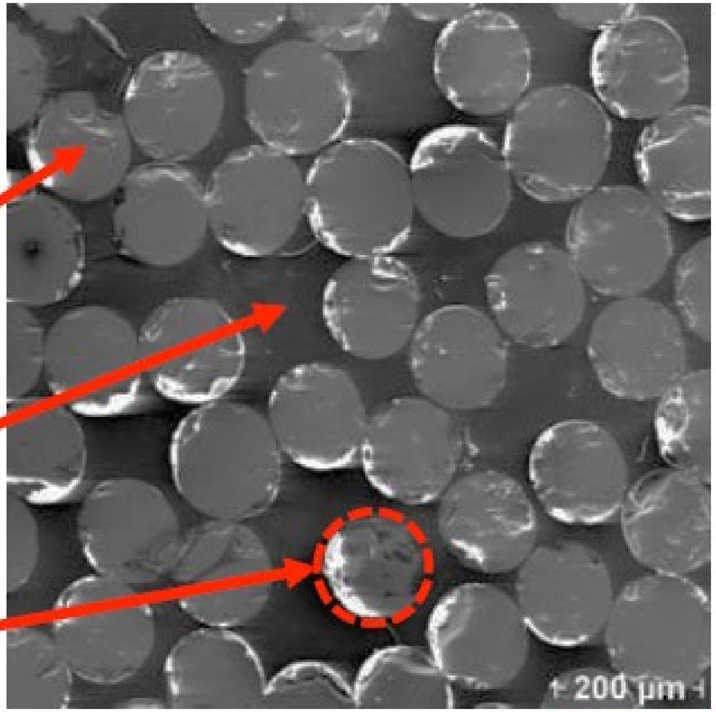


What is a composite material?

- The lexical meaning leads to any material that consists of more than two phases…
- Structural composite materials:
  - Materials having strong fibers (or other strengthening mean) surrounded by a weaker matrix material. The matrix serves to distribute the fibers and also to transmit the load to them.

What is an (advanced) composite material?

e.g. glass fibres *mixed* into a polymer resin



Fibre–matrix interface

200 µm

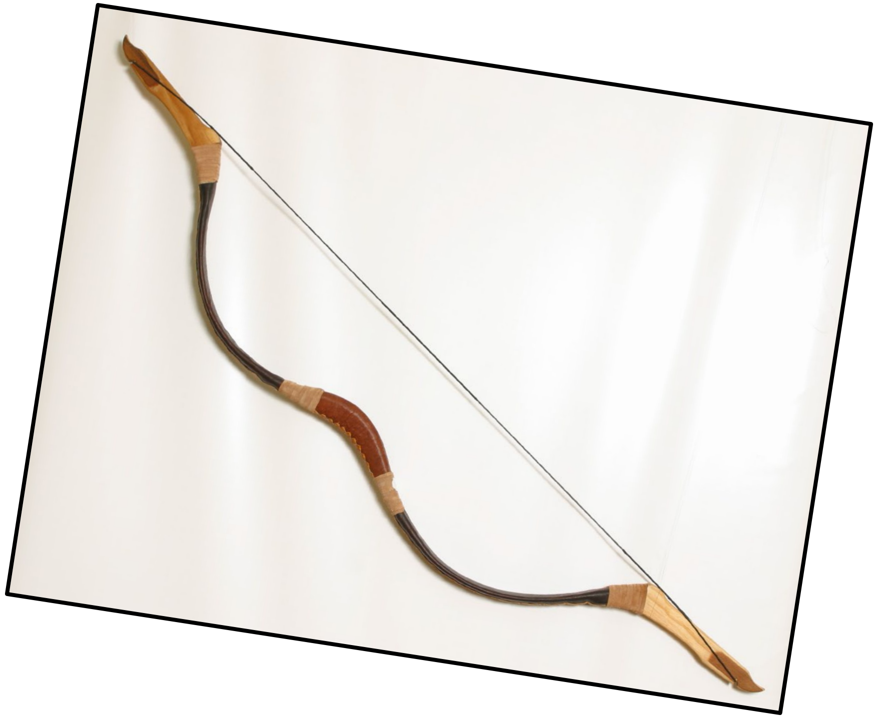
Are they new?

- Composites are used since the ancient times
- Mesopotamia (glued wood strips at dif. Angles to create plywood)
- Mongolian arcs
- Japanese swords
- Achilles buckler
  - more…

www.compositeslab.com/composites-101/history-of-composites

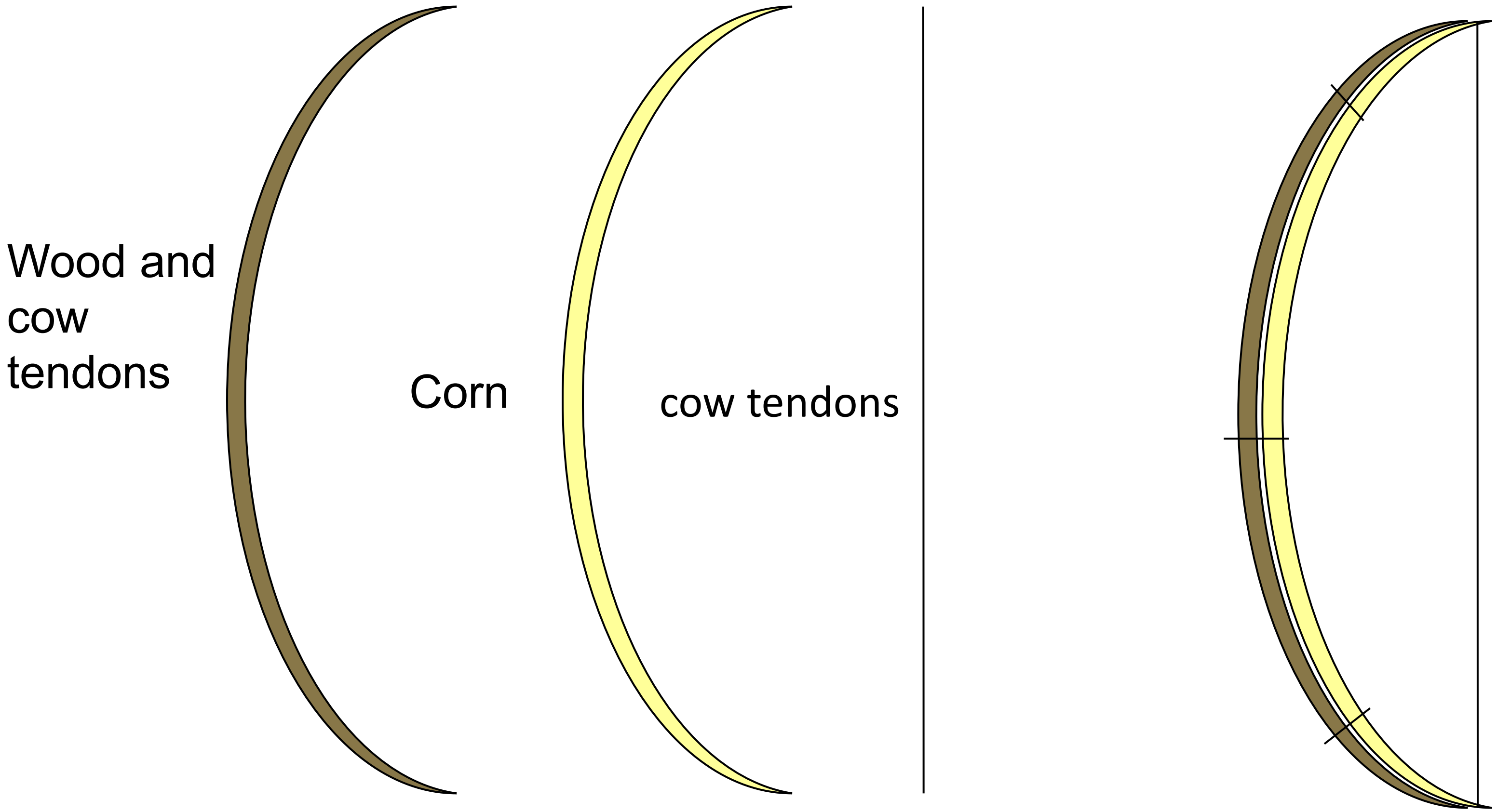
The Mongolian arcs

- Mongol Bow is a composite bow made of wood, tendons, and horn held together by a glue made from fish bladder, with the compressed parts made of corn,



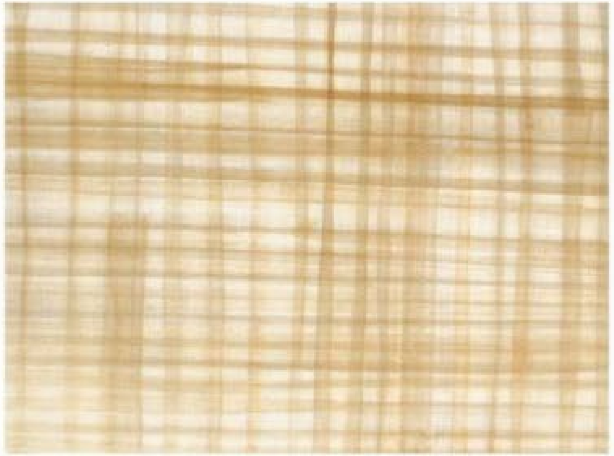
http://www.viahistoria.com/SilverHorde/main.html?MongolArchery.html

The Mongolian arcs



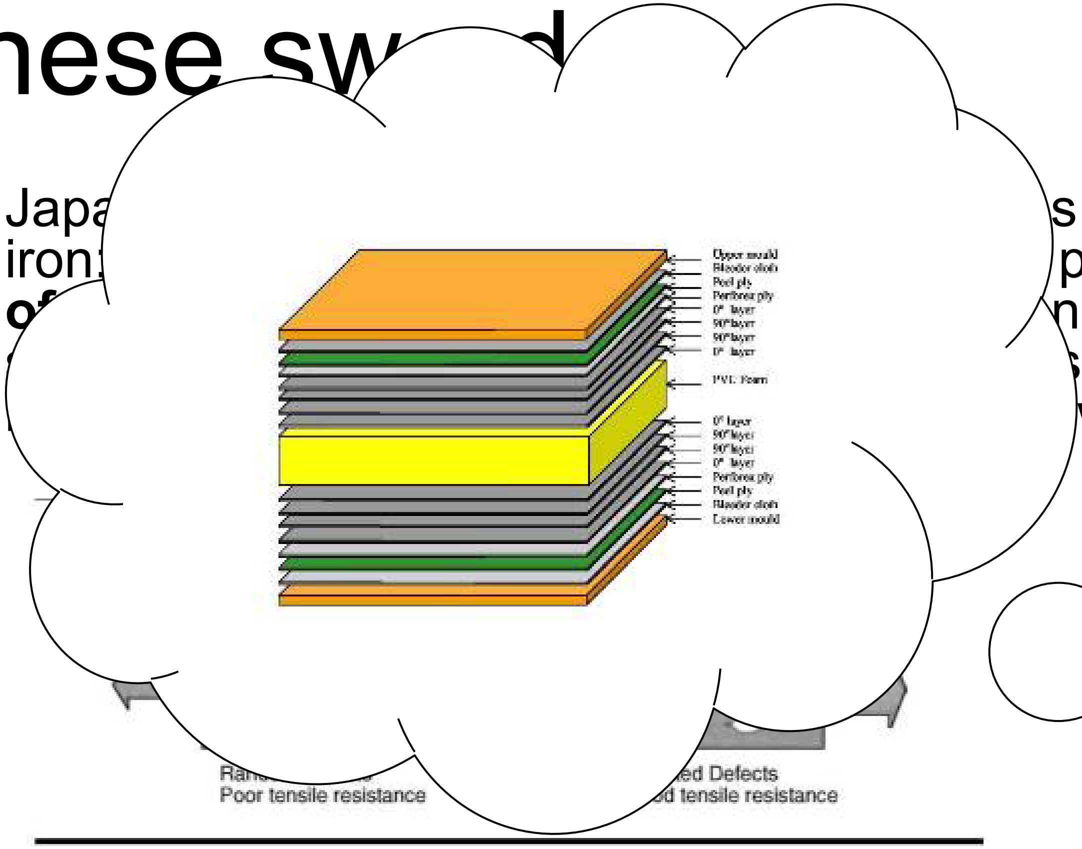
Papyrus (Egypt, <4000 BC)

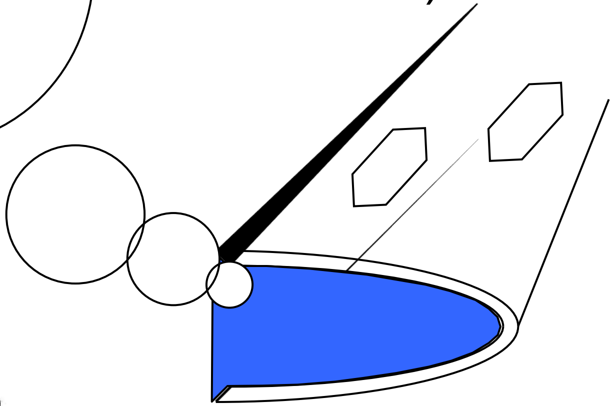
- Laminated writing material from the papyrus plant (Bio!)



Japanese sw d

- Japa s made of steel and soft iron: paste, **with orientation of** n, then formed into a U sword then has good wich structure)





References in ancient text

- References to highly interesting structures exhibiting elements of almost modern technology can also be found in the Homeric epics. The shields of Achilles and Ajax Telamonius – son of Telamon, king of Salamis – are presented **as laminated structures consisting of successive layers** of different metals, and metal and leather layers respectively and are characteristic examples of the advanced knowledge of the science and technology of materials and structures possessed by the Mycenaean Greeks. Metals of particular interest in this respect were hard bronze, tin and pure gold (shield of Achilles) and hard bronze and calf's leather (shield of Ajax). The manufacture of Achilles' armor – by Hephaestus – is described in detail in the Iliad. The description refers to a laminated composite structure, consisting of five consecutive metal laminates with very different mechanical properties. In fact, the shield consists of two external laminates of hard bronze, two internal ones of tin and a central one of pure (soft) gold. This structure exhibits maximum penetration resistance, as proved by a complete numerical simulation of its elastoplastic behavior at large deformations, when impacted by the tip of a piercing element, an arrow or spear for example. The shield of Ajax presented a similar configuration, which according to Homer was a multi-layered structure consisting of eight consecutive laminae - an external lamina of hard bronze and seven layers of calf's leather underneath. The impressive impact properties of this structure are also praised in the Iliad:

  - "…The spear struck the sevenfold shield in its outermost layer – the eighth which was of bronze – and went through six other layers but in the seventh hide it stayed…" from Iliad's description of the duel between Ajax and Hector. These unique detailed descriptions, which also include the weapon's battle behavior, constitute the first known applications of laminated structures in human history*.

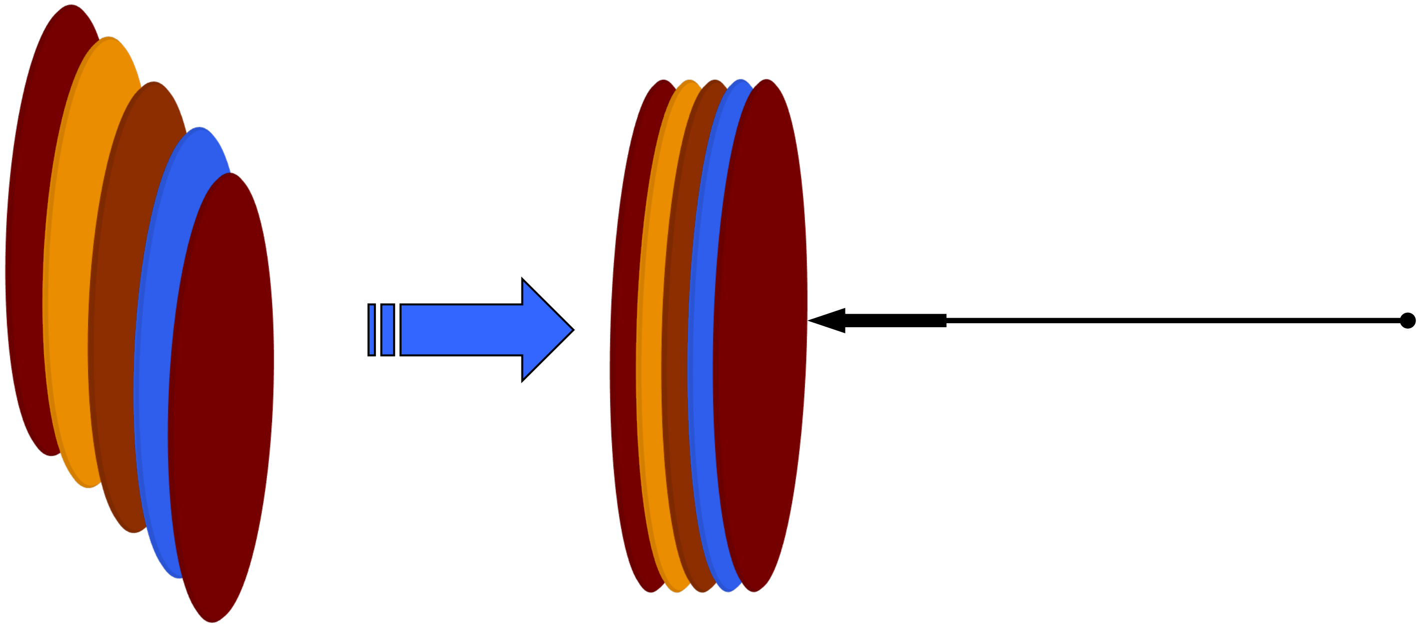
- Also in the Bible, Exodus 5.15-18 it is described how the people mixed straws with mad to fabricate bricks…

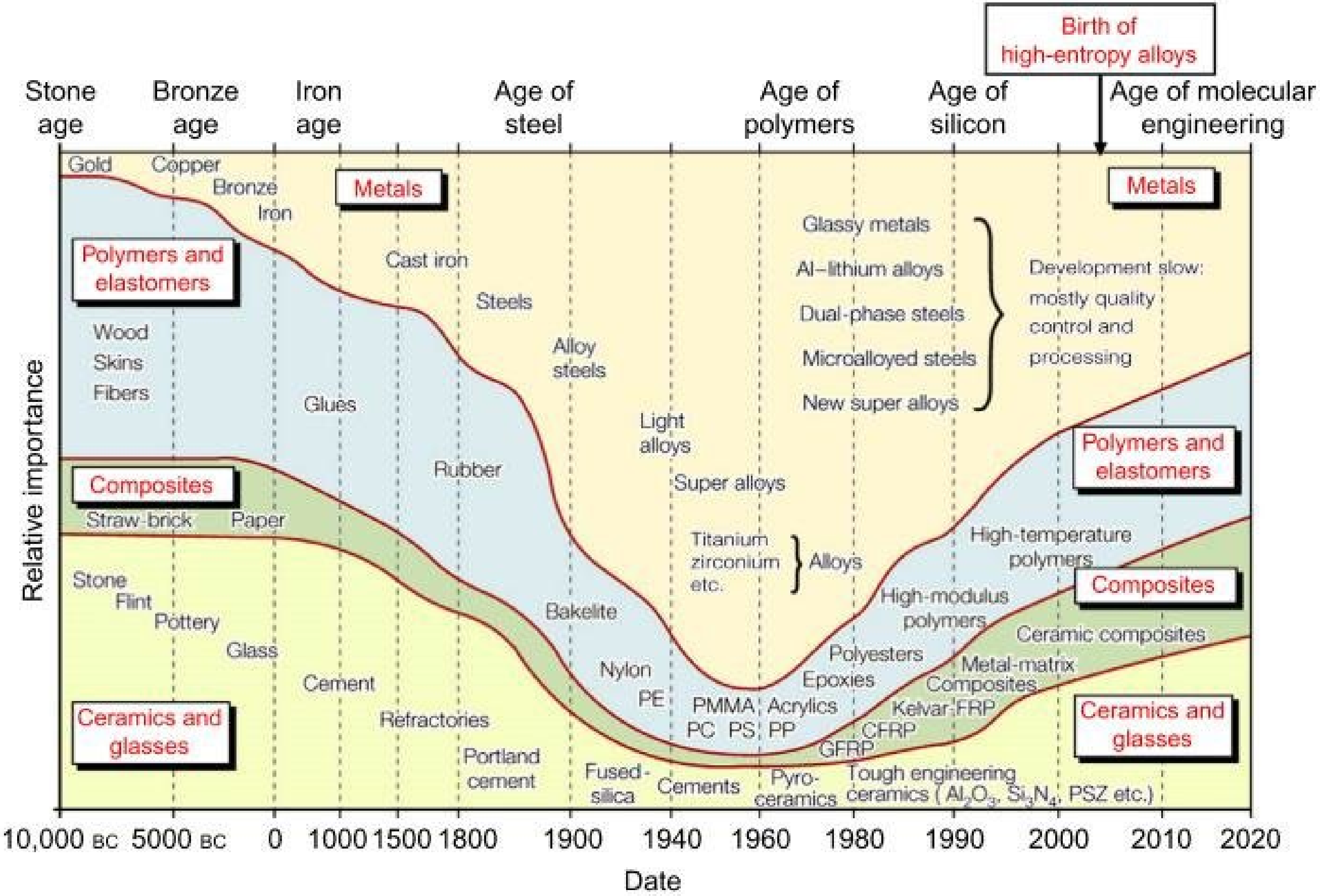
* A. P. Vassilopoulos, T. Keller, Fatigue of fiber-reinforced composites, Springer 2011

https://kosmossociety.chs.harvard.edu/?p=20932

Achilles' buckler

- In ancient Greece (<1000 BC): Bucklers were made from different layers of metal, leather, wood and (soft) gold to provide shielding against impact.



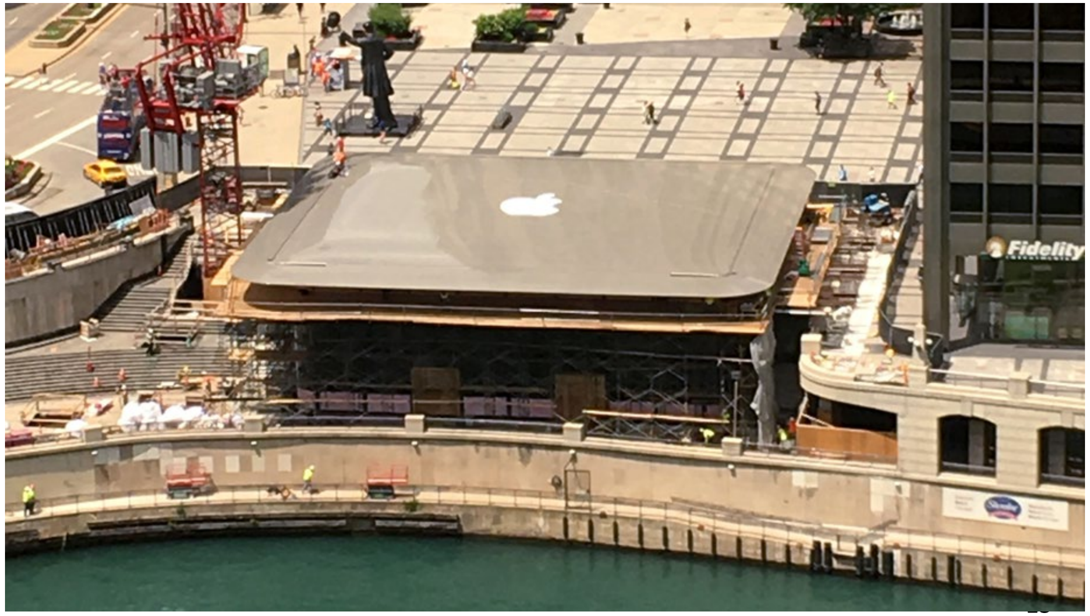

Birth of high-entropy alloys
Stone age
Bronze age
Iron age
Age of steel
Age of polymers
Age of silicon
Age of molecular engineering
Gold
Copper
Bronze
Iron
Metals
Polymers and elastomers
Wood
Skins
Fibers
Glues
Cast iron
Steels
Alloy steels
Light alloys
Super alloys
Titanium zirconium etc.
Alloys
Glassy metals
Al–lithium alloys
Dual-phase steels
Microalloyed steels
New super alloys
Development slow: mostly quality control and processing
Metals
Polymers and elastomers
Composites
Straw-brick
Paper
Rubber
Bakelite
Nylon
PE
PMMA
Acrylics
PC
PS
PP
Polyesters
Epoxies
High-temperature polymers
High-modulus polymers
Composites
Ceramic composites
Metal-matrix Composites
Kelvar-FRP
CFRP
GFRP
Stone
Flint
Pottery
Glass
Cement
Refractories
Portland cement
Fused-silica
Cements
Pyro-ceramics
Tough engineering ceramics (Al_2O_3, Si_3N_4, PSZ etc.)
Ceramics and glasses
Ceramics and glasses
Relative importance
10,000 BC
5000 BC
0
1000
1500
1800
1900
1940
1960
1980
1990
2000
2010
2020
Date

Contemporary composite structures


Fidelity

Composite projects in Switzerland and abroad

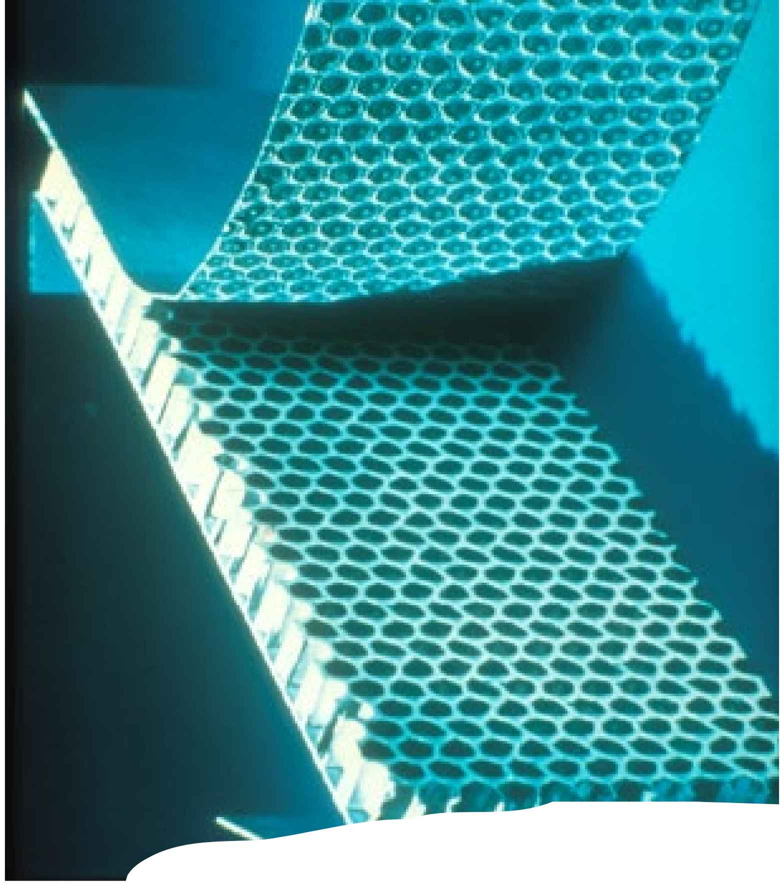
Foster + Partners - Apple's Steve Jobs Theater Pavilion (Cupertino, California)

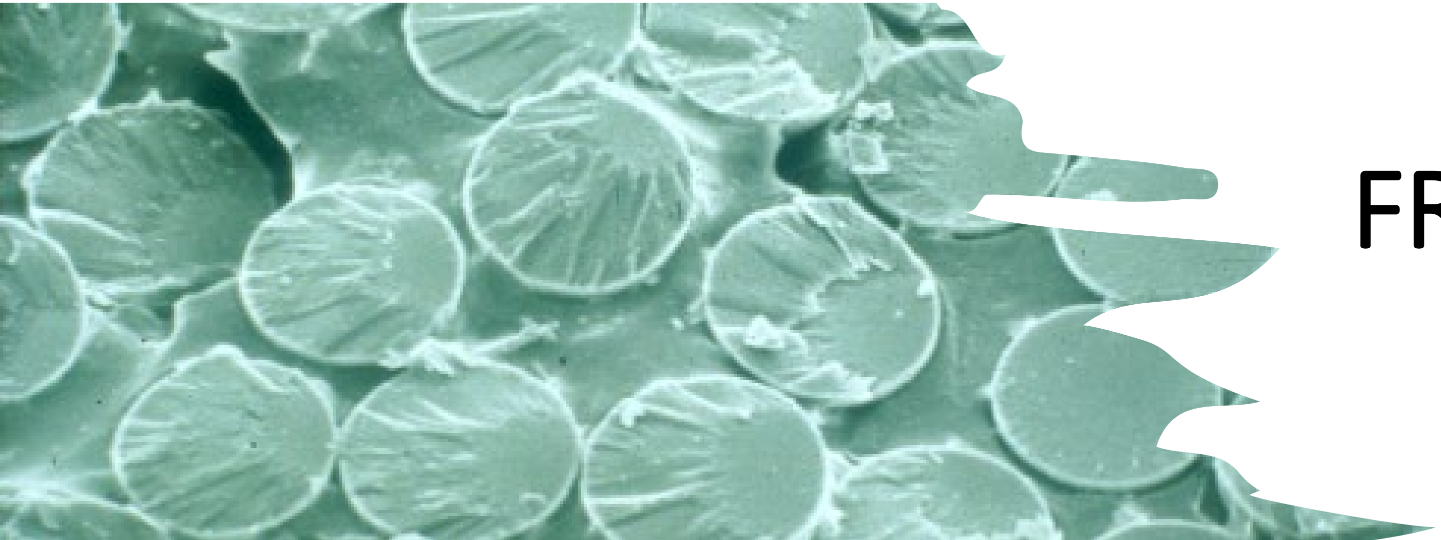


Apple shop - Chicago

Composite projects in Switzerland and abroad

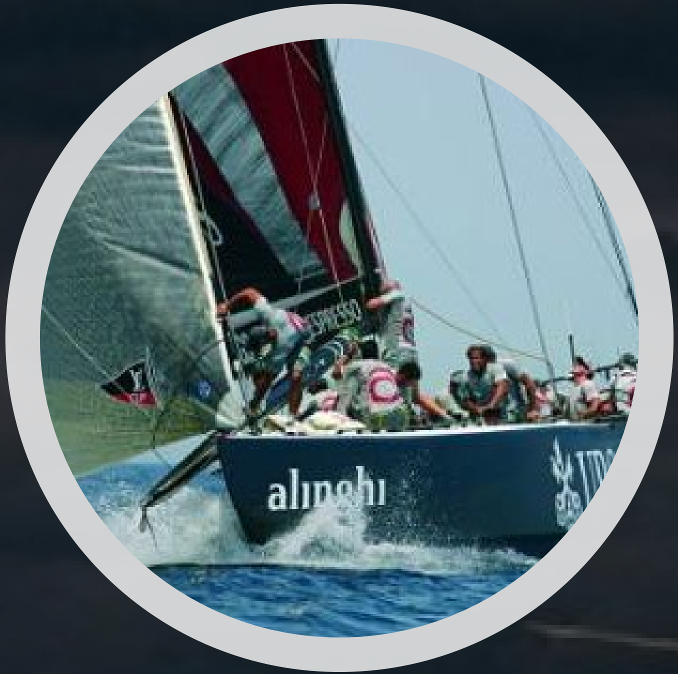
- Weighing 80.7 tons (73.2 metric tons), the impressive roof structure is described by the design team as the "largest carbon-fibre roof in the world". It is made up of 44 identical radial panels, which were assembled on site and then lifted into place in one go on top of the 41m diameter pavillion.
- https://www.dezeen.com/2018/11/21/steve-jobs-theater-pavilion-foster-partners-apple-park/

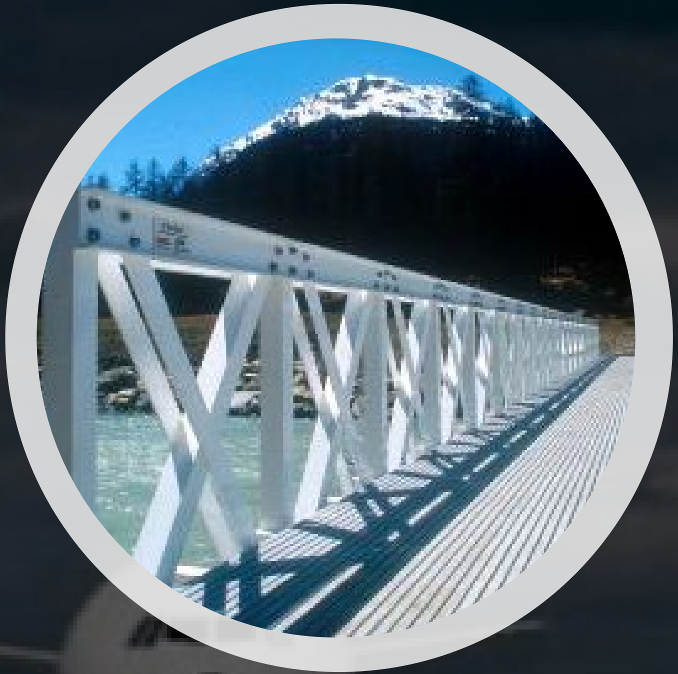




FRP Materials

Applications

Applications

The Startlink – lightweight building systems

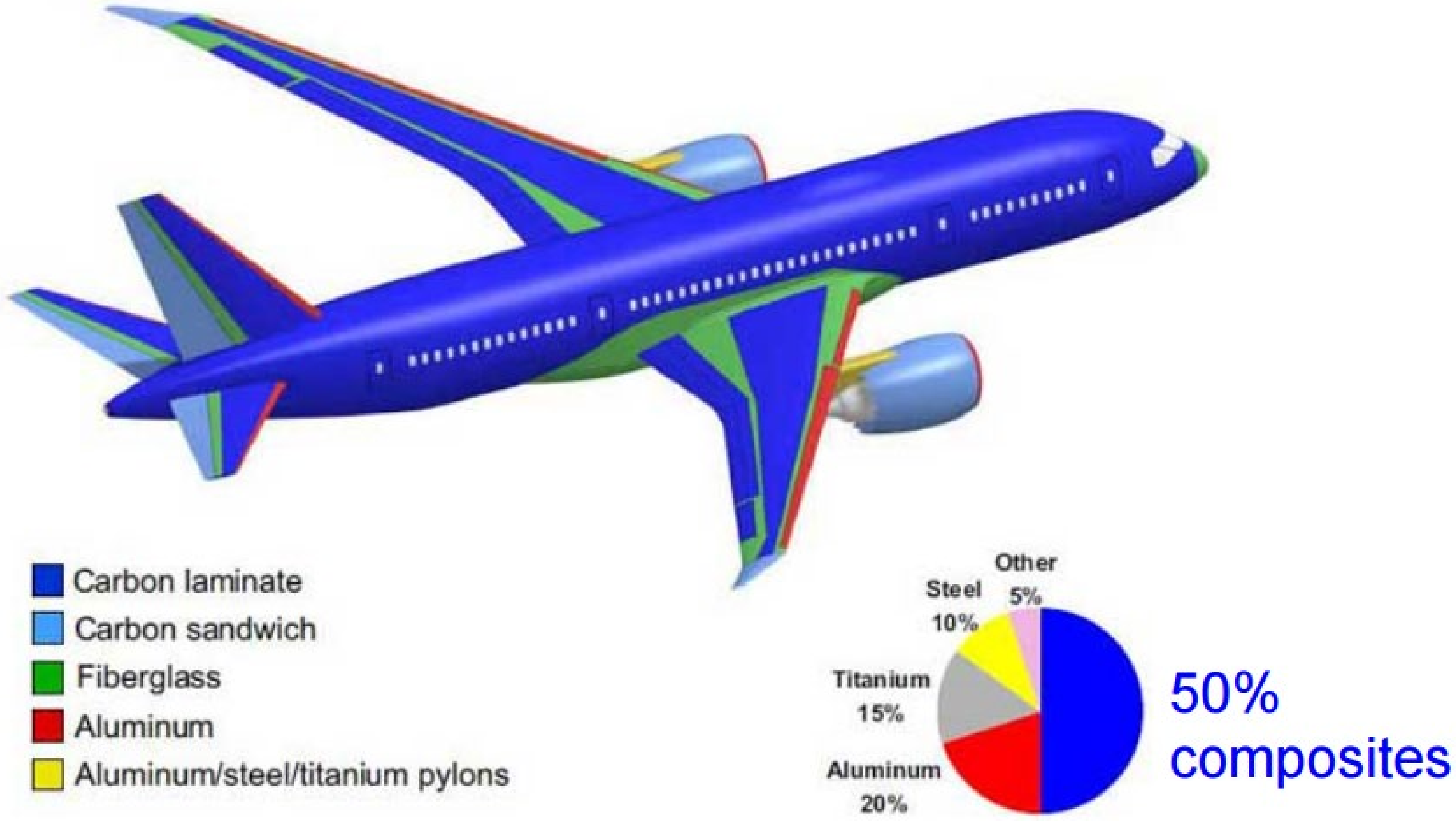
Composites profiles used in trains/trams

CFRP tubes – pavilion

Trench shoring system

(non conductive)

Boeing 787 Dreamliner



WHAT CAN BE MADE USING COMPOSITE MATERIALS?

The range of applications is very large. A few examples are shown below.

- **Electrical, Electronics**
  - Insulation for electrical construction
  - Supports for circuit breakers
  - Supports for printed circuits
  - Armors, boxes, covers
  - Antennas, radomes
  - Tops of television towers
  - Cable tracks
- **Buildings and Public Works**
  - Housing cells
  - Chimneys
  - Concrete molds
  - Various covers (domes, windows, etc.)
  - Swimming pools
  - Facade panels
  - Profiles
  - Partitions, doors, furniture, bathrooms

WHAT CAN BE MADE USING COMPOSITE MATERIALS?

Road Transports	Body components	Complete body	Wheels, shields, radiator grills,	Transmission shafts	Suspension springs
Bottles for compressed petroleum gas	Chassis	Suspension arms	Casings	Cabins, seats	Highway tankers, isothermal trucks
Rail transports:	Fronts of power units	Wagons	Doors, seats, interior panels	Ventilation housings	

WHAT CAN BE MADE USING COMPOSITE MATERIALS?

Bridges
Wind energy (Wind turbine rotor blades)

Marine Transports:
- Hovercrafts
- Rescue crafts
- Patrol boats
- Trawlers
- Landing gears
- Anti-mine ships
- Racing boats
- Pleasure boats
- Canoes
- All composite passenger aircrafts

Air transports
- All composite gliders
- Many aircraft components: radomes, leading edges, ailerons, vertical stabilizers
- Helicopter blades, propellers
- Transmission shafts
- Aircraft brake discs

WHAT CAN BE MADE USING COMPOSITE MATERIALS?

- **Space Transports**
- Rocket boosters
- Reservoirs
- Nozzles
- Shields for atmosphere reentrance

- **General mechanical applications**
- Gears
- Bearings
- Housings, casings
- Jack body
- Robot arms
- Fly wheels
- Weaving machine rods
- Pipes
- Components of drawing table
- Compressed gas bottles
- Tubes for offshore platforms
- Pneumatics for radial frames
- Sports and Recreation
- Tennis and squash rackets
- Fishing poles
- Skis

Based on

traditional

Design concepts

A composite fuselage section

The wing lower cover for Airbus' A350 XWB measures approximately 32 meters long by six meters wide, making it the largest carbon fiber part ever produced in civil aviation.

Eyecatcher Building

In the construction engineering field, composites have been initially used to replace conventional materials like steel, or concrete in order to achieve lightweight, easily assembled structures. A typical example of this concept is the Eyecatcher building in Basel, Switzerland. A 15-m-tall, five-story, mobile, lightweight building, it is the tallest multistory GFRP building in the world.

Location 1999: Basel-Mustermesse

Location 2002: Basel-Dreispitz

The pontresina bridge

- The Pontresina bridge is a temporary lightweight pedestrian bridge, installed each year in the autumn and removed in the spring. Two 2x12.50-m truss girder spans, with adhesively-bonded joints in one span (fully load-bearing) and bolted joints in the other span, were used and additional structural safety was provided by a redundant truss and joint configuration.

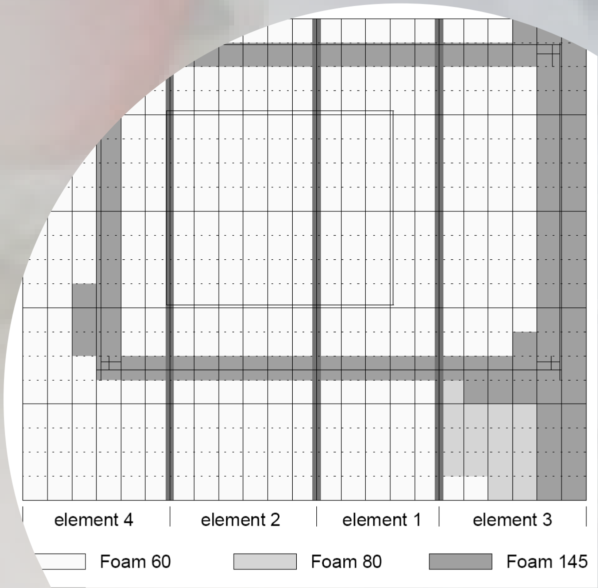
The pontresina bridge

The pontresina bridge

Novartis roof

- The sandwich roof construction integrates static, building physical and architectural functions, **allowing the prefabrication of the entire roof in only four lightweight elements that were easily transported to the site and rapidly installed**.
- The cutting of foam blocks with a computerized numerical control machine and adhesive bonding proved to be advantageous procedures for the fabrication of the complex roof shape, without the use of expensive molds.

CNC-cutting of 460 individual foam blocks



Roof installation on site: simple transport and installation of large-scale elements

Adhesively bonded joints

Prefabrication

The degree of prefabrication guaranteed a high-quality fabricated composite structural element, quality control of fabrication since it can be performed in well-controlled laboratory conditions, and results in reduced construction times compared to conventional building procedures. In special cases, bridge structures for example, the advantage is even greater since prefabrication and fast installation also means reduced traffic interference. The lightweight characteristic of composite materials can in this case also offer considerable savings in dead loads and therefore allow the bridge widening (on the same foundation) to accommodate more traffic.

Avançon Bridge, Bex, 2012: GFRP-balsa sandwich bridge deck

Old one-lane bridge

Bridge deck fabrication

Installation

Pre-assembly on site

Free formability

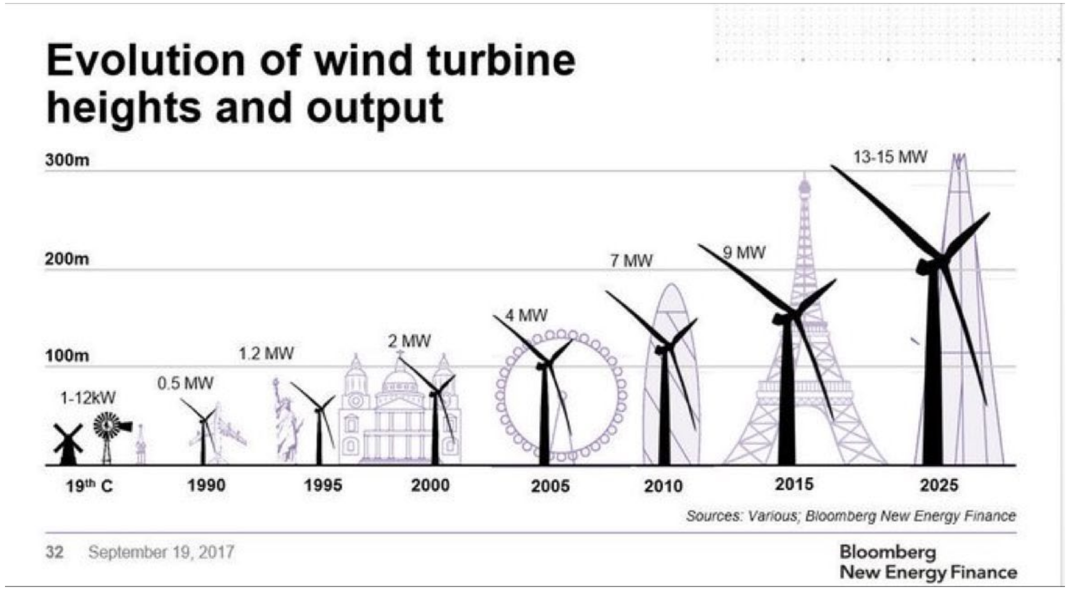
Although for the above-mentioned examples and numerous other applications the substitution of conventional materials by FRP composites has been proved successful, **this practice prevents engineers from taking advantage of one of the most attractive characteristics of composite materials**. These “advanced” materials allow engineers to adopt a different approach to design problems, propose alternative design concepts (**based on the free formability and lightweight characteristics of composites**) and redesign structures. It is thanks to this free formability concept and the superior specific mechanical properties offered by FRP composites that the wind industry grew so rapidly during the last quarter of the 20th century and is still growing by using hybrid tailor-made materials in order to meet the requirements for today’s “huge” wind turbine rotor blades

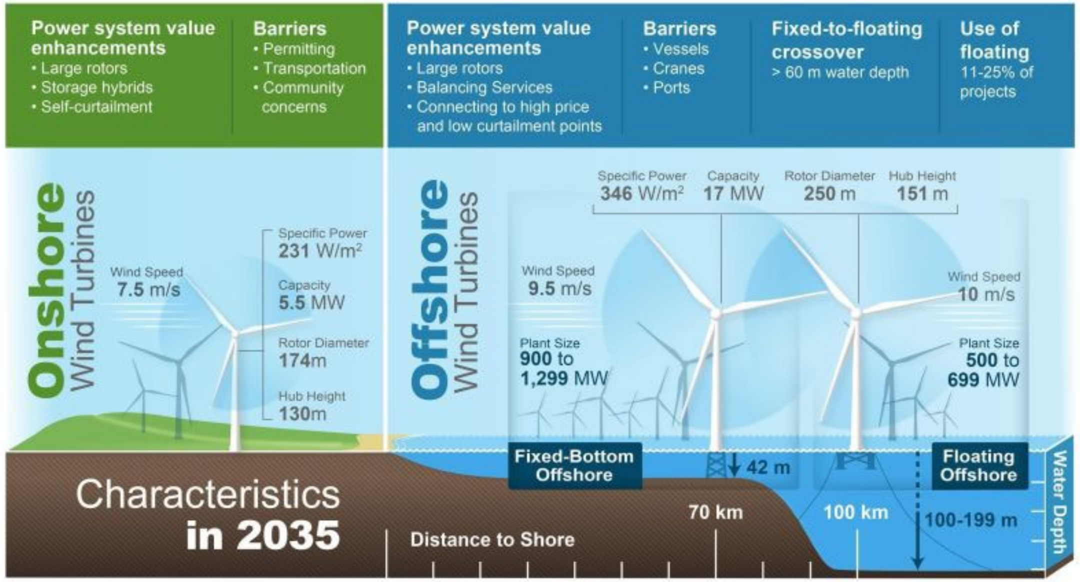
Differentiating the perceptual design concept!

The world's largest wind turbine blade on the road

This is the world's largest wind turbine blade en route to the largest offshore wind turbine in the world, in Methil, Scotland. At an incredible 273.95 feet (83.5 meters) long by 13.7 feet (4.2 meters) wide, the blade had to be transported all the way from Denmark, where it was manufactured —a logistical nightmare.

It was installed on a 7-megawatt test offshore turbine made by Samsung Heavy Industries, which will start producing energy in 2015. Here's a video of the installation, from April 4:

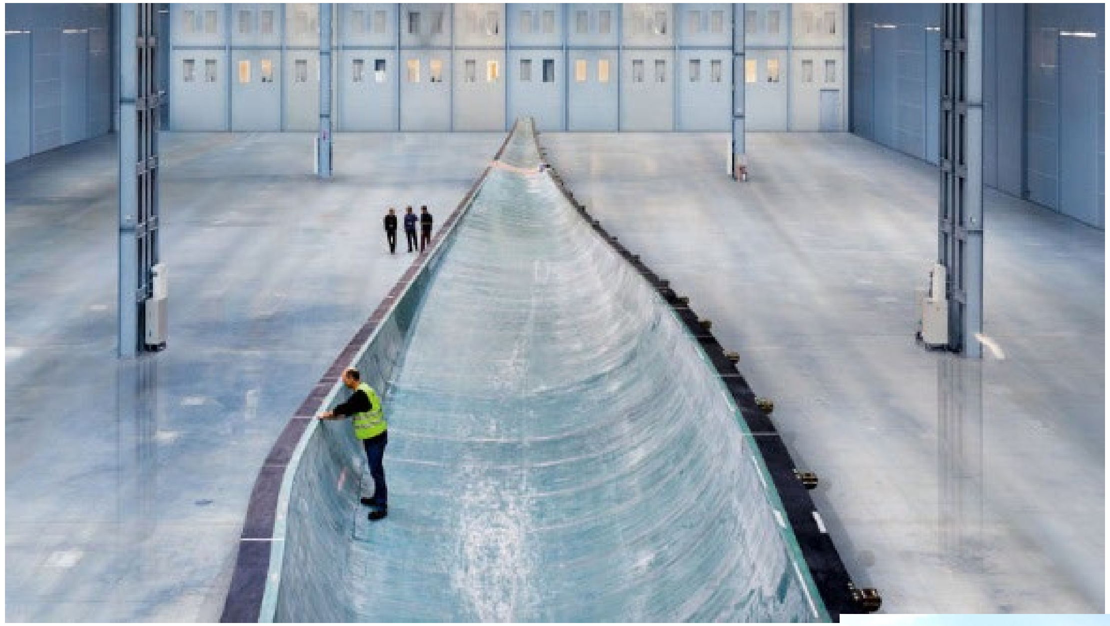




The longest wind turbine rotor blade (2020)

At 107 meters,
LM Wind Energy's blades
for the Haliade-X
12MW

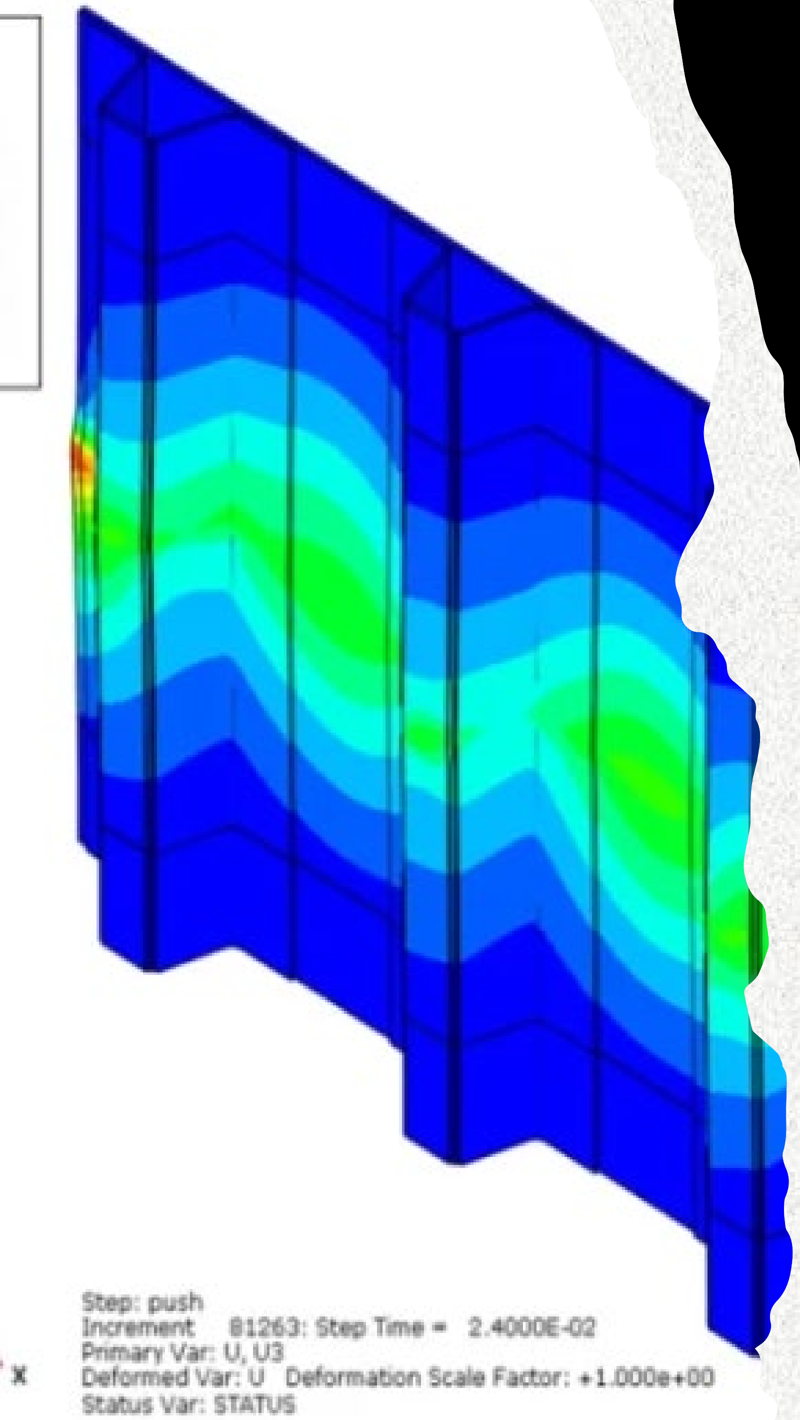
Hybrid G/C composites



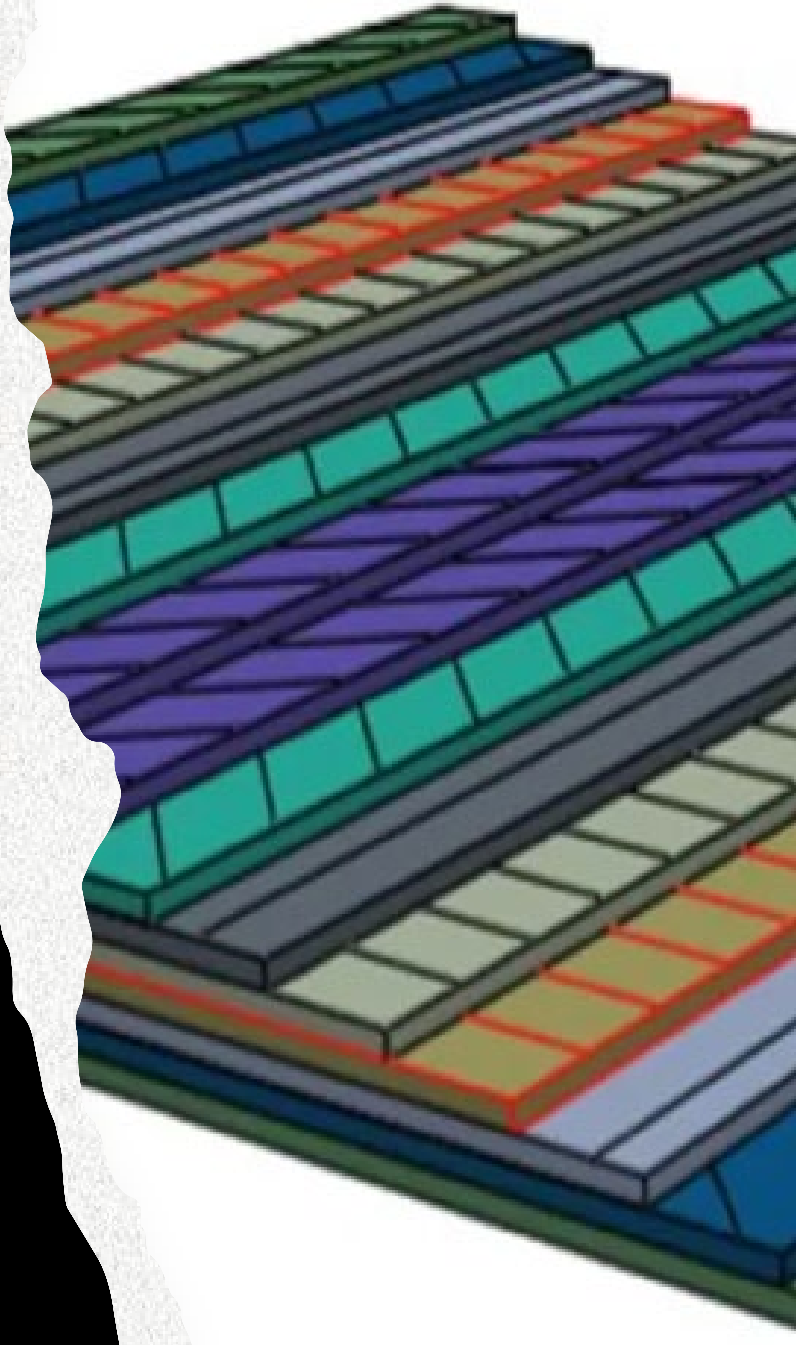
How to fabricate such big structures?

How to support such big structures?
The foundation in Rotterdam of the Haliade-X

Source: https://www.ge.com/news/reports/extreme-measures-107-meters-worlds-largest-wind-turbine-blade-longer-football-field-heres-looks-like#:~:text=Top%20and%20above%3A%20At%20107,12MW%20are%20the%20world's%20longest.



How do we analyze composite structures

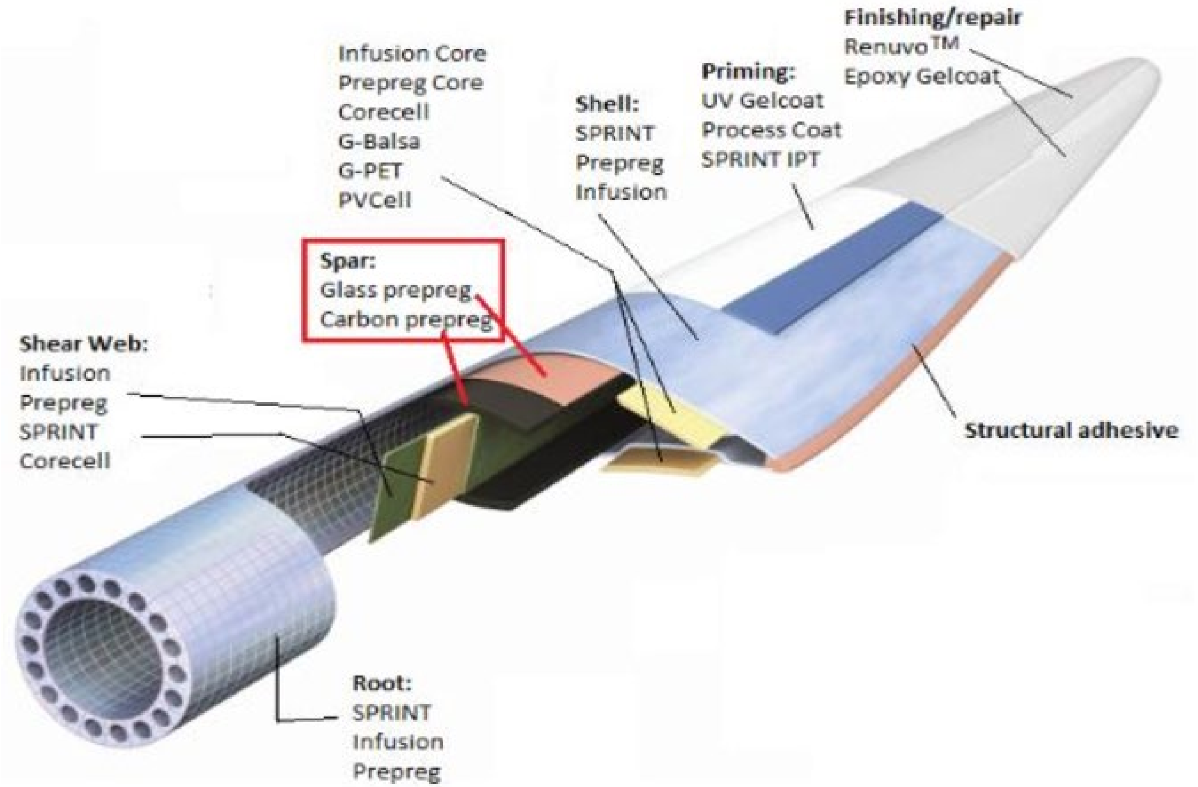


https://enterprise.trimech.com/composite-structures-analysis-engineer/

Life cycle of a composite structure

or else – from fibers and resin to composite structures

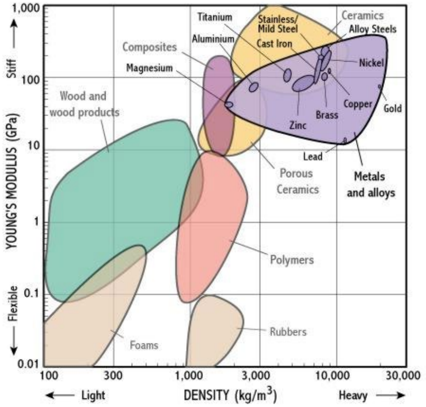
Concept



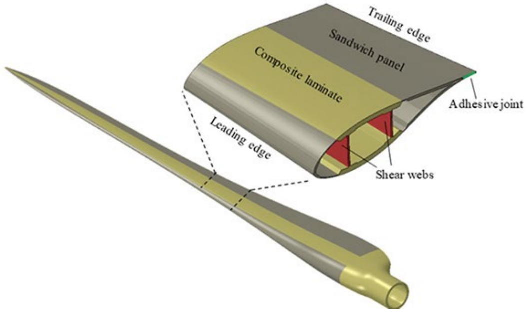
Life cycle of a composite structure

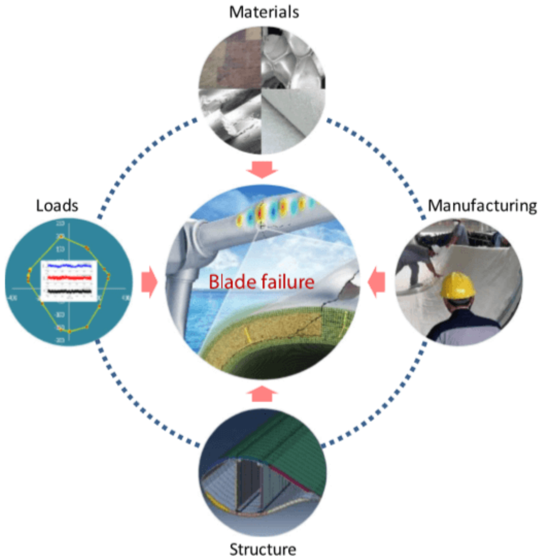
or else – from fibers and resin to composite structures

Concept



Design

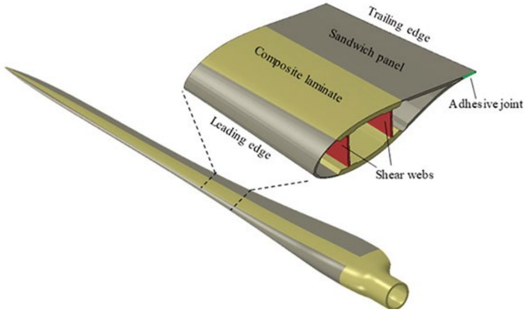




Material Testing

Life cycle of a composite structure

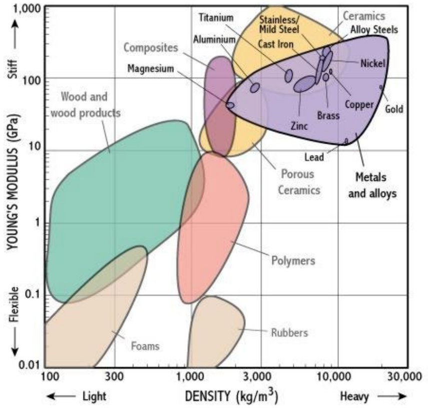
or else – from fibers and resin to composite structures



Material Testing

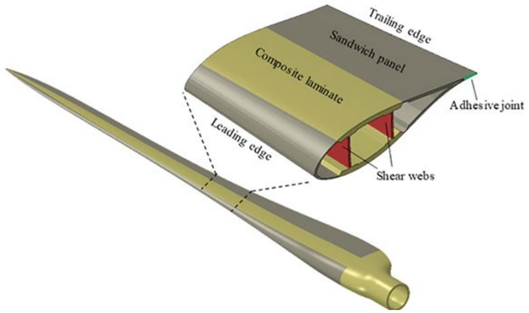
Manufacturing

Design verification



Design

Life cycle of a composite structure



Material Testing

Manufacturing

Design verification

End of life strategy
Reuse
Recycle

End of life scenario

Landfilling - https://www.bloomberg.com/news/features/2020-02-05/wind-turbine-blades-can-t-be-recycled-so-they-re-piling-up-in-landfills

Can composites be recycled?

The disposal of composite waste in cement kilns is widely believed to be an effective option, resulting in energy and materials recovery.

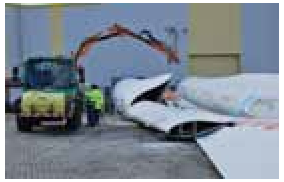


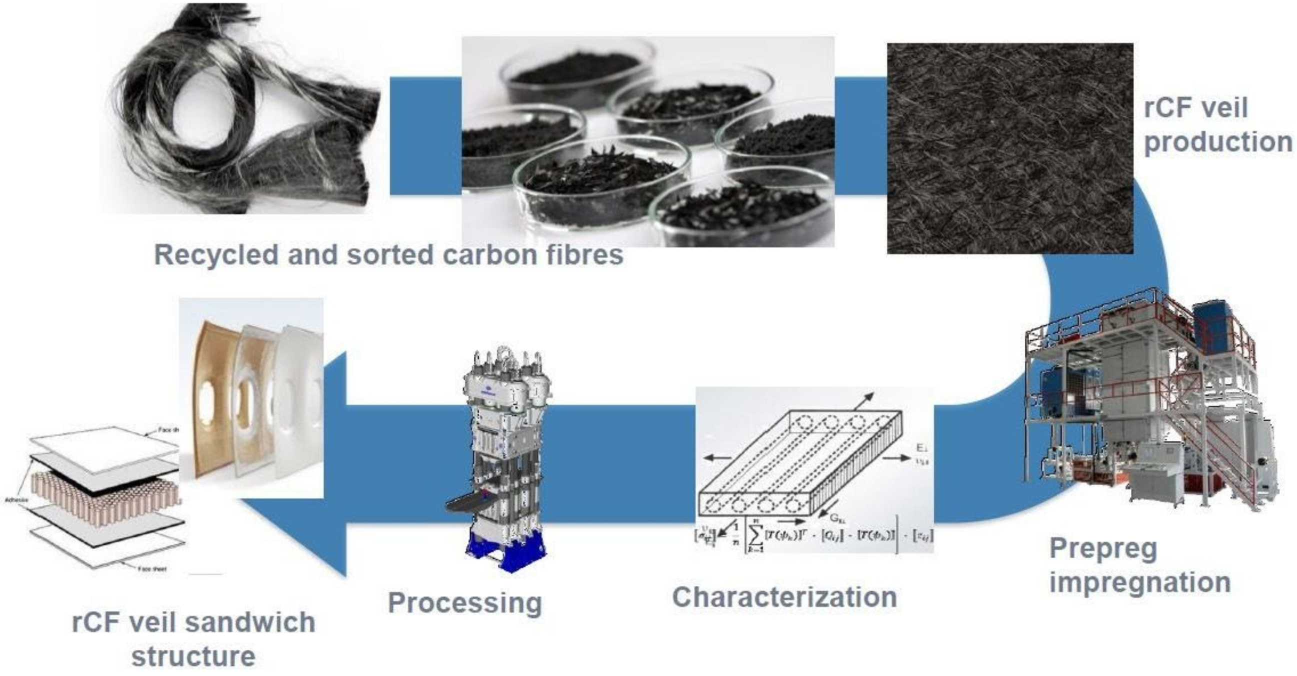
Fig.1 : Unloading of windmill blades at processing site
Fig.2 : Part storage prior to mechanical treatment
Fig.3 : Mobile sawing equipment to reduce transport costs
Fig.4 : Typical composite regrind, made from ground windmill blade

Co-processing is the simultaneous use of composite regrind as raw material and as a source of energy in cement manufacturing, to replace natural mineral resources (material recycling) and fossil fuels such as coal, petroleum and gas (energy recovery). In this process, the composites regrind used for co-processing is both an alternative fuel and raw material (AFR).

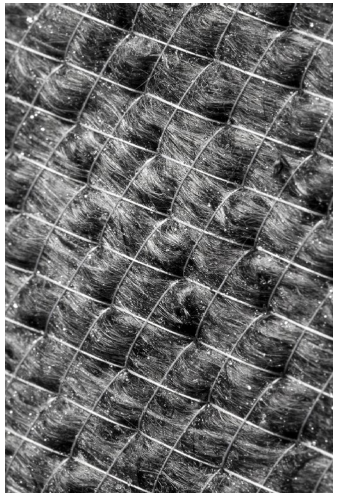
After their useful life saving energy and helping to reduce Eco-footprint in many applications, composite regrind can reduce Eco-footprint and CO_2 emissions of cement manufacturing.

Can composites be recycled?

Carbon fibers can be recovered and recycled from carbon fiber reinforced polymers (CFRP) with around half a dozen companies around the world specializing in this work



https://www.compositesworld.com/blog/post/recycling-carbon-fiber-for-structural-applications



Mechanical **carding** is used by SGL Automotive Carbon Fibers (Wackersdorf, Germany) to process CF scrap from weaving and preform kitting for the BMW i-series CFRP Life Module production into stitched nonwoven materials (left) which are then molded into the i3's rear seat structure and roofs for both the i3 and i8 (right). SOURCE: BMW

Do composites fail?

Course objectives

Learn about composites

Understand the advantages/disadvantages of composites

Learn about the use of composites, their placement in the market and their future

Learn how to design a composite structure

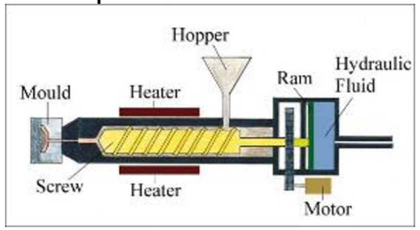
Design a simple composite structure

Obtain Transversal skills – Team/project management, writing a scientific report, hands on experience…

Advanced Composites in Engineering Structures
Course layout

Introduction

- Types of composites
- Reinforcements
- Matrix materials
- Interfaces
- Macture procedures



Structural foam injection

Mechanics of composite materials

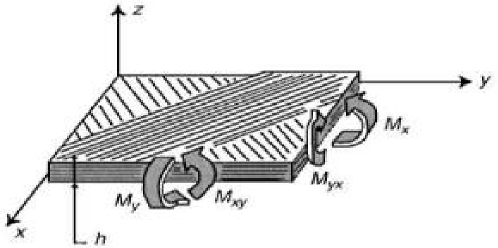
- Theory of elasticity for anisotropic media
- Classical lamination theory

$$\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{Bmatrix}=\begin{bmatrix}S_{11} & S_{12} & 0\\ S_{21} & S_{22} & 0\\ 0 & 0 & S_{66}\end{bmatrix}\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{Bmatrix}$$

Practice

Applications and dimensioning

- Laboratory experience
- Present applications of composites
- Perform dimensioning of a structure



44/44	Name First Name	Sciper	Gender	Section	e-Mail	Semester of registration
14	Cheron Paul Martin Hugo	414227	Male	GM_ECH	paul.cheron@epfl.ch	Autumn semester
1	Abbet Antoine Pierre	356936	Male	GC	antoine.abbet@epfl.ch	Master semester 1
24	Guilhot Gaspard Henri	299651	Male	GC	gaspard.guilhot@epfl.ch	Master semester 3
19	Fantinati Ian Dimitri	345851	Male	GC	ian.fantinati@epfl.ch	Master semester 1
11	Cavagna Giovanni	413691	Male	GM	giovanni.cavagna@epfl.ch	Master semester 1
17	Di Gifico Giorgio	415242	Male	GC_ECH	giorgio.digifico@epfl.ch	Autumn semester
18	El Haouat Adnane	311262	Male	GM	adnane.elhaouat@epfl.ch	Master semester 3
23	Gremaud Nicolas	347306	Male	GC	nicolas.gremaud@epfl.ch	Master semester 1
2	Ambrós Somolinos Eric	416168	Male	GM_ECH	eric.ambrossomolinos@epfl.ch	Autumn semester
4	Ansermoz Paul	357363	Male	GC	paul.ansermoz@epfl.ch	Master semester 1
41	Savoja Francesco Maria	396336	Male	GM	francesco.savoja@epfl.ch	Master semester 3
43	Thoumas Edouard	362532	Male	GC	edouard.thoumas@epfl.ch	Master semester 1
44	Yuan Shuai	413592	Male	GM_ECH	shuai.yuan@epfl.ch	Autumn semester
15	Couturier Gaël Alain François Patrick	387406	Male	GC	gael.couturier@epfl.ch	Master semester 3
37	Nikolic David	329481	Male	GC	david.nikolic@epfl.ch	Master semester 1
35	Mehta Dhruv Natwar	417182	Male	GC_ECH	dhruv.mehta@epfl.ch	Autumn semester
25	Halevi Teo Samuel	329561	Male	GM	teo.halevi@epfl.ch	Master semester 3
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26	Jaunin Samuel Jacques-Henri	346182	Male	MX	samuel.jaunin@epfl.ch	Master semester 3
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32	Maitrot Adrien Gérard Jacky	299891	Male	GM	adrien.maitrot@epfl.ch	Master semester 3
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34	Martín-Oar Faustmann Manuel	417205	Male	GC_ECH	manuel.martin-oarfaustmann@epfl.ch	Autumn semester
21	Gasser Antonin Louis	327563	Male	GM	antonin.gasser@epfl.ch	Master semester 1