International Spring School on Forefront Alloys and Advanced Materials for Extreme Conditions

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Current advances and emerging needs in aeronautical materials: could nanocrystalline alloys offer the desired breakthrough?

Prof. Spiros Pantelakis

University of Patras
Laboratory of Technology
& Strength of Materials

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ACARE Goals – Vision 2020

Environmental goals compared to 2000:

- Reduction of fuel consumption and CO_2 emissions by 50%.
- Reduction of NOx emissions by 80%.
- Reduction of perceived external noise by 50%
- Substantial progress in reducing the environmental impact of the manufacture, maintenance and disposal of aircraft

Safety goals compared to 2000:

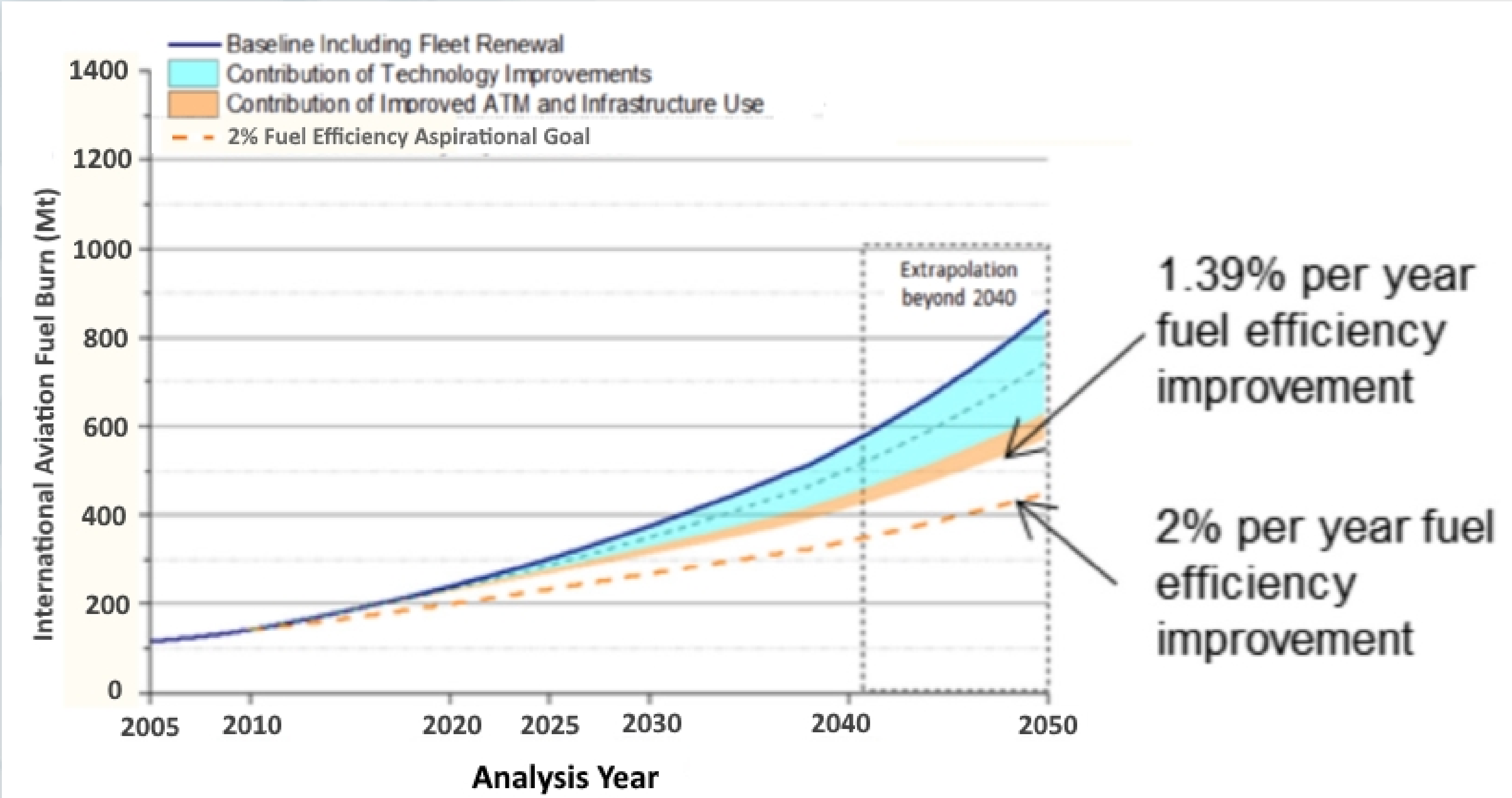
- Reducing accidents by 80%.
- Drastic reduction in human error and its consequences on flight safety.

ACARE - Goals

Emission reduction - Increased safety - Reduced cost

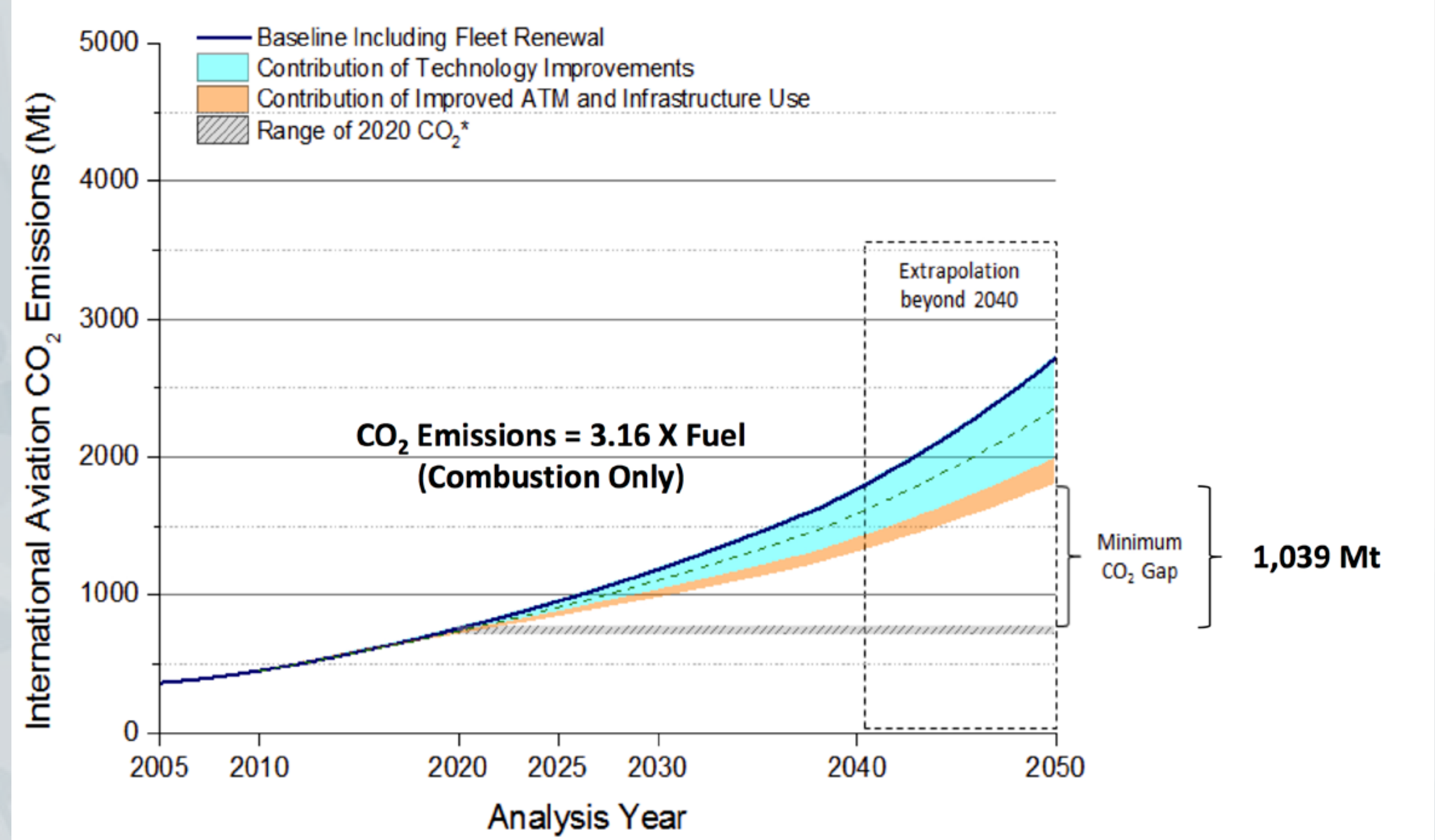
- Reduction in overall fuel consumption
  - Reduction in parasitic drag
  - Weight reduction
    - Optimization of the synergy between design and development of lighter and stronger materials
      - Manufacturing techniques suitable to process the advanced materials of today at a reasonable cost
      - Innovative design concepts allowing to take full advantage of the properties of advanced materials
- Increase engine efficiency

Environmental trends in Aviation from 2005 to 2050



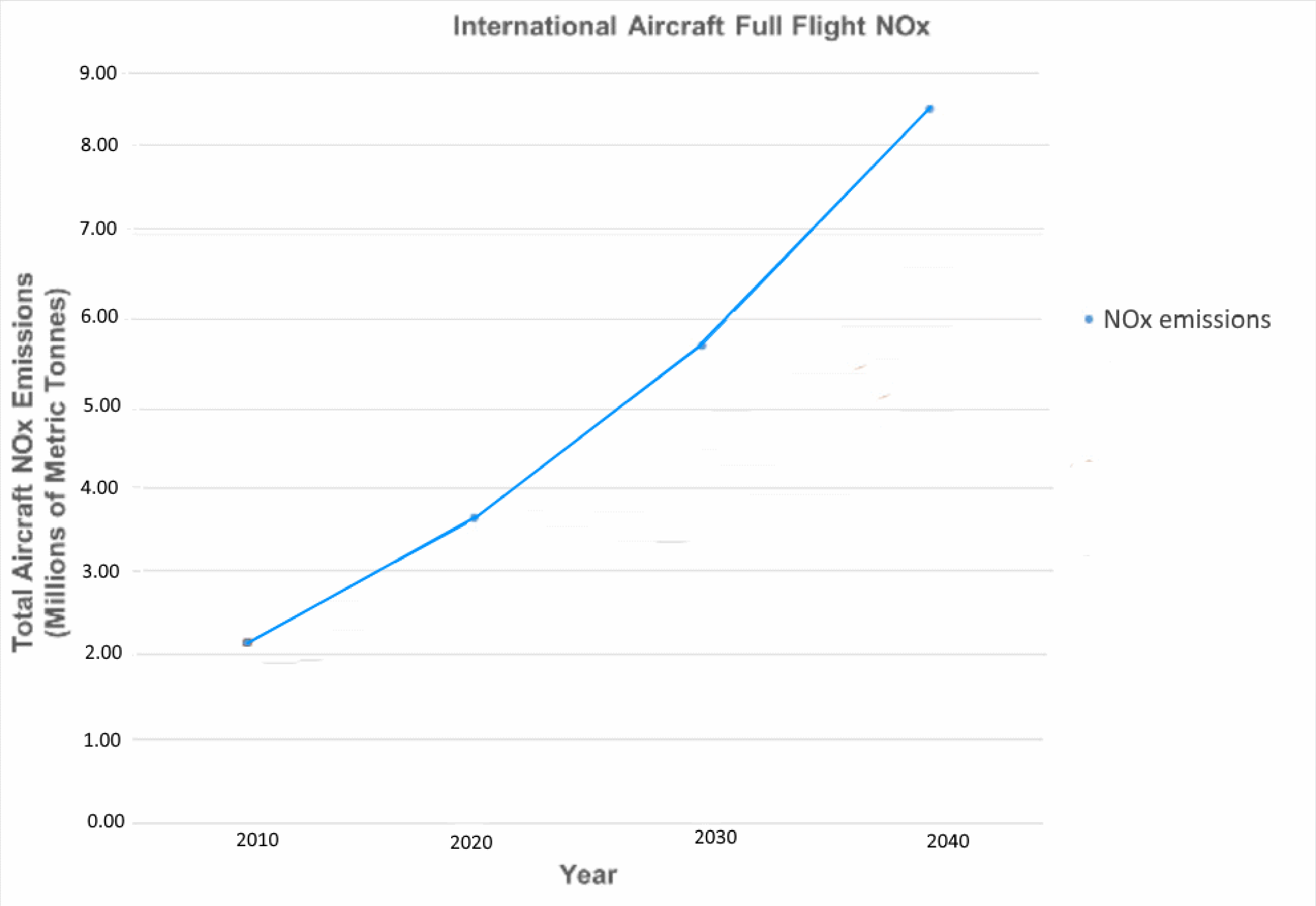
Results for global full-flight fuel burn for international aviation from 2005 to 2040, and then extrapolated to 2050, considering the contribution of aircraft technology, improved air traffic management (ATM), and infrastructure use (i.e., operational improvements) to reduce fuel consumption. The figure also illustrates the fuel burn that would be expected if ICAO's 2 per cent annual fuel efficiency aspirational goal were achieved.

Environmental trends in Aviation from 2005 to 2050



Full-flight CO2 emissions for international aviation from 2005 to 2040, and then extrapolated to 2050, considering the CO2 emissions associated with the combustion of jet fuel, assuming that 1 kg of jet fuel burned generates 3.16 kg of CO2.

Environmental trends in Aviation from 2005 to 2050



Flight Path 2050 - Objectives

2050 A.C, Planet Earth

Environmental goals compared to 2000:

- 75% reduction in CO_2 emissions per passenger kilometre and a 90% reduction in NO_x emissions.
- The perceived noise emission of flying aircraft is reduced by 65%.
- Aircraft movements are emission-free when taxiing.
- Air vehicles are designed and manufactured to be recyclable.
- Europe is established as a centre of excellence on sustainable alternative fuels.

Safety goals compared to 2000:

- Less than one accident per ten million commercial aircraft flights.
- Weather and other hazards from the environment are precisely evaluated and risks are properly mitigated.
- Air vehicles are resilient by design to current and predicted on-board and on-the-ground security threat evolution, internally and externally to the aircraft.

Flight Path 2050 - Goals

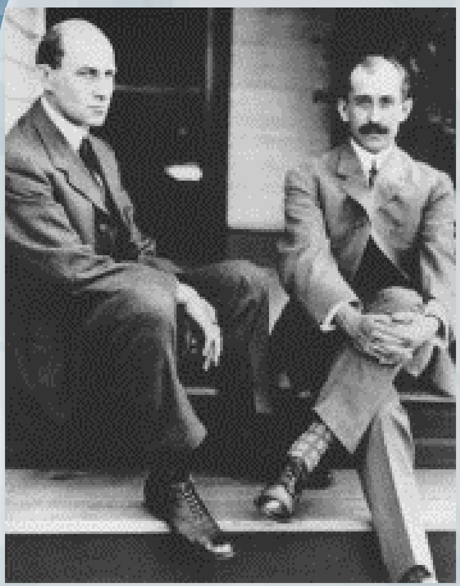
Development of aerostructures relies on the development of new materials with improved specific properties and novel manufacturing techniques.

Specific goals:

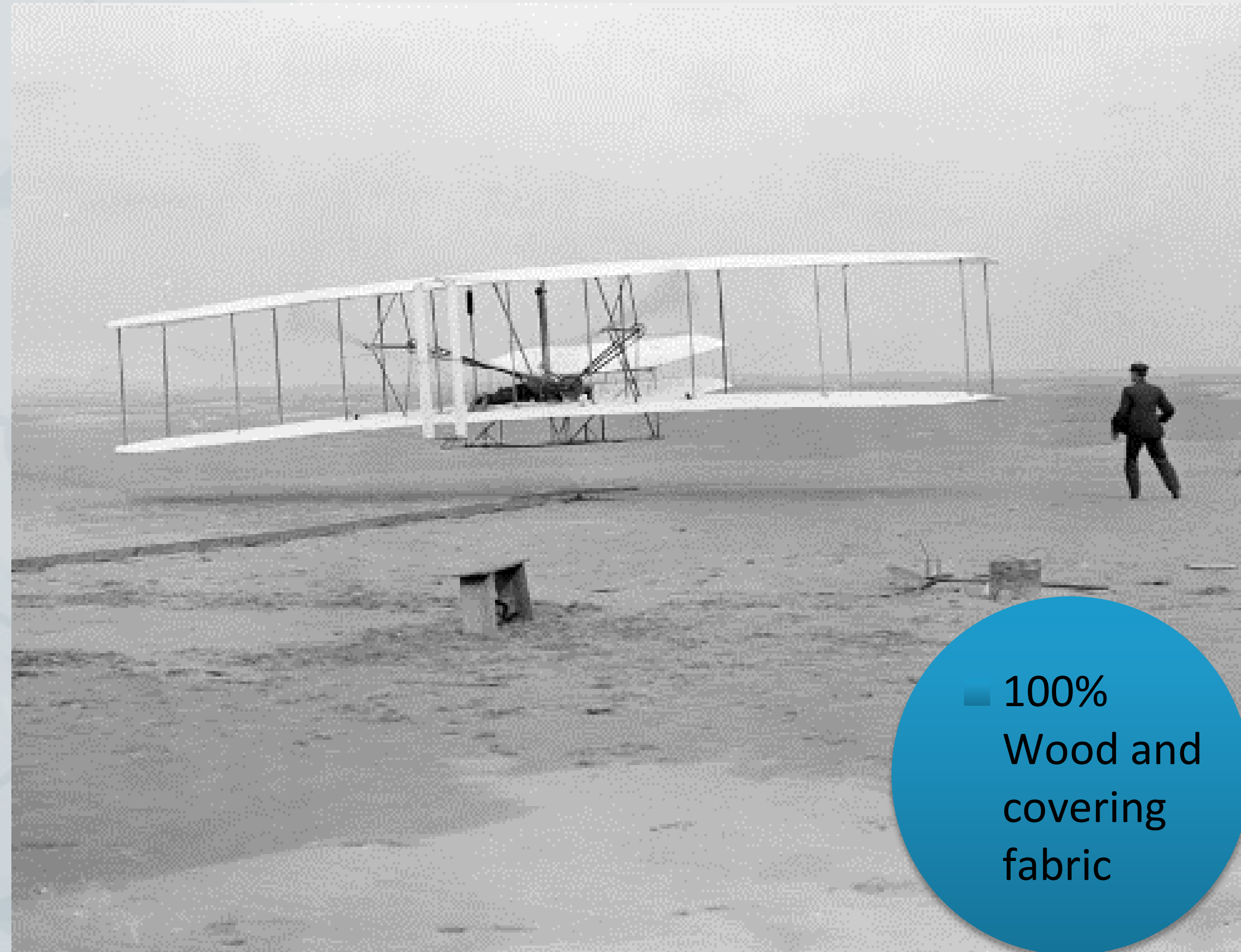
- Increased strength-to-weight ratio,
- Reduced cost and
- Environment friendliness

Evolution of aeronautical materials

Orville and Wilbur Wright, Ohio, 1904



Orville and Wilbur Wright



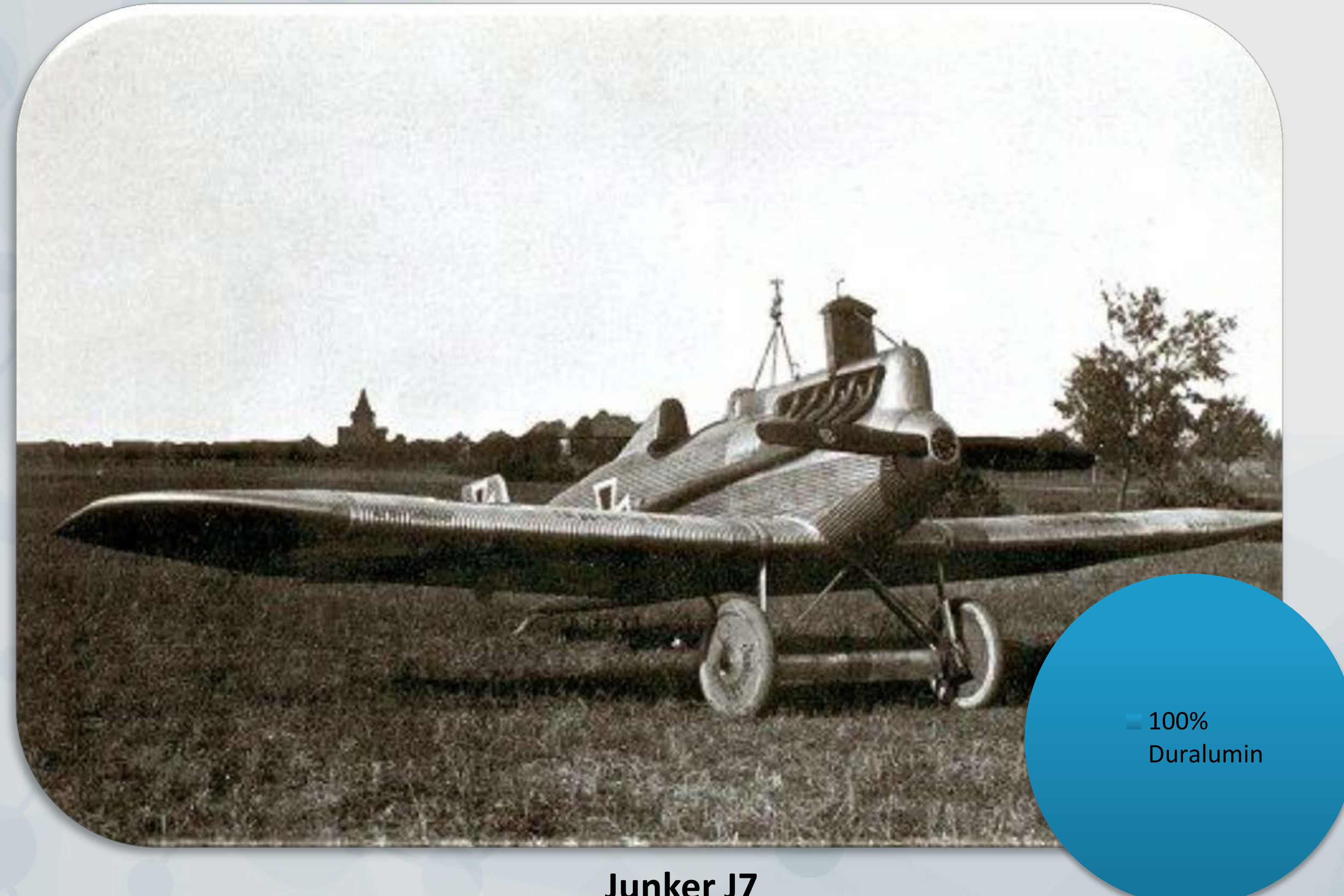
- 100% Wood and covering fabric

The first aircraft of the Wright brothers

Evolution of aeronautical materials

Junker J1

Evolution of aeronautical materials



Junker J7

Evolution of aeronautical materials

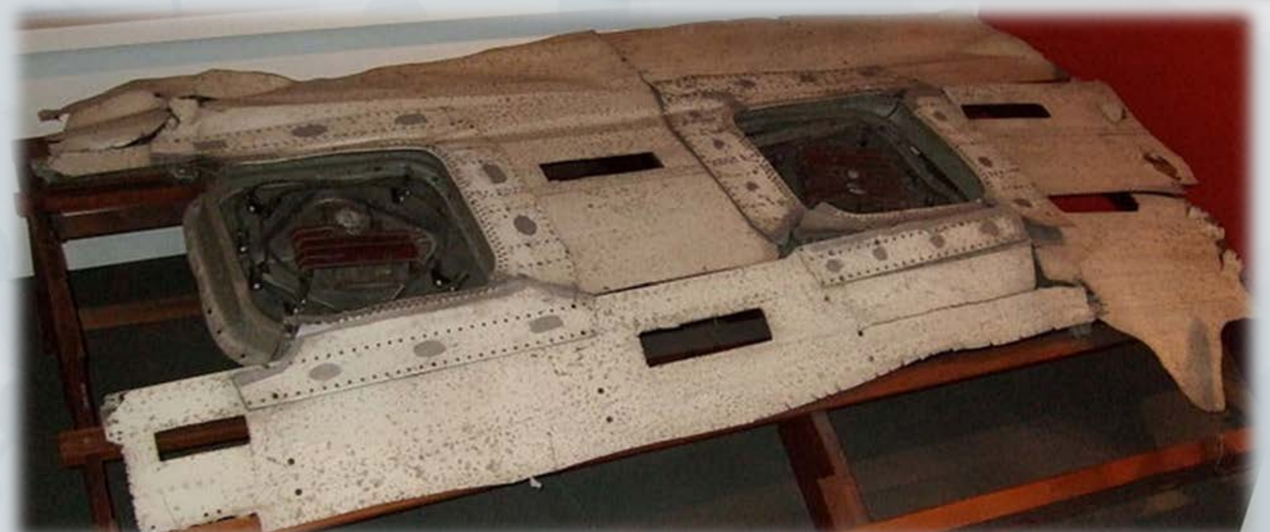
De Havilland Comet

Evolution of aeronautical materials

Accidents of aircraft Comet

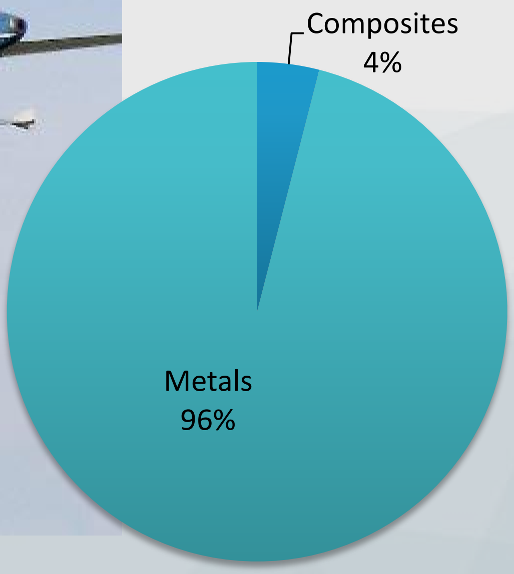
- 3 March 1953: A Canadian Pacific Airlines Comet crashed during takeoff at Karachi, Pakistan.

- Three fatal Comet crashes due to structural problems, specifically on 2 May 1953, on 10 January 1954, and on 8 April 1954, led to the grounding of the entire Comet fleet.
- After design modifications were implemented, Comet services resumed in 1958.



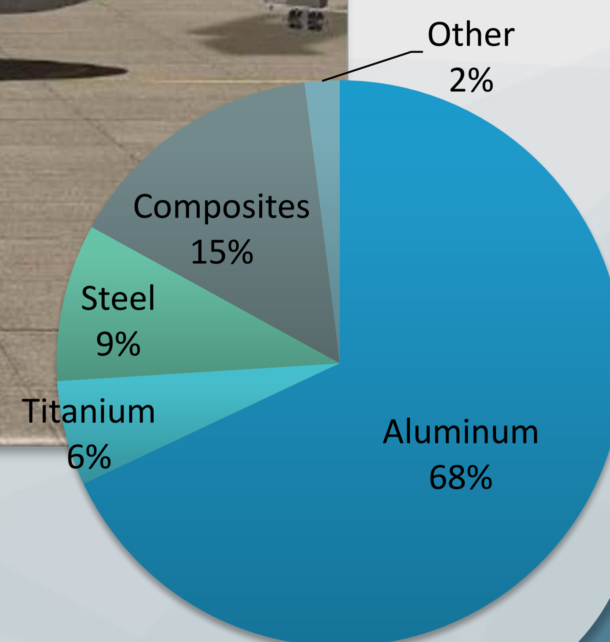
Evolution of aeronautical materials

The A300 would feature the first use of 4% composite materials of any European passenger large aircraft.

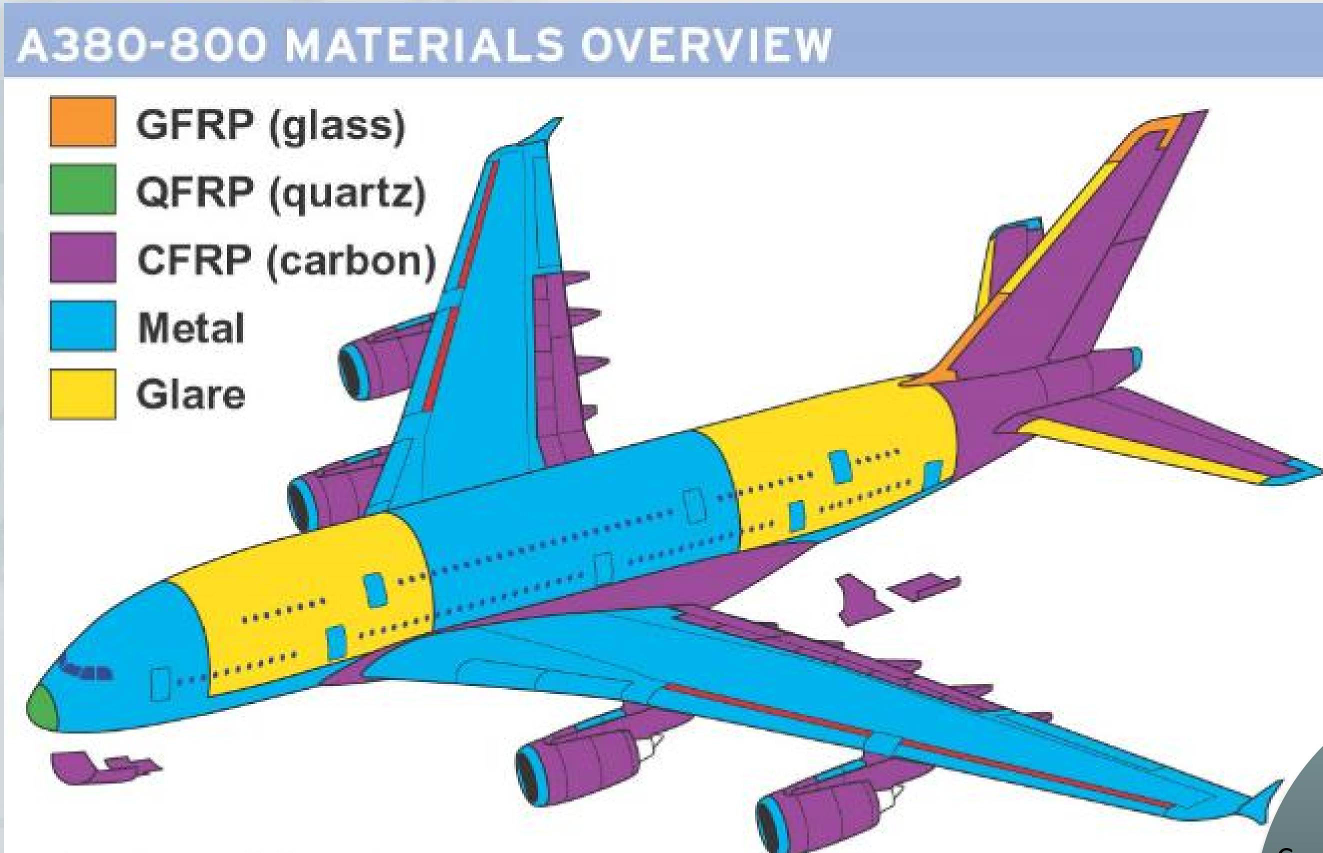


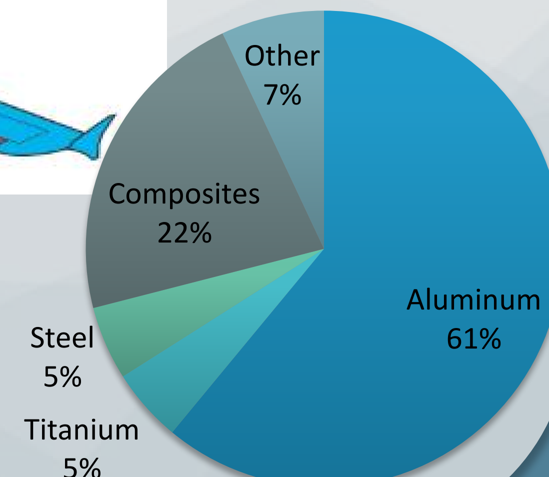
A300: The first twin-engine wide-body aircraft in the world

Evolution of aeronautical materials

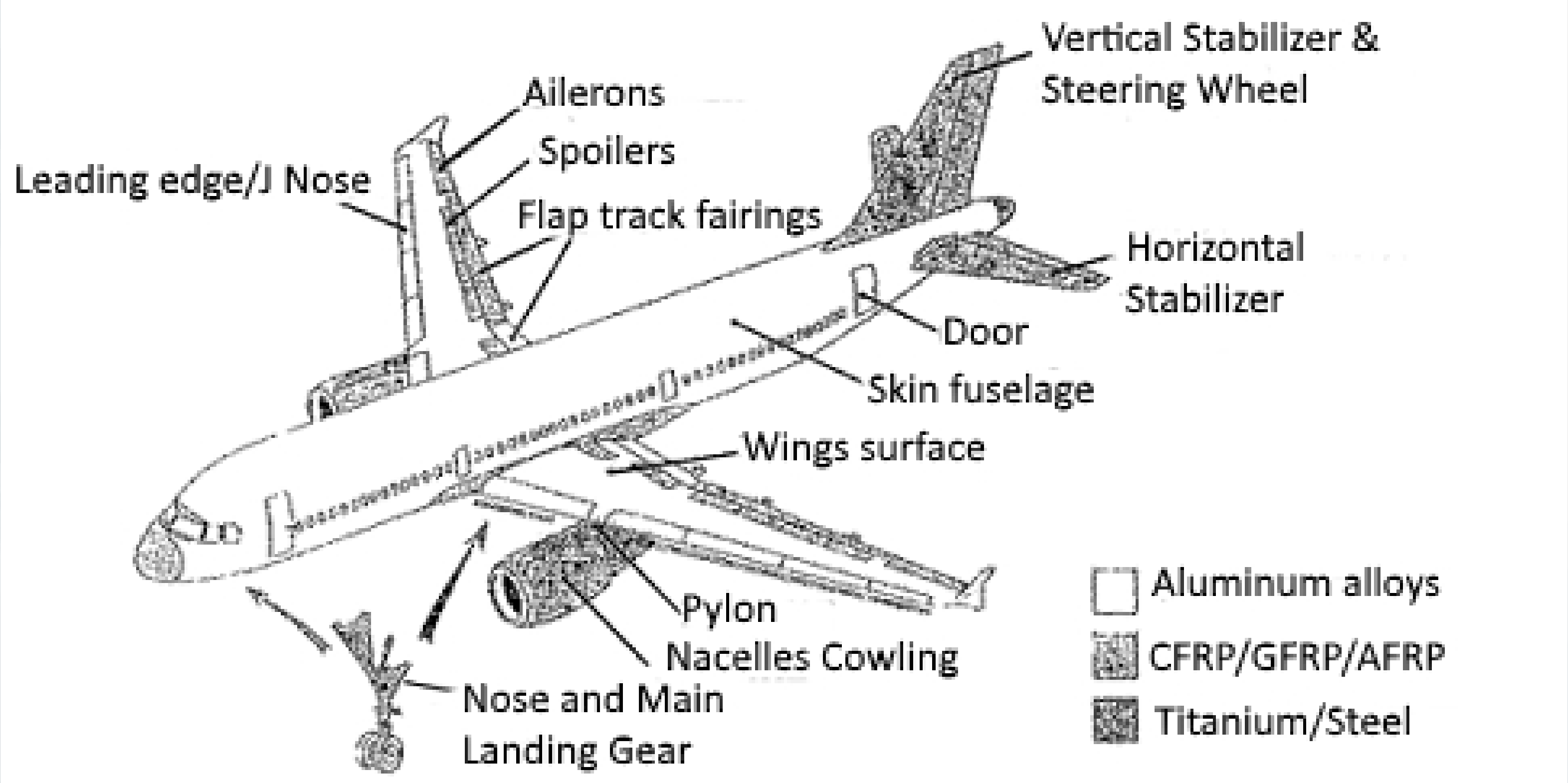


Evolution of aeronautical materials





Evolution of aeronautical materials



- **Not-movable parts: Metallic**
- **Movable parts: Composites**
- **Engines and pylons: Steel/Titanium**
- **Landing gear: Steel**

Evolution of aeronautical materials

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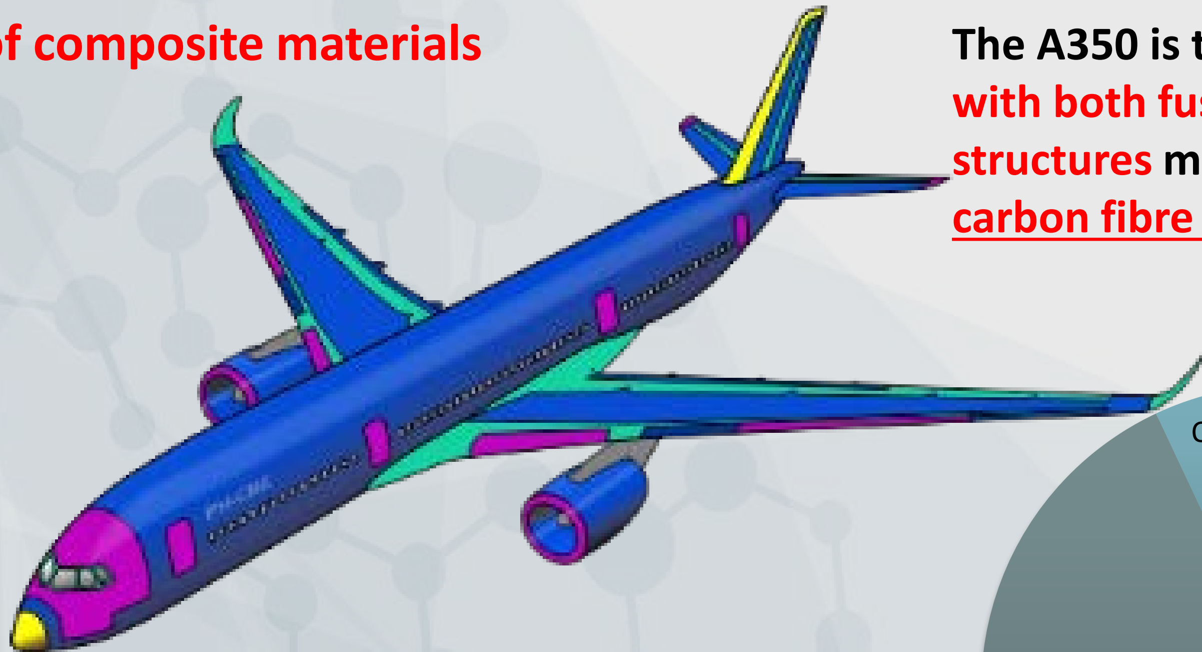
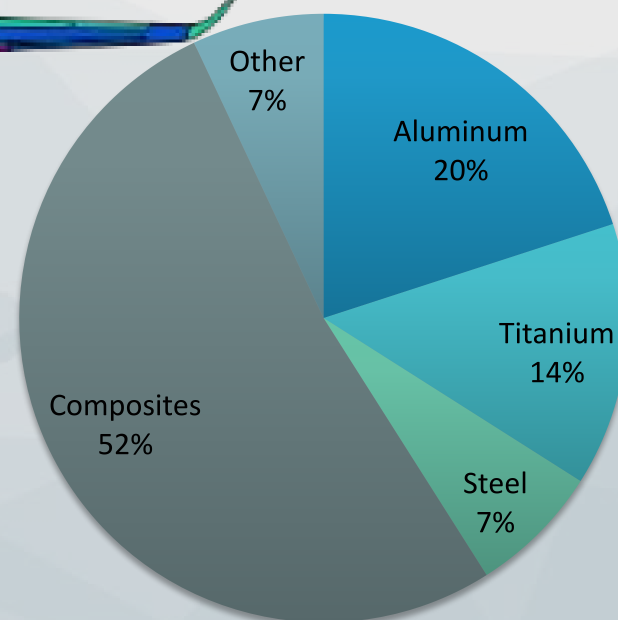
Airbus A350 Composite Locations

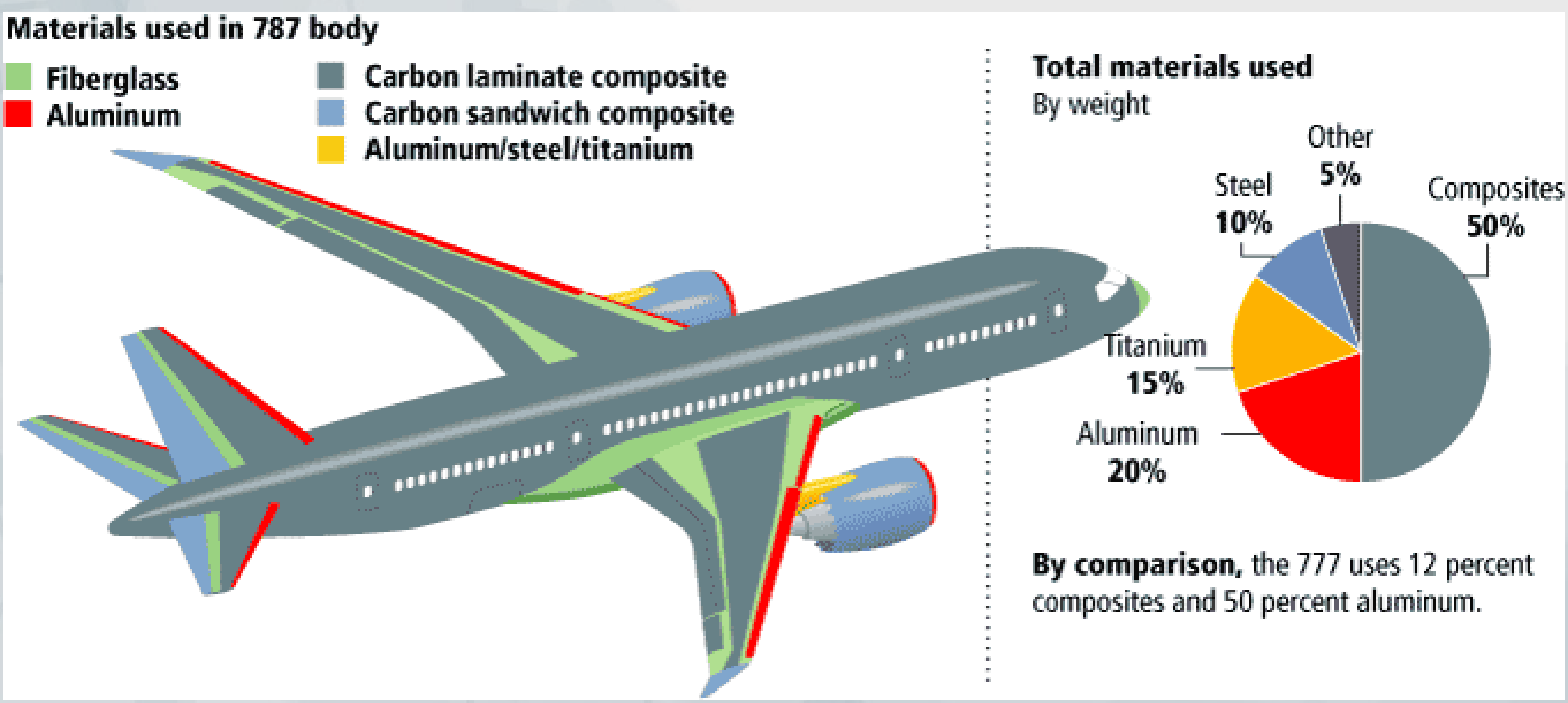
52% of composite materials



The A350 is the first Airbus aircraft with both fuselage and wing structures made primarily by carbon fibre reinforced polymer.



Evolution of aeronautical materials



Weight reduction

The latest development in the field of aerospace materials arises from the use of application-specific materials.

- The **A380**, which at **61 %** has the lowest percentage of **aluminum** by weight of all flying Airbus models, has 20 different alloys and tempers compared to the six ulitized on the A320/330 aircraft.

- The **A380** also features the application of **a new material, GLARE**, for fuselage skins which shows improved fatigue and impact properties at a lower density than existing materials.

- Extensive use of GLARE and CFRPs in A380 has led to **weight reduction of 15 tones** compared to what would be if metallic materials were used.

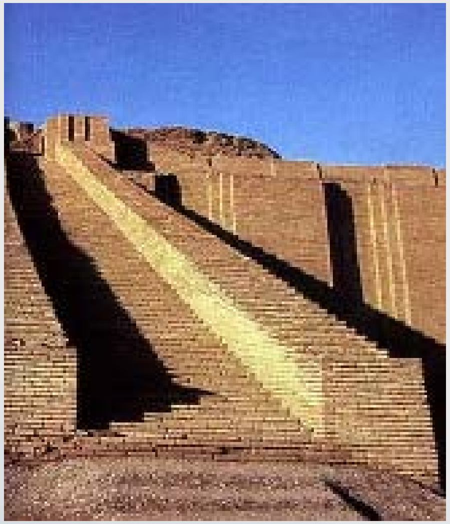
Composites usage over the years in Commercial Aircraft Industry

Back to future

"Composite materials-Counting backwards"

Egypt, Mesopotamia , 3000 B.C.

- Egyptians and Mesopotamian settlers used a mixture of mud and straw to create strong and durable buildings. Straw continued to provide reinforcement to ancient composite products including pottery and boats.



Ziggurat, Mesopotamia-Iraq

Shield of Achilles

Ancient Greece, 1100 B.C.

- The shield consists of two external laminates of hard bronze, two internal ones of tin and a central laminate of pure, i.e., soft, gold.

Back to future

Daedalus and Icarus *Crete 1500 B.C.*

Wings:

fully morphing

Materials:

fully biocomposed

CO_2 & NO_X emmisions:

close to zero

Joining of the structure:

adhesives

Light structures is a matter of design not a matter of weight!!

The material selection is one major driver in the light structures design philosophy. The main criterion for the material selection is the **specific properties** of the material; they are defined as the ratios of the mechanical properties (Young Modulus, Ultimate Tensile Strength and Yield Strength) to specific weight:

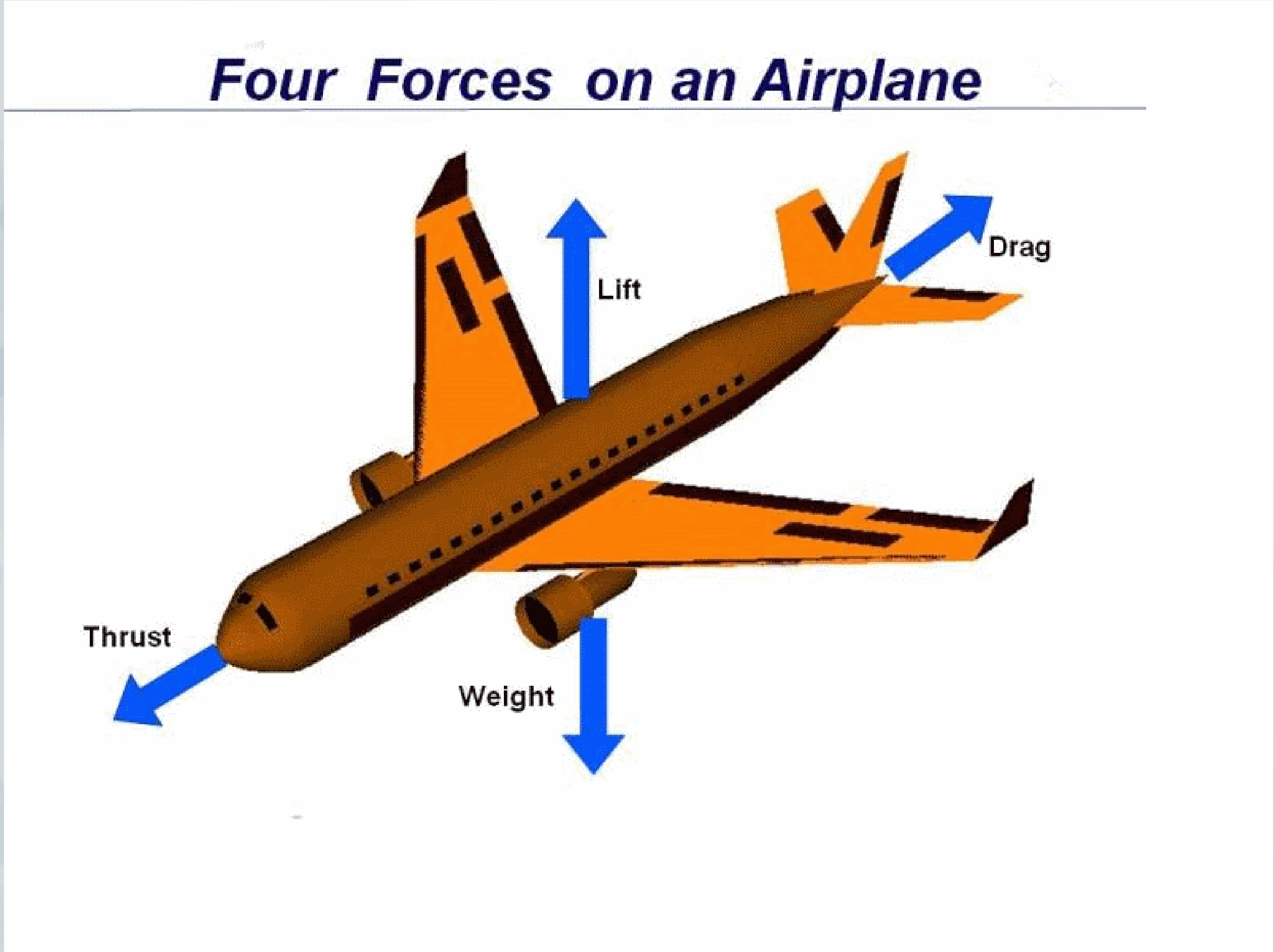
Specific Young modulus: E/ρ

Specific Yield Strength: R_p/ρ

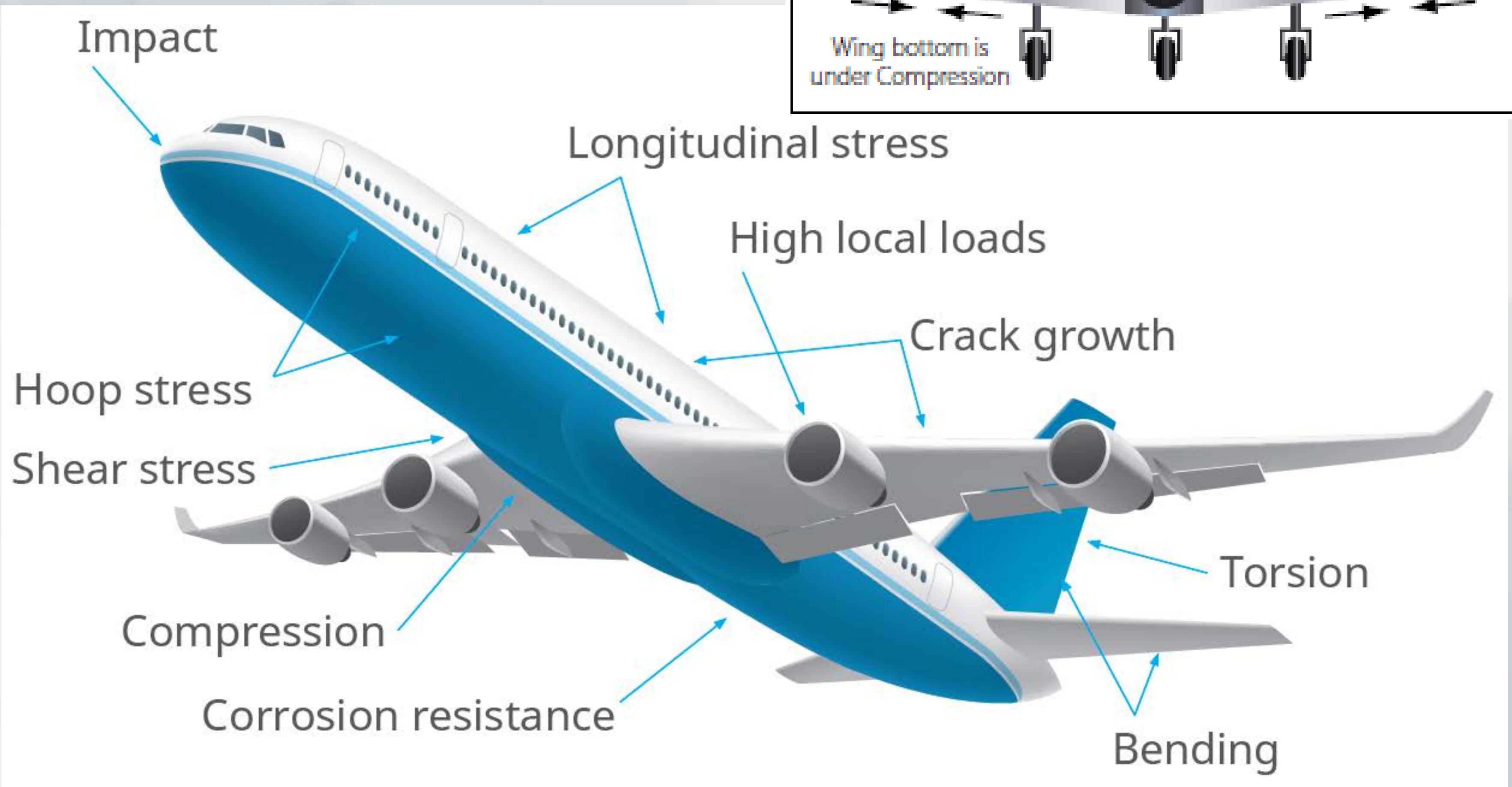
Specific Tensile Strength: R_m/ρ

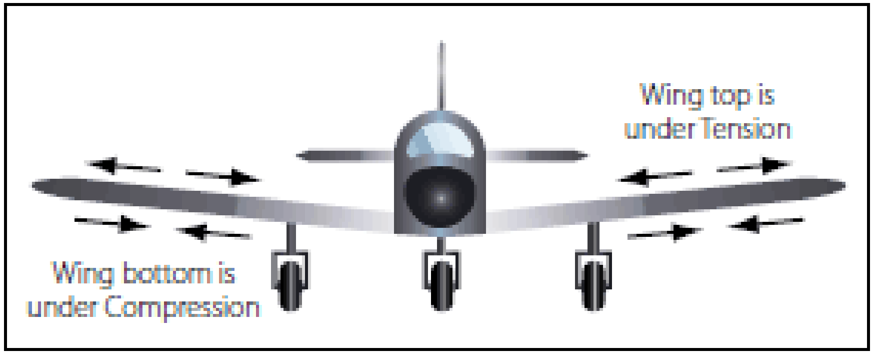
Ductility and fatigue behavior are also of essential concern.

Forces on an Airplane



Airframe structural requirements





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Aircraft structural materials

Aluminum-based alloys

Alloy	Main alloying elements (% wt)	Typical grain size	Ultimate Tensile Strength (MPa)	Young Modulus (GPa)	Density *(g/cm3)*	Elongation at fracture (%)
2024 T3	4% Cu - 1.5% Mg- 0.5% Mn	40µm	448	73.1	2.78	18
7075	0.25% Cr-1.5% Cu- 0.5% Fe- 2.5% Mg -0.4%Si - 5% Zn	30µm	572	71.7	2.81	11
6063	0.9% Mg - 0.6% Si- 0.35% Fe	15µm	241	68.9	2.70	12
8024	4.2% Li – 0.2% Zr- 0.1% Si- 0.12% Fe	25µm	340	77	2.54	13

Magnesium-based alloys

Alloy	Main alloying elements (% wt)	Typical grain size	Ultimate Tensile Strength (MPa)	Young Modulus (GPa)	Density *(g/cm3)*	Elongation at fracture (%)
AZ31C-F	97% Mg - 2.5% Al - 0.5% Zn	15µm	260	45	1.77	15
AZ61A-F	92% Mg - 6.5% Al - 0.4% Zn - 0.1% Mn	25µm	310	45	1.80	16

Aircraft structural materials

Titanium-based alloys

Alloy	Main alloying elements (% wt)	Typical grain size	Ultimate Tensile Strength (MPa)	Young Modulus (GPa)	Density *(g/cm3)*	Elongation at fracture (%)
Ti-6Al-4V Grade 5	89.4% Ti – 6% Al – 4% V – 0.4% Fe – 0.2%O	40 µm	950	114	4.43	14
Ti-5Al-2.5Sn Grade 6	90.6%Ti - 5%Al – 3%Sn – 0.1%C – 0.2%O – 0.05%Fe- 0.05%N – 0.02%H	35µm	861	110	4.48	16

Nickel-based alloys

Alloy	Main alloying elements (% wt)	Typical grain size	Ultimate Tensile Strength (MPa)	Young Modulus (GPa)	Density *(g/cm3)*	Elongation at fracture (%)
INCONEL X-750	70%Ni – 15%Cr – 7.5%Fe – 2.5%Ti – 1%Nb – 1%Co – 1%Mn – 0.5%Cu – 0.5%Si – 1%Al	35µm	1250	214	8.28	30
NIMONIC 80A	69%Ni – 21%Cr – 2%Ti – 2%Co – 2%Fe – 1%Mn – 1%Si – 1.8%Al – 0.2%Cu	40µm	1250	222	8.19	30

Aircraft structural materials

Composite materials

Material	Ultimate Tensile Strength (MPa)	Young Modulus (GPa)	Density *(g/cm3)*
Carbon fiber reinforced epoxy resin (unidirectional)	1550	137.8	1.55
Glass fiber reinforced epoxy resin (unidirectional)	965	39.3	1.85
Kevlar fiber reinforced epoxy resin (unidirectional)	1378	75.8	1.38
Boron fiber reinforced Al 6061-matrix	1109	220	1.55

Metals vs Composite materials

Specific properties of aeronautical materials

Aeronautical Structural Materials		Density (gr/cm3)	Specific Young modulus (MPa*cm3/gr)	Specific strength (MPa*cm3/gr)
Metals	2024 T3	2.78	26290	161.15
	7075	2.81	25510	203.55
	6063	2.70	25518	89.25
	AZ31C-F	1.77	25420	146.89
	Ti-6Al-4V Grade 5	4.43	25730	214.44
	INCONEL X-750	8.28	25845	150.96
Composites	Kevlar fiber reinforced epoxy resin	1.38	46086	927.53
	Carbon fiber reinforced epoxy resin	1.55	89873	1443
	Carbon fiber reinforced thermoplastic (CFRTP)	1.57	85350	915.50

Metals vs Composite materials

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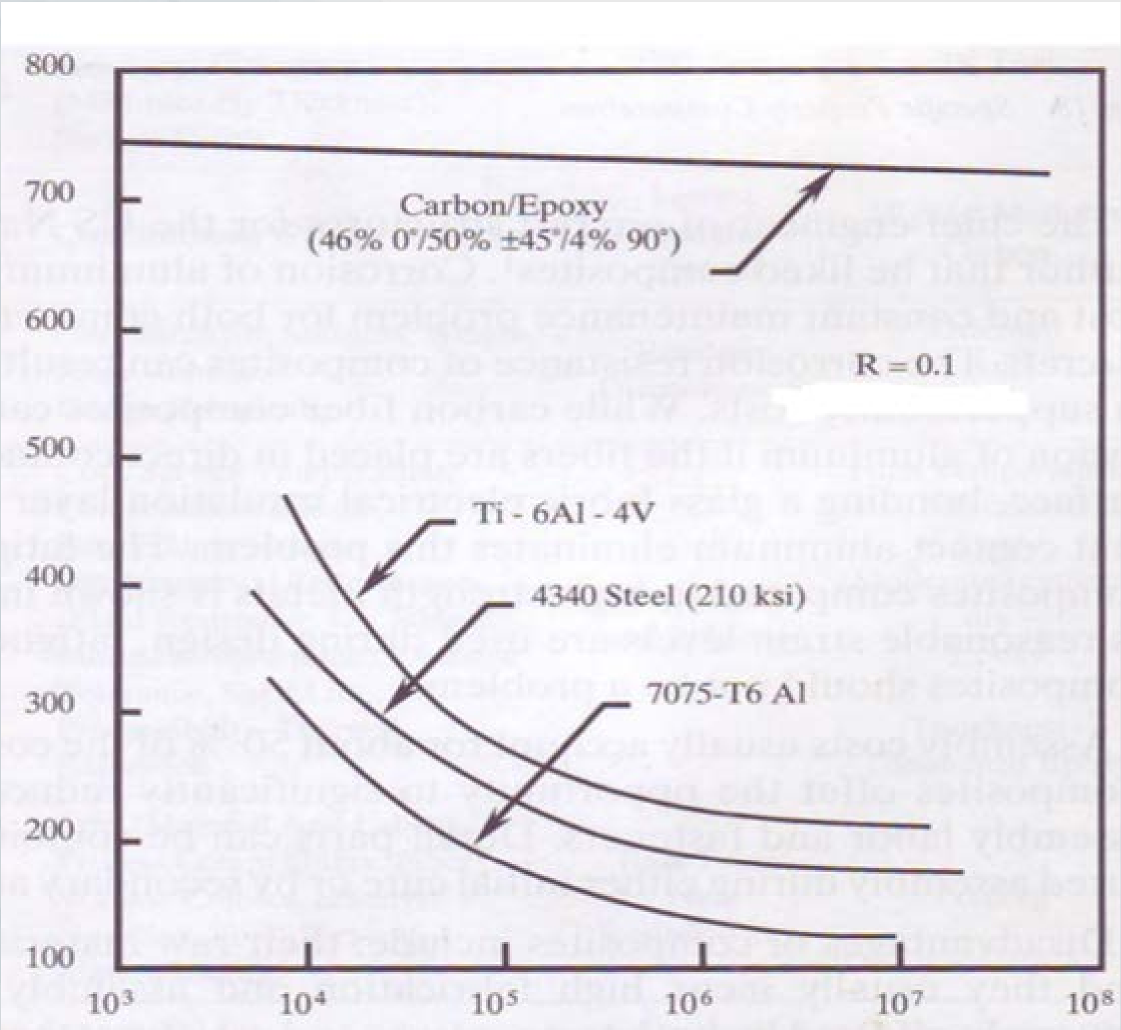
Fatigue behavior of metals and composite materials



Fatigue strength/ density x 10^3 in.

Cycles of failure N

Metals vs Composite materials

Composite materials

Advantages

- High strength-to-weight ratio
- Tailored mechanical properties in various directions
- Corrosion resistance
- Impact resistance
- Design flexibility
- Fatigue resistance

Drawbacks

- Reduced electrical conductivity
- Inferior fire resistance
- Brittleness
- Unpredictability
- Lack of recyclability (thermosettings)

Metals

Advantages

- Complex shapes
- High ductility
- Damage resistance
- Conductive
- Easy to fabricate
- Joinable by various methods
- Cost effective

Drawbacks

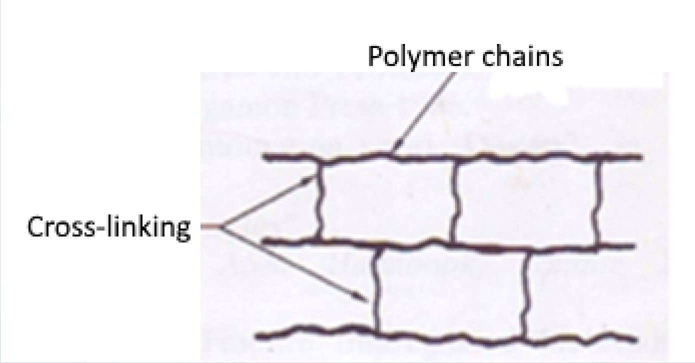
- Heavy structures (low strength-to-weight ratio)
- Prone to corrosion damage
- Inferior creep resistance

Thermosettings and thermoplastics

Thermosetting materials

- More resistant to high temperatures than thermoplastics
- Highly flexible design
- Cost-effective
- Thermal stability
- Chemical resistance

- Cannot be recycled
- More difficult to surface finish
- Cannot be remolded or reshaped
- Limited storage time

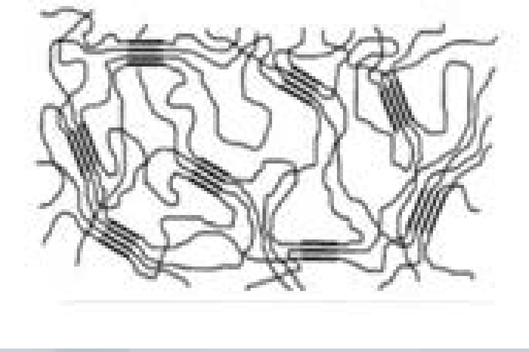


Cross-linked molecular **chains**

Thermoplastics materials

- Highly recyclable
- High-impact resistance
- Remolding/reshaping capabilities
- Hard crystalline or rubbery surface options

- Can melt if heated
- Generally more expensive than thermoset



Polymer chains linked by Van der Waals forces

From Differential to Integral structures

- Trends in aircraft manufacture are towards creation of integral structures via manufacturing processes such as welding, casting and forging, high-speed machining, rather than the traditional riveting.
- This is mainly driven by manufacture cost saving in future metallic aircraft structures. Integral structures also bring the benefits of reduction in part counts, weight saving and simplification in inspection.
- However, unlike structures fabricated by mechanical fastening techniques, integral structures do not contain redundant structural members that could act as crack stoppers or retarders; they hence lack fail safety capability, and regulators penalize such structures by imposing extra design safety factors.

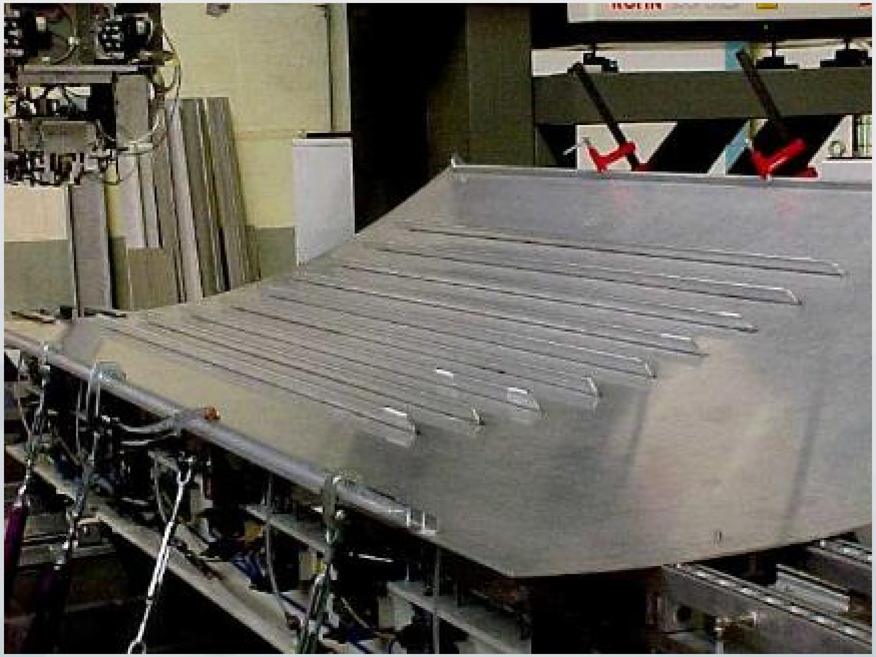
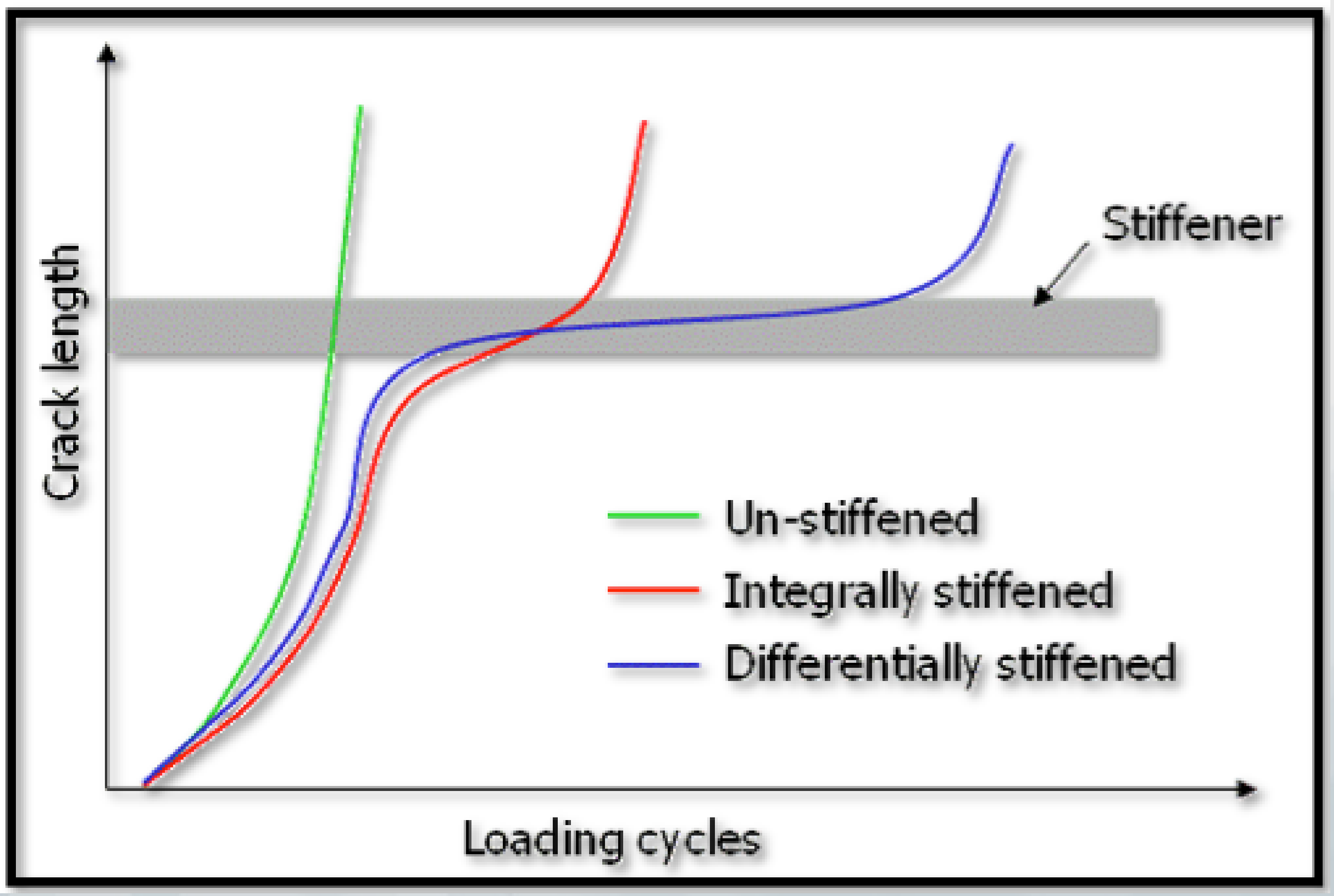


Fig.6. Laser welded aluminum fuselage panel

Novel manufacturing techniques

From Differential to Integral structures



From differential to integral structures

A part of fuselage using the differential approach (riveting technique)

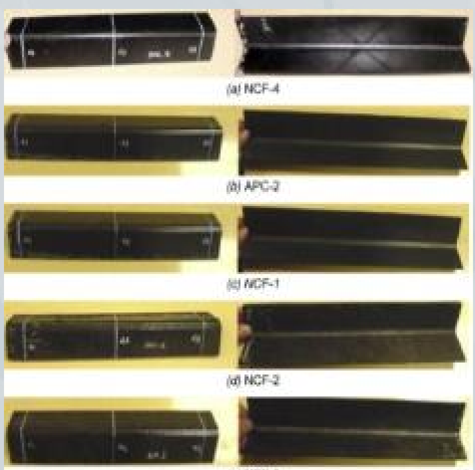
A part of fuselage using the integral approach (autoclave, RTM, etc)

Novel manufacturing techniques

From thermosettings to thermoplastic components

Realization of **metallic** integral structures is based on the development of specific manufacturing processes, such as ***welding***, ***casting***, ***forging***, ***large-scale extrusion***, and ***high-speed machining***, which will permit modular prefabrication of large sections of an aircraft before final assembly.

Realization of **composite** integral structures passes through development of advanced and efficient manufacturing techniques such as ***autoclave, RTM, preforming,*** development of new manufacturing techniques for extending use of ***thermoplastics*** and development of new assembly techniques such as ***adhesive bonding.***



Stiffeners made from thermoplastic NCF material.

A helicopter canopy made from thermoplastic composite material.

Assembly concepts

Composite aircraft components are mainly assembled by mechanical fasteners.

Advantages:

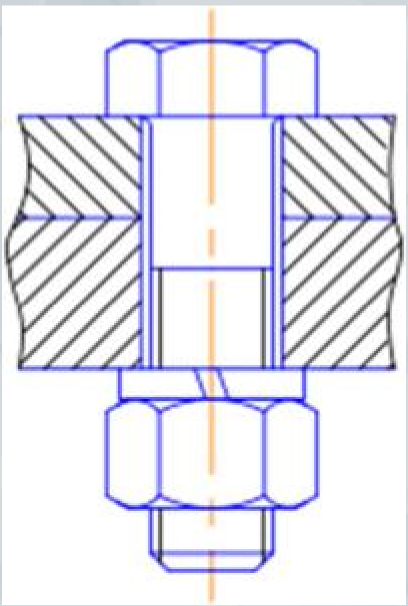
- Tolerance to the effects of environment and fatigue,
- Ease of inspection,
- Capability for repeated assembly,
- High reliability, and
- No special surface preparation required.

Disadvantages:

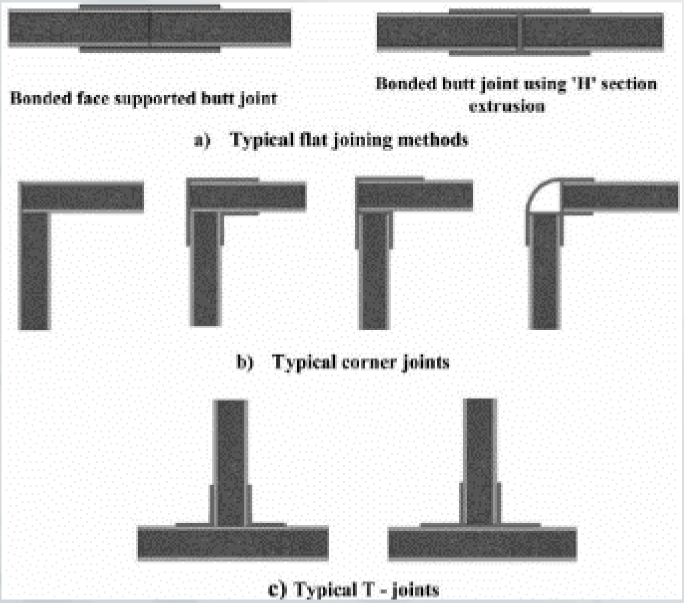
- Introduction of *concentrated loads* for connecting lugs with *thicker laminates,*
- Limited mechanical performance: low in-plane stiffness, low out-of-plane strength, bearing strength and low resistance to delamination/damage tolerance of fastened areas,
- Current design practices give non-optimal joining systems that are poor in terms of weight penalties and cost efficiency: composite designs are often rejected in favor of traditional metallic concepts

Assembly concepts

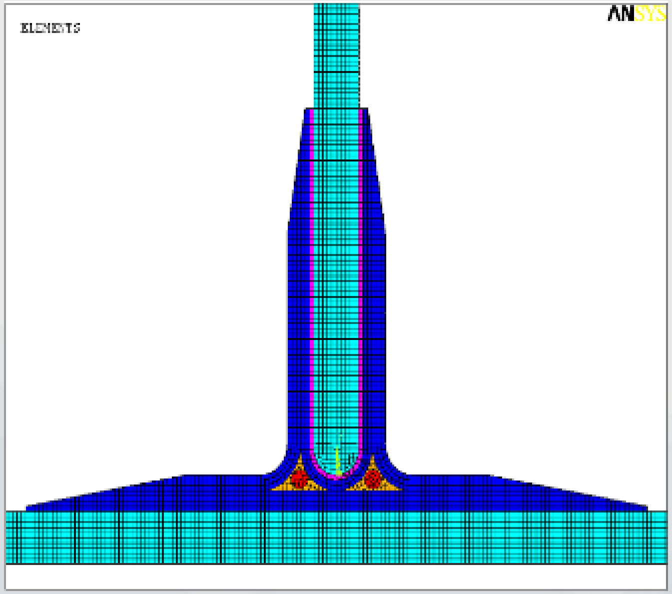
From bolted joints to adhesive bonding



Bolted joint



Bonded joint



T-shape Bonded joint

Material properties' degradation

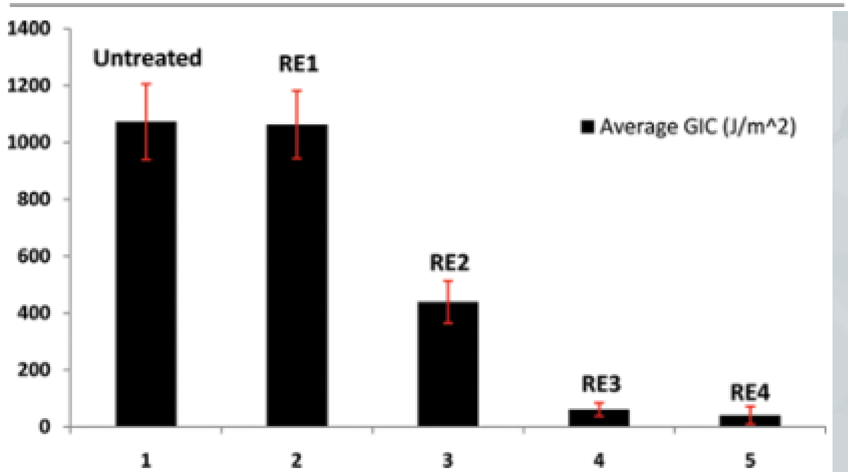
Adhesive bonded joining is preferred over conventional mechanical fastening, especially for components made from composite or polymeric materials. The material properties of adhesives are associated with the contamination effect. The contamination on the adherend's surface tends to generate interfacial defects, e.g., weak bonds (kissing bonds), which cannot be detected by conventional NDT methods.

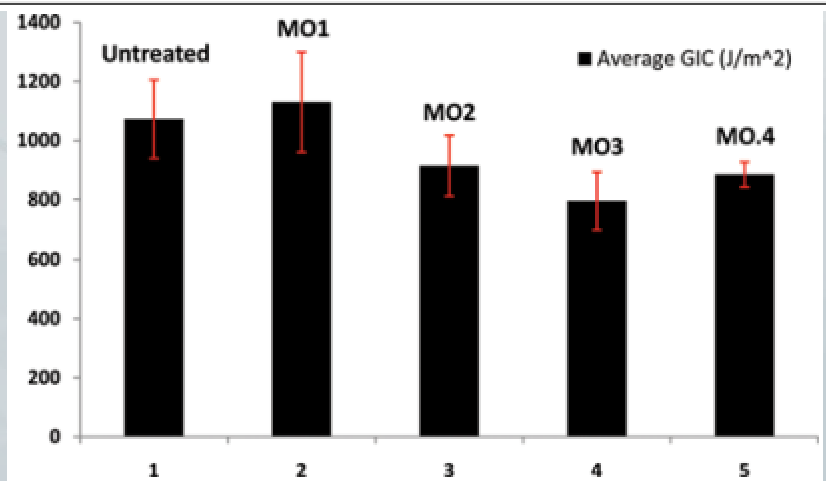
TABLE 1 Contamination Levels Corresponding to Release Agent Concentration

Level of contamination	Concentration of Frekote in solution	Average Si concentration (at %)
RE1	1%	2.5
RE2	5%	5.8
RE3	10%	7.3
RE4	20%	10.1

TABLE 3 Selected Salts and Resulting Humidity Conditions for the Moisture Contamination

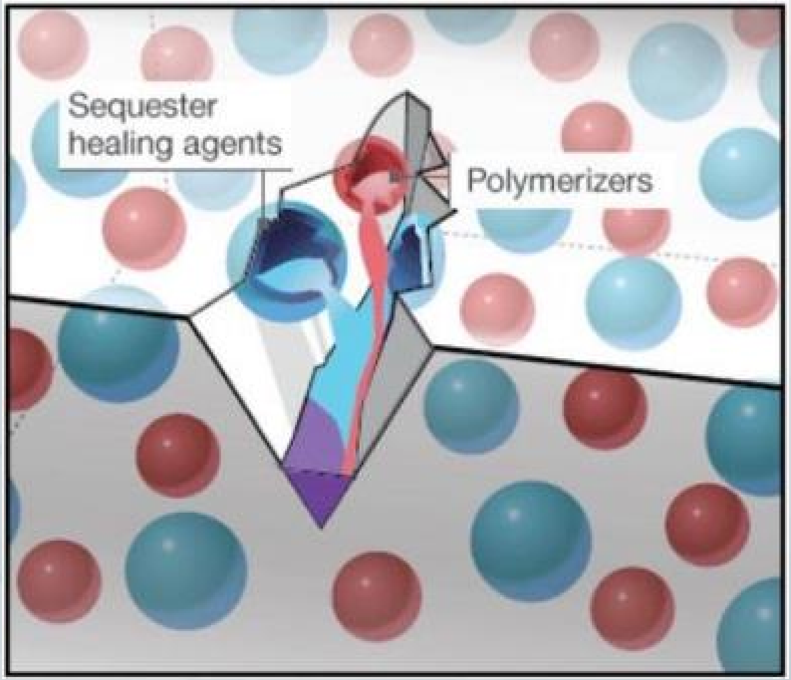
Level of contamination	Type of salt	Resulting relative humidity (%)	Average mass uptake (wt%)
MO1	$MgCl_2$	28.5 (*30*)	0.45
MO2	NaCl	75 (*75*)	0.80
MO3	K_2SO_4	99 (*95*)	1.13
MO4	Pure demineralised water	99 (*100*)	1.24





Multifunctional materials

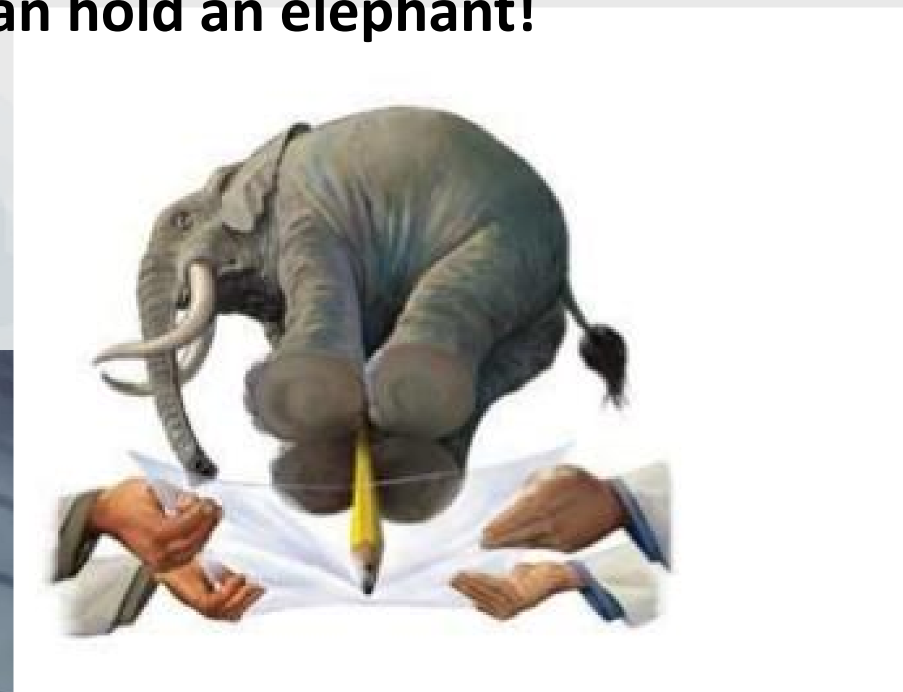
A material system, which **contains nano- or micro- substitutes** and they could be either in the same or in a different phase from the main material and **exhibits either reinforced structural properties or it demonstrates at least an additional function** other than it serves usually, or the combination of the above mentioned, can be defined as **multifunctional material.**

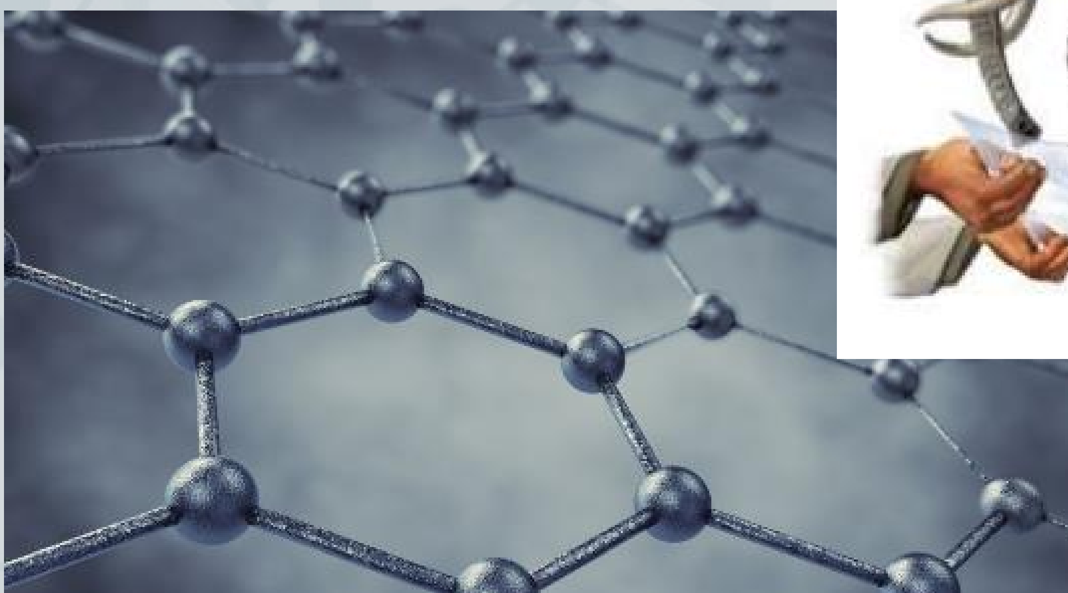


Advanced composite materials

Graphene: So strong that can hold an elephant!

- **Young's modulus: ~1 TPa**
- **Tensile strength: ~1100 GPa**





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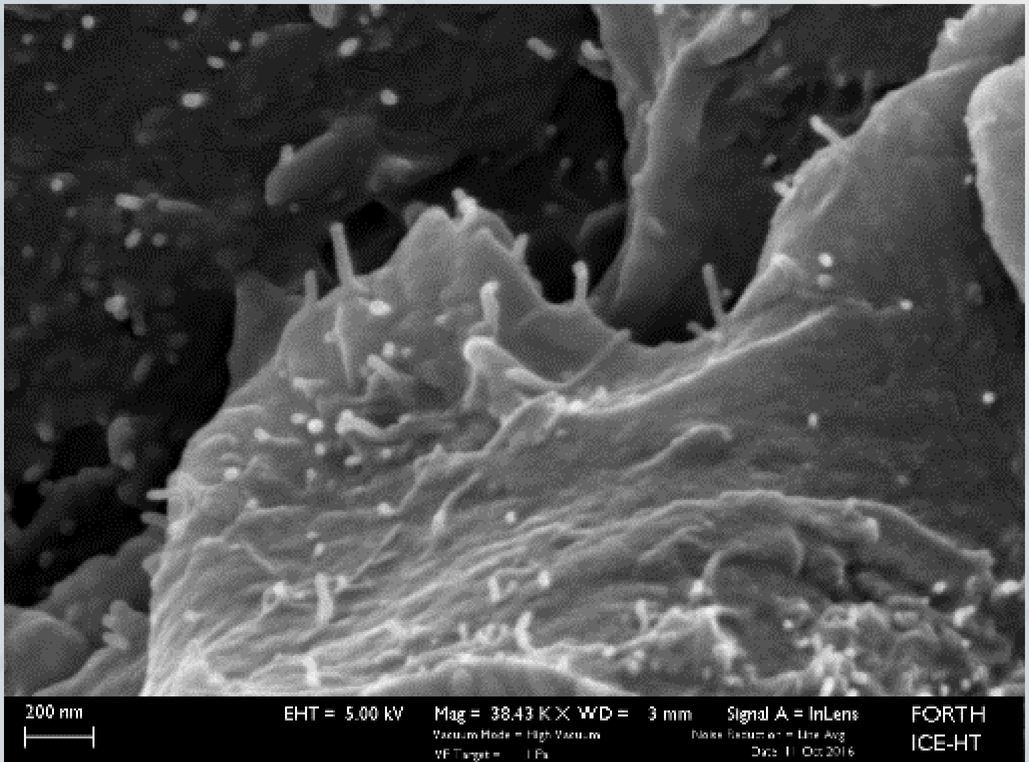
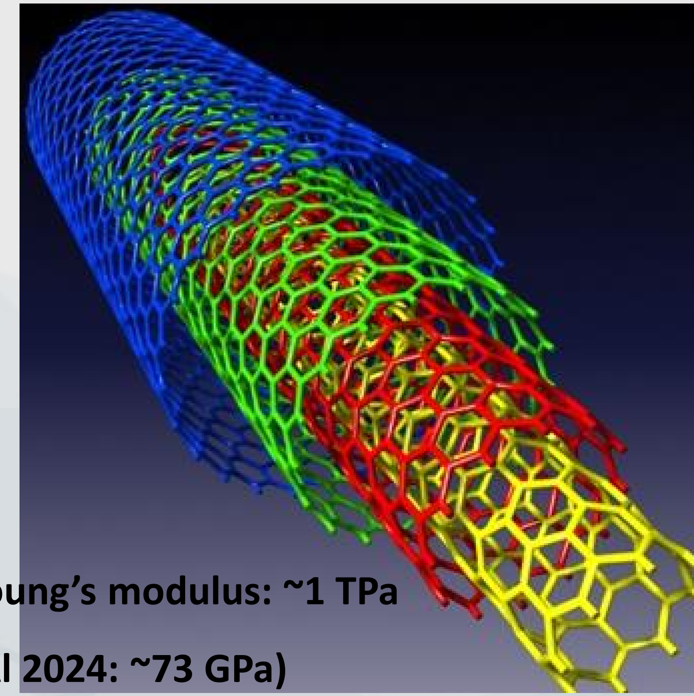
Advanced composite materials

Carbon nanotubes





Diameter: as small as few nanometers

Length: a few nanometers to several micron

Young's modulus: ~1 TPa

(Al 2024: ~73 GPa)

Tensile strength: ~60 GPa

(Al 2024: ~480 MPa)

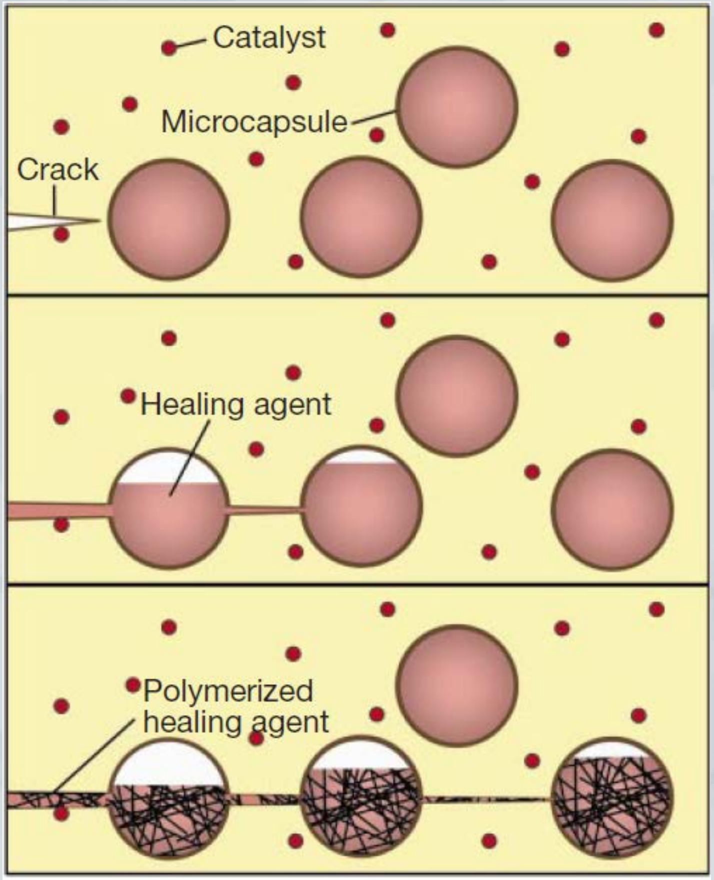
Electrical conductivity: ~109 A/cm2

(copper: 106 A/cm2)

Advanced composite materials

Self-healing materials

Structural polymers are susceptible to damage in the form of cracks, which form deep within the structure where detection is difficult and repair is almost impossible.



Self-healing materials have the ability to autonomically heal cracks, inspired by the self-healing biomaterials.

- The material incorporates a **microencapsulated healing agent** that is released upon crack intrusion.
- Polymerization of **the healing agent is then triggered by contact with an embedded catalyst**, bonding the crack faces.

Problems to be solved

To take advantage of the improved properties of the multifunctional materials there is a need to assess the effect of the additives on the mechanical behavior of the material.

- possible **degradation** of the mechanical behavior of the material (e.g. strength, fatigue, etc.)

The new multifunctional materials reveal the significance of the material production quality on the entire multifunctional materials' concept as it affects directly the degree of internal defects.

The advancement of high quality multifunctional material production techniques at affordable effort and cost would appreciably enhance the use of this promising category of materials in aircraft structural applications.

Nanocrystalline materials

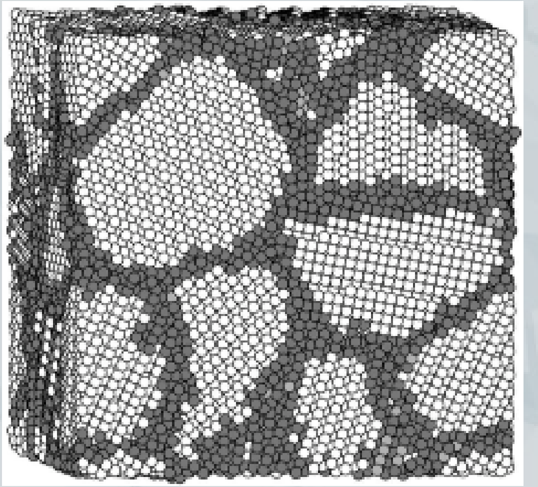
ICARUS SUPERMAT

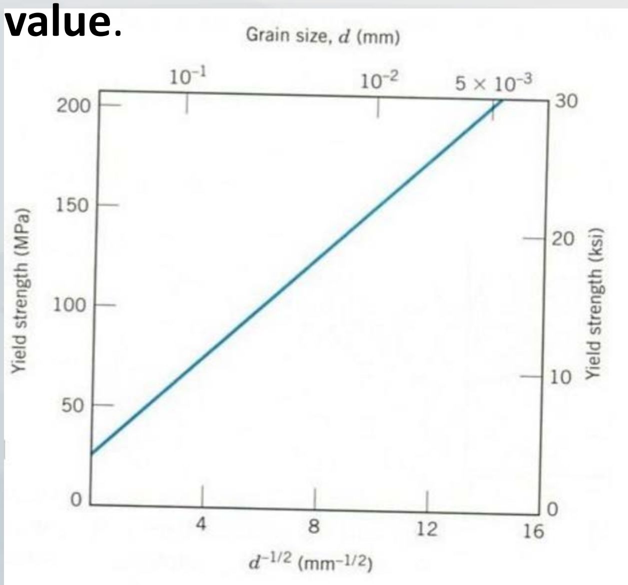
Definition:
Metallic alloys with **grain dimensions of the order of 100nm or less**.

Motivation:
By assuming the validity of the Hall-Petch equation:

$$\sigma_Y = \sigma_o + kd^{-1/2}$$

where σ_Y stands for the yield strength of polycrystalline, σ_o for the yield strength of one single crystal, k is a constant and d is the grain size, one may expect **a huge increase on the yield strength value**.





Nanocrystalline materials

Problem definition:

- The grain boundaries produce **an increase in the Gibbs free energy** of the system.
- Grain growth is a consequence of the driving force reducing free energy.
- Grain boundaries are dominant at the volume fraction of nanocrystalline materials. They play also a significant role to their overall mechanical behavior.

BUT: What about ductility and fatigue??

In addition, the validity of the Hall-Petch equation is under a certain value of the nano-grain severily questioned.

Nanocrystalline materials

Advantage:
Nanocrystalline materials present significant material properties (Young's Modulus, Ultimate Strength, etc) at ambient temperature.

Objective: Elimination of the driving force by producing a metastable equilibrium state.

Material stabilization

Kinetic mechanism
- Reduces mobility of GB
- Does not eliminate free energy driving force

Thermodynamic mechanism
- Creation of metastable equilibrium state
- Driving force eliminates at a critical grain size

Nanocrystalline materials

Nanocrystalline alloys on the basis of relevant aircraft metals

Nanocrystalline aluminum-based alloys

Base material (%wt)	Alloying elements (% wt)	Grain size	Ultimate Strength (MPa)	Young Modulus (GPa)	Density *(g/cm3)*	Elongation at fracture (%)
90% Al	10% Zr	58nm	*766*	-	-	-
93% Al	3%Fe – 2%Ti – 2%Cr	50nm	*690*	97	-	0.02
90% Al	10% Fe	30nm	683	44.3	-	-
92.5% Al	7.5% MWCNT	34.2 nm	*450*	-	-	-
84.2% Al	11.9%Cu-3.5%Ce-0.3%Zr-0.1%Mn	70.3nm	*523*	-	-	-
92.5% Al	7.5% Mg	30nm	*1166*	-	-	-

Nanocrystalline magnesium-based alloys

Base material (%wt)	Alloying elements (% wt)	Grain size	Ultimate Strength (MPa)	Young Modulus (GPa)	Density *(g/cm3)*	Elongation at fracture (%)
73% Mg	27% Ti	66 nm	*480*	-	-	-
85% Mg	15% Ti	76 nm	-	-	-	-

Nanocrystalline materials

Nanocrystalline alloys on the basis of relevant aircraft metals

Nanocrystalline titanium-based alloys

Base material (%wt)	Alloying elements (% wt)	Grain size	Ultimate Strength (MPa)	Young Modulus (GPa)	Density *(g/cm3)*	Elongation at fracture (%)
59%Ti	49%Ni	64nm	-	-	-	-
91%Ti	9%Mg	15nm	-	-	-	-
88.5%Ti	6.3%Al – 3.5%Mo – 1.7%Zr	30nm	1900	-	--	-

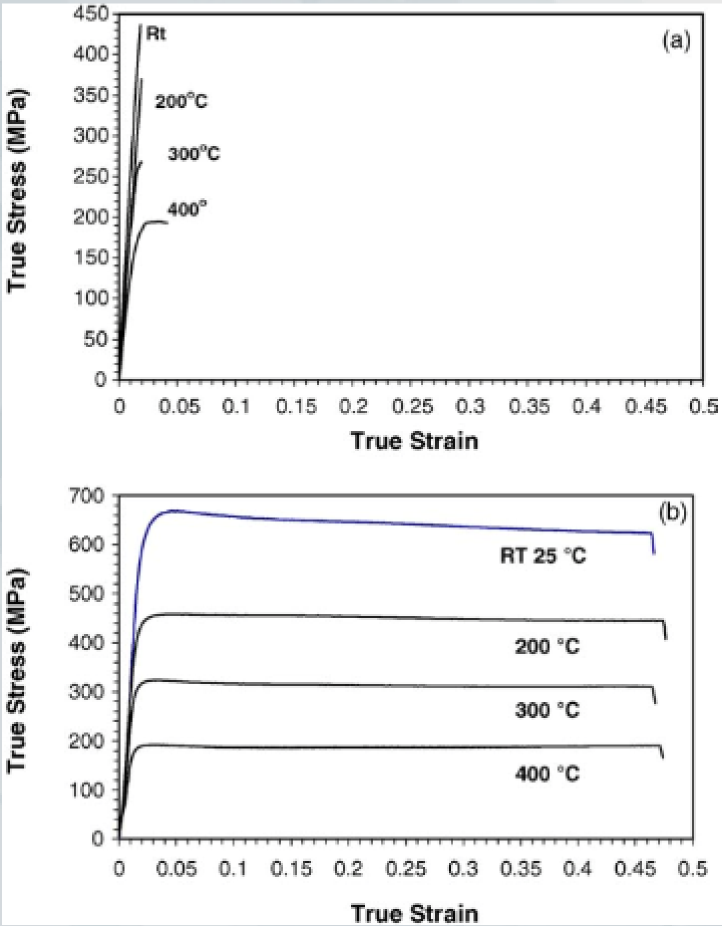
Nanocrystalline nickel-based alloys

Base material (%wt)	Alloying elements (% wt)	Grain size	Ultimate Strength (MPa)	Young Modulus (GPa)	Density *(g/cm3)*	Elongation at fracture (%)
86%Ni	14%W	10nm	*2600*	-	-	-
60%Ni	40%Mo	5nm	*2288*	-	-	-
98%Ni	2%P	-	1550	-	-	9.5
56%Ni	44%Cu	20nm	*1889*	-	-	-

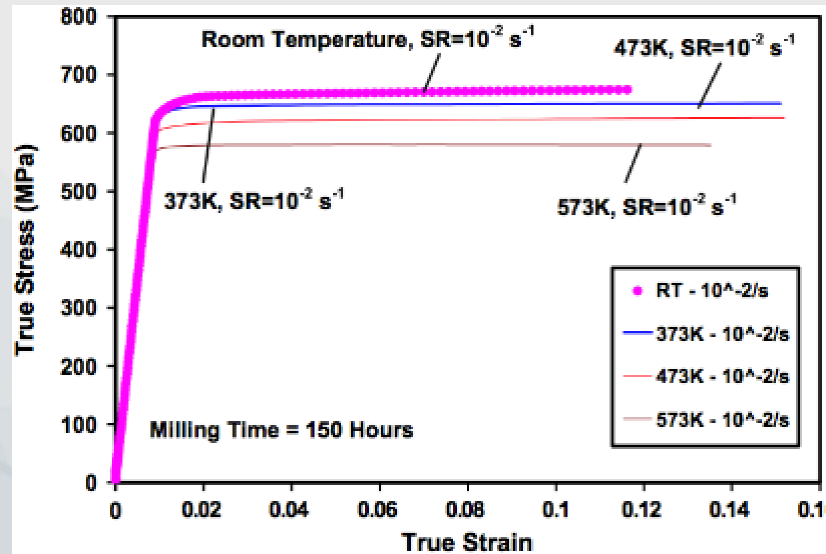
Nanocrystalline materials

ICARUS SUPERMAT

Indicative stress-strain curves



The stress–strain curves of the extruded nc 93%Al-3%Fe-2%Ti-2%Cr alloy under constant strain rate at different temperatures:
(a) tensile tests and (b) compressive tests [1]

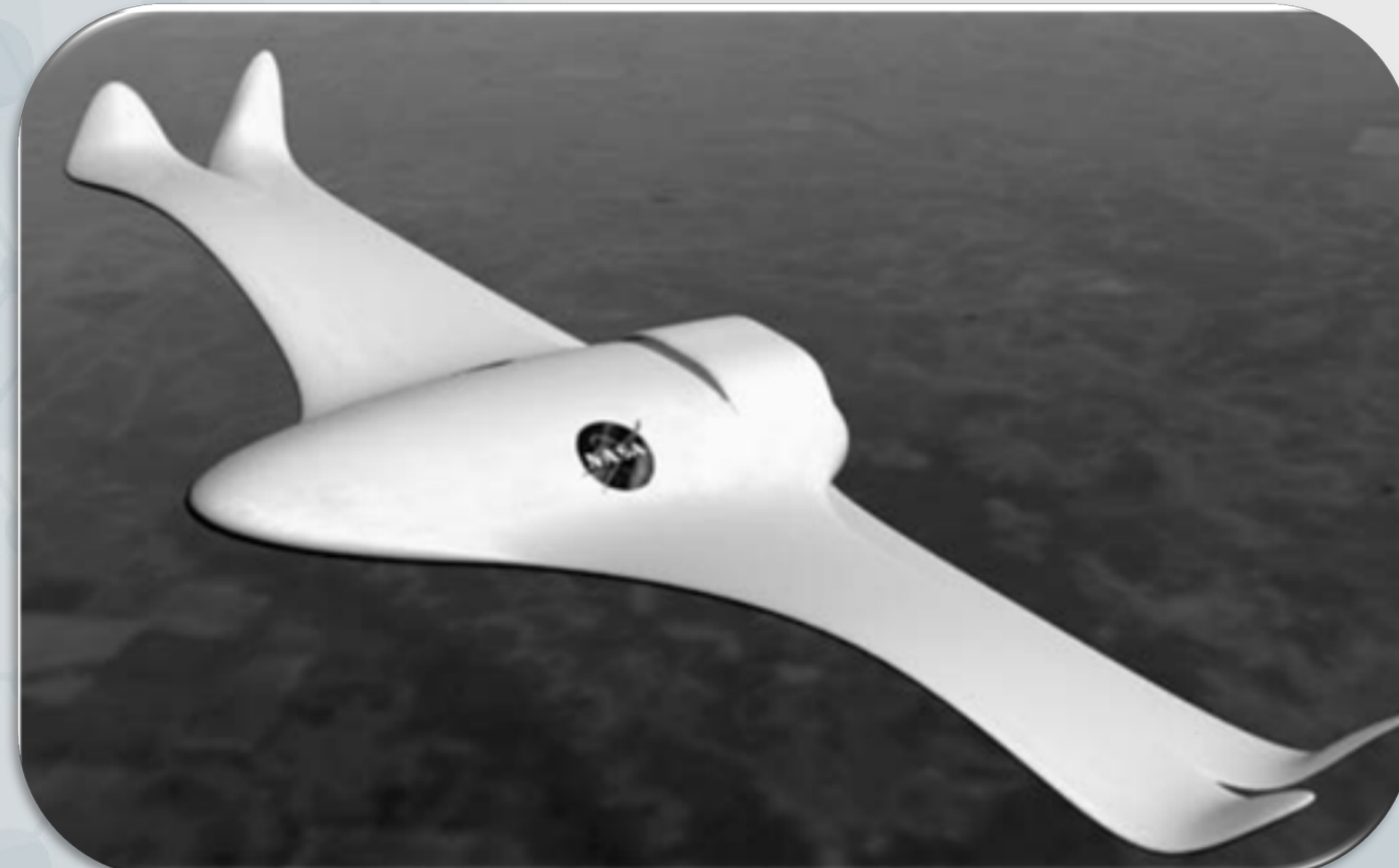


The compressive stress–strain response of sintered 90%Al-10%Fe nc alloy [2]

[1] Shaw, L.L. and Luo, H. (2007b) 'Deformation behavior and mechanisms of a nanocrystalline multi-phase aluminum alloy', *Journal of Materials Science*, 42(5), pp. 1415–1426.
[2] Baig, M., Ammar, H.R. and Seikh, A.H. (2016) 'Thermo-mechanical responses of nanocrystalline Al–Fe alloy processed using mechanical alloying and high frequency heat induction sintering', *Materials Science and Engineering: A*, 655, pp. 132–141.

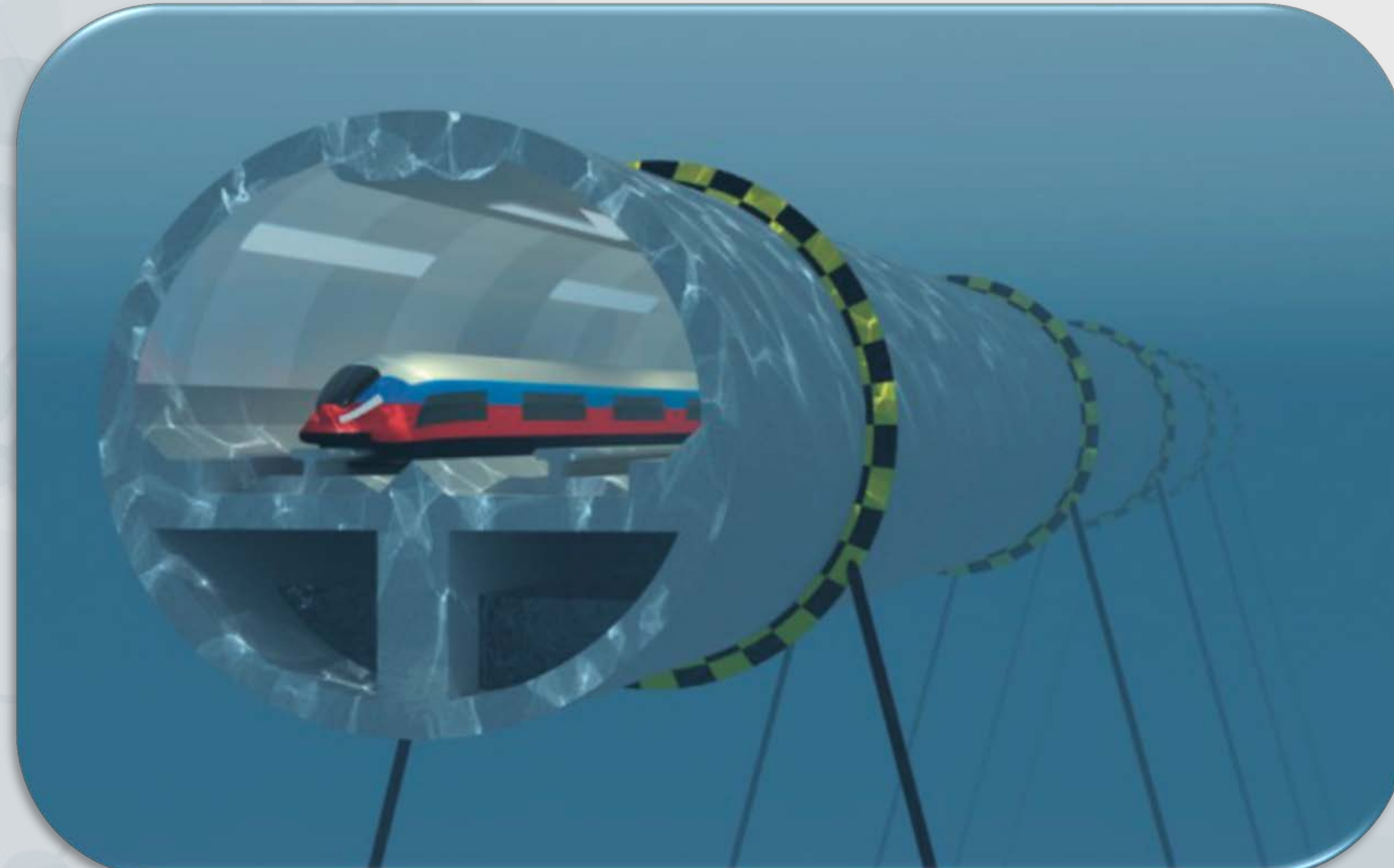
The Future of Aeronautics

The Future of Aeronautics



The Future of Aeronautics

ICARUS SUPERMAT



Artist's impression of a high speed connection between an offshore airport and a land based terminal. This could be a vacuum tube transport modality

The Future of Aeronautics

The airport of the future

Is evolutionary progress sufficient to meet the challenges of tomorrow???

Thank you!

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