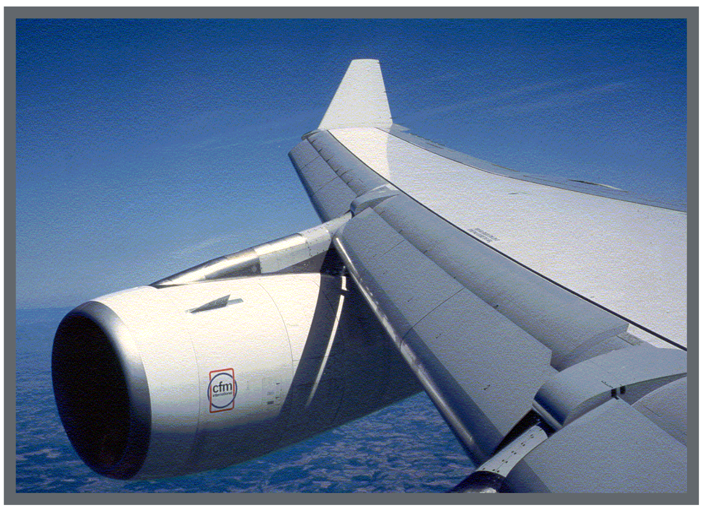
sonaca

AERONAUTICAL MATERIALS

Sonaca Engineering – D. Gueuning



sonaca

TABLE OF CONTENT

TABLE OF CONTENT

TABLE OF CONTENT

TABLE OF CONTENT

PART 1 : INTRODUCTION

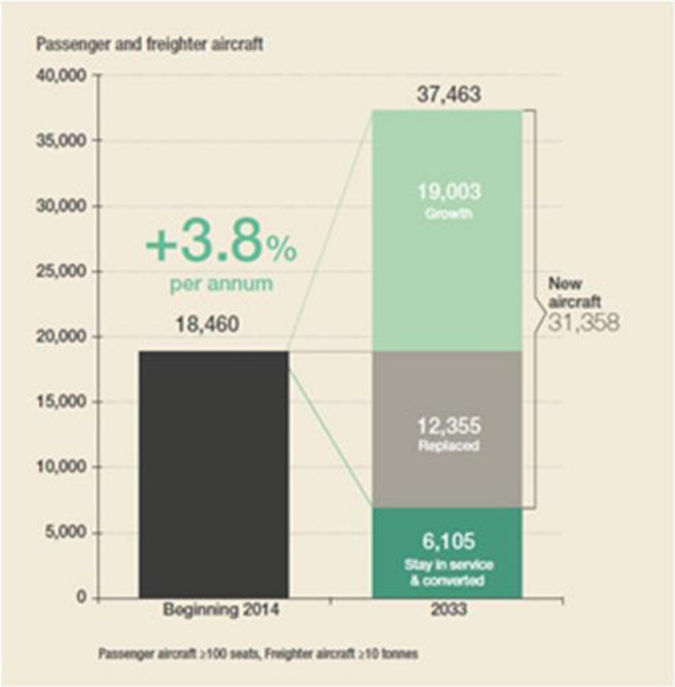
PART 2: METALLIC MATERIALS

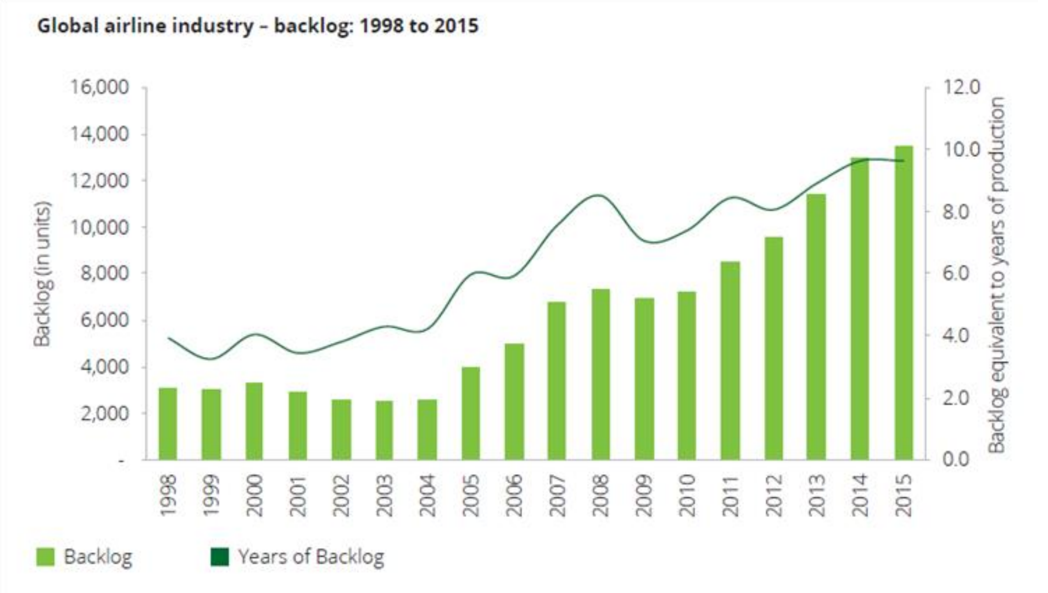
PART 3: COMPOSITE MATERIALS

PART 1 : INTRODUCTION

“Global Aircraft Market Forecast 2014-2033” (Airbus source)

“Global Airline Backlog 1998-2015”





PART 1 : INTRODUCTION

1.1. **Material Challenges for a New Aerostructure Product**

1.2. Material Distribution on Recent Aircrafts

1.3. Material Selection in Function of Application

1.4. Usage and growth of composites in the aerospace industry

1.1. Material Challenges for a New Aerostructure Product

Mass reduction

Light alloys with high specific properties : Al-Cu-Li, Al-Mg-Sc, Al-Mg-Li, Titanium

Advanced Composite Materials

Cost reduction

Reduction of scraps (increase of fly-to-buy ratio)

Mastering of the manufacturing processes

New manufacturing and assembly processes allowing more integrated structures

NEW PRODUCT

Increase of the structure performances

Materials with high strength and high damage tolerance

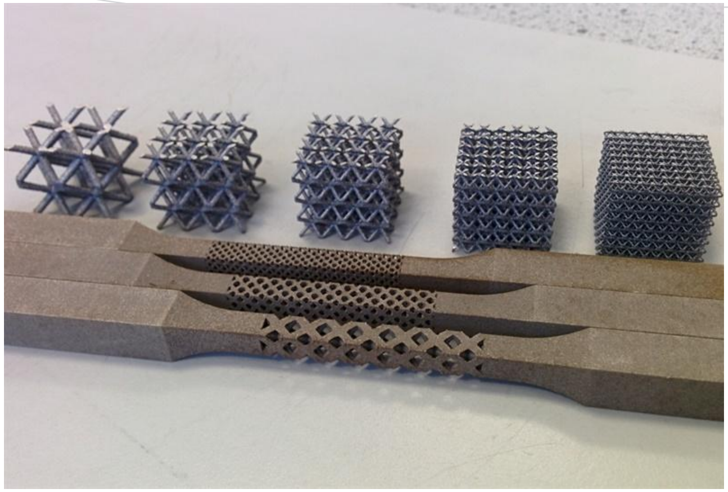
Multi-functional materials

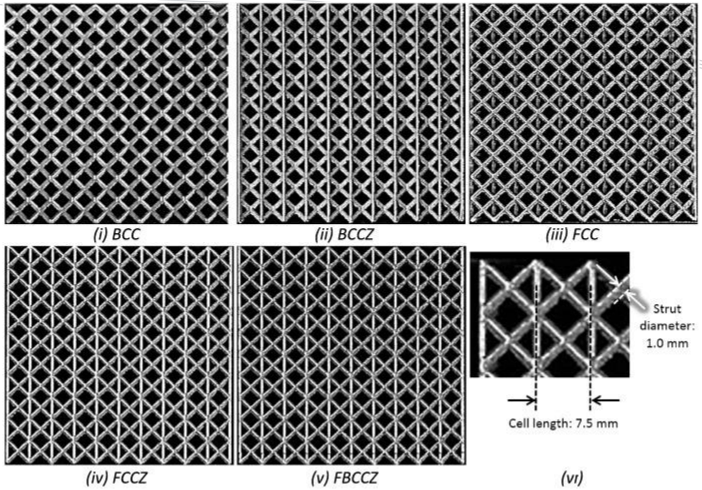
Reduction of environmental and human hazards

Deletion and replacement of prohibited substances : REACH

Recycling

The lightest metal in the world : the micro-lattice (in development at major aerospace OEM's)





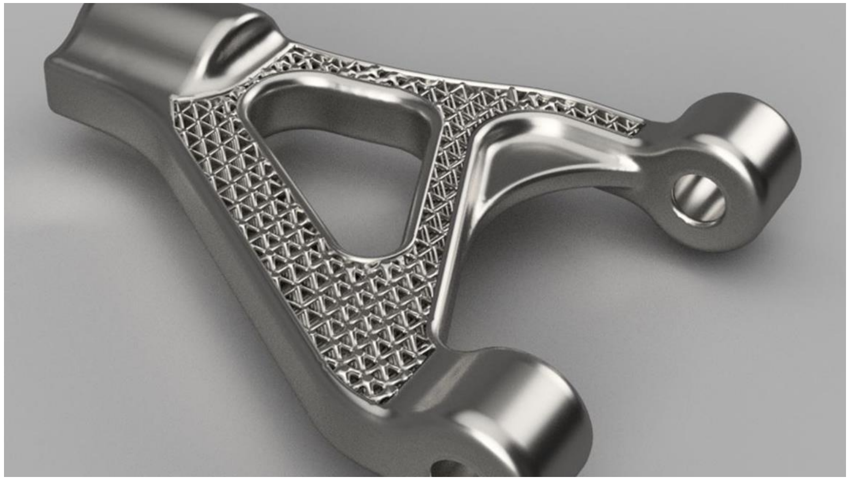


Image courtesy of Autodesk

Material is Ti-6Al-4V

PART 1 : INTRODUCTION

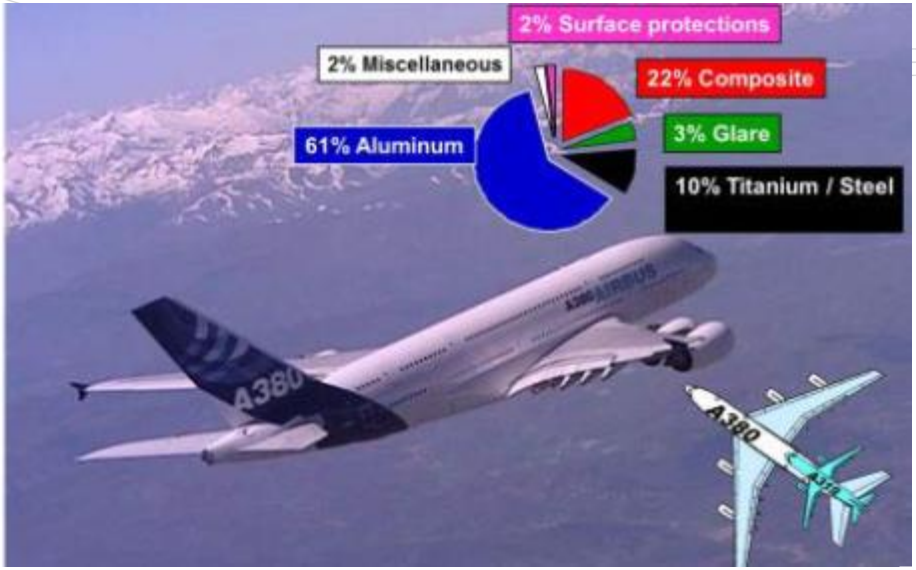
1.1. Material Challenges for a New Aerostructure Product

1.2. Material Distribution on Recent Aircrafts

1.3. Material Selection in Function of Application

1.4. Usage and growth of composites in the aerospace industry

1.2. Material Distribution on Recent Aircrafts



Material distribution on A380

A350 – Material breakdown

PART 1 : INTRODUCTION

1.3. Material Selection in Function of Application (1)

- **Aluminium alloys**
  - Choice based upon the high strength-to-density ratio
  - Relatively cheap and well known material
  - Very good toughness resistance (use in impact sensitive areas)
  - Main applications : fuselage, wings, slats, ….

- **Titanium alloys**
  - Main use for machined, forged and casted parts requiring very good mechanical properties or for parts exposed to temperature effects
  - Used for structural parts in contact with carbon composites (galvanic compatibility)
  - Used for complex shapes thanks to their superplastic forming capabilities …..
  - Main applications : nacelle structures, engine parts and engine pylons, heat pipes, de-icing systems,….

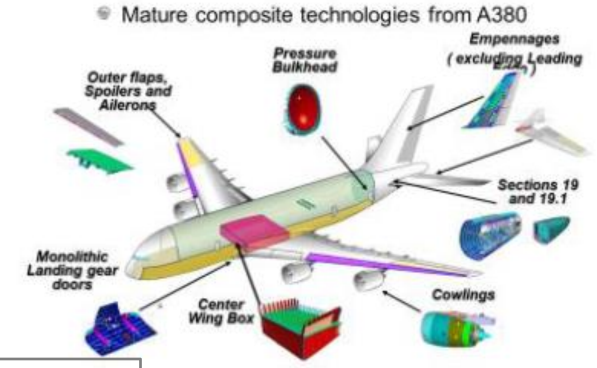
- **Steel alloys**
  - Used for applications requiring a very high mechanical resistance (up to Ftu of 1800 MPa), for parts exposed to high temperatures and for parts with limited space allocation…
  - Main applications : landing gear, engine parts, flap and slat tracks

1.3. Material Selection in Function of Application (2)

- **Carbon fiber reinforced polymeric matrix composites (CFRP)**
  - Choice based upon the very high strength-to-density ratio allowing significant mass reduction (e.g. : A350 aircraft)
  - Suitable for parts requiring very high stiffness (aircraft control surfaces)
  - Very expensive material : not always suitable for short range aircraft
  - Applications :
    - Vertical fin, tailplane, central wing box, outer flaps, spoilers and ailerons (A380)
    - Almost the whole fuselage, empennage, and wing (A350)

CFRP Fuselage

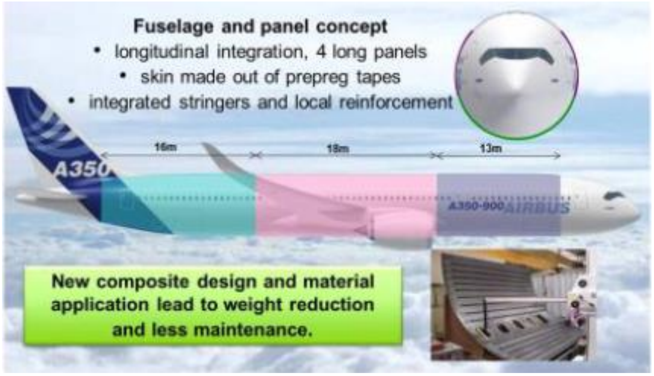
History of Composite Structures on Airbus Programmes



A380

EVOLUTION

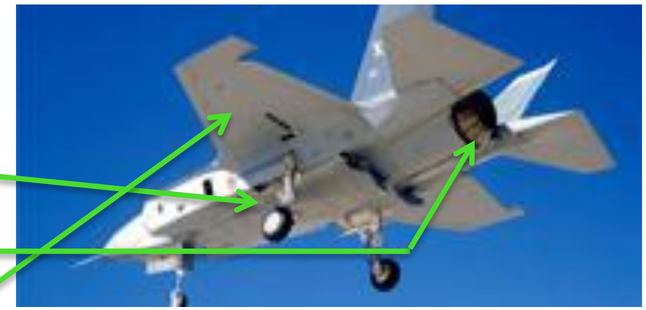
A350



1.3. Material Selection in Function of Application (3)

❑ Materials & densities

- ➢ Water : 1,0
- ➢ Steel : 7,8
- ➢ Titanium : 4,7
- ➢ Aluminium : 2,7
- ➢ Glass composite : 1,9
- ➢ Carbon composite : 1,6



PART 1 : INTRODUCTION

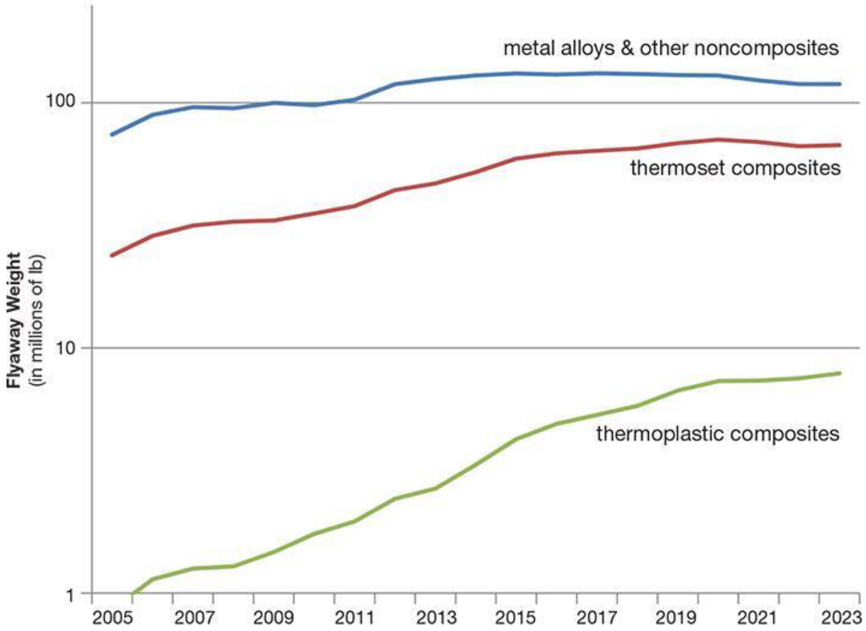
1.1. Material Challenges for a New Aerostructure Product

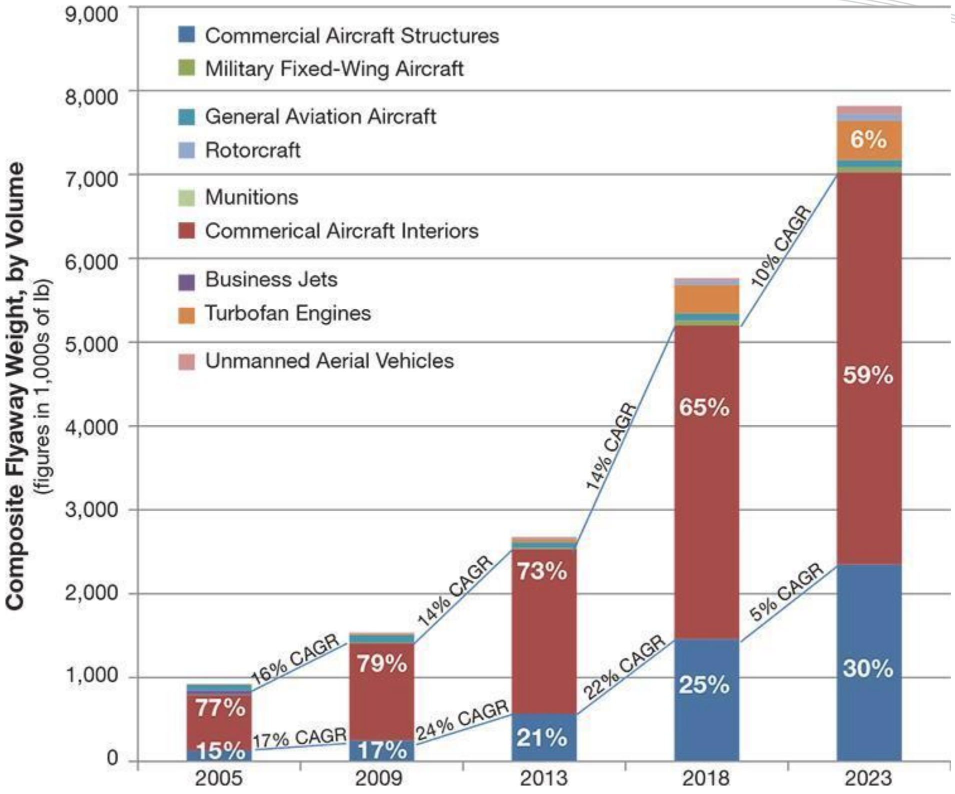
1.2. Material Distribution on Recent Aircrafts

1.3. Material Selection in Function of Application

1.4. Usage and growth of composites in the aerospace industry

1.4. Usage and growth of composites in the aerospace industry





PART 2 : METALLIC MATERIALS

PART 2 : METALLIC MATERIALS

2.1. Introduction to Aerospace Aluminium Alloys

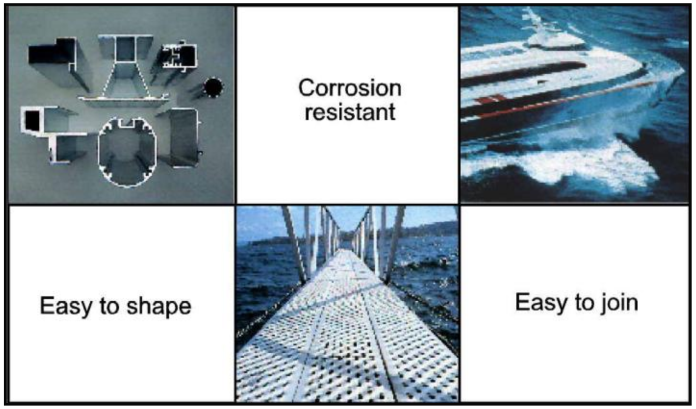
2.2.Introduction to Aerospace Alloy Steels

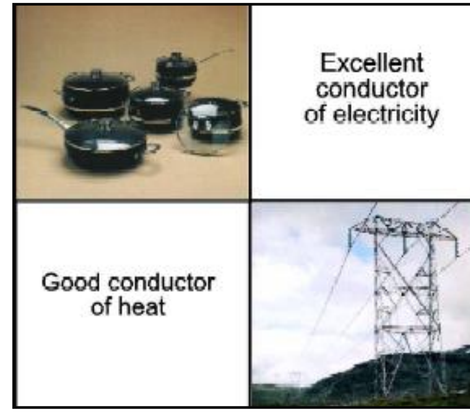
2.3.Introduction to Aerospace Titanium Alloys

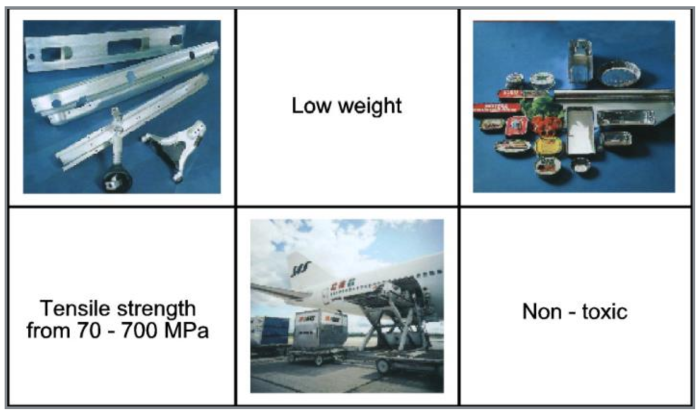
2.4.Material Design Allowable

2.1. Introduction to Aerospace Aluminium Alloys

2.1.1. Generalities on aluminium alloys (1)







2.1. Introduction to Aerospace Aluminium Alloys

2.1.1. Generalities on aluminium alloys (2) : Overall requirements for A/C's

- Reduced component weight :
  mainly determined by alloy, design and manufacturing

- Reduced component cost :
  mainly influenced by material, buy to fly ratio, manufacturing & assembly

- Reduced maintenance costs :
  driven by alloy, design and manufacturing

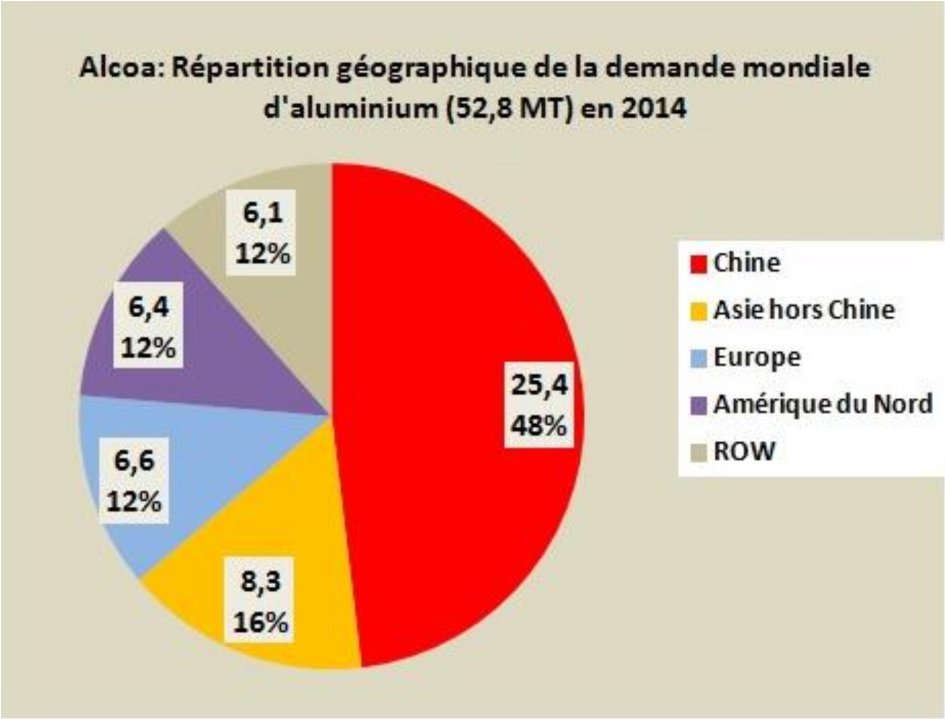
Short term solutions require
weight/cost reduction without manufacturing & design change (drop-in solution)
to allow for fast ramp-up & to avoid recertification
-> existing alloys or improved versions

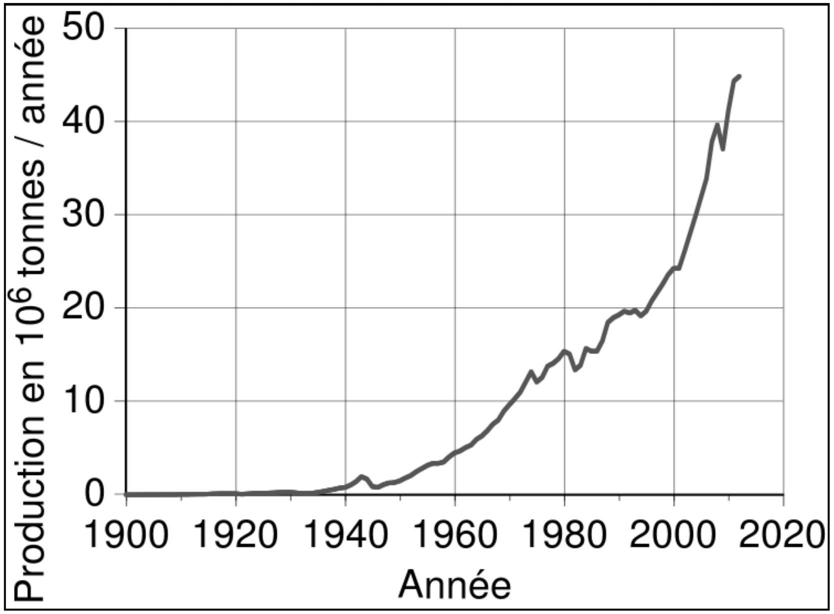
Long term solutions allow
new alloy concepts combined with
advanced manufacturing/assembly
technologies (re-design)

Depending on overall target : alloys/concepts for short term to long term solutions required

2.1. Introduction to Aerospace Aluminium Alloys

2.1.1. Generalities on aluminium alloys (3)

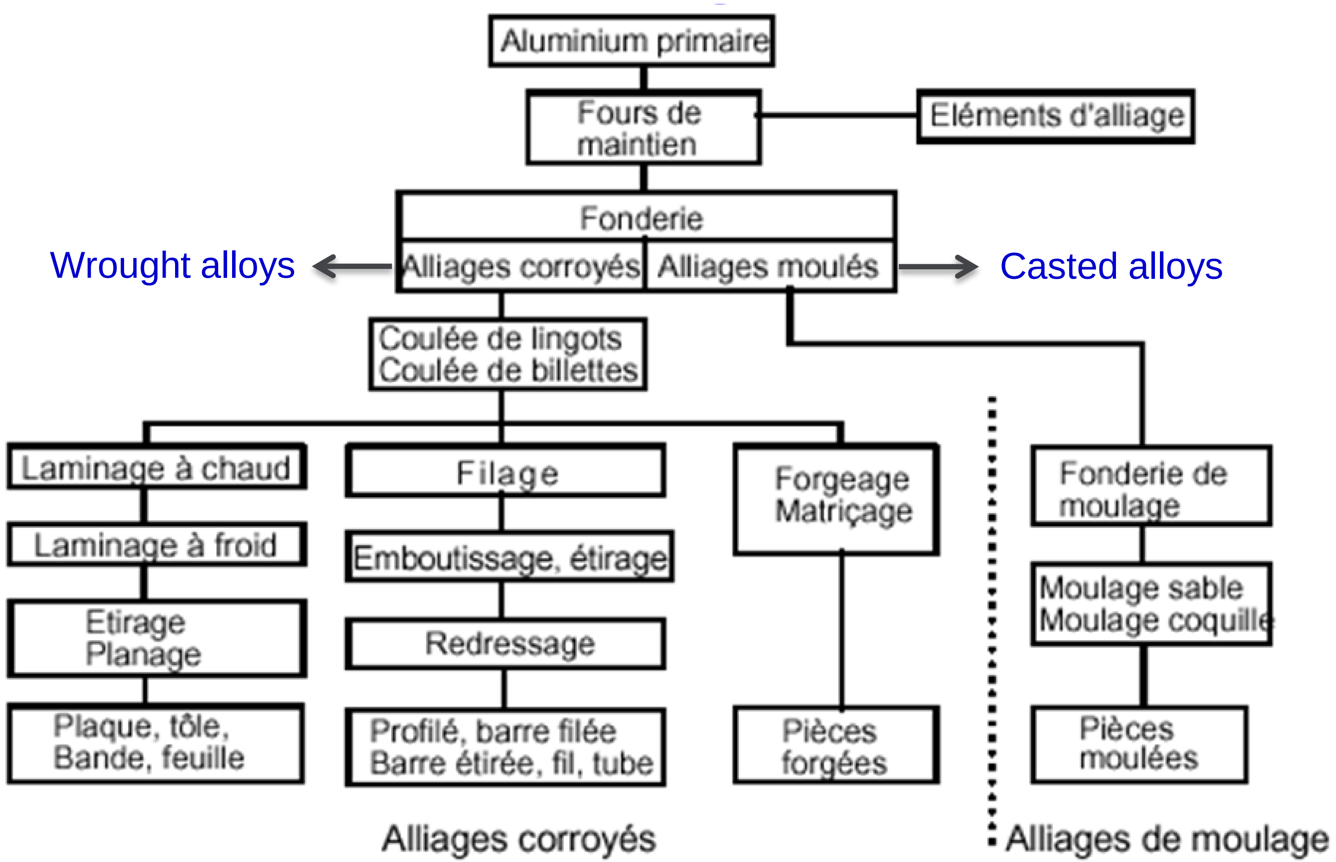




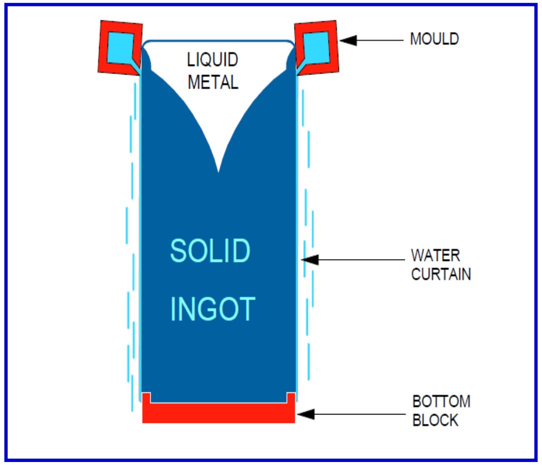
2.1. Introduction to Aerospace Aluminium Alloys

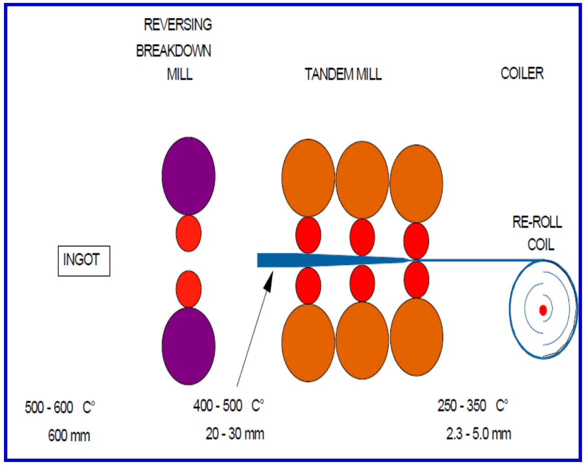
2.1.2. Elaboration : Semi-finished products (1)

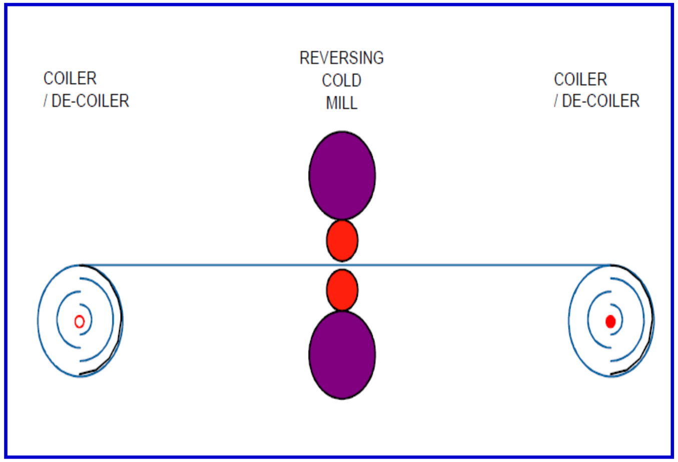
The manufacturing of aluminium alloys



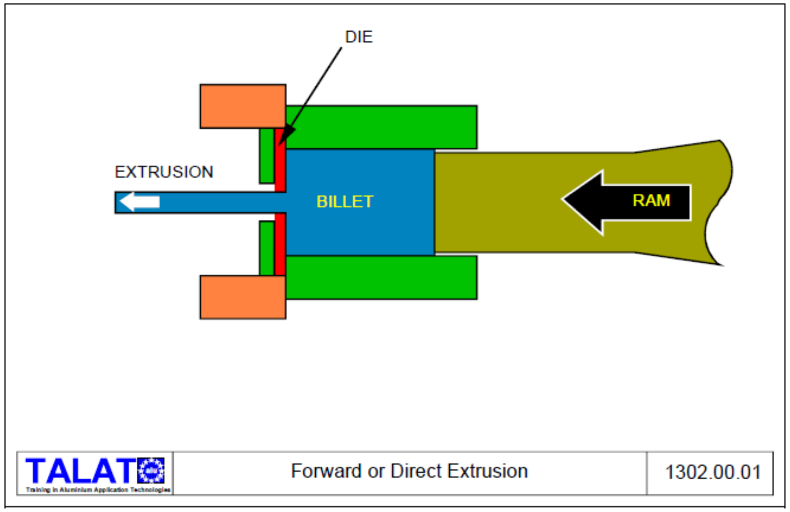
2.1.2. Elaboration : Flat products (2)





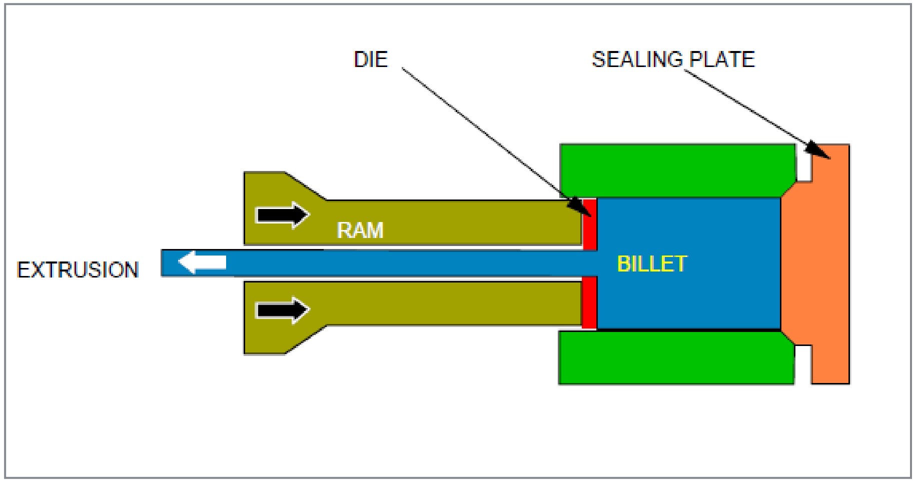


2.1.2. Elaboration : Extrusions (3)

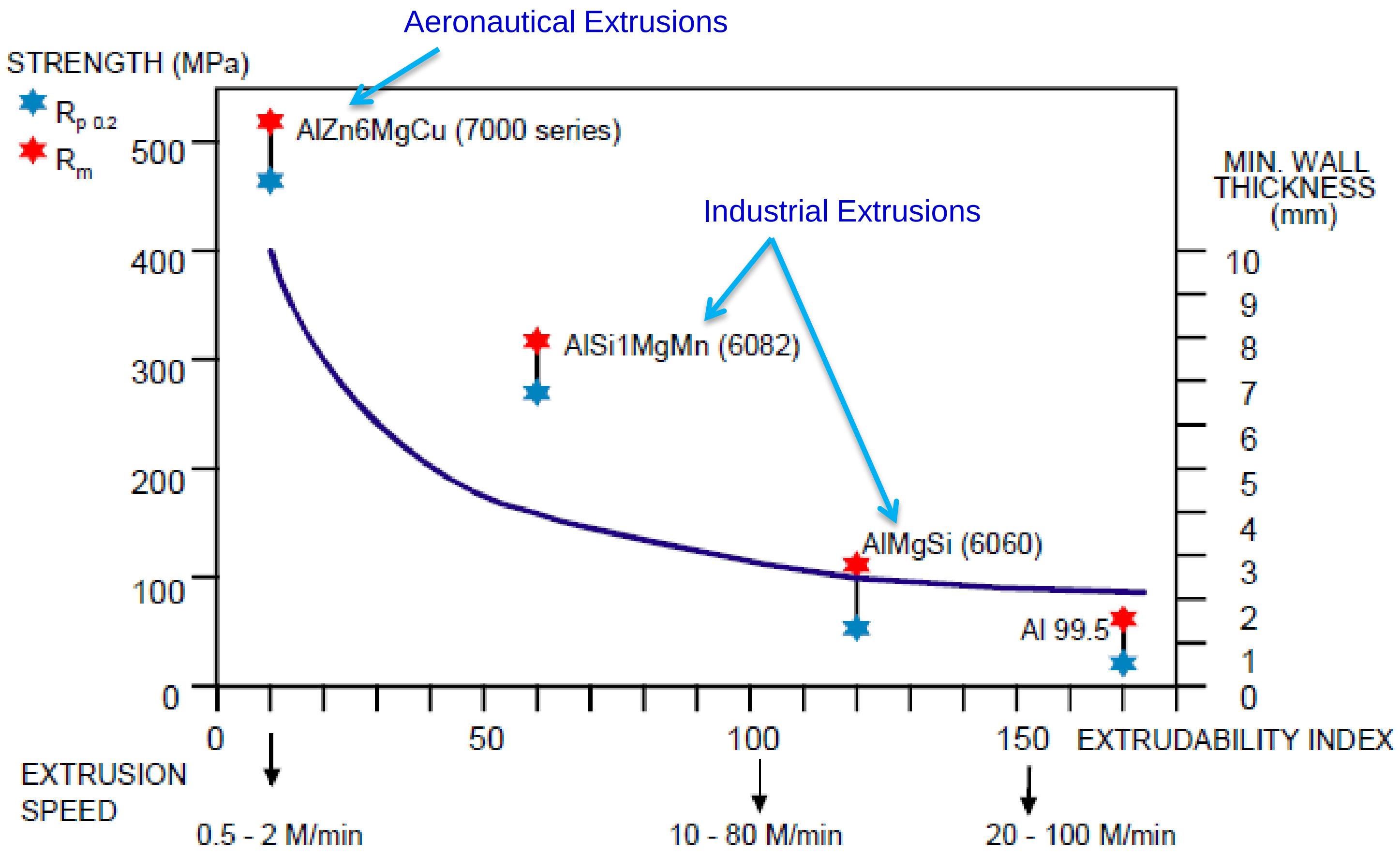


Direct extrusion

Indirect extrusion



2.1.2. Elaboration : Extrusions (4)



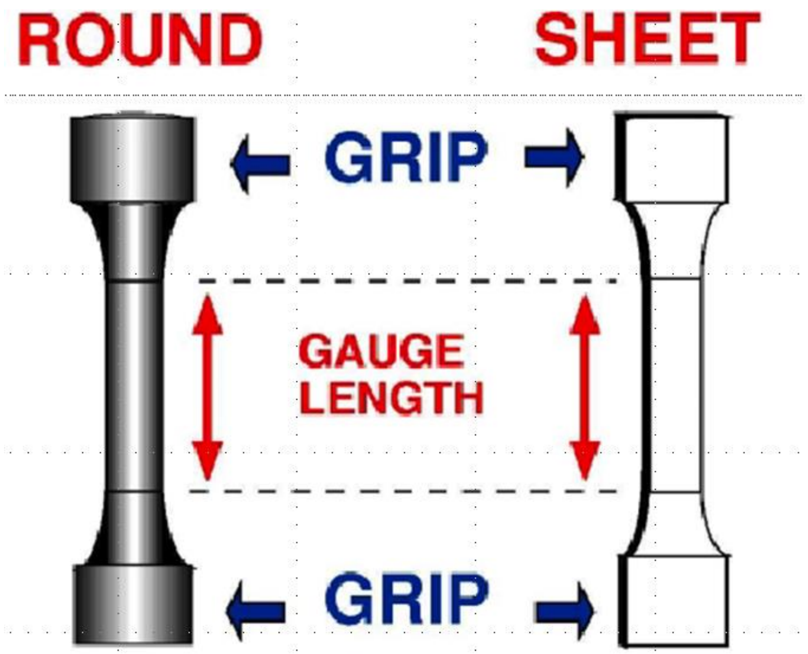
2.1. Introduction to Aerospace Aluminium Alloys

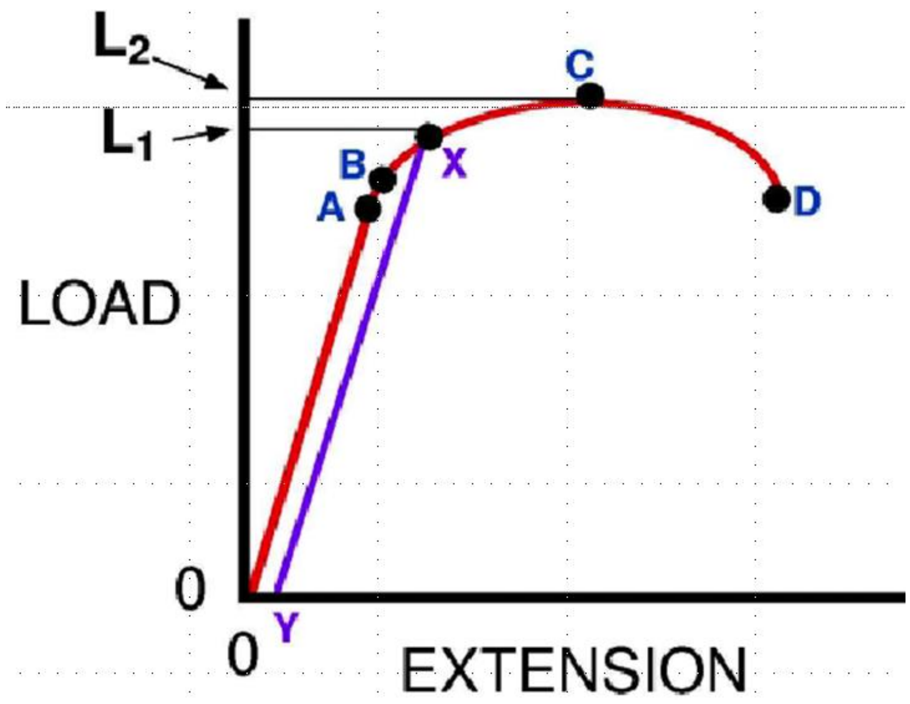
2.1.3. General criteria for aerospace alloy selection

- ❑ Static Properties (tensile, flexion, shear, …)
- ❑ Fatigue
- ❑ Damage tolerance (toughness and crack propagation resistance)
- ❑ Corrosion resistance
- ❑ Manufacturing (formability, machinability)
- ❑ Cost

2.1.3. General criteria for aerospace alloy selection

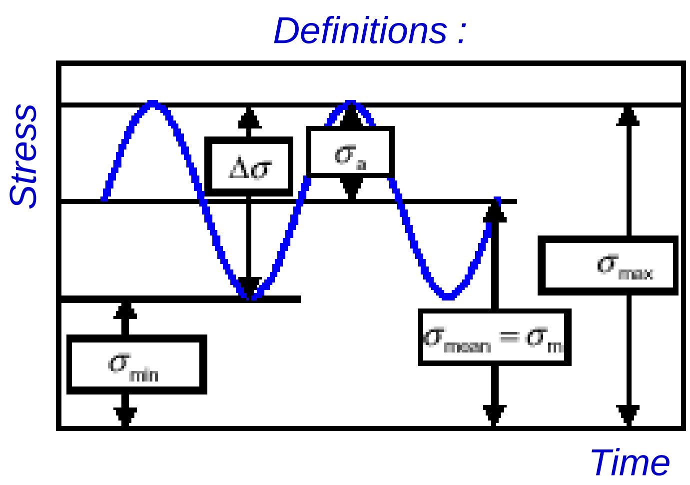
A. Tensile strength

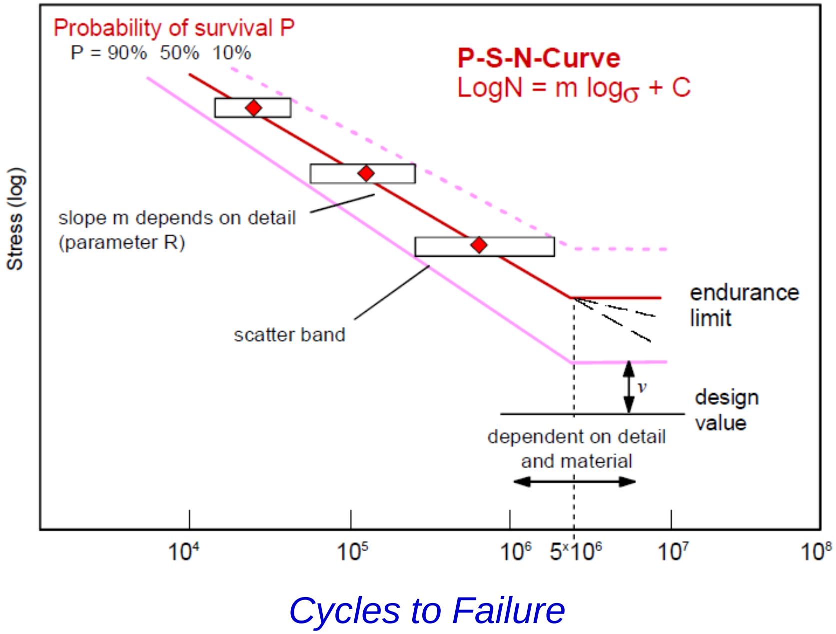




2.1.3. General criteria for aerospace alloy selection

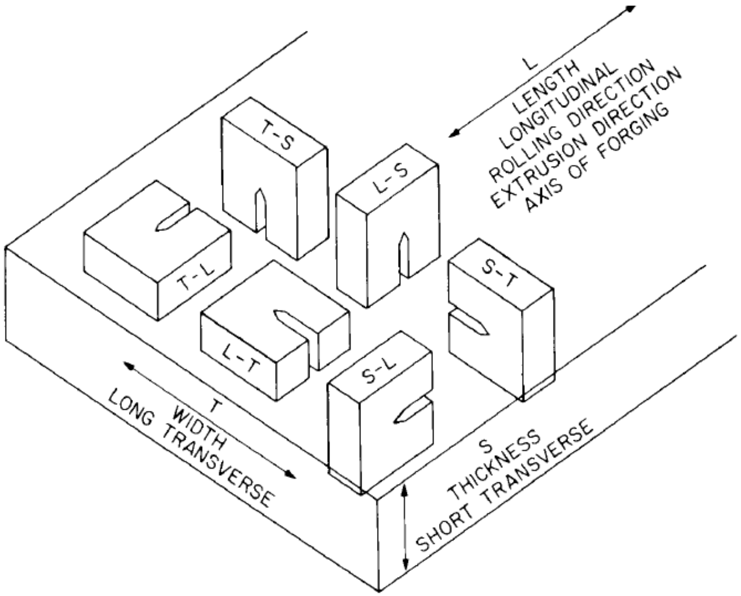
B. Fatigue behaviour





2.1.3. General criteria for aerospace alloy selection

C. Fracture toughness resistance



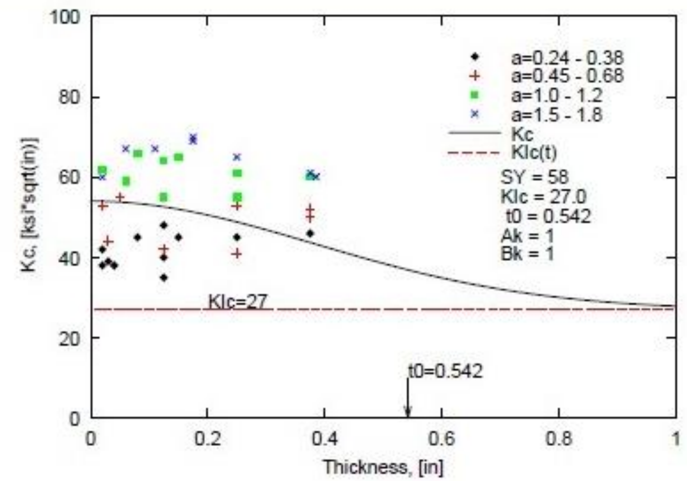
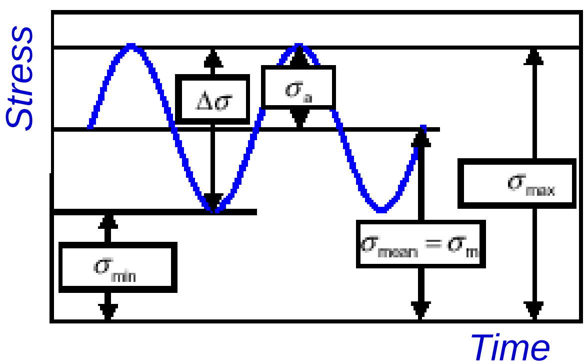


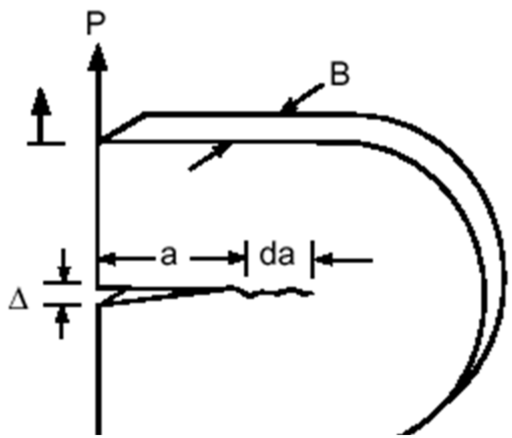
Figure – Kc vs. thickness showing R-curve effect for Aluminum 2219-T87

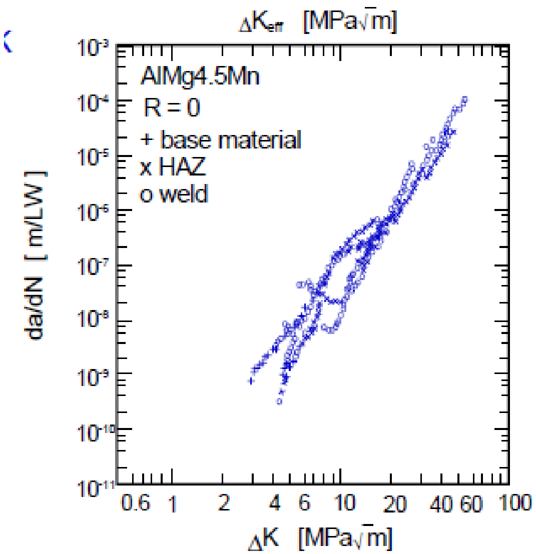
2.1.3. General criteria for aerospace alloy selection

D. Crack propagation resistance

Definitions :







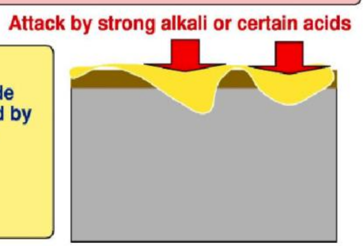
2.1. Introduction to Aerospace Aluminium Alloys

2.1.3. General criteria for aerospace alloy selection

E. Corrosion resistance

General corrosion.

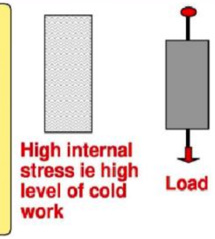
The natural oxide film is dissolved by strong alkaline solutions and certain acids



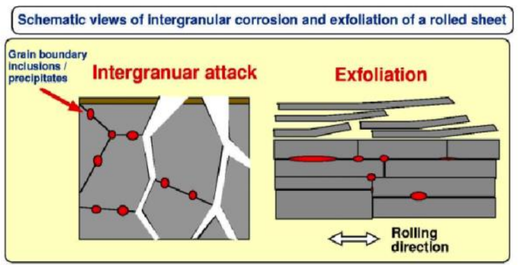
Stress corrosion.

Stress corrosion occurs in some susceptible aluminium alloys † in certain conditions of stress (internal and/or external) combined with certain microstructures coupled with exposure to a corroding environment eg salt water.

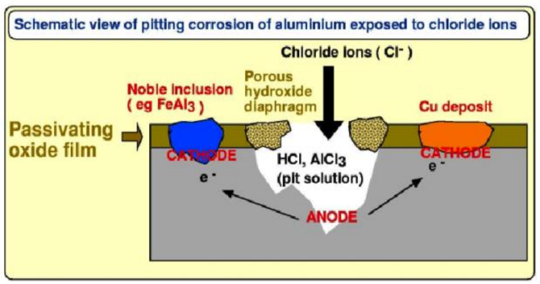
† eg Al-Cu, Al-Mg, Al-Zn-Mg



Intergranular corrosion / exfoliation

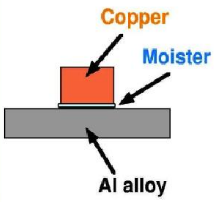


Pitting corrosion



Galvanic corrosion.

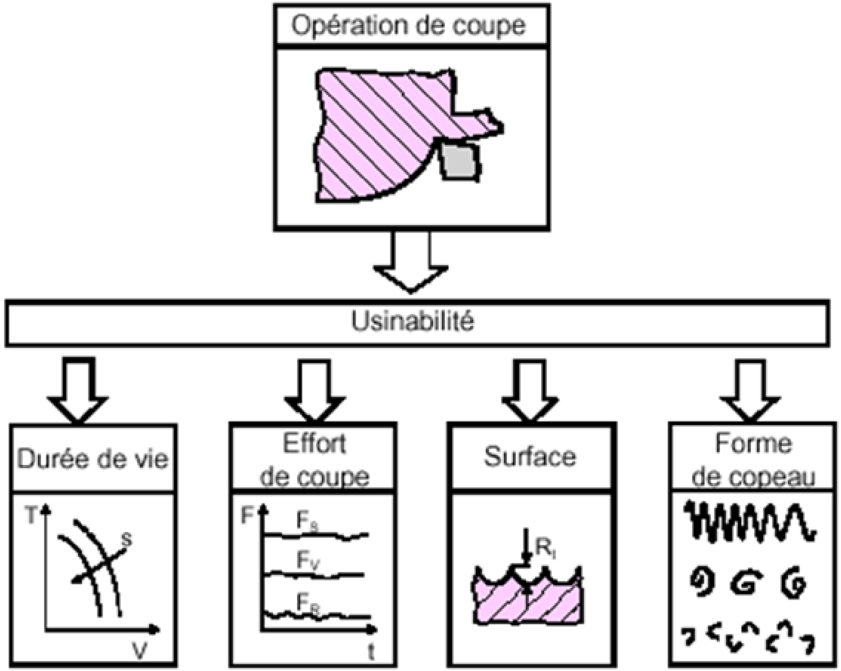
Galvanic corrosion may occur if an aluminium alloy is in damp or wet contact with another dissimilar metal, particularly if the aluminium alloy is strongly electronegative in the couple (which is often the case).



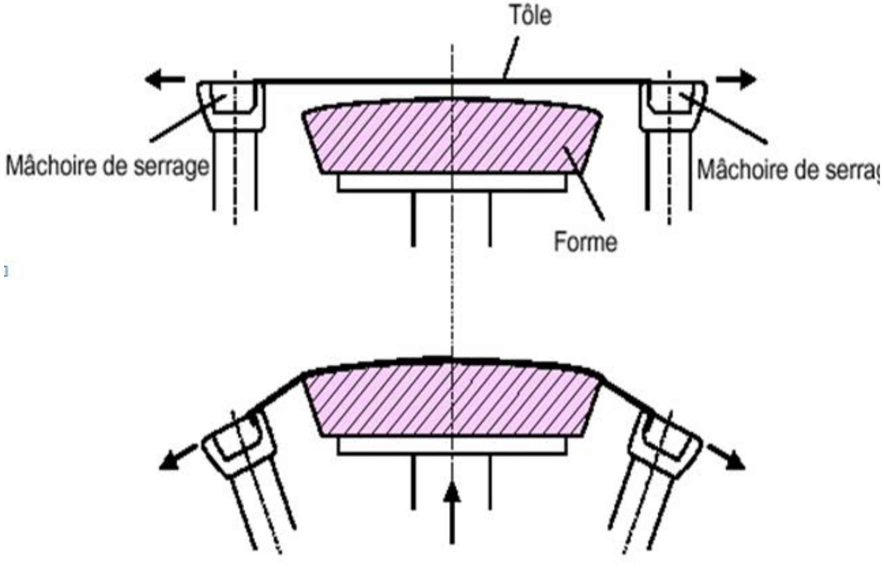
2.1.3. General criteria for aerospace alloy selection

F. Manufacturing

Definition of usinability



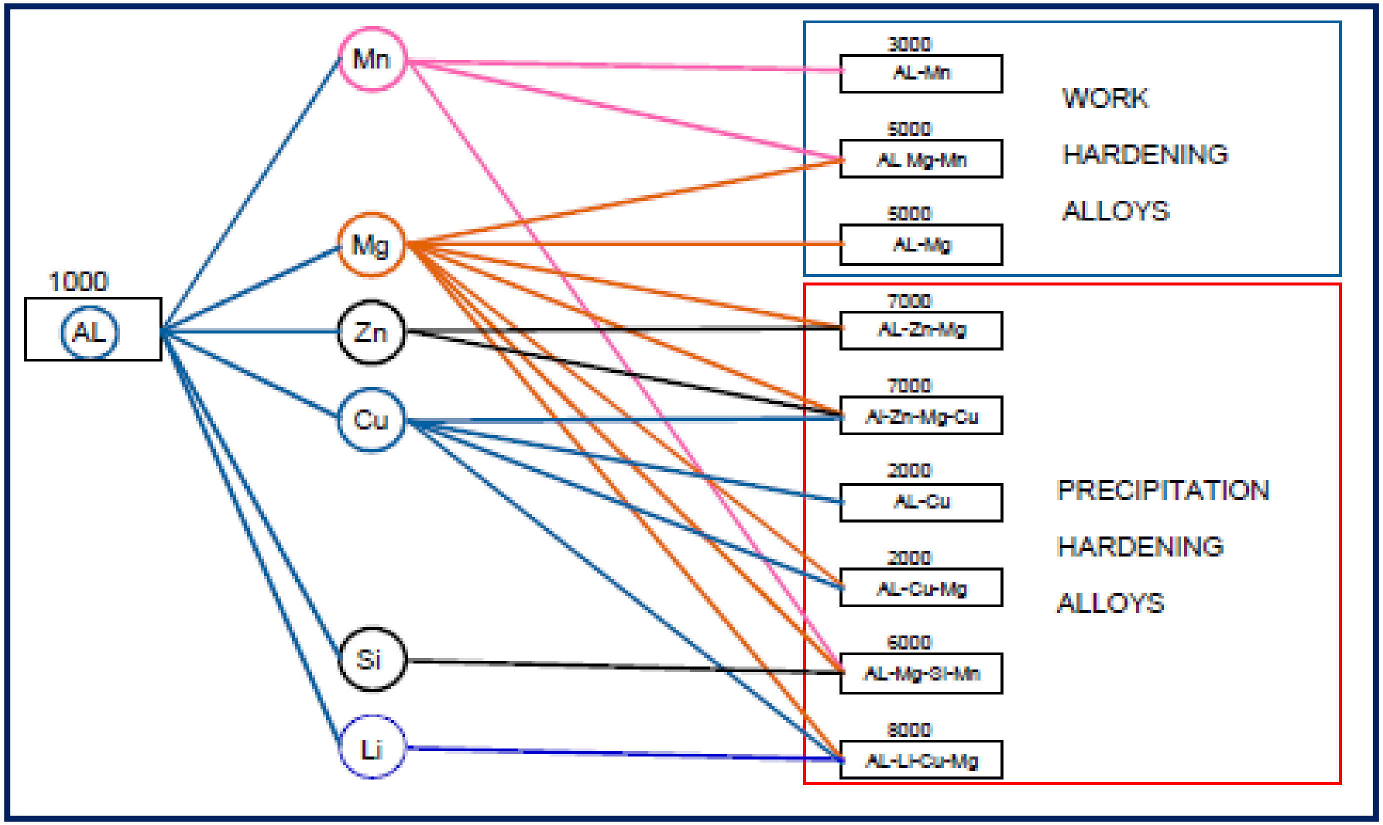
Stretchability



2.1. Introduction to Aerospace Aluminium Alloys

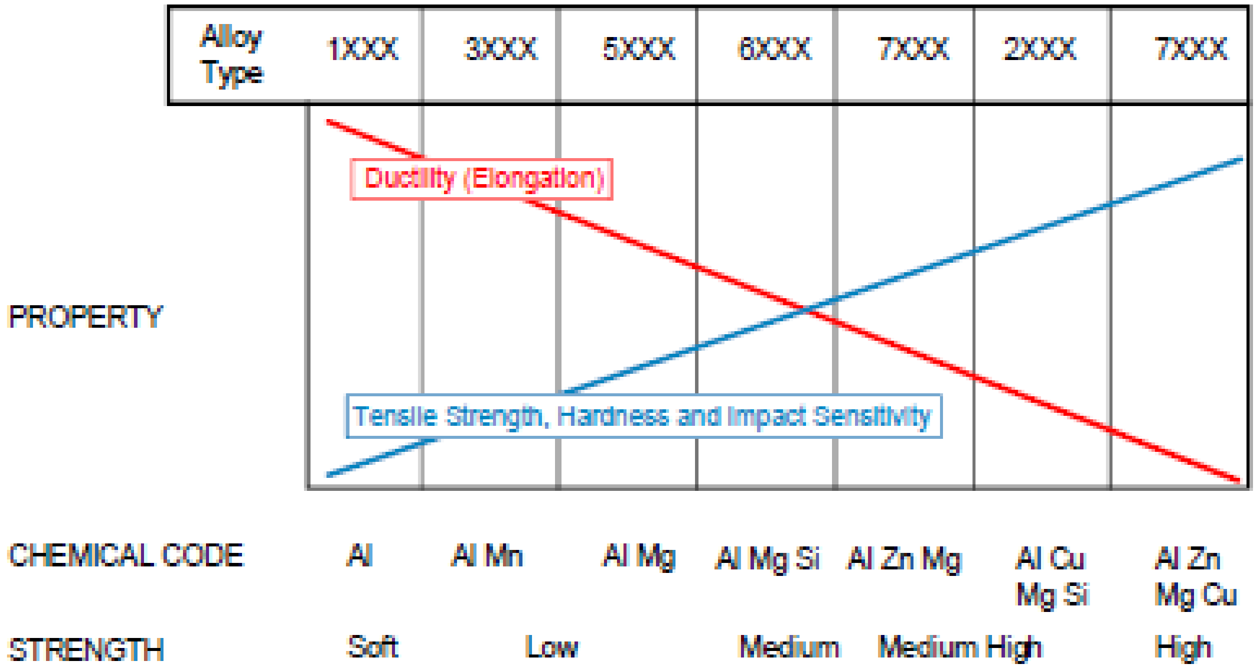
2.1.4. Aluminium alloy families

A. Main families of Aluminium Alloys (1)



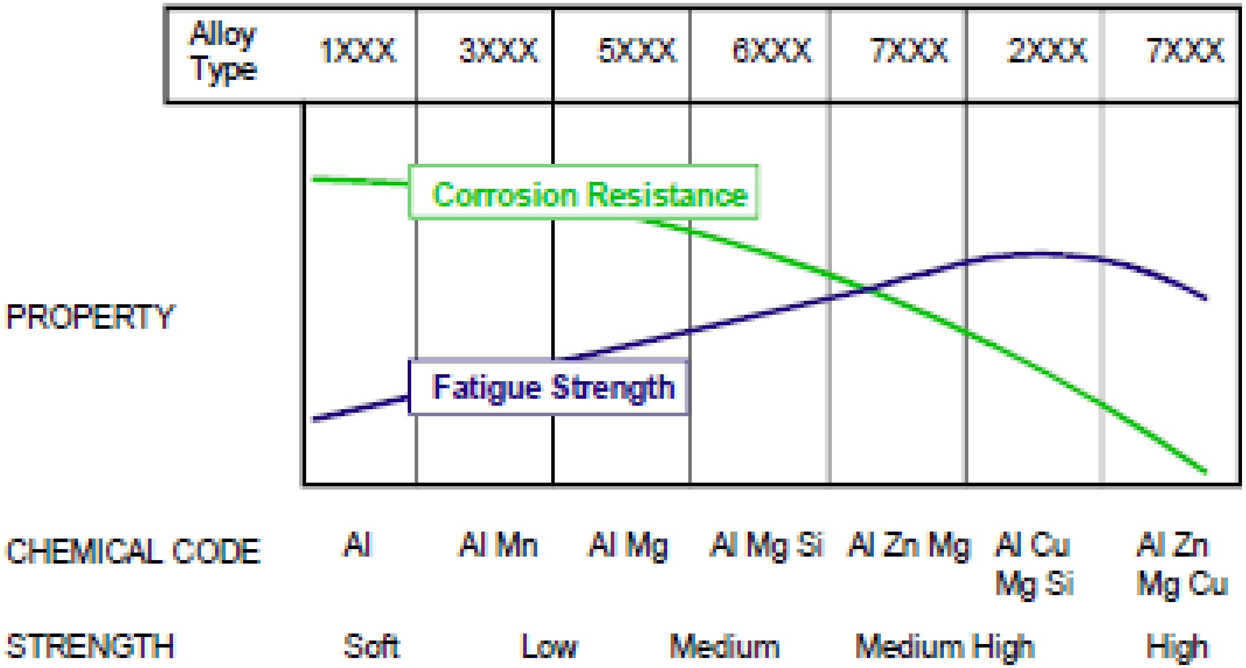
2.1.4. Aluminium alloy families

A. Main families of Aluminium Alloys (2)



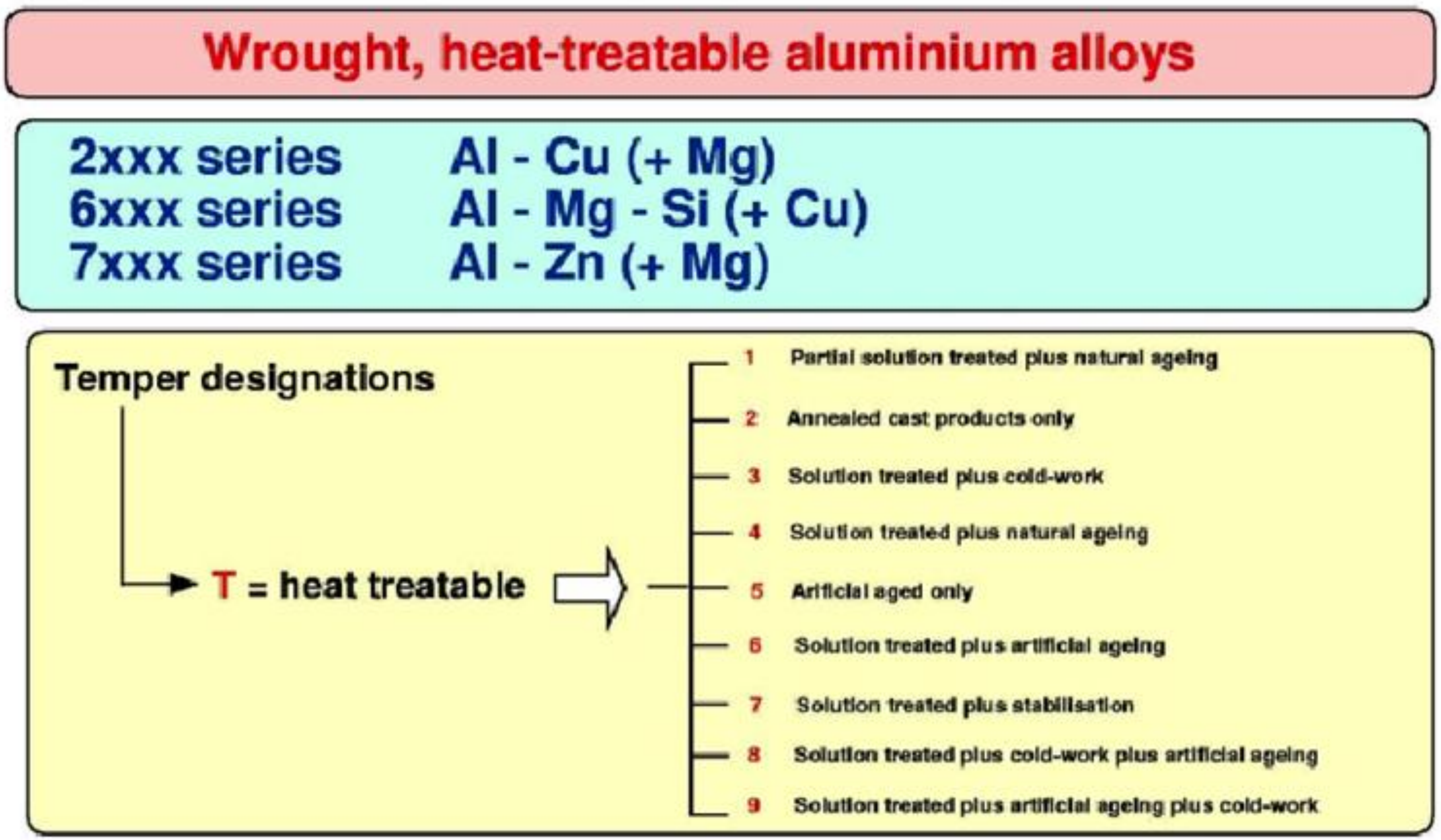
2.1.4. Aluminium alloy families

A. Main families of Aluminium Alloys (3)



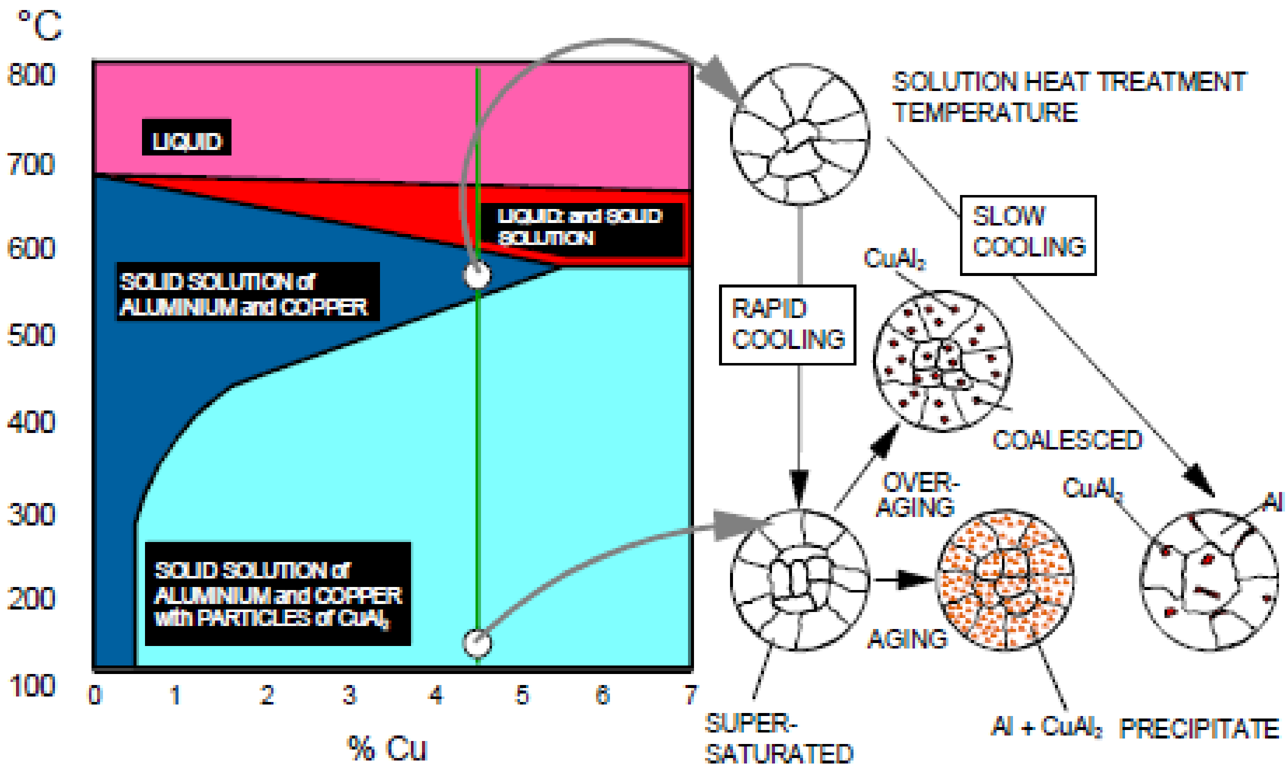
2.1.5. Aluminium alloys : Thermal conditions

A. Classification (1)



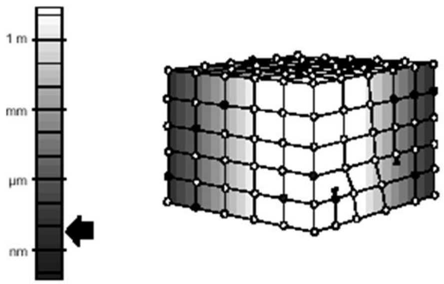
2.1.5. Aluminium alloys : Thermal treatments

B. Structural hardening (1)

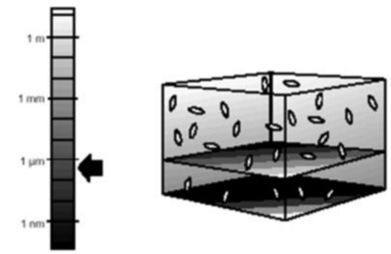


2.1.5. Aluminium alloys : Thermal treatments

B. Structural hardening (2)

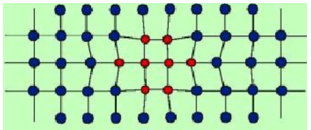


Ageing

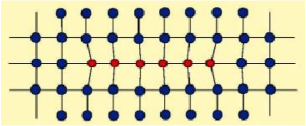


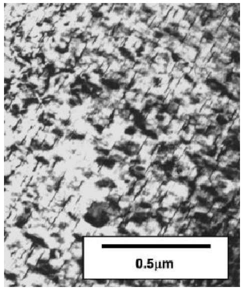
GP Zones

Al/Cu



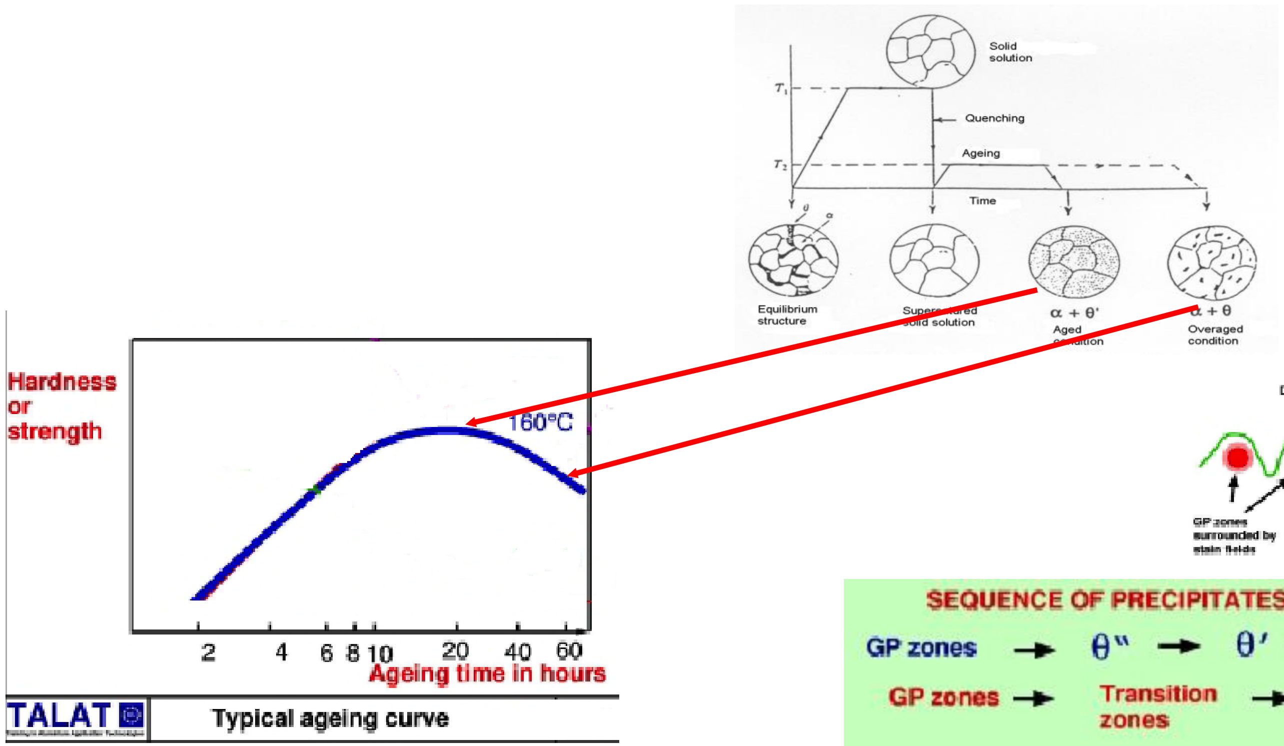
Al/Zn

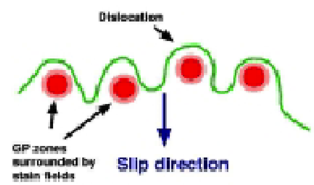




2.1.5. Aluminium alloys : Thermal treatments

B. Structural hardening (3)





SEQUENCE OF PRECIPITATES in Al - 4%Cu

GP zones →	θ" →	θ' →	θ
GP zones →	Transition zones →		Equilibrium precipitate (bct $CuAl_2$)

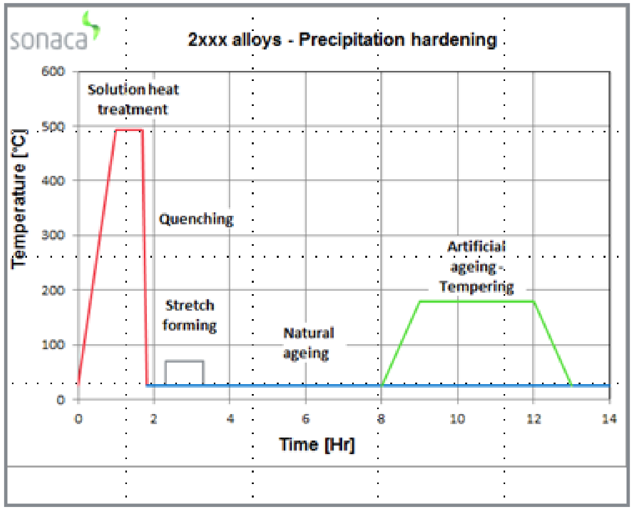
2.1. Introduction to Aerospace Aluminium Alloys

2.1.5. Aluminium alloys : Thermal treatments

C. Sonaca application and internal data (1)

❑ **Solution heat treatment (Al. alloys 2xxx/6xxx/7xxx) and quenching**

- Product forms (extrusions, bars, sheets, plates, forgings, ….)
- Dissolve alloying elements (Cu, Mg, …) and coarse precipitates in Al.matrix
- Ternary phases diagram (Al-Cu-Mg)
- High temperature/quick quench
- Surface cleanliness
- Metastable ductile state
- Straightening, stretch forming
- Spring back



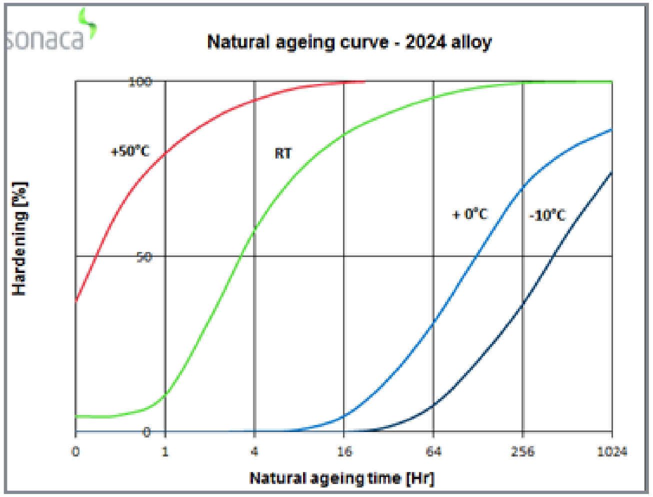
2.1. Introduction to Aerospace Aluminium Alloys

2.1.5. Aluminium alloys : Thermal treatments

C. Sonaca application and internal data (2)

❑ **Solution heat treatment (Al. alloys 2xxx/6xxx/7xxx) and quenching**

- Precipitation hardening («Guinier-Preston» zones formation and stable precipitates)
- Variable precipitation kinetic
- Hardening Hysteresis – Temperature
- Natural / artificial ageing (Txxxx)



2.1. Introduction to Aerospace Aluminium Alloys

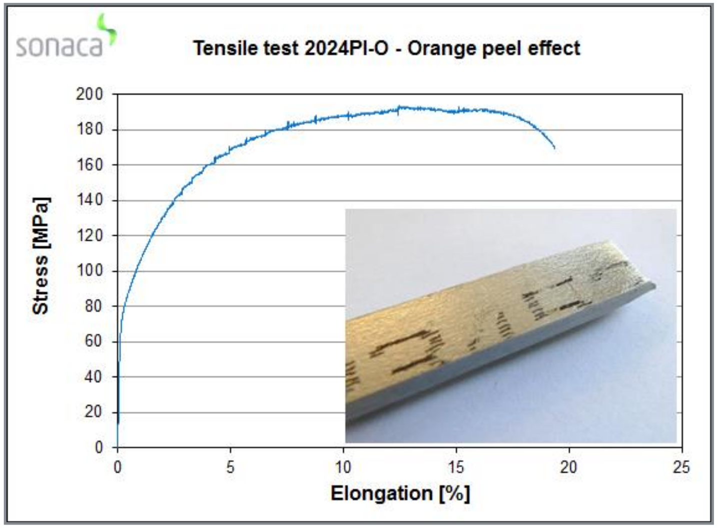
2.1.5. Aluminium alloys : Thermal treatments

C. Sonaca application and internal data (3)

- **Solution heat treatment (Al. alloys 2xxx/6xxx/7xxx) and quenching**

Cautions

- Coarse grains due to recrystallization « orange peel effect »
- Excessive quench deformation
- Excessive Cu diffusion in cladding



2.1. Introduction to Aerospace Aluminium Alloys

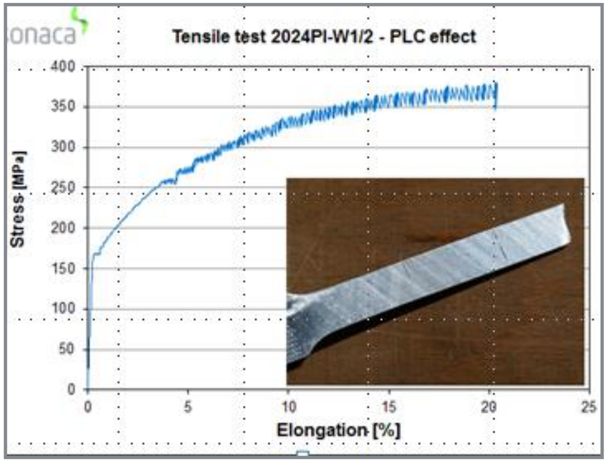
2.1.5. Aluminium alloys : Thermal treatments

C. Sonaca application and internal data (4)

❑ **Solution heat treatment (Al. alloys 2xxx/6xxx/7xxx) and quenching**

Cautions (cont'd)

- Portevin-Le-Chatelier (« PLC ») effect (fct % elongation)
  Deformation and Ageing dynamics (Solutes interaction with dislocations)
  NL curves instabilities
- Lüders effect

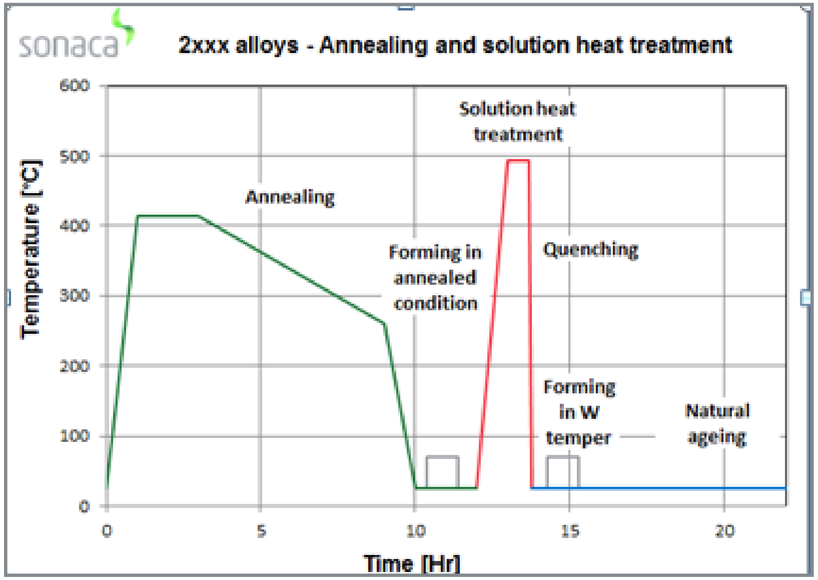


2.1.5. Aluminium alloys : Thermal treatments

C. Sonaca application and internal data (5)

- ❑ **Annealing for severe forming operation (caution)**

- ➢ Product forms (extrusions, bars, sheets, plates, forgings, ….)



2.1.6. The specifications

A. Objectives

❑ **Aim : To adequately define the minimum required properties of the materials in function of their application**

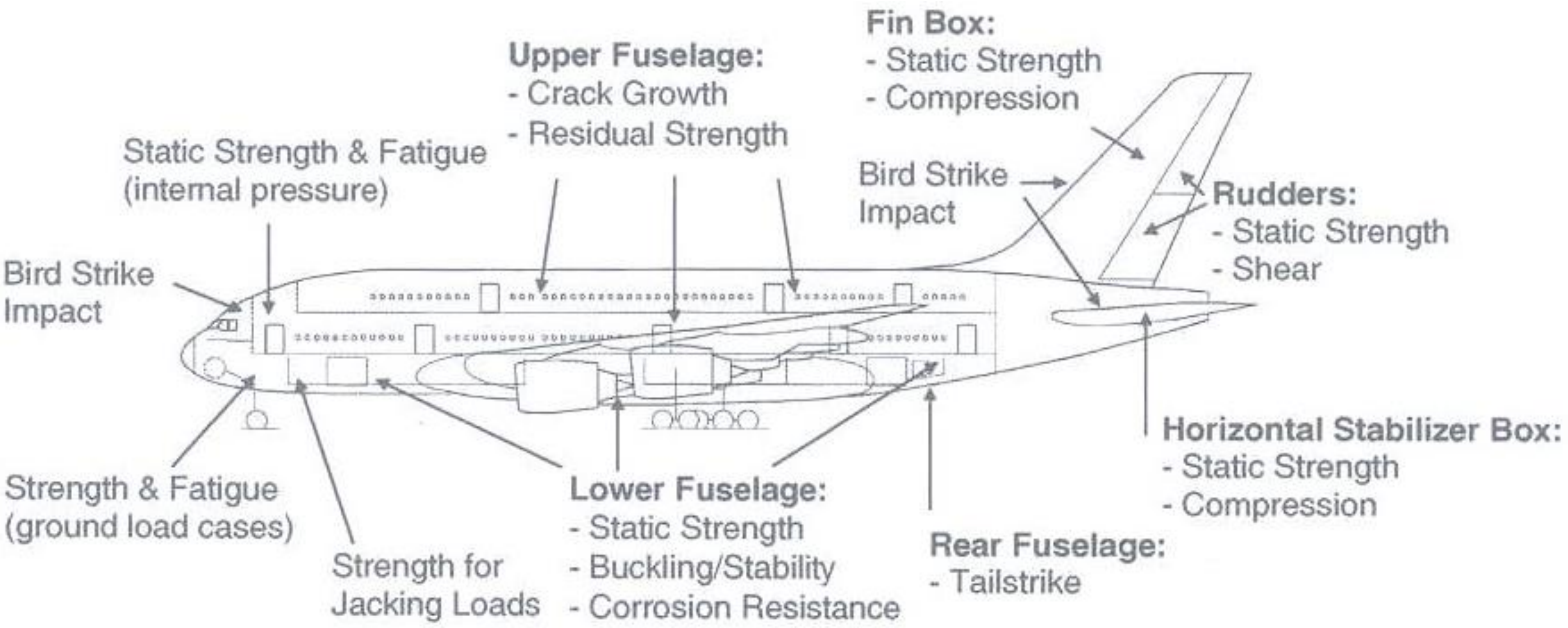
- Stress requirements and in-service behaviour
- Aesthetical requirements
- Manufacturing requirements

❑ **Important differences between the specifications**

- Identification of the required properties
- Values of the required properties

2.1.6. The specifications

B. Requirements based upon the application (Fuselage)



2.1.6. The specifications

B. Requirements based upon the application (Wing)

2.1. Introduction to Aerospace Aluminium Alloys

2.1.6. The specifications

C. Examples of content

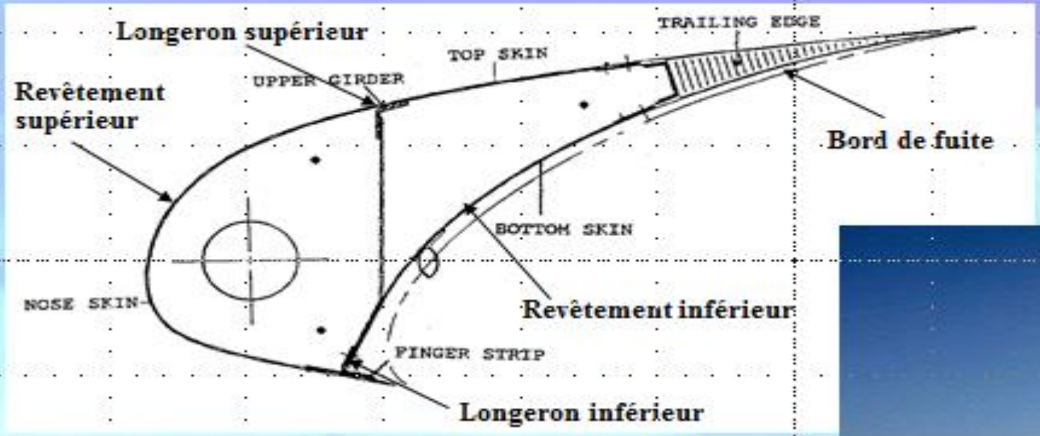
Property	AIR9048 (dec 1978)	AMS 4202 issue C	MEP 02-013 rev G	AIMS 03-02-009 issue 3
Fty L/LT/ST (MPa)	? / 340 / 350	365 / 365 / 352	365 / 365 / 352	365 / 365 /350
Ftu L/LT/ST (MPa)	? / 430 / 440	448 / 448 / 441	448 / 448 / 441	450 / 450 / 440
A L/LT/ST (%)	? / 7/ ? (A5.65)	10% / 8% / 3% (A4D)	10% / 8% / 3% (A4I	9%/7%/3% (A5D)
KIc L-T/T-L/S-L (MPam0,5)	? / 31,5 / ?	? / ? / 27	? / ? / 27	44/36/27
E (GPa)	?	?	?	70 - 74
Ec (GPa)	?	?	?	71 - 75
Fcy L/LT/ST (MPa)	? / ? / ?	? / ? / ?	? / ? / ?	340/370/370
Fbry 1,5 (MPa)	?	?	?	530
Fbru 1,5 (MPa)	?	?	?	670
Fbry 2 (MPa)	?	?	?	615
Fbru 2 (MPa)	?	?	?	860
SCC LT (MPa)	255	?	?	75% Fty in LT
Fatigue curve	?	?	criteria (1 level)	min curve
Crack propagation curve	?	?	?	min curve
Electrical conductivity	criteria	criteria	criteria	criteria
Batch uniformity	?	?	?	criteria

Example : 7475 T7351, thickness : 85mm

2.1.7. Aluminium alloy applications on an aircraft

A. Sonaca application : Slat materials

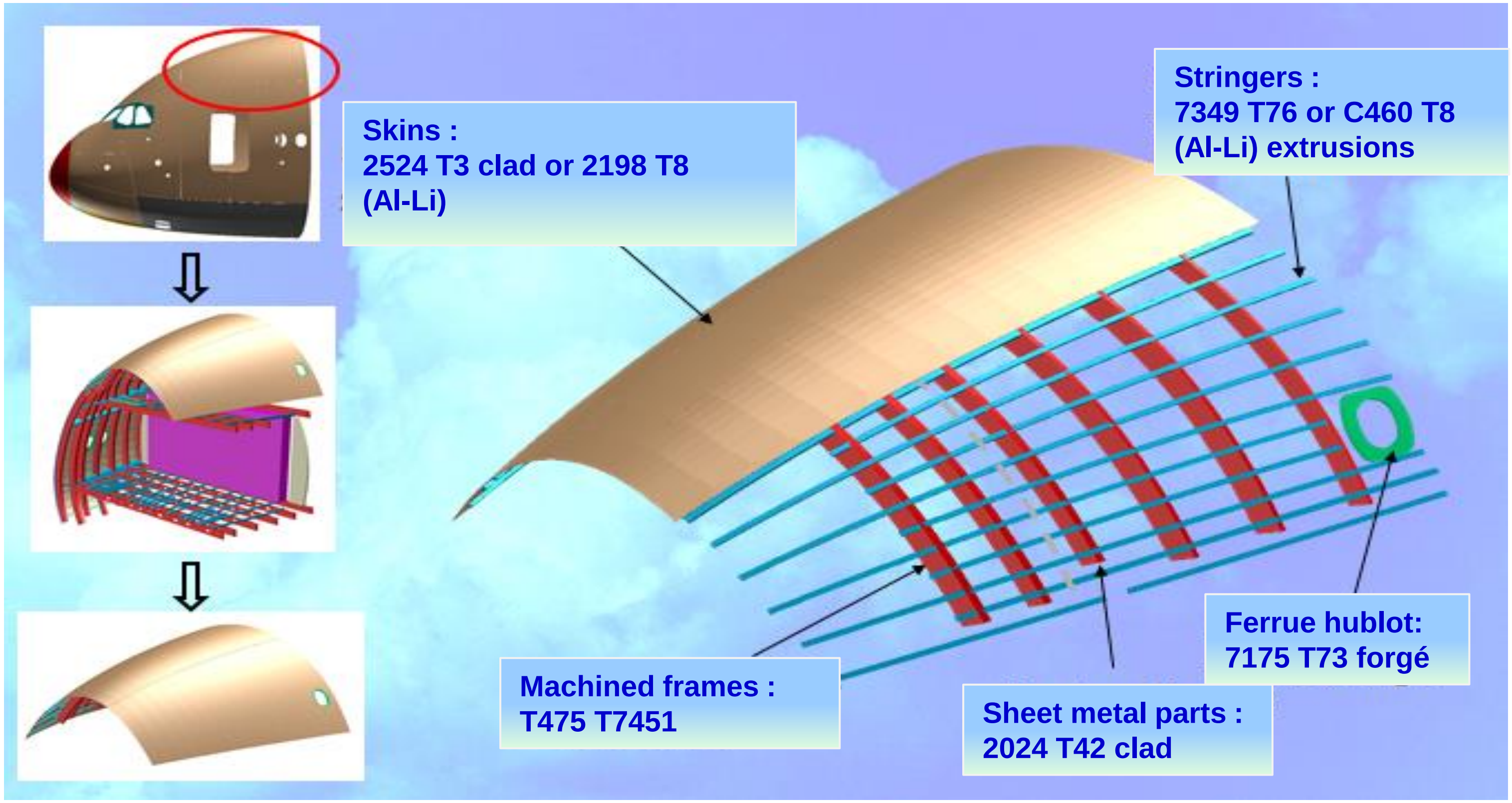
Application SONACA : matériaux d'un bord d'attaque



1. Revêtement supérieur (tôlé en 2024 T42 plaqué)
2. Longeron supérieur (extrudé en 7050 T73651)
3. Revêtement inférieur (Tôlé en 2024 T42 plaqué)
4. Tube de dégivrage (tube titane soudé)
5. Longeron inférieur (extrudé en 2024 T3511)
6. Bord de fuite (structure sandwich métallique)

2.1.7. Aluminium alloy applications on an aircraft

B. Sonaca application : Nose upper skin panel materials



2.1. Introduction to Aerospace Aluminium Alloys

2.1.8. New developments : The Al-Li alloys (1)

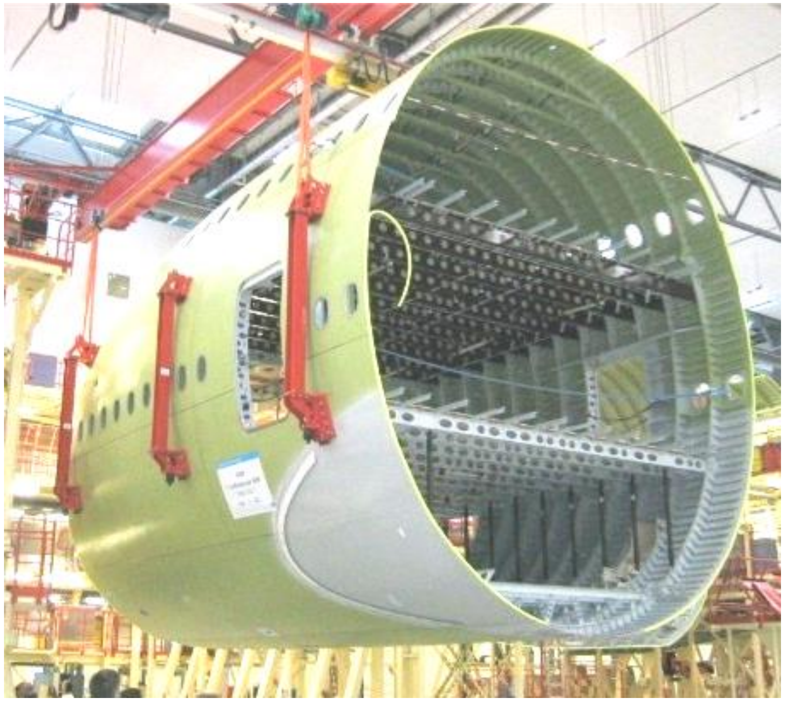
- **Generations of Al-Lithium Alloys**

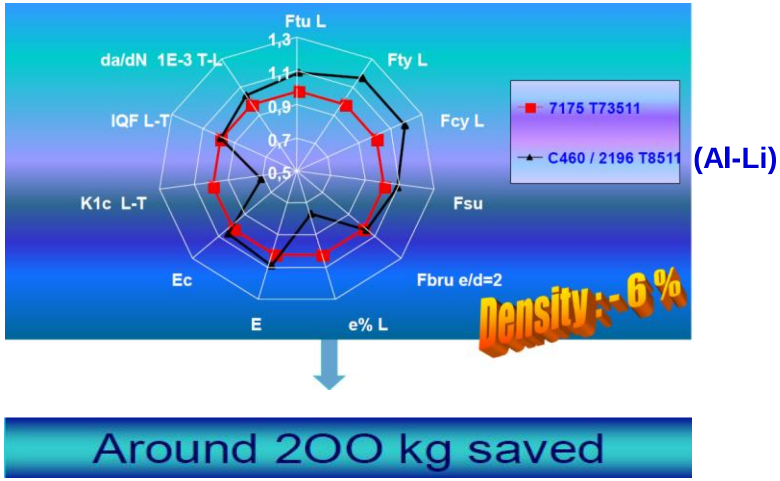
  - 1st Generation : C. 1955 - 1970
  - 2nd Generation : C. 1980 - 2000
  - 3rd Generation : C. 2000 - today

- **Key characteristics of Al-Lithium Alloys**
  - Low density
  - High strength
  - High stiffness / modulus
  - Improved fatigue and damage tolerance properties
  - Excellent corrosion resistance
  - High temperature resistance / properties

- **Lower density and improved durability translates to a lighter structure with reduced operating costs or improved performance**

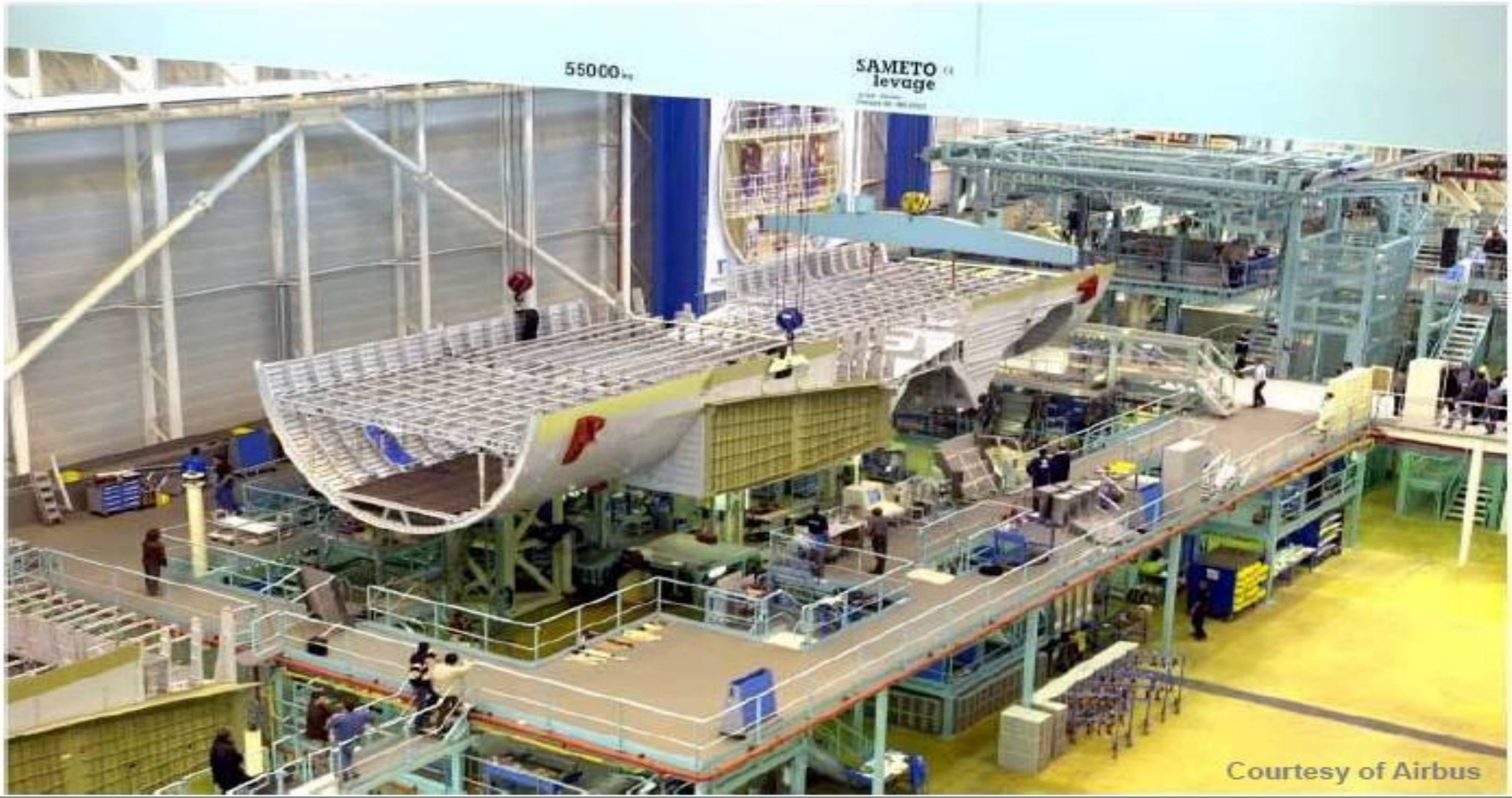
2.1.8. New developments : The Al-Li alloys (2)



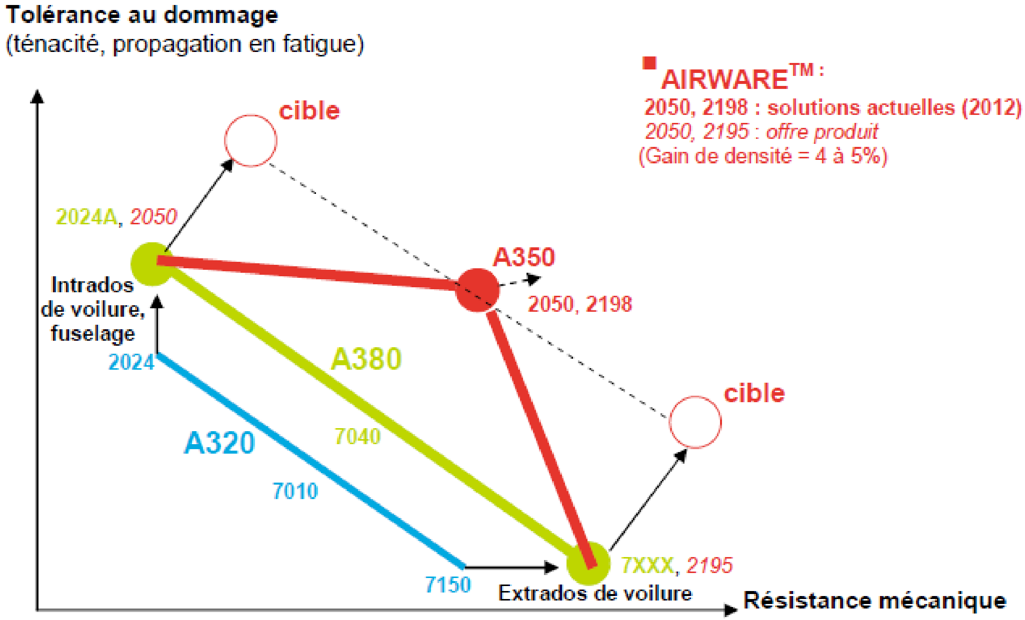


Main extrusion floor beams of the A380 A/C

2.1.8. New developments : The Al-Li alloys (3)



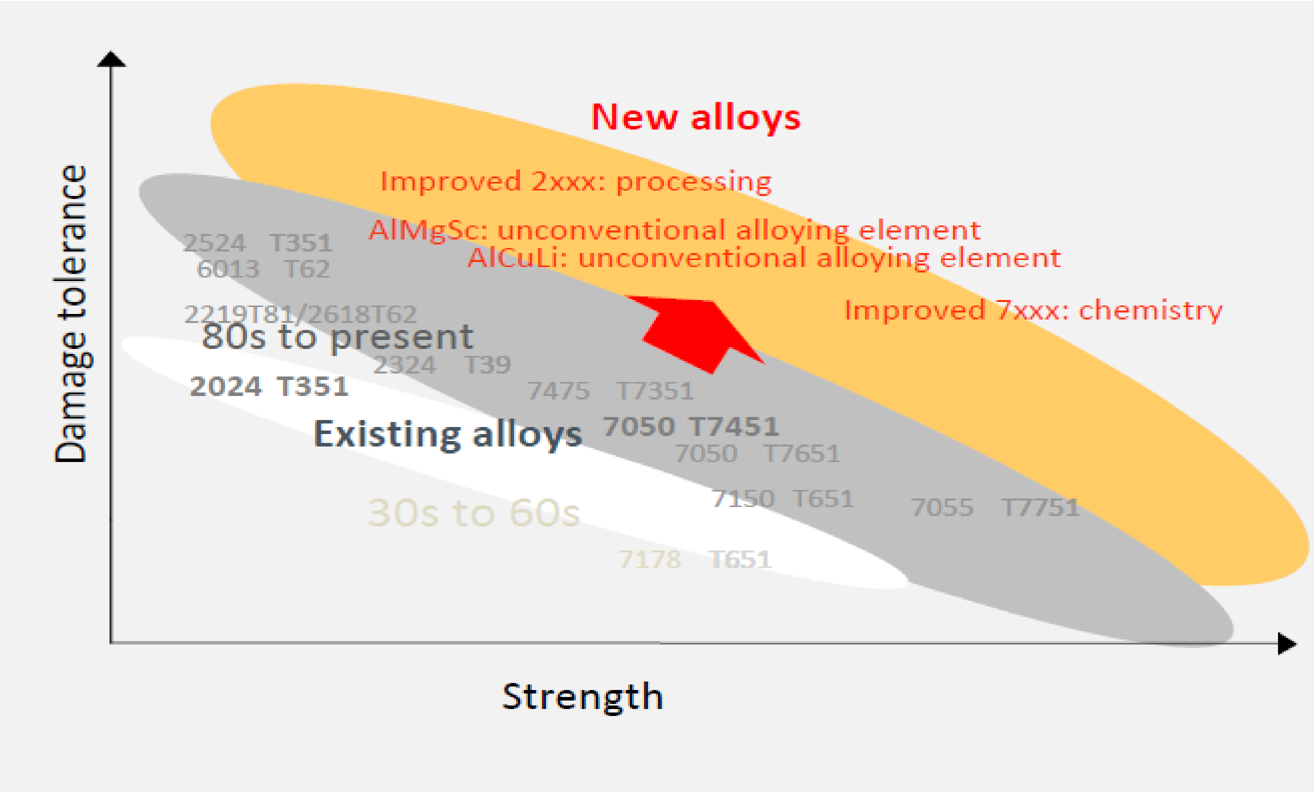
2.1.8. New developments : The Al-Li alloys (4)



Al-Cu-Li Alloys =
Intermediate solution between existing metallic structures and the composite structures

Schematic evolution of the mechanical performances « Damage tolerance versus mechanical strength » of aluminium alloys for aircraft generations such as A320, A380, A350 and future (targets)

2.1.9. New developments : Other aluminium alloys



Potential for chemistry and processing optimisation

PART 2 : METALLIC MATERIALS

2.1. Introduction to Aerospace Aluminium Alloys

2.2. Introduction to Aerospace Alloy Steels

2.3. Introduction to Aerospace Titanium Alloys

2.4. Material Design Allowable

2.2. Introduction to Aerospace Alloys Steels

2.2.1. Current aerospace alloy steel families (1)

- **Carbon steels and low alloy steels (class A)**
  - High mechanical strength achieved by quenching & tempering
  - Ex. : 4130, 4340, 8630, S82, S98, S99, S132, E35NCD16H, 16NCD13, …

- **Martensitic stainless steels (class B)**
  - 12% Cr Min
  - High resistance to corrosion
  - High resistance to friction
  - Ex. : 403, 410, 416, 431, S80, Z15 CN 17-03

- **Note**
  - Stainless Steel = 12 % Cr min in order to achieve a compact and resistant film of Cr_2O_3

2.2. Introduction to Aerospace Alloys Steels

2.2.1. Current aerospace alloy steel families (2)

- **Austenitic stainless steels (class C)**
  - 12% Cr Min, High Ni percentage
  - High resistance to corrosion
  - Residual austenite (Ms ~~0°C)
  - Ex. : 302, 316, 321, 347, S129, Z2CN18-10

- **Precipitation hardening steels (class D)**
  - High mechanical strength by precipitation
  - High resistance to corrosion (1)
  - Composition : PH13-8 Mo : 13% Cr – 8% Ni // 15-5PH : 15%Cr - 5% Ni
  - Precipitation of intermetallic compounds (ex : Ni_3Mo, ….)
  - Ex. : Maraging 250 (BS-S162), PH 13-8 Mo (AMS 5629), PH 15-7 Mo (AMS 5520), 17-4 PH (AMS 5643), 15-5PH (AMS5659)

(1) *Note* : Except for « Maraging 250 steel »

PART 2 : METALLIC MATERIALS

2.1. Introduction to Aerospace Aluminium Alloys

2.2. Introduction to Aerospace Alloy Steels

2.3. Introduction to Aerospace Titanium Alloys

2.4. Material Design Allowable

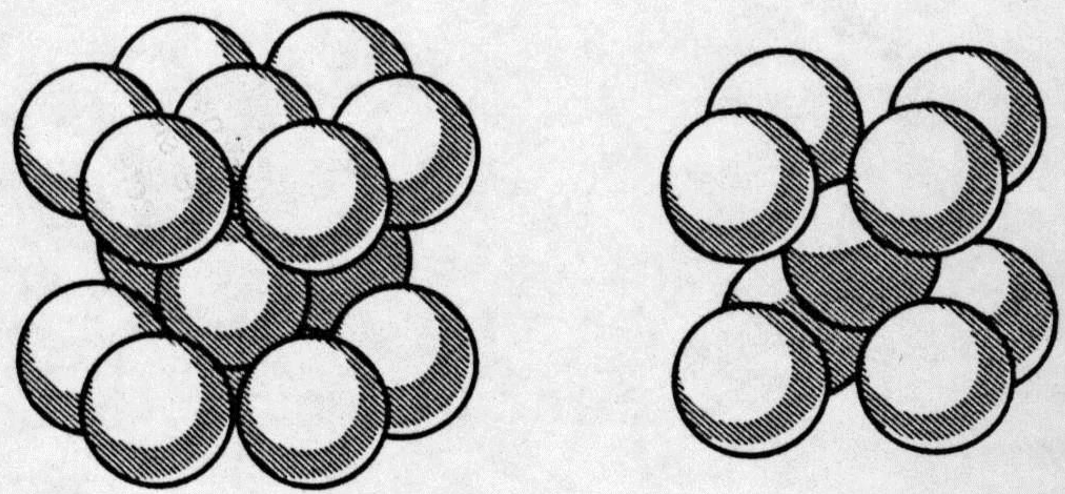
2.3. Introduction to Aerospace Titanium Alloys

2.3.1. Main interests in titanium alloys

- High strength to density ratio
- High fatigue and fracture toughness resistance
- High corrosion resistance
- High temperature resistance (creep resistance, ….) up to +600°C

2.3.2. Cristalline structure

- **Cristal structures of pure titanium**
  - CC : Ti β stable above 883°C
  - HC : Ti α stable below 883°C (compact structure)



(a) hexagonal, close-packed (b) cubic, body centered

2.3. Introduction to Aerospace Titanium Alloys

2.3.2. Cristalline structure (2)

- **Influence of other alloying elements**
- « Stabilizers α » : Al, O… (stability of α phase at a temperature higher than 883°C)
- « Stabilizers β » : V, Mo … (stability of β phase at a temperature lower than 883°C)

- Formation of secondary phases (ex : phase ω Ti_3Al)

2.3.3. Families of titanium alloys (1)

- **Pure titanium**
  - Various grades (concentrations in O and Fe)
  - Good resistance to corrosion
  - Low mechanical properties (./. purity)
  - Ex. : BS-TA 2, BS-TA 3

- **α and near-α alloys**
  - Good mechanical resistance to high temperature
  - Good weldability due to low sensitivity to thermal effects
  - Low forgeability
  - Ex. : Ti-5Al-2.5Sn

2.3.3. Families of titanium alloys (2)

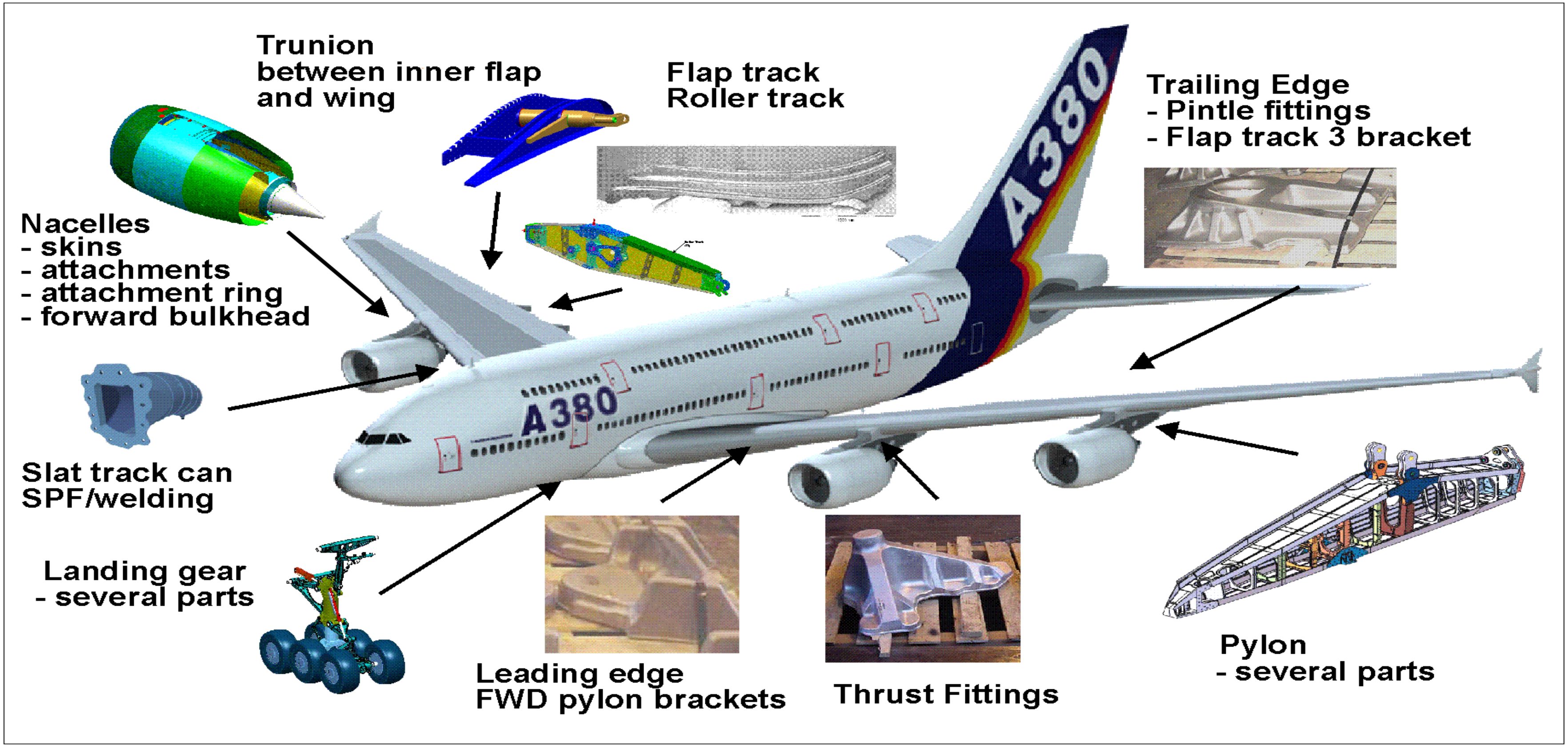
- **α - β alloys**
  - Hardening by heat treatment
  - Precipitation by ageing of the metastable β phase obtained by quenching
  - Medium to high mechanical resistance
  - Ex. : Ti-6Al-4V

- **β alloys**
  - Metastable
  - High hardening possible but low ductility and low temperature resistance
  - High mechanical resistance
  - Good forgeability and formability when solution heat treated

2.3. Introduction to Aerospace Titanium Alloys

2.3.4. Typical Ti applications on an aircraft

About 9% in mass of the total A380 aircraft



PART 2 : METALLIC MATERIALS

2.1. Introduction to Aerospace Aluminium Alloys

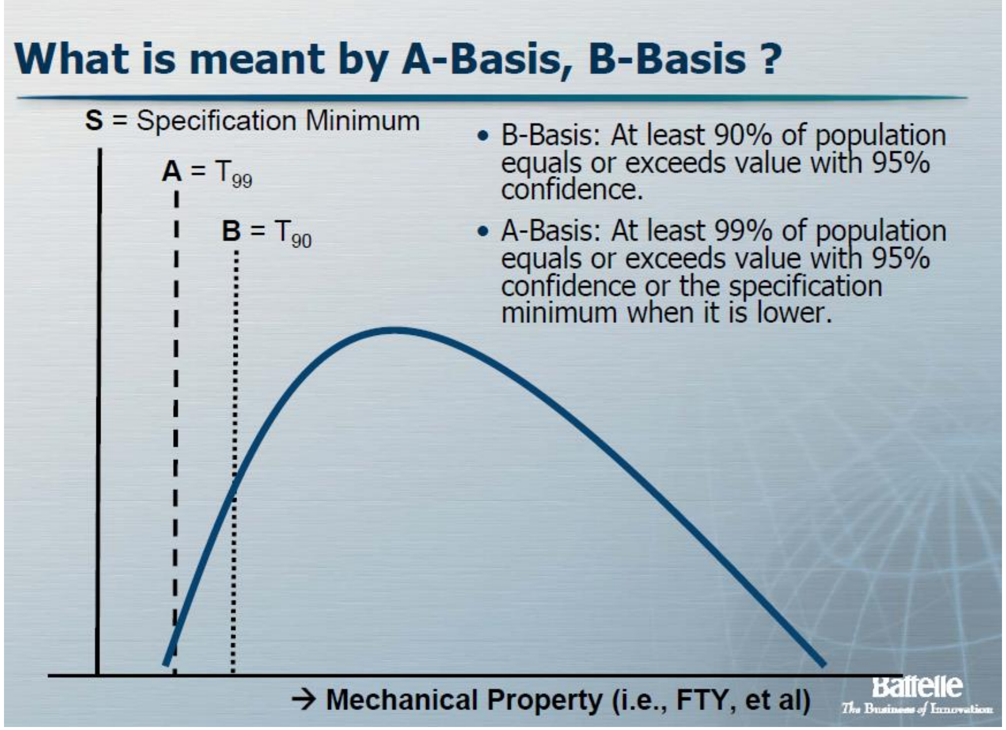
2.2. Introduction to Aerospace Alloy Steels

2.3. Introduction to Aerospace Titanium Alloys

2.4. Material Design Allowable

2.4.1. What's an allowable ?

- **A mechanical property value is defined as an allowable when it has a statistical basis**



Basis corresponds to:

- A distribution law (normal, student,…)
- A level of reliability
- A level of confidence

2.4. Material Design Allowable

2.4.2. Approved sources

- For the aerospace industry, sources have to be FAA, EASA, ANAC,… approved
- MMPDS (formelly MIL-HDBK) is the main source available for metallic materials

2.4.3. Requirements for MMPDS **(« Metallic Materials Properties Development and Standardization »)**

- Must have a public specification, typically an SAE AMS (Aerospace Materials Specification)
- Required tests : tensile, compression, shear, bearing, stress-strain curves, modulus, physical properties
- Recommended tests : elevated temperature, fatigue, fracture toughness, crack growth
- *Exceptions* : high temperature applications do not require secondary properties fasteners and joints (different requirements)

2.4. Material Design Allowable

2.4.4. Standard mechanical properties

- **Properties with a statistical A or B basis**
  - Tensile properties : tensile strength (F_{tu}) yield strength (F_{ty})
  - Compressive yield strength : F_{cy}
  - Bearing properties : F_{bry} and F_{bru} at and edge distances e/D = 1,5 & 2
  - Ultimate shear strength : F_{su}

- **Properties with a typical basis**
  - E,υ, α (thermal expansion), κ (thermal conductivity)
  - Non-linear material curves:

$$\varepsilon_{true} = \ln(1+\varepsilon_{nominal})$$

$$\sigma_{true} = \sigma_{nominal}(1+\varepsilon_{nominal})$$

ε_p : true plastic strain

if $\sigma \leq \sigma_{y0,2}$	if $\sigma > \sigma_{y0,2}$
Ramberg-Osgood	Hollomon
$\varepsilon_p = 0{,}002 \cdot \left(\frac{\sigma}{\sigma_y}\right)^N$	$\varepsilon_p = \left(\frac{\sigma}{K}\right)^{1/n} - \frac{\sigma}{E}$

  - Fatigue and crack propagation

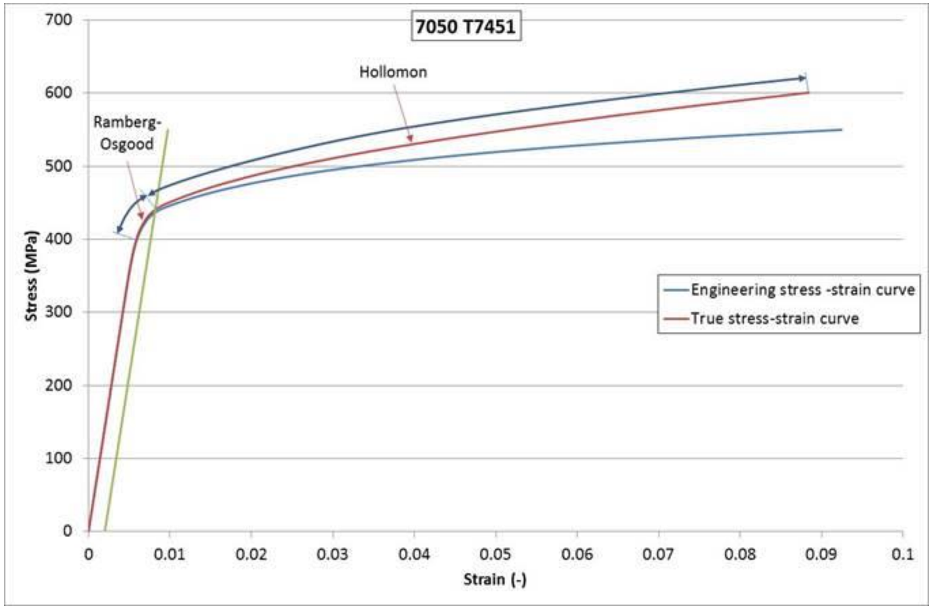
- **Properties with S typical basis**
  - Elongation (value from AMS specification)

- **All properties are orientation dependent (L, LT, ST)**

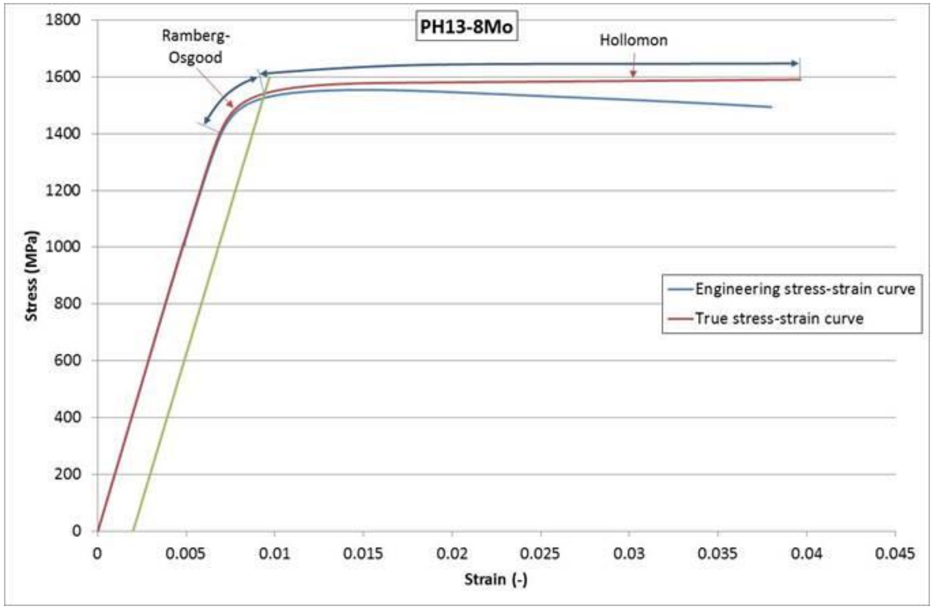
sonaca

Examples of non-linear material curves

7050 T7451 Aluminium Alloy



PH13-8 Mo Stainless Steel



2.4. Material Design Allowable

2.4.5. Table summary

MMPDS-09
1 April 2014

Table 3.2.4.0(e_1). Design Mechanical and Physical Properties of Clad 2024 Aluminum Alloy Sheet and Plate

Specification	AMS 4462 and AMS-QQ-A-250/5[a]							
Form	Flat sheet							
Temper	T3							
Thickness, in.	0.008-0.009		0.010-0.062		0.063-0.128		0.129-0.249	
Basis	A	B	A	B	A	B	A	B
Mechanical Properties:								
F_{tu}, ksi:								
L	59	60	60	61	62	63	63	64
LT	58	59	59	60	61	62	62	63
F_{ty}, ksi:								
L	44	45	44	45	45	47	45	47
LT	39	40	39	40	40	42	40	42
F_{cy}, ksi:								
L	36	37	36	37	37	39	37	39
LT	42	43	42	43	43	45	43	45
F_{su}[b], ksi	37	37	37	38	38	39	39	40
F_{bru}[b,c], ksi:								
(e/D = 1.5)	96	97	97	99	101	102	102	104
(e/D = 2.0)	119	121	121	123	125	127	127	129
F_{bry}[b,c], ksi:								
(e/D = 1.5)	68	70	68	70	70	73	70	73
(e/D = 2.0)	82	84	82	84	84	88	84	88
e, percent (S-Basis):								
LT	10	...	[d]	...	15	...	15	...
E, 10^3 ksi:								
Primary	10.5							
Secondary	9.5				10.0			
E_c, 10^3 ksi:								
Primary	10.7							
Secondary	9.7				10.2			
G, 10^3 ksi	...							
μ	0.33							
Physical Properties:								
ω, lb/in.^{3}	0.100							
C, K, and α	...							

Last Revised: Apr 2014, MMPDS-09, Item 13-18
a Mechanical Properties were established under MIL-QQ-A-250/5.
b Grain direction unknown.
c Bearing values are "dry pin" values per Section 1.4.7.1. See Table 3.1.2.1.1.
d See Table 3.2.4.0(f).

Specification
Temper
Thickness range
Statistical basis
Data with a statistical basis
Data with a typical basis

2.4.6. Joint allowable

- The lap shear strength of an assembly is not a fundamental property of the materials involved but a technological characteristic of the assembly

Examples: Type of fasteners

Hi-lite

Blind bolt

Bolt & screw

2.4.6. Joint allowable

A. Test data

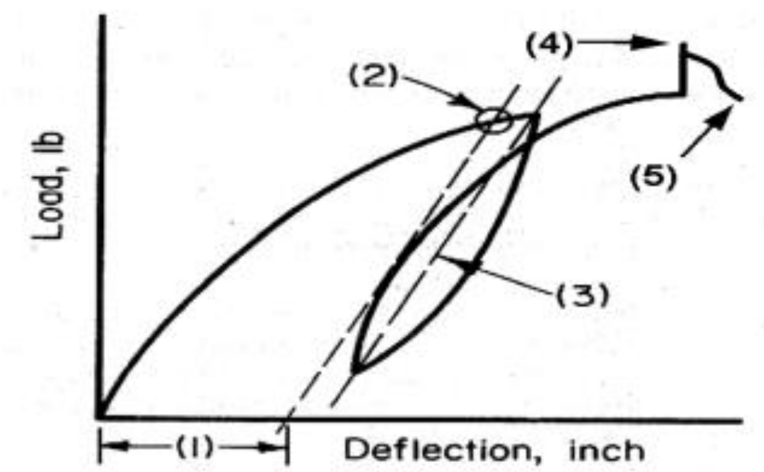


Figure 9.7.1.2(d). Sample alternative secondary-modulus load-deflection curve.

(1) Offset, per yield definition given in Section 9.7.1.1.
(2) Joint yield.
(3) Alternative secondary-modulus line.
(4) Joint ultimate.
(5) Coupon failure.

Tests depend of:

- The fastener type
- The thickness of sheets (t)
- The diameter of the fastener (D)
- The head type (countersunk or not)

Regression model

$$P/D^2 = A_0 + A_1 * (t/D) + A_2 * \ln(t/D)$$

2.4.6. Joint allowable

B. Summary

Table 8.1.2.2 (s). Static Joint Strength of Solid 100° Flush Head Alumunim Alloy (7050-T73) Solid Rivets in Machine Countersunk Aluminum Alloy Sheet

Rivet Type	MS20426E (F_{su} = 41 ksi)[a]			
Specification	NASM 20426			
Sheet Material	Clad 7075-T6			
Rivet Diameter, in.	1/8	5/32	3/16	1/4
(Nominal Hole Diameter, in.)[b]	(0.1285)	(0.159)	(0.191)	(0.257)
	Ultimate Strength, lbs. (Estimated Lower Bound)			
Sheet thickness, in.:				
0.040	318[c]	...	...	...
0.050	393	492[c]	...	...
0.063	440	606	745[c]	...
0.071	469	642	840	...
0.080	502	683	898	...
0.090	531	728	952	1430[c]
0.100	...	773	1005	1570
0.125	...	814	1140	1755
0.160	...	...	1175	2010
0.190	...	...	...	2125
Rivet shear strength[d]	531	814	1175	2125
	Yield Strength[e], lbs. (Conservatively Adjusted Average)			
Sheet thickness, in.:				
0.040	257	...	...	...
0.050	330	399	...	...
0.063	423	515	607	...
0.071	469	586	693	...
0.080	502	666	789	...
0.090	531	728	896	1175
0.100	...	773	1005	1320
0.125	...	814	1140	1680
0.160	...	...	1175	2010
0.190	...	...	...	2125
Head height (ref.), in.	0.042	0.055	0.070	0.095

Last Revised: Apr 2012, MMPDS-07, Item 09-40

a Data supplied by Lockheed Ga. Co., Air Force Materials Laboratory, Allfast, Cherry Fasteners, Douglas Aircraft Co., and Huck Mfg. Co.

b Load allowables developed from tests with hole diameters of 0.130, 0.158, 0.191, and 0.256 ± 0.003 inch.

c The values in the table above the horizontal line in each column are for knife-edge condition and the use of fasteners in this condition is undesirable. The use of knife-edge condition in design of military aircraft requires the specific approval of the procuring agency.

d Shear strength based on area computed from nominal hole diameters in Table 8.1.2(b) and F_{su} = 41 ksi.

e Permanent set at yield load: 4% of the nominal hole diameter.

Fastener reference

Fastener specification

Sheet material

Fastener diameter

Ultimate load

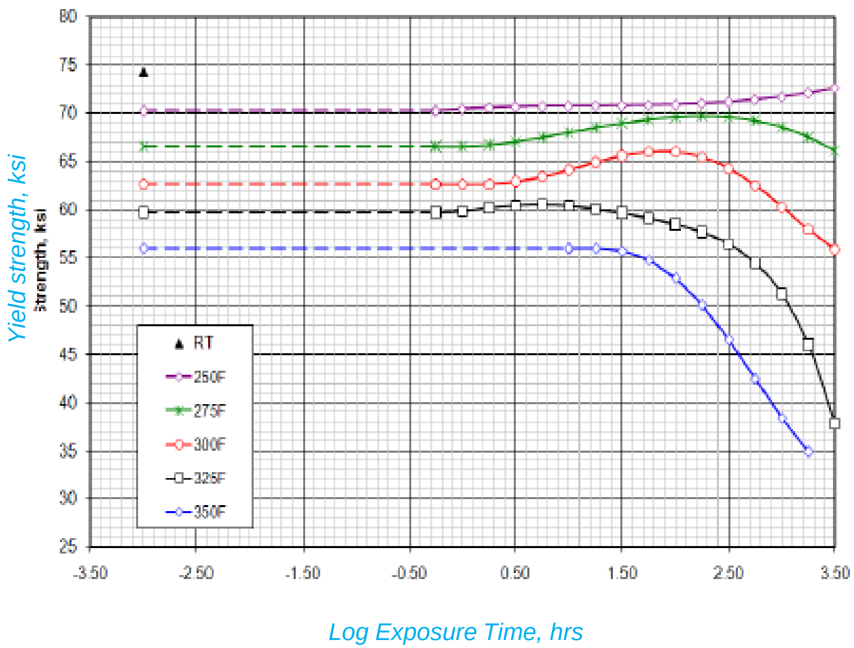
Rivet pure shear

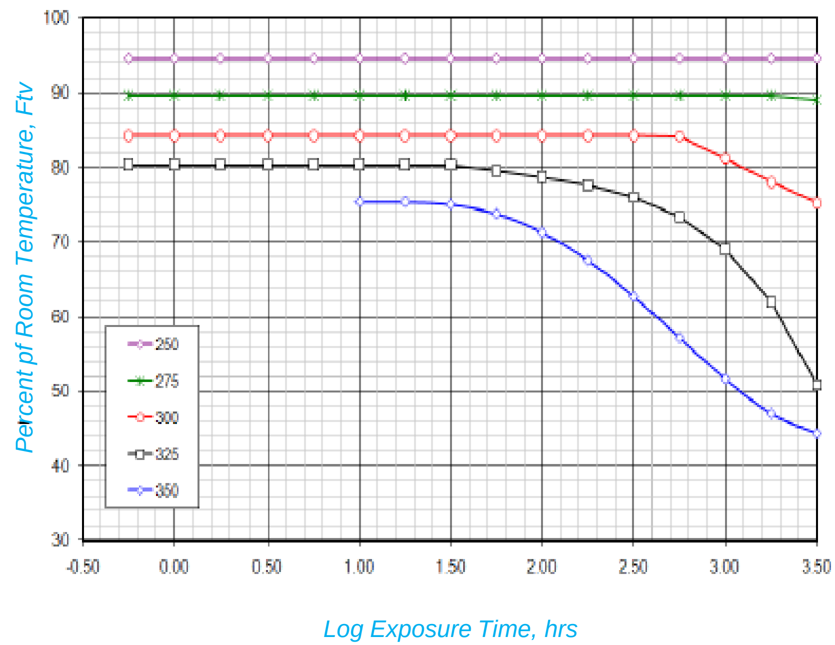
Yield load

2.4. Material Design Allowable

2.4.7. Influence of temperature

- ❑ Design allowable for temperature influence on mechanical properties are defined as a percentage of reduction (or increase) W.R.T. the RT value





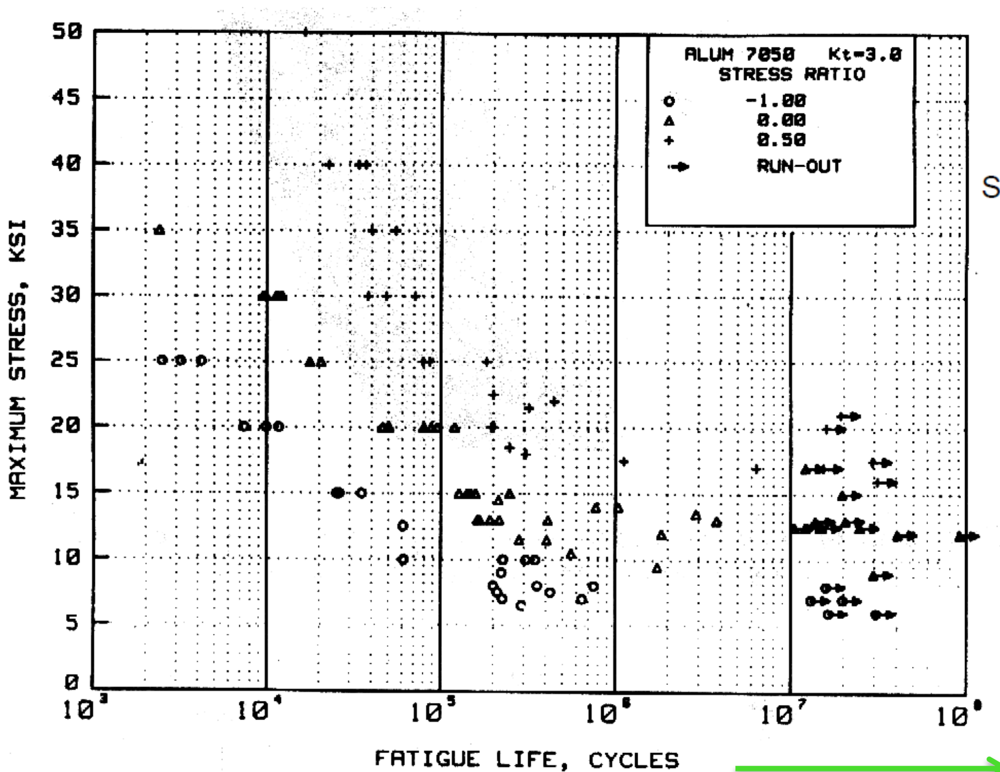
- ❑ Design allowable are truncated above RT value
- ❑ No increase in mechanical property shall be considered for design

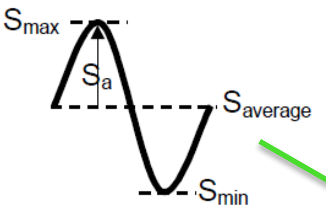
sonaca

2.4. Material Design Allowable

2.4.8. Fatigue

- ❑ Only high cycle fatigue is considered : $\sigma_{max} \leq Fty$





Stress Ratio $R = \frac{S_{min}}{S_{max}}$

Number of cycles at failure

2.4. Material Design Allowable

2.4.8. Fatigue (2)

- **Fatigue experimental data is fitted with a general law**

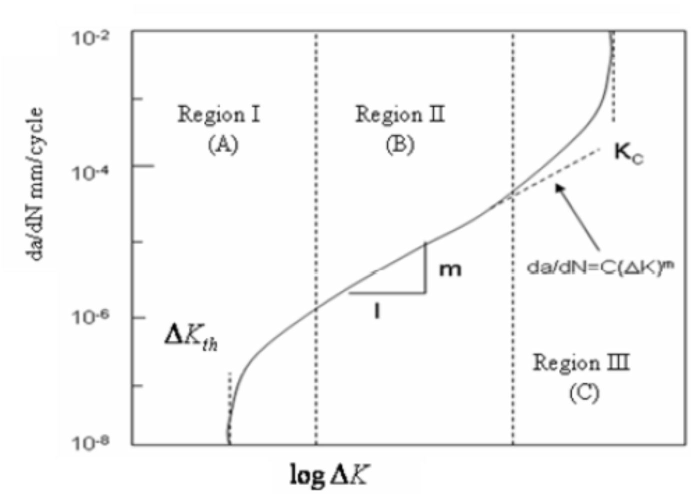
$$log(N_f) = a_1 + a_2 \cdot log(S_{max} \cdot (1 - R)^{a_3} - a_4)$$

Légende :	
N_f	: *number of cycles at failure*
S_{max}	: max *net stress*
R	: *stress ratio*
a_1, a_2, a_3, a_4	: *fit parameters*

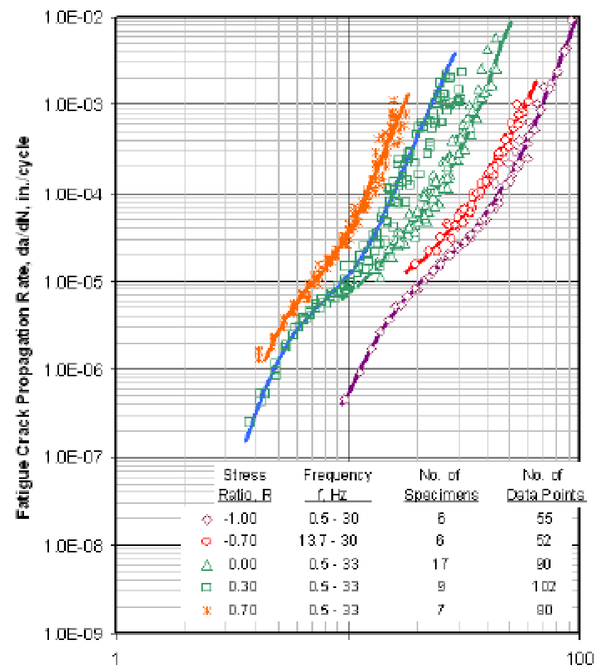
- **No statistical basis used for stressing**

- **The safety comes from the scatter factor applied on the design life goal of the aircraft (total number of flights on the aircraft)**
  - The scatter factor equals 5 for class 1 parts (very critical parts)
  - The scatter factor equals 3 for less critical parts

2.4.9. Fatigue crack growth (1)



Propagation speed as a function of the stress ratio R



Légende :

a	: *crack length*
ΔK_{th}	: *threshold stress concentration factor*
ΔK	: *stress concentration*
K_c	: *toughness*
da/dN	: *propagation length per cycle*
R	: *stress ratio*
f	: *frequency*

2.4. Material Design Allowable

2.4.10. Environmental influence on fatigue and fatigue crack growth

- **Humidity and environmental conditions influence :**
  - Fatigue by creating defects on the surface
  - Fatigue crack growth by corroding the head of the crack

- **Temperature influences :**
  - Fatigue by reducing the yield strength of the material
  - Crack propagation by increasing the crack propagation speed

- **These effects are considered for the stressing of the part when relevant to its exposure on the aircraft**

PART 3 : COMPOSITE MATERIALS

PART 3 : COMPOSITE MATERIALS

3.1. The Evolution of Composites in Aerospace Industry

3.2. Introduction to Composite Materials

3.3. Composite Product Forms

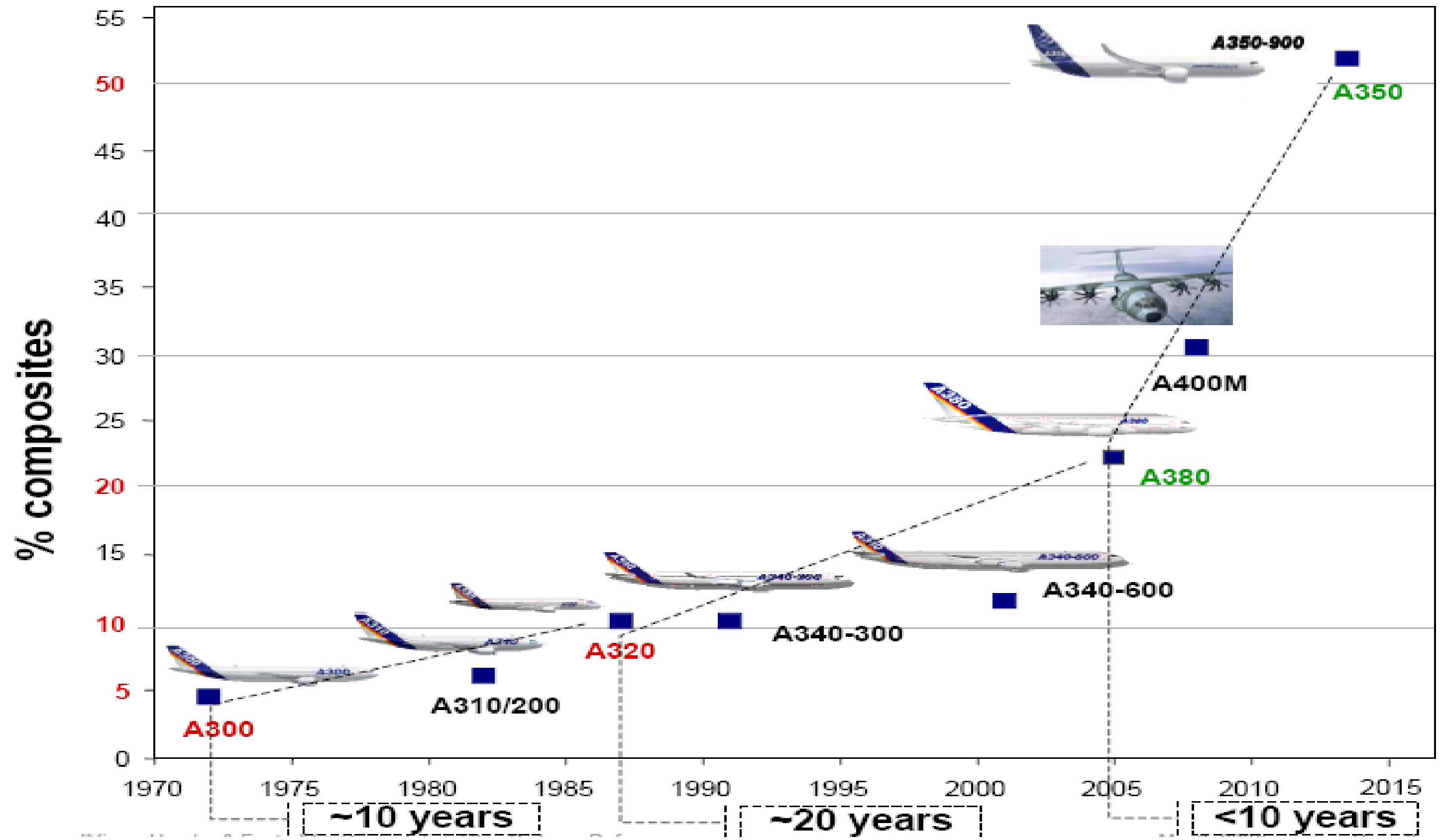
3.4. Composite Laminates

3.5. Composite Prepreg Ply Properties

3.6. Composite Material Characterization

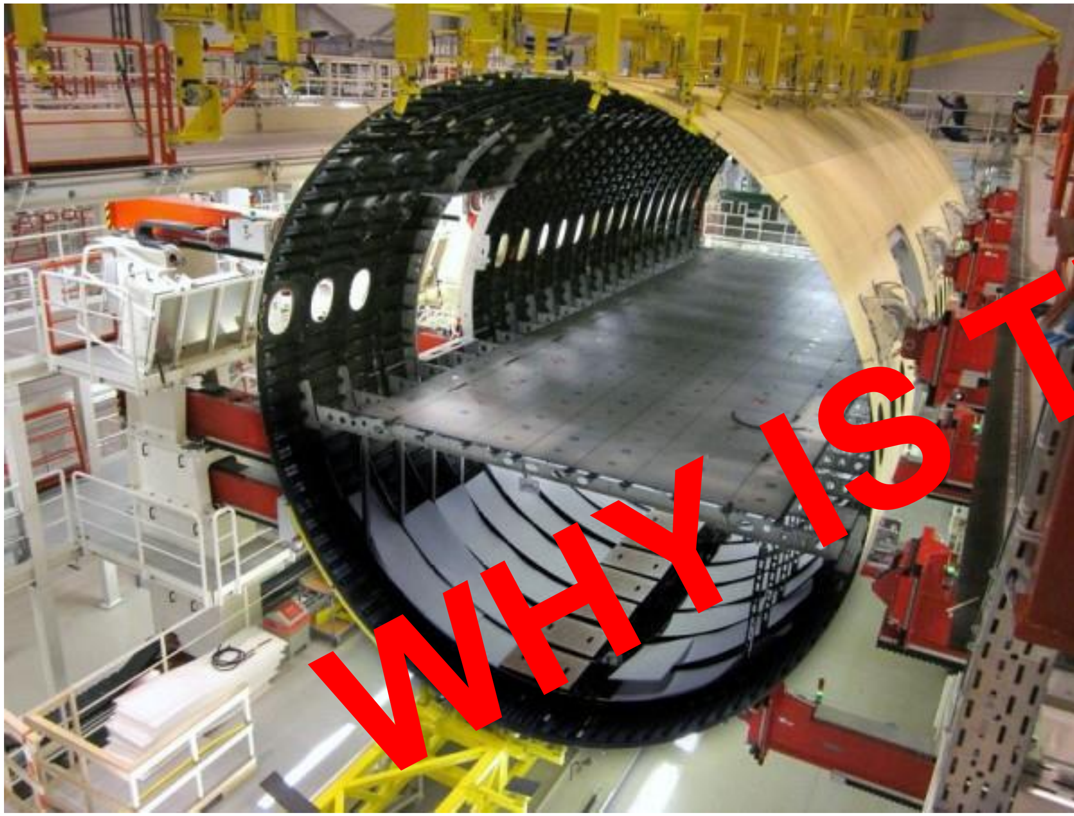
3.1. The Evolution of Composite in Aerospace Industry

Composite structural weight evolution



Hudge acceleration in last 10 years with the introduction of Full CFRP wing (A400M), then Fulll CFRP fuselage (A350XWB)

Airbus A350XWB and Boeing 787 : 50% carbon fiber reinforced composites by weight

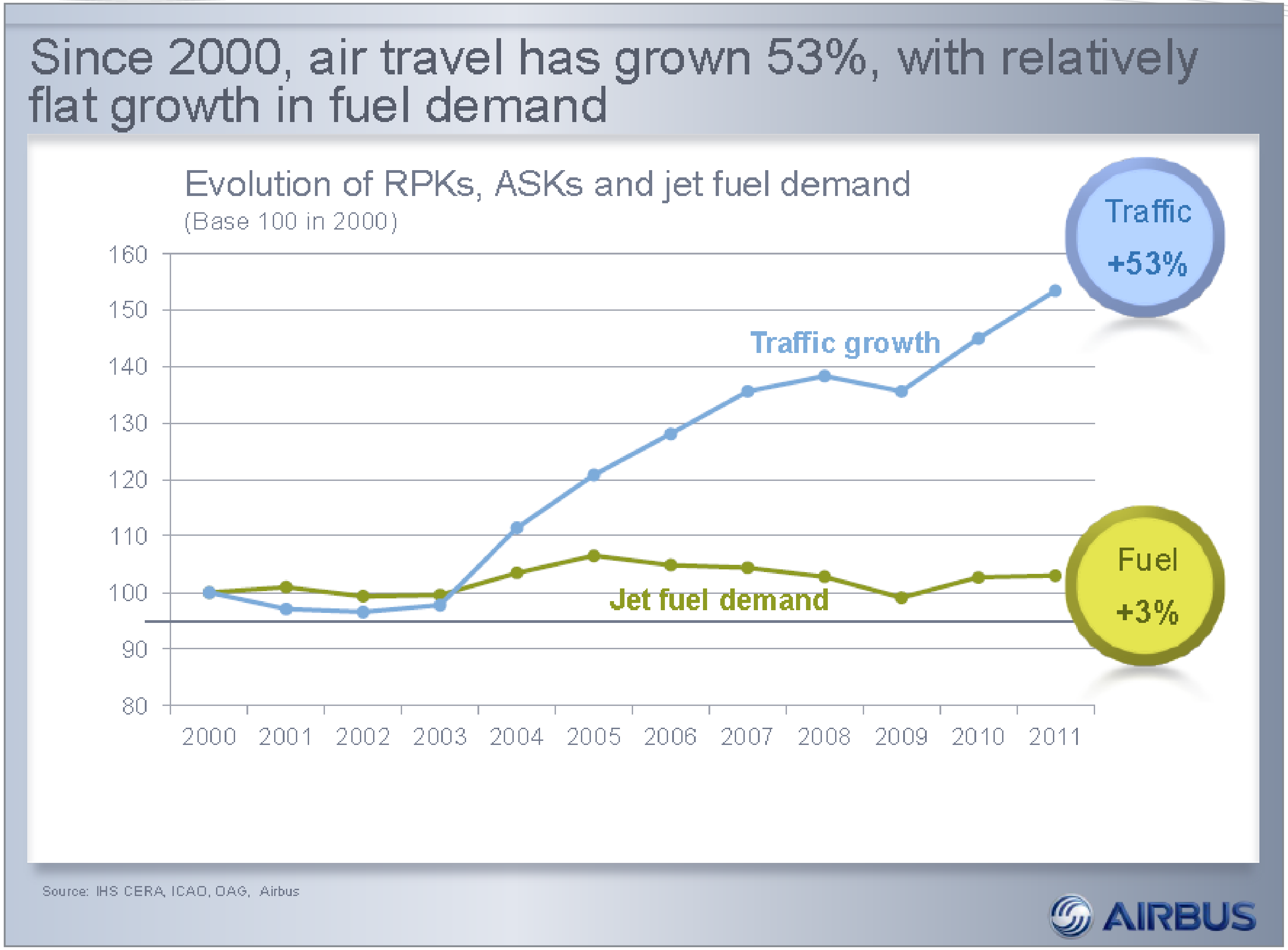


WHY IS THIS?

A350XWB composite keel beam

3.1. The Evolution of Composite in Aerospace Industry

Green in spite of growth



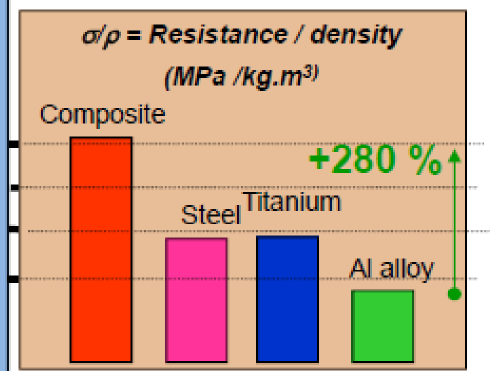
sonaca

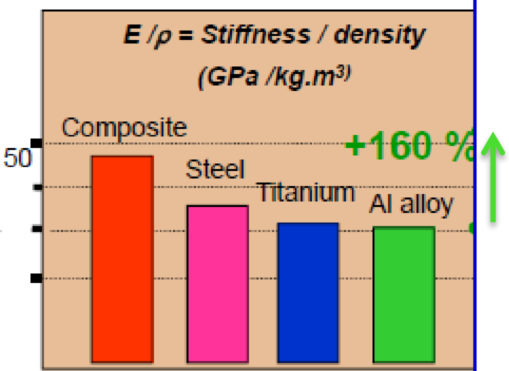
3.1. The Evolution of Composite in Aerospace Industry

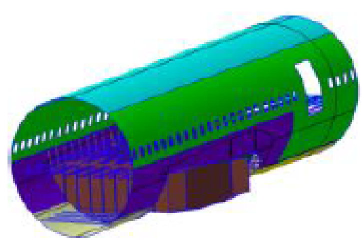
Carbon/epoxy structures : The advantages

CFRP main interest for design:

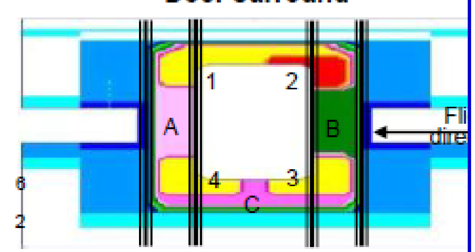
- **Low density – High specific strength**
- **No corrosion**
- **No fatigue**
- **Dream material for designer:**
  - ***Several fibers*** – High strength - High modulus
  - ***Several matrix***: epoxy, thermoplastics
  - ***Several processes***
    - Co-curing
    - Co-bonding
    - Injection – LRI
  - ***Through lay-up*** : possibility of creating the ***ideal material*** for each case







Door surround



STELIA

Carbon/epoxy structures : The drawbacks

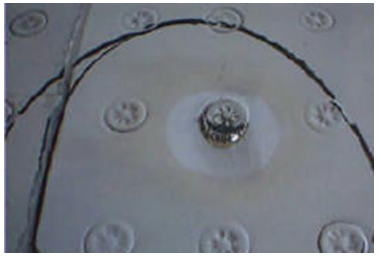
- **Low electrical conductivity implying :**
  - Generation of electro-magnetic interferences (EMI) on equipments
  - Low electrostatic discharge capability
  - Sensitive to lightning strike damages
- **Impact strength reduction (multi element damages) :**
  - Bird strike – hail – stones – tire burst – Jet-way strikes
- **Material is created during part manufacturing**
  - Stress characteristics are sensitive to manufacturing quality

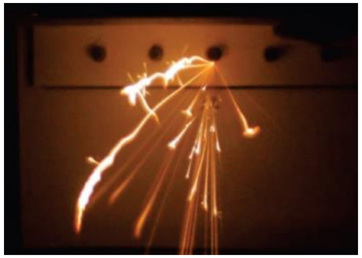
3.1. The Evolution of Composite in Aerospace Industry

Typical lightning strike damages on aircraft

Lightning strike on a flying airplane

Fuselage swept stroke damage





Fastener sparkling damage

Typical impact damages on composite aircraft structures

- **The impacts :**
  - Birds (4lbs, 180m/s)
  - Tire debris (1kg, 100m/s)
  - Hail
  - Metallic debris
  - Debris on runways (Gravel projections,….)

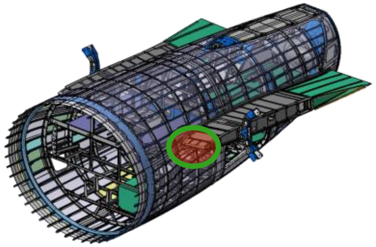
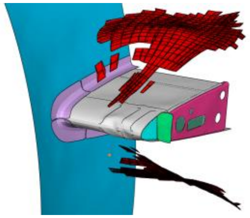




- **The requirements :**
  - Protection of the wing front spar against fuel leakage (explosion risk,…)
  - Residual strength after impact damage of the structures (“get home“ loads)
  - Protection of some critical systems





sonaca

PART 3 : COMPOSITE MATERIALS

3.2. Introduction to Composite Materials

3.2.1. Role of the reinforcement and of the matrix

REINFORCEMENT
- Mechanical characteristics
- Stiffness

+

MATRIX
- Cohesion between fibres
- Transfert of load fluxes between plies
- Environmental resistance
- Temperature resistance

COMPOSITE MATERIAL

Principaux renforts pour composites

Materials	E_L (MPa)	$\sigma_L\ (MPa)$	A% rupture	ρ (g/cm^3)
Carbon HR	230.000	3.530	1,5	1,75
Carbon IM	297.000	5.490	1,9	1,8
Carbon HM	377.000	4.410	1,2	1,8
Carbon THM	580.000	3.920	0,7	1,94
Kevlar 49	124.000	3.620	1,9	1,45
Kevlar 29	70.000	3.620	3,7	1,44
AUG4	75.000	450	10	2,8
Epoxyde	4.500	130	2	1,2

Advantages / Disadvantages

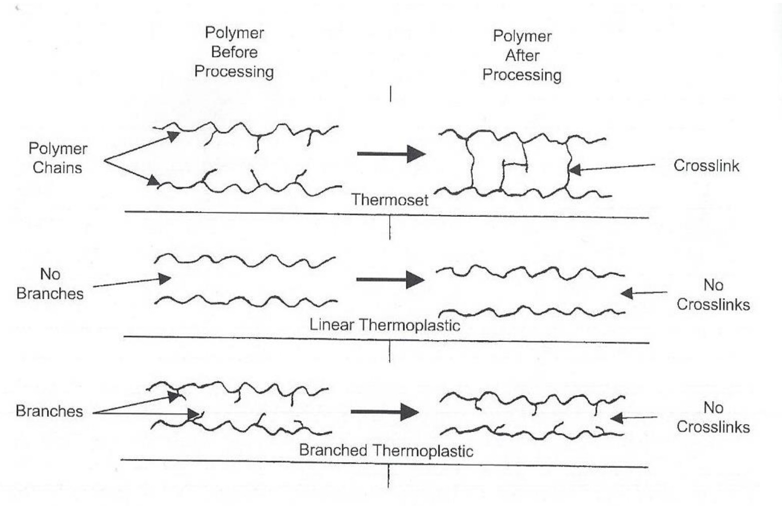
METALLIC MATERIALS
- Isotropy
- Plasticity
- Greater experience
- Sensible to corrosion
- Sensible to fatigue

COMPOSITE MATERIAL
- Low sensitivity to fatigue
- High strength to density ratio
- Greater optimisation (anisotropy)
- No plasticity
- Sensible to impacts, shocks

3.2.2. The matrix

A. Thermoset versus Thermoplastic

- **Thermoset polymers (3D structure)**
  - La formation de liaisons covalentes, de haute énergie, dans toutes les directions interdira le ramollissement du polymère en cas d'élévation de température.
  - Les matrices thermodurcissables ont un état initial liquide, elles utilisent éventuellement la chaleur pour durcir et en produisent lors de la réaction exothermique de polymérisation. Une fois durcie, une résine thermodure ne peut plus retrouver son état initial, même par un apport de chaleur, le cycle est irréversible. La réaction conduisant au durcissement est purement chimique

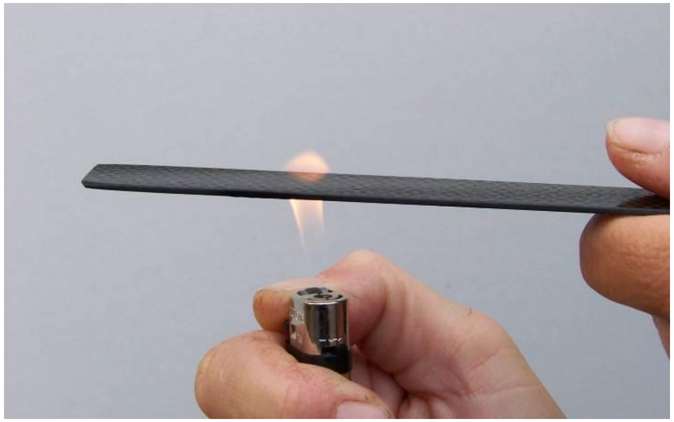


- **Thermoplastic polymers (linear macro-molecules)**
  - Les résines thermoplastiques sont composées de macromolécules linéaires. Celles-ci sont reliées par des liaisons de faible énergie. L'élévation de température se traduira par un ramollissement progressif de la matière mais elle reprendra sa consistance initiale lors du refroidissement.
  - Les matrices thermoplastiques ont un état initial solide et nécessitent un apport de chaleur (fusion) pour être mises en forme ou imprégner un renfort fibreux. A température ambiante, elles reviennent à leur état solide initial. Le cycle est toujours réversible.

3.2.2. The matrix

B. Thermoplastics matrices (1)

- **Why thermoplastics?**
  - Unique processing through melting and cooling => low cost designs
  - High material toughness => low weight designs
  - Recyclable material
  - Excellent fire, smoke & toxicity (FST) properties



3.2.2. The matrix

B. Thermoplastics matrices (2)

- **Welding of thermoplastics**

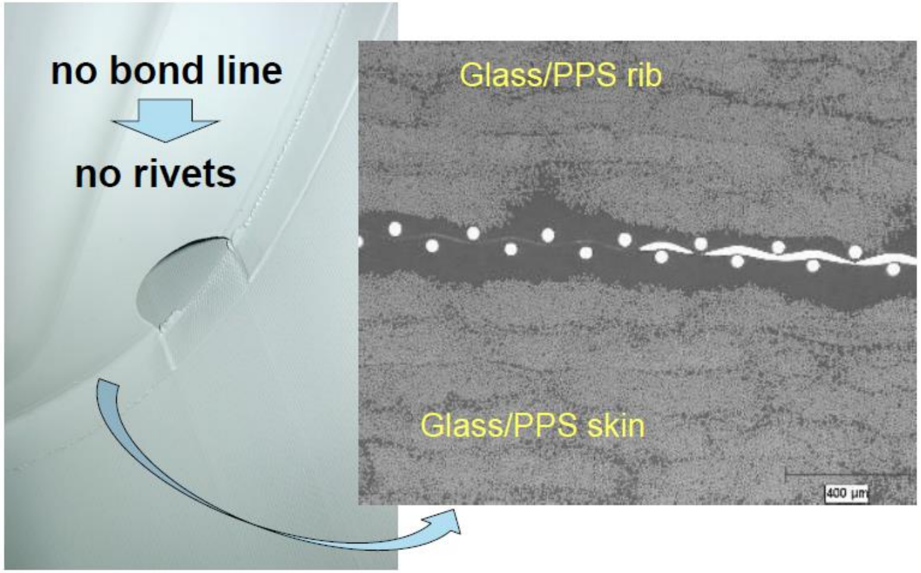
- Welding makes it possible to eliminate or reduce drilling and expensive bolts

- Currently applied in aerospace
  - Ultrasonic welding
  - Resistance welding
  - Induction welding

3.2.2. The matrix

B. Thermoplastics matrices (3)

- **Resistance welding of thin-skinned multirib design**



3.2.2. The matrix

C. Matrix properties

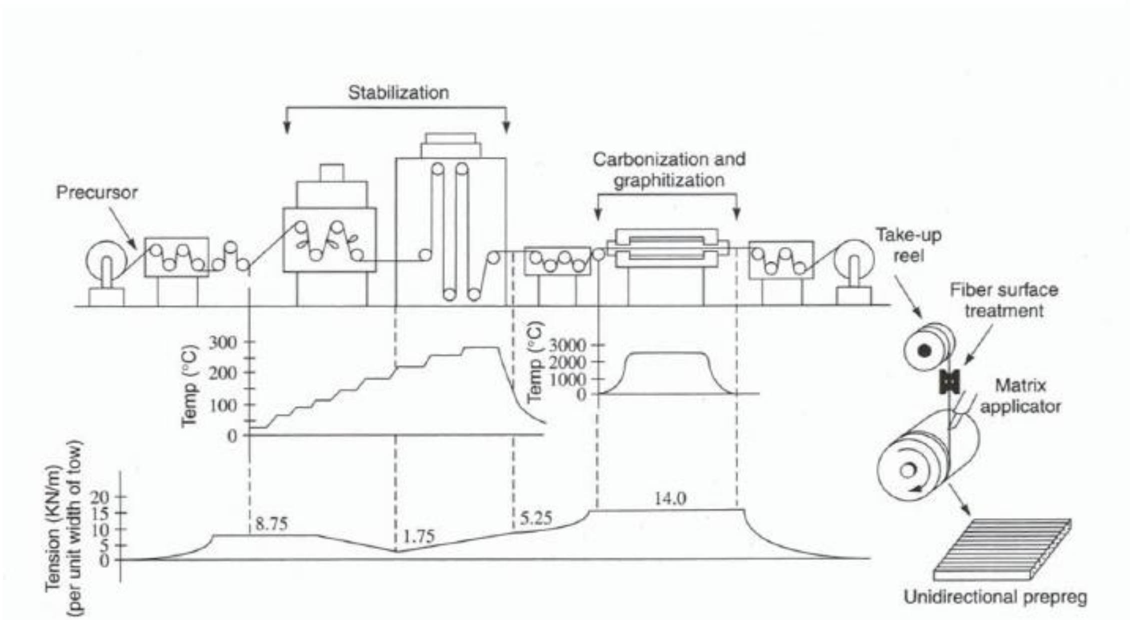
Thermoset Polymers Properties	THERMOSETTING POLYMER		
	Epoxy	Bismaleimide	Polyimide
Density (kg/m3)	1100 - 1400	1320	1430 - 1890
Tensile modulus (GPa)	2 - 6	3.6	3.1 - 4.9
Shear modulus (GPa)	1.1 - 2.2	1.8	
Tensile strength (MPa)	35 - 130	48 - 78	70 - 120
Compressive strength (MPa)	100 - 200	200	
Elongation (%)	1 - 8.5	1 - 6.6	1.5 - 3
Coeff. of thermal expansion (x10-6/°C)	45 - 70	49	90
Thermal conductivity (W/m/°C)	0.1 - 0.2		
Specific heat (J/kg/°K)	1250 - 1800		
Glass transition temperature (°C)	50 - 250	250 - 300	280 - 320
Water absorption (%) {24h @ 20°C}	0.1 - 0.4		0.3
Shrinkage on curing (%)	1 - 5		

Thermoplastic Polymers Properties	THERMOPLASTIC POLYMER		
	PEI	PPS	PEEK
Density (kg/m3)	1270	1340	1320
Tensile modulus (GPa)	3	3.3	
Tensile strength (MPa)	105	70 - 75	92 - 100
Compressive strength (MPa)	140	110	
Elongation (%)	60	3	150
Coeff. of thermal expansion (x10-6/°C)	62	54 - 100	
Thermal conductivity (W/m/°C)			
Glass transition temperature (°C)	217	85	143
Water absorption (%) {24h @ 20°C}	0.25	0.2	0.1

3.2.3. The reinforcements

A. Production of carbon fibers

- PAN fiber (polyacrylonitril) precursor
- Stabilization of the fiber at 200-300°C in oxyding atmosphere with tension
- Carbonisation at 1000 – 1800°C in inert atmosphere
- Graphitisation at 3000°C in totally inert atmosphere
- Fiber dimension caracterized by filament number (e.g. 4K, 6K, …..)



3.2.3. The reinforcements

B. Properties of carbon fibers

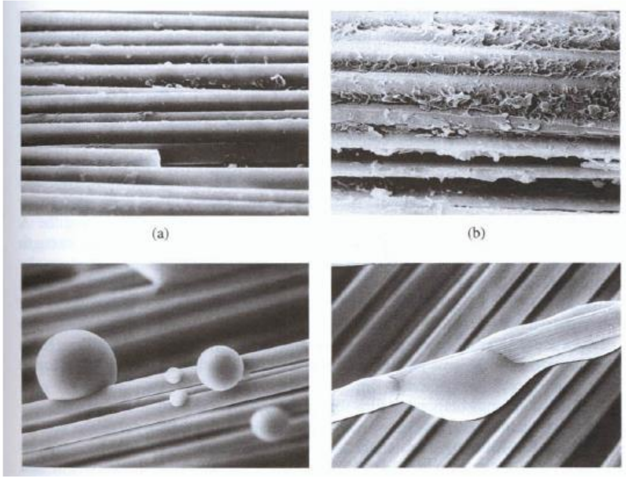
Carbon / graphite fibers Properties	PAN			Pitch
	IM	HM	UHM	type-P
Diameter (um)	8 - 9	7 - 10	7 - 10	10 - 11
Density (kg/m3)	1780 - 1820	1670 - 1900	1860	2020
Tensile modulus (GPa)	228 - 276	331 - 400	517	345
Tensile strength (MPa)	2410 - 2930	2070 - 2900	1720	1720
Elongation (%)	1.0	0.5	0.3 - 0.4	0.4 - 0.9
Coeff. of thermal expansion (x10-6/°C)				
Fiber direction	-0.1 to -0.5	-0.5 to -1.2	-1.0	-0.9 to - 1.6
Perpendicular to fiber direction	7 - 12	7 - 12		7.8
Thermal conductivity (W/m/°C)	20	70 - 105	140	
Specific heat (J/kg/°K)	950	925		
	Toray, Hercules, Zoltek			

3.2.3. The reinforcements

C. Surface treatment of the fibers

- Surface treatment of fibers
  - Fibers protection during manufacturing process
  - Protection against oxidation (carbon)
  - Chemical barrier
  - Fiber/matrix interface improvement (increase of the adhesion or creation of a chemical link)
  - Modification of the wettability of the fibers
  - Improvement of the mechanical characteristics of the fiber
  - Gives anti-static properties to the fiber (for glass)

Effect of surface treatment on matrix bonding
(a) : Poor bonding
(b) : Good bonding
(c) : Poor fiber-matrix attraction
(d) : Good fiber-matrix attraction

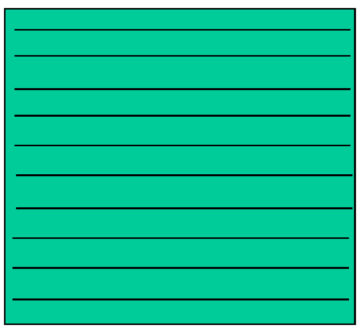


(c) (d)

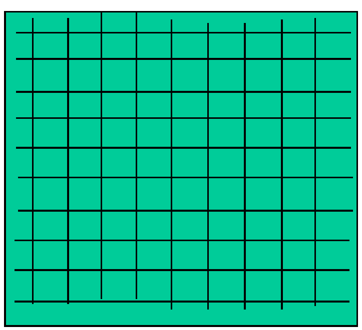
PART 3 : COMPOSITE MATERIALS

3.3. Composite Product Forms

- Composites referred to by type of fiber/type of Matrix (AS4/8552)
- Layers can be fiber only for « wet » layup (adding resin), or can be « prepreg » (already containing the resin)



Tape – all fibers aligned in single direction

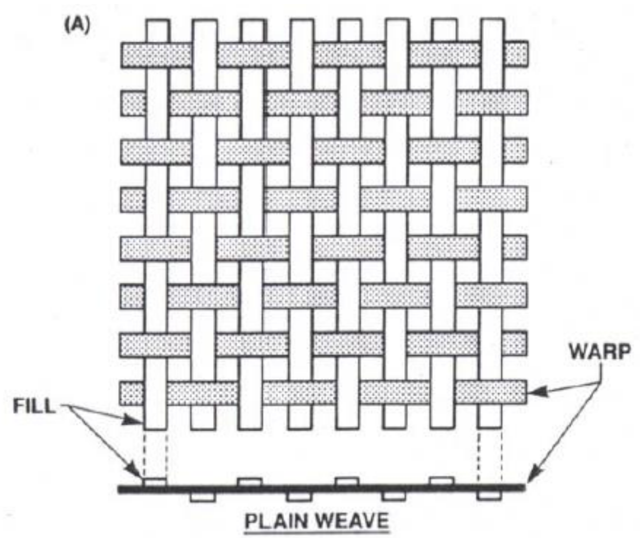


Cloth – fibers aligned in mutiple (usually two directions)
Plain weave : over and under one fiber at a time
Satin weave : over several then under one fiber
AGP280/8552

- 3000 filaments per yarn
- 5 harness weave (over four under one)

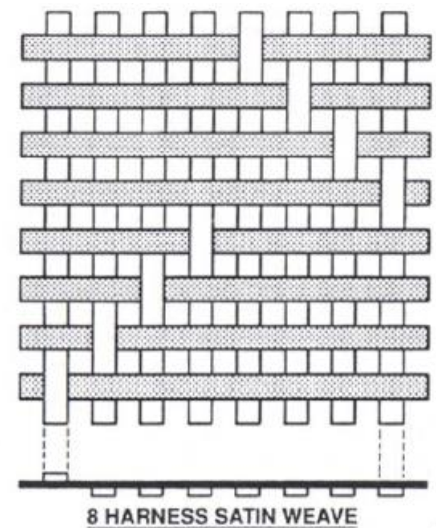
Forms of woven cloth (1)

Plain weave or taffeta



Le plus simple des tissages, chaque mèche passe alternativement au-dessus puis en-dessous de la mèche suivante
Très peu déformable, propriétés mécaniques faibles

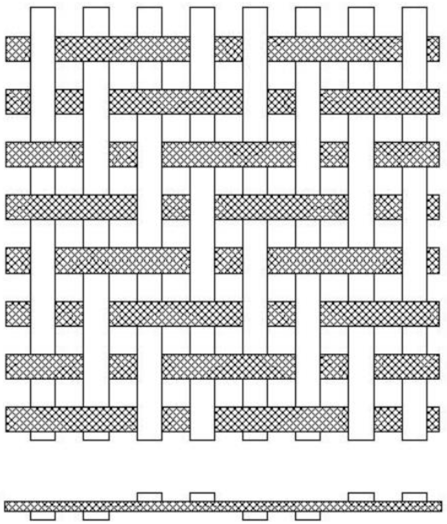
8 harness satin weave



Chaque mèche de trame passe au-dessus d'une chaîne et ensuite en-dessous de X mèches de chaîne. La mèche de trame suivante est décalée de une mèche de chaîne. Le nombre de mèches qui constitue une période complète s'appelle l'armure ou harness (par exemple : satin de 8 ou 8 harness satin).
Excellente drapabilité et très bonnes propriétés mécaniques.

Forms of woven cloth (2)

The twill 2x2



Chaque mèche de trame passe au-dessus et en-dessous d'un nombre égal de mèches de chaine et vice-versa..
La mèche de trame suivante est décalée de une mèche de chaîne (par exemple : sergé de 2).
Très bonne drapabilité et bonnes propriétés mécaniques. C'est le compromis le plus souvent utilisé.
Le sergé est parfois appelé « Basket Weave » ou aussi « tissage à double chevron».

Non crimp fabric

- 100% des mèches dans le sens de la chaîne
- Les fibres sont maintenues par une légère couture transversale (renfort sec)
- On peut disposer des mèches dans d'autres axes par couches superposées
  - Biaxial (0°/90° ou +/- 45°)
  - Multi-axial (0°/90°/+/-45°)
  - Autres angles peuvent être définis à la demande

Dans ce cas, il ne s'agit plus de métiers à tisser mais de machine de drapage automatique

PART 3 : COMPOSITE MATERIALS

3.4. Composites Laminates

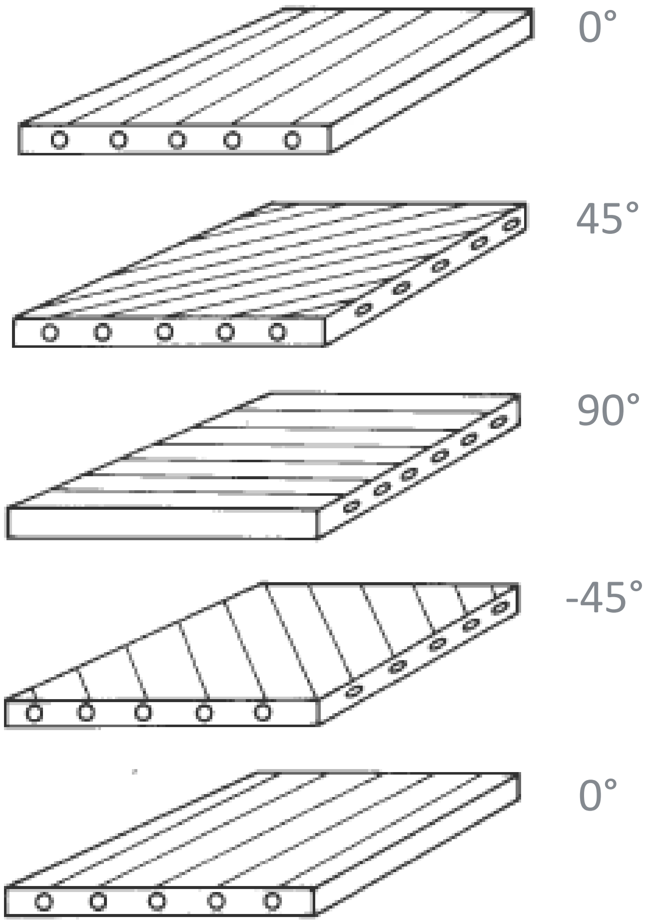
3.4.1. Laminate definition

- Two or more materials combined on a macroscopic scale to form a useful material
- Ideal for structure application where high strength-to-weight and stiffness-to-weight ratios are required
- Conventional composites limited to in-plane distributed loads

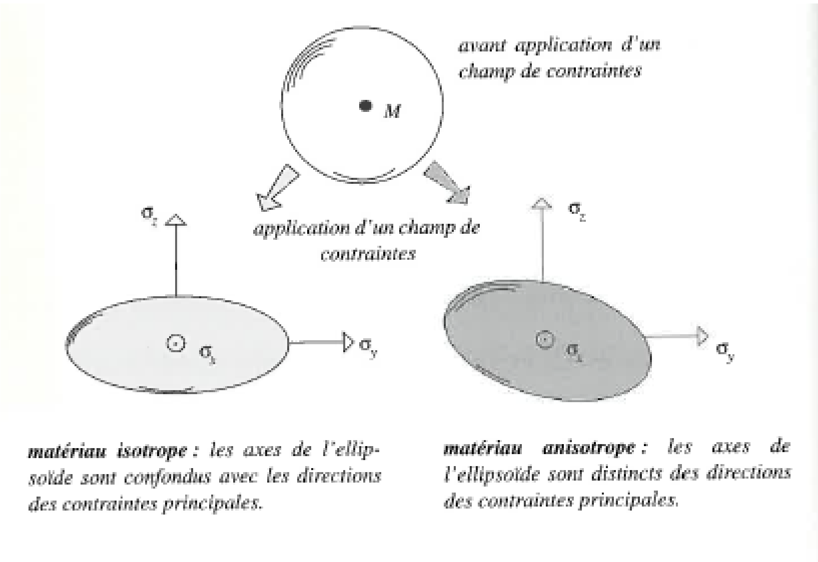
3.4. Composites Laminates

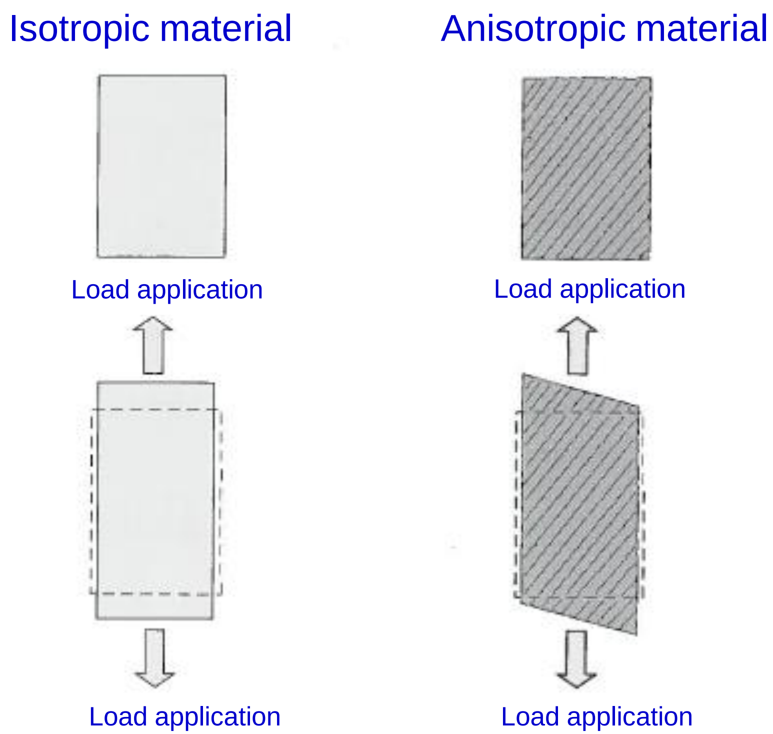
3.4.2. Laminate construction

- ❑ Common industry practice to reduce allowed orientation angles to four : 0°, 45°, -45°, 90°
- ❑ Laminates with similar number of same orientations share similar properties (belong to same family)
- ❑ Family convention : %0° / %+/-45° / %90°
  - 50/40/10 (50% 0° plies, 40% +/-45° plies, 10% 90° plies)
  - 25/50/25(25% 0° plies, 50% +/-45° plies, 25% 90° plies)

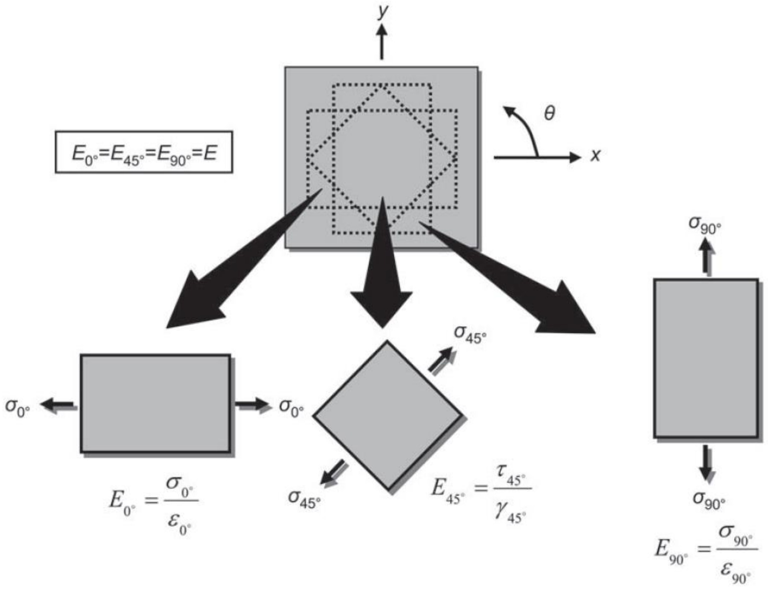


3.4.3. Isotropy (metals) versus anisotropy (composites) (1)

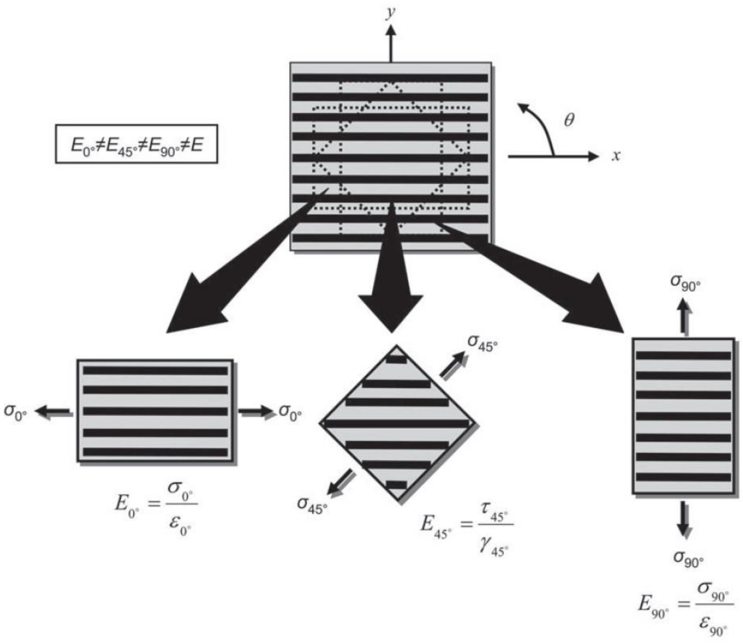




3.4.3. Isotropy (metals) versus anisotropy (composites) (2)



Element of isotropic material under stress

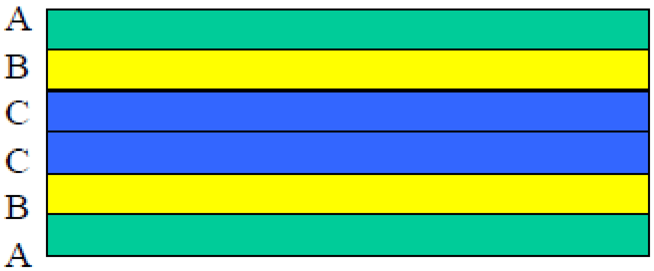


Element of composite ply material under stress

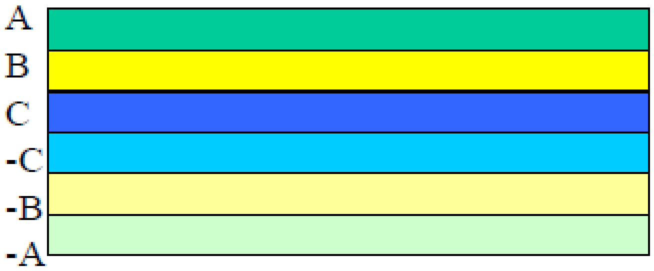
3.4. Composites Laminates

3.4.4. Symetry

- Symmetric laminate implies that the material and orientation of layers above the laminate midplane are identical to those below.



- Antisymmetric laminate implies that the material of layers above the laminate midplane are identical to those below, but the orientations are of opposite sign



3.4.5. Balance

- Balanced laminate implies that for every (+) oriented layer there exists a (-) oriented layer of the same material

[45,0,90,- 45,0,90]	balanced, unsymmetric
[45,0,90,- 45,90,0,45]	unbalanced, symmetric
[10,0,45,- 45,-10,38,-38]	balanced, unsymmetric
[45,- 45,0,90,0,- 45,45]	balanced, symmetric

- Design rule is to try to achieve, as much as possible, a balanced and symmetric laminate

3.4.6. Laminate shortland convention

- Disregarding material hybrids, the convention is to list the plies in stacking order, referencing the orientation

=> [45, -45, 0,0,45, -45,90,-45,45,0,0,45,-45,90,-45,45,0,0,-45,45]

==> $[+/45, 0_2, +/-45,90, -/+ 45,0]_s$

(30/60/10)

- Remove one of the centerline 0 plies

=> [45,-45, 0,0,45,-45,90,-45,45,0,45,-45,90,-45,45,0,0,-45,45]

==> $[+/45, 0_2, +/-45,90, -/+ 45,0]_{0s}$

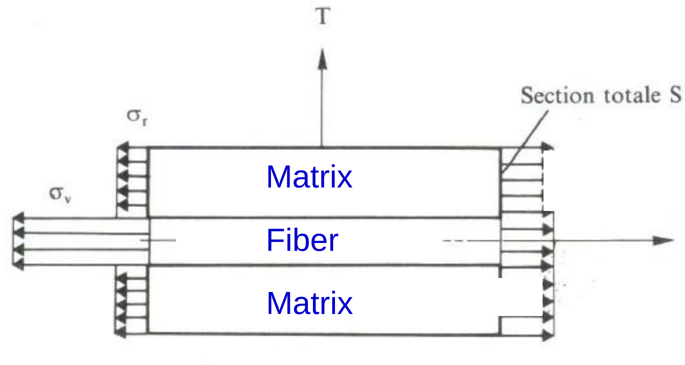
(26/63/11)

3.4.7. Mixing low for resin and reinforcement

$$\sigma_f = E_f \times \varepsilon_L \quad (1)$$

$$\sigma_m = E_m \times \varepsilon_L \quad (2)$$

$$F = \sigma f\,.S_f + \sigma_m.S_m$$



$$= \varepsilon_{laminate}$$

From (1) and (2) :

$$F = (Ef\,.S_f + E_m.S_m)\varepsilon_L \quad (3)$$

$$E_L = \frac{\sigma_L}{\varepsilon_L} = \frac{F}{S.\varepsilon_L}$$

From (3) :

$$E_L = E_f\,\frac{Sf}{S} + E_m\,\frac{S_m}{S}$$

$$\frac{S_m}{S} = (1 - \varphi)$$ and Sf + Sm = S

Young modulus in L direction : $\boldsymbol{E_L = \varphi.E_f + (1-\varphi).E_m}$

Principal Poisson ratio $\frac{\varepsilon_T}{\varepsilon_L}$: $\boldsymbol{\nu_{LT} = \varphi.\nu_f + (1-\varphi).\nu_m}$

PART 3 : COMPOSITE MATERIALS

3.5. Composite Prepreg Ply Properties

3.5.1. Physical properties of uncured prepregs and cured laminates (typical)

	Property	Carbon Fabrics		Carbon Tapes			Glass Fabrics	
Prepreg	Material description	W3T282 or W3C282	F3T584 or F3C584	95 g/m²	145 g/m²	190 g/m²	120	7781
	% Flow @ 350°F, 50 psi (177°C, 345 kPa)	9–22	9–22	11–24	11–24	11–24	15–30	10–30
	% Resin content (dry)	38–42	35–39	35–39	35–39	35–39	42–48	36–40
Laminate	Cured thickness per ply – in (cm)	0.0072 (0.018)	0.0135 (0.034)	0.0039 (0.010)	0.0059 (0.015)	0.0078 (0.020)	0.0045 (0.011)	0.010 (0.025)
	% Fiber volume	61	62	55	55	55	38	45

3.5. Composite Prepreg Ply Properties

3.5.2. Mechanical properties (autoclave) of cured laminates (typical)

Property	Temp °F (°C)	Carbon Fabrics		Carbon Tapes			Glass Fabrics	
		W3T282	W3T584	T3T095	T3T145	T3T190	120	7781
Tensile strength, ksi (MPa)	75 (24)	82.6 (570)	88.4 (610)	180.8 (1247)	197.5 (1362)	196.3 (1353)	53.4 (368)	66.9 (461)
Tensile modulus, msi (GPa)	75 (24)	8.81 (60.7)	9.24 (63.7)	19.55 (134.8)	19.19 (132.3)	19.12 (131.8)	3.47 (23.9)	4.30 (29.7)
Tensile strain	75 (24)	9,762	10,024	9,267	10,345	10,142		
Tensile strength, ksi (MPa)	350 (177)	78.5 (541)	84.0 (579)		187.6 (1260)		38.1 (263)	55.8 (385)
Tensile modulus, msi (GPa)	350 (177)	8.37 (57.7)	8.78 (60.5)		18.23 (125.7)		2.94 (20.3)	3.46 (23.9)
Compression strength, ksi (MPa)	75 (24)	94.0 (648)	96.6 (666)	206.0 (1420)	193.3 (1333)	175.8 (1212)	68.7 (474)	71.2 (491)
Compression modulus, msi (GPa)	75 (24)						3.41 (23.5)	4.36 (30.1)
Compression strength, ksi (MPa)	160 (71)	83.4 (575)	84.9 (585)	182.7 (1260)	167.4 (1154)	171.8 (1185)		
Compression strength, ksi (MPa)	350 (177)						50.0 (345)	51.2 (353)
Compression modulus, msi (GPa)	350 (177)						3.11 (21.4)	3.83 (26.4)
Short beam shear, ksi (MPa)	–65 (–54)	10.50 (72)	9.46 (65)	18.92 (130)	17.99 (124)	17.76 (122)		
Short beam shear, ksi (MPa)	75 (24)	10.72 (74)	10.40 (72)	16.06 (111)	16.16 (111)	15.92 (110)		
Short beam shear, ksi (MPa)	270 (132)	8.05 (56)	6.99 (48)	10.87 (75)	10.48 (72)	10.96 (76)		
Short beam shear, ksi (MPa)	350 (177)	6.73 (46)	6.88 (47)		9.82 (68)			
Interlaminar shear, ksi (MPa)	75 (24)						2.99 (21)	3.37 (23)
Interlaminar shear, ksi (MPa)	350 (177)						2.24 (15)	2.61 (18)

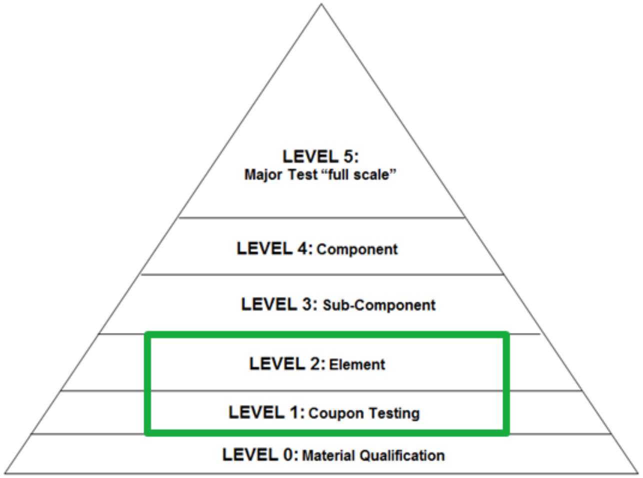
PART 3 : COMPOSITE MATERIALS

3.6. Composite Material Characterization

3.6.1. Building block approach testing

- **Level 1 :**
  - The level 1 (“coupon”) is the phase of generic coupon testing meant to characterize lamina & laminate for the selected material system representing anticipated lay-up configurations and thicknesses. The phase is also meant for evaluation of damage resistance and for verification of failure criteria to be used during design process

- **Level 2 :**
  - The level 2 (“element”) is the phase where structural design features are characterized at their simplest form



3.6. Composite Material Characterization

3.6.2. Basic characterization used for process control

A. Physico-chemical tests

Test	Level	Outputs
Density	NA	ρ [g/cm^3]
Fibre volume fraction	NA	FVF [%]
Void volume fraction	NA	VVF [%]
Differential Mechanical Analysis (DMA)	NA	Tg onset, Tg loss, Tg peak [°C]
Micrographic cuts	NA	-

B. Mechanical tests

Interlaminar Shear Strength (ILSS)	NA	Ultimate strength (Mpa)

sonaca

3.6. Composite Material Characterization

3.6.3. Full characterization for qualification (mechanical tests)

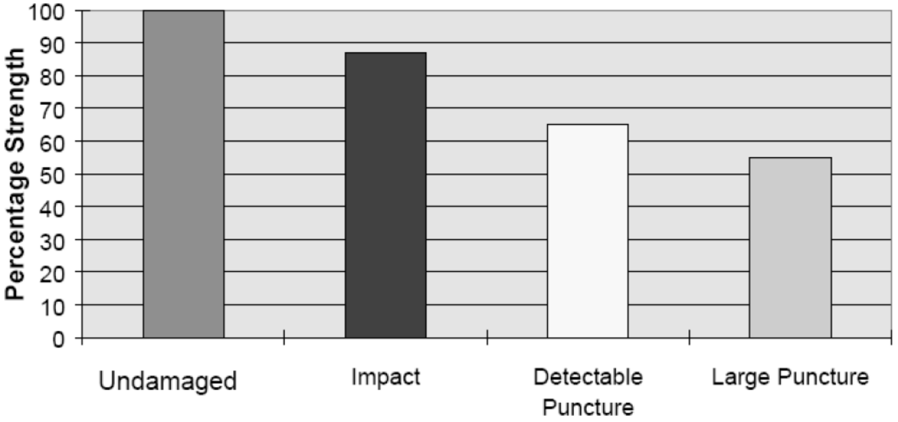
Test	Level	Outputs
Tensile	1	Modulus, ultimate strength and strain
Compression	1	Modulus, ultimate strength and strain
Shear	1	Modulus, ultimate strength
Flexure	1	Modulus, ultimate strength
In Plane Shear (IPS)	1	Modulus, ultimate strength
Fatigue	1	Endurance limit
Impact (BVID, VID)	1	BVID or VID energy
Compression after impact (CAI)	1	Strain cut-off
Curved beam strength	1	Ultimate strength
Peel ply (sandwich structure)	1	Peel torque [mm.kg/mm]
Fracture thoughness mode 1 (G_{1C})	1	G_{1C} [J/m²]
Fracture thoughness mode 2 (G_{2C})	1	G_{2C} [J/m²]

3.6.4. Other tests

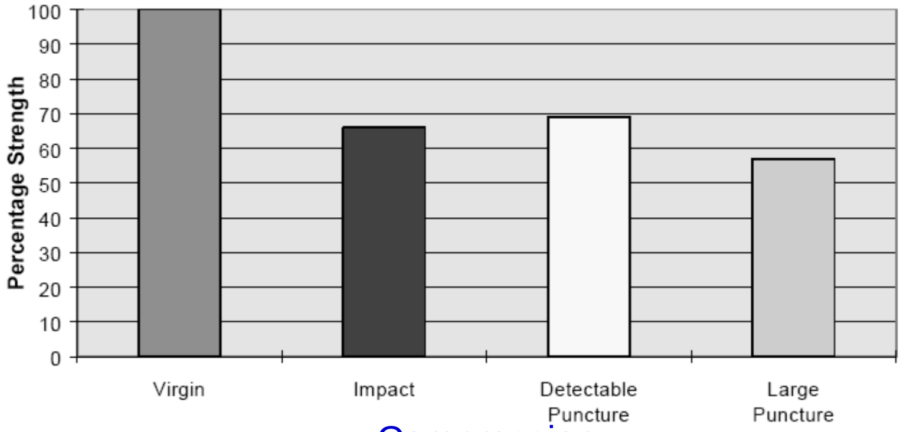
Test	Level	Outputs
Single shear bearing	2	Ultimate shear strength
Fastener pull through	2	

3.6. Composite Material Characterization

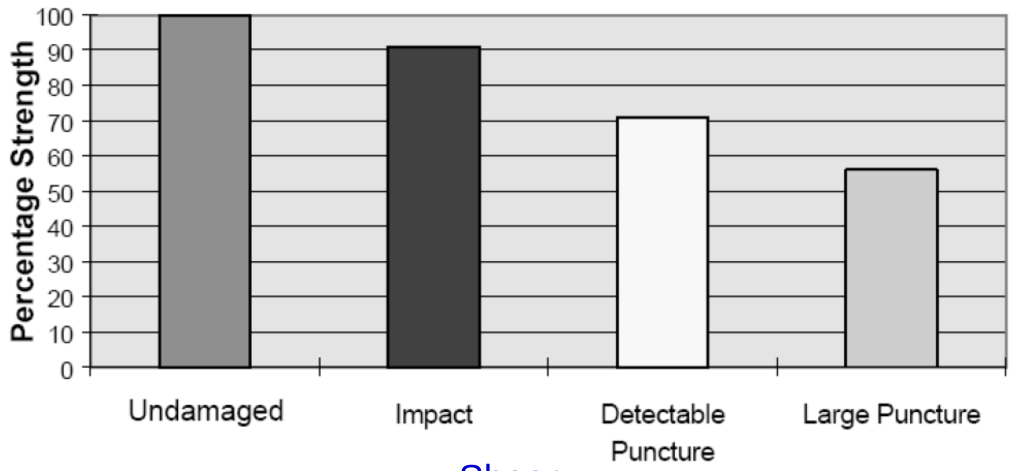
3.6.5. Damage effect on composite material properties



Longitudinal tension



Compression



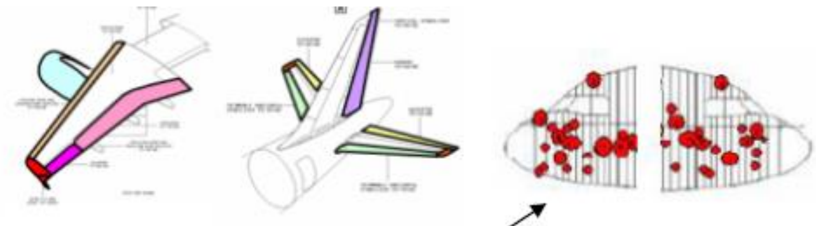
Shear

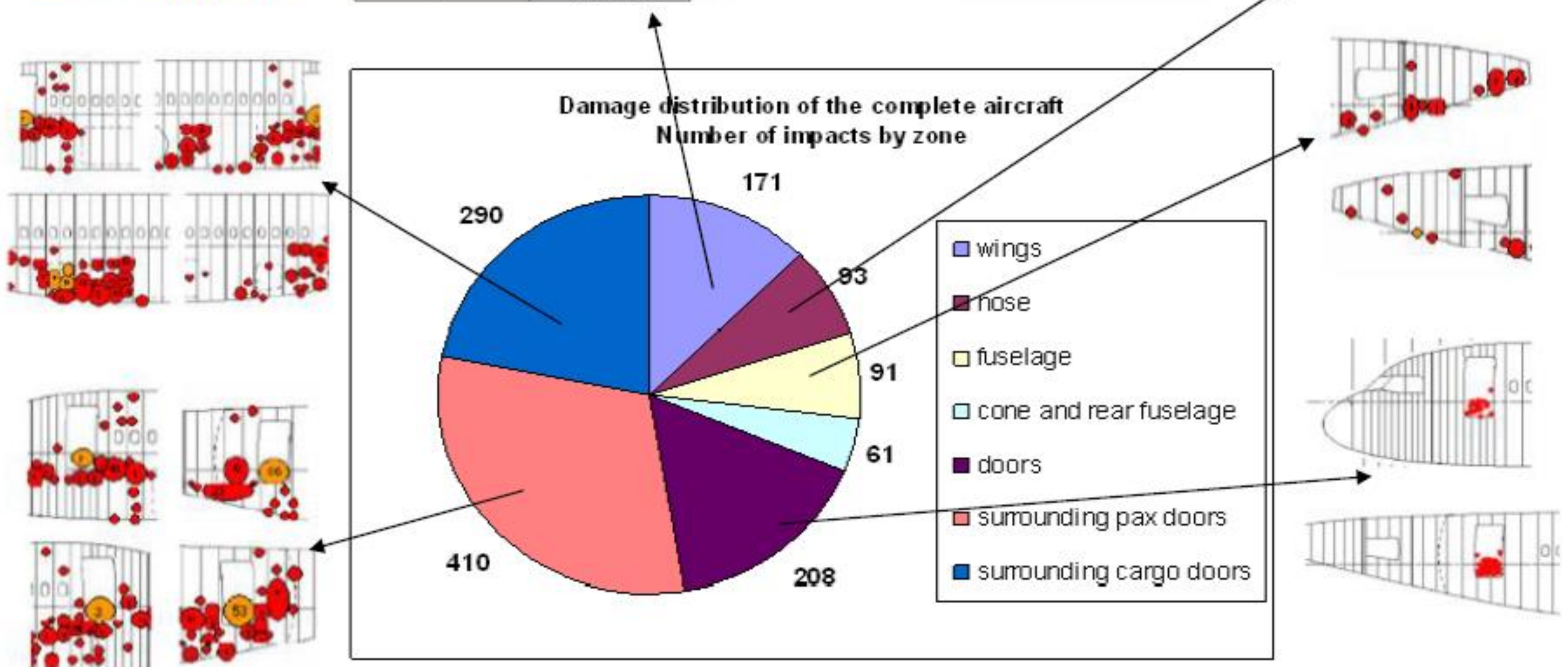
3.6.6. Composite of impact resistance and damage tolerance

77 Aircrafts

1324 impacts

Numbers of impacts	Impacted zones
32	Engine
37	Slat
56	Flap
2	Aileron
3	Wing tip
26	THS Leading edge
10	THS tip
3	Elevator
1	Rudder
1	Undefined

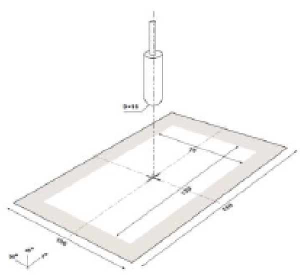


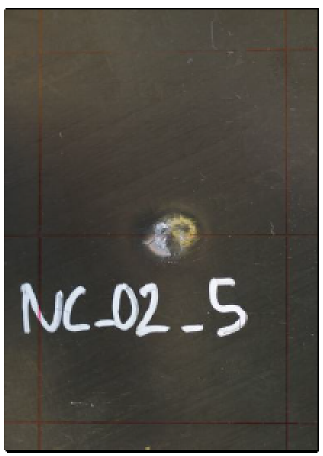


Optimized design to integrate robustness as a sizing criteria
(combination location/energy/shape of the impact) to improve aircraft operability

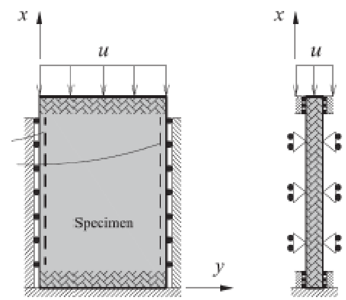
3.6.7. Composite damage tolerance policy (1)

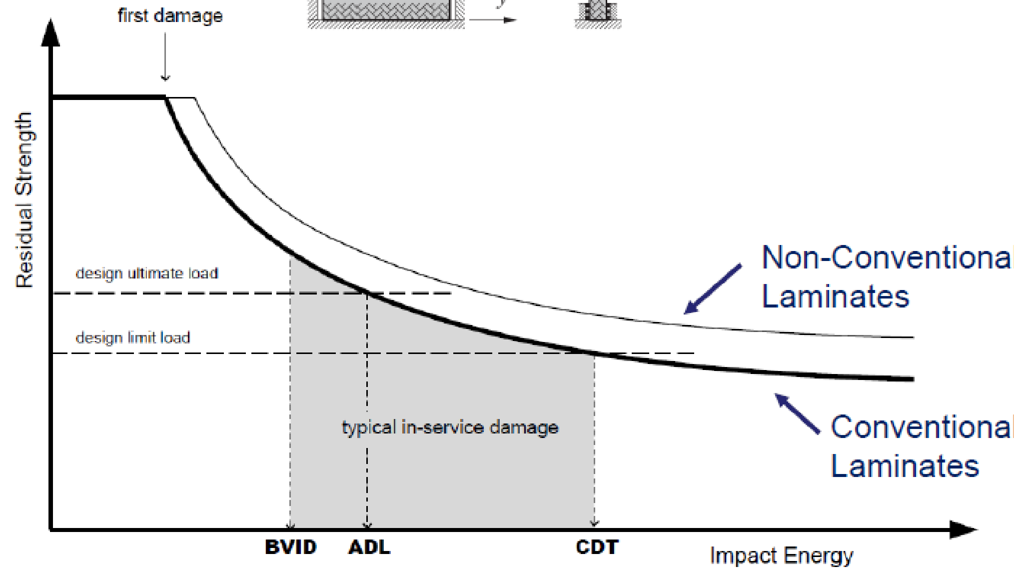
Low Velocity Impact





Compression After Impact





BVID : Barely Visible Impact Damage - ADL : Allowable Damage Limit - CDT : Critical Damage Threshold

List of References for Composites Materials

- « Matériaux composites », 5ème édition, Daniel Gay, Edition Lavoisier « Hermes Science », 2005.
- « Composites Materials » : Engineering and Science, F.L. Matthews & R.D. Rawlings, CRC Press, Woodhead Publishing Ltd, 2007.
- « Design and Manufacture of Composite Structures », Geoff Eckold, Woodhead Publishing Ltd, 1994.
- « Initiation au Comportement et Fabrication des Structures en Matériaux Composites », Stage GME 815 Sonaca, Eurosae Formation Continue, Robert Piquet, 2008.
- « Matières Premières », Wallonie Aerotraining Network asbl, Alain Kinard, 2014.
- « Pré-post Fabrication », Wallonie Aerotraining Network asbl, Alain Kinard; 2014.
- « Eléments de Mécanique des Stratifiés », Wallonie Aerotraining Network, asbl, Alain Kinard, 2014.
- « Structural Composites Materials », F.C. Campbell, ASM International, 2010.