Introduction to Aerospace Engineering

Lecture slides

Selection of material & structure

Strength & stiffness

Faculty of Aerospace Engineering

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TU Delft
Delft University of Technology

Introduction

Outline of lectures/lecturer

- 15/11 Material physics & properties / environment
- 22/11 Structures
- 29/11 Loads
- 6/12 Materials & manufacturing
- 13/12 Selection of materials & structures / space
- 20/12 Design & certification / fatigue & durability
- 10/1 Manufacturing & joining

- Lecturer
  - Name: René Alderliesten
  - Room: NB0.45
  - Email: R.C.Alderliesten@tudelft.nl

Learning objectives

Student should be able to...

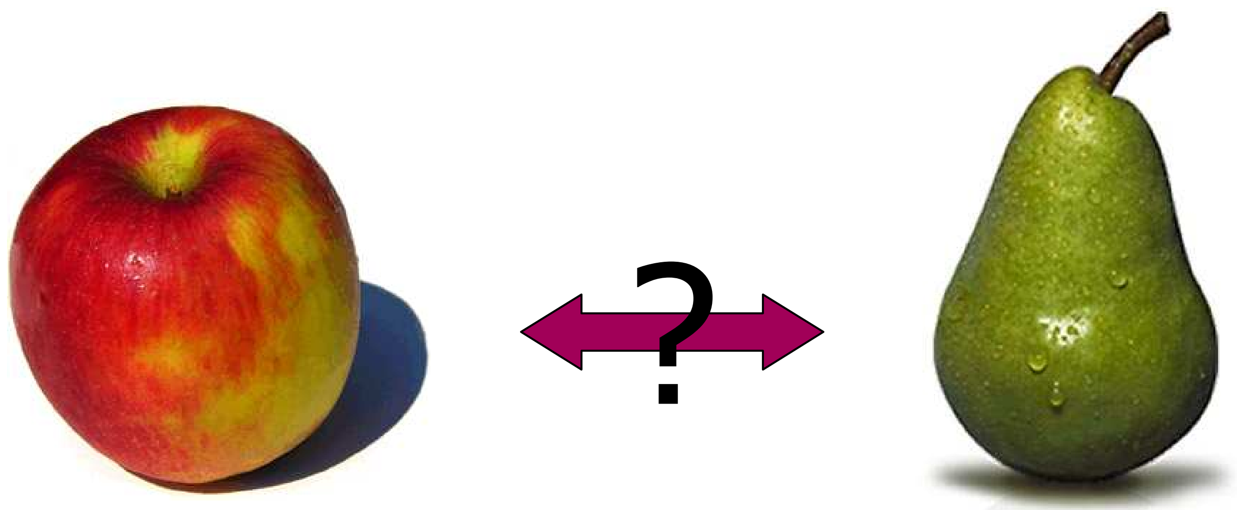
- Discuss structural performance in terms of material and geometrical aspects
- Explain why different criteria are used to compare material properties in different structures

Selecting the best criterion

Structural performance

- Structural performance is a function of
  - Material properties
  - Geometrical aspects

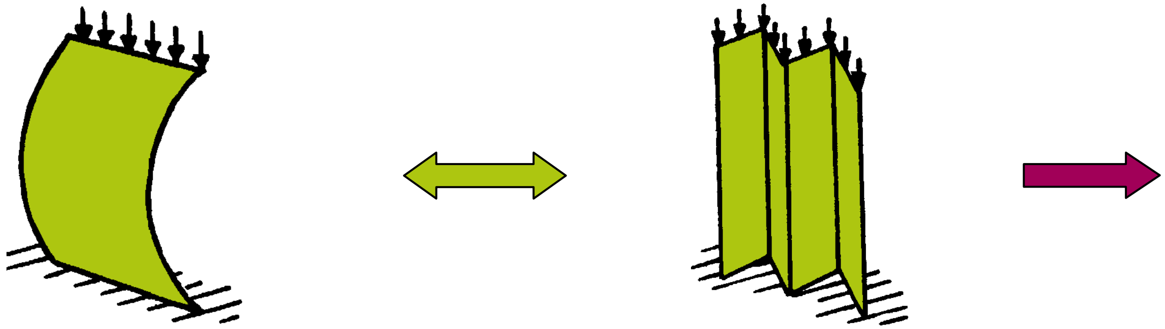
which can be optimized with respect to
  - Weight
  - Cost
  - …



Selecting the best criterion

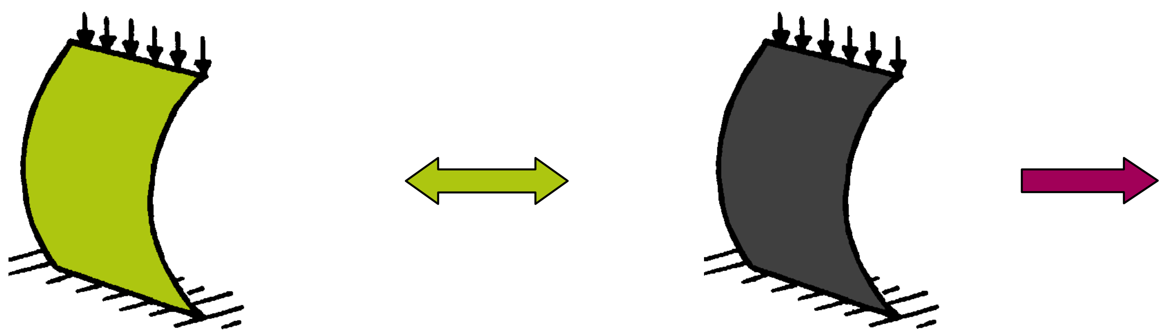
Structural performance - Example

- Structural performance at minimum weight (compression-buckling)
  - Equal material – variation in geometry/shape



$f\left(W, t, L, \ldots\right)$

  - Equal geometry – variation in material



$f\left(\rho\right)$

Selecting the best criterion

Structural performance - Example

- Structural performance at minimum weight (compression-buckling)
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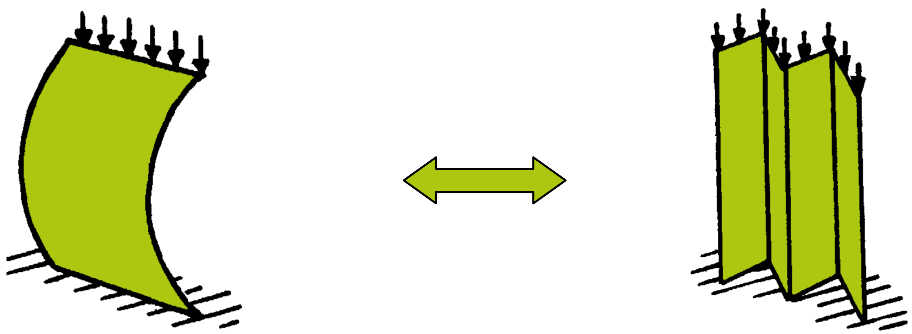
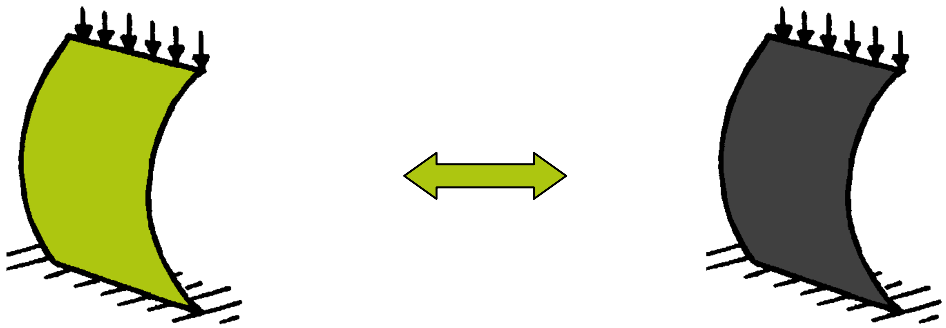


  - Characteristic equation: $P = const \frac{E}{1-\nu^2}\left(\frac{t}{b}\right)^2 tb$
  - Weight: $W = Lbt\rho$
  - Structural efficiency (load/weight): $\frac{P}{F} = const\left(\frac{P_c}{L^2}\right)^{2/3}\frac{\sqrt[3]{E}}{\rho}$

Selecting the best criterion

Structural performance - Example

- Structural performance at minimum weight (compression-buckling)
  - Equal geometry – variation in material



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  - Weight: $W = Lbt\rho$
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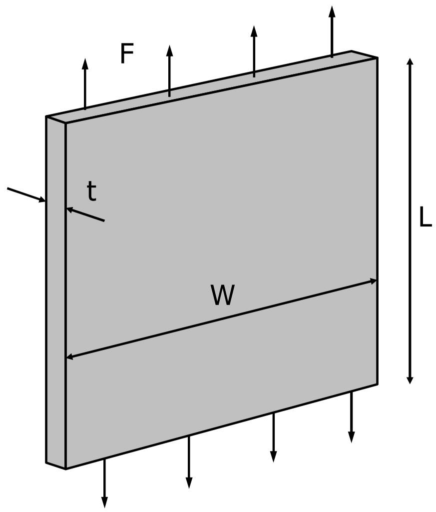
Selecting the best criterion

Material tensile strength & stiffness

- Material property at minimum weight
  - Tensile strength
    $$\frac{\sigma_u}{\rho}$$
  - Tensile stiffness
    $$\frac{E}{\rho}$$



- Example

7475-T761:	σ_u = 517 MPa	E = 72 GPa	ρ = 2.8 g/cc
HSLA steel:	σ_u = 1500 MPa	E = 210 GPa	ρ = 7.8 g/cc
Panel:	W = 1000 mm	t = 1 mm	

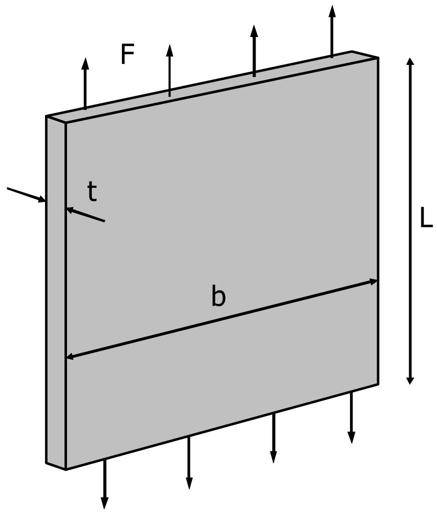
Selecting the best criterion

Material tensile strength & stiffness

- Comparing failure load

$$F_{7475} = \sigma_{u,7475}\, b\, t = 517\, kN$$

$$F_{steel} = \sigma_{u,steel}\, b\, t = 1500\, kN$$



- Example
  - 7475-T761: σ_u = 517 MPa E = 72 GPa ρ = 2.8 g/cc
  - HSLA steel: σ_u = 1500 MPa E = 210 GPa ρ = 7.8 g/cc
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Selecting the best criterion

Material tensile strength & stiffness

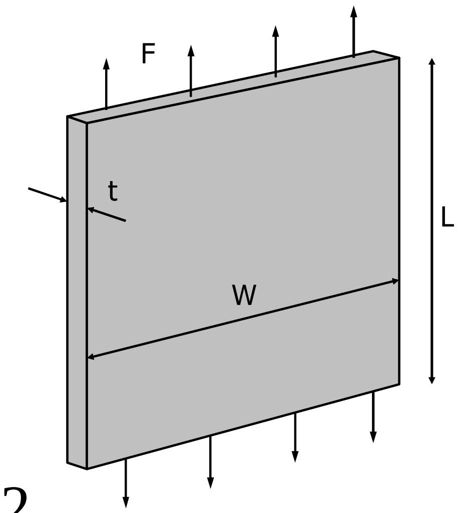
- Comparing failure load

$$F_{7475} = \sigma_{u,7475}\, b\, t = 517\, kN$$

$$F_{steel} = \sigma_{u,steel}\, b\, t = 1500\, kN$$

- Specific tensile strength

$$\frac{\sigma_{u,7475}}{\rho} = \frac{517}{2.8} = 185 \quad \Longleftrightarrow \quad \frac{\sigma_{u,steel}}{\rho} = \frac{1500}{7.8} = 192$$



Selecting the best criterion

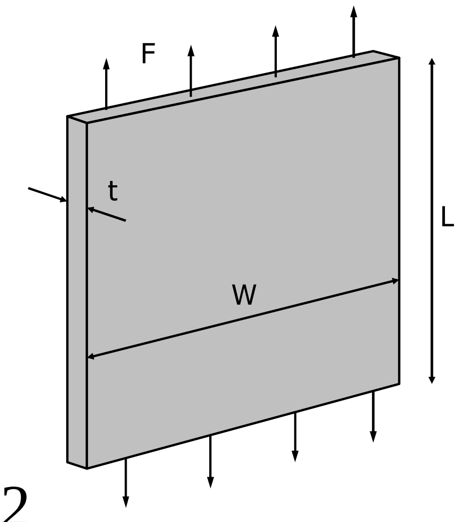
Material tensile strength & stiffness

- Comparing failure load

$$F_{7475} = \sigma_{u,7475}\, b\, t = 517\, kN$$

$$F_{steel} = \sigma_{u,steel}\, b\, t = 1500\, kN$$

x2.9



- Specific tensile strength

$$\frac{\sigma_{u,7475}}{\rho} = \frac{517}{2.8} = 185 \quad \longleftrightarrow \quad \frac{\sigma_{u,steel}}{\rho} = \frac{1500}{7.8} = 192$$

x2.8

- Specific tensile stiffness

$$\frac{E_{7475}}{\rho} = \frac{72}{2.8} = 25.7 \quad \longleftrightarrow \quad \frac{E_{steel}}{\rho} = \frac{210}{7.8} = 26.9$$

Selecting the best criterion

Buckling stability

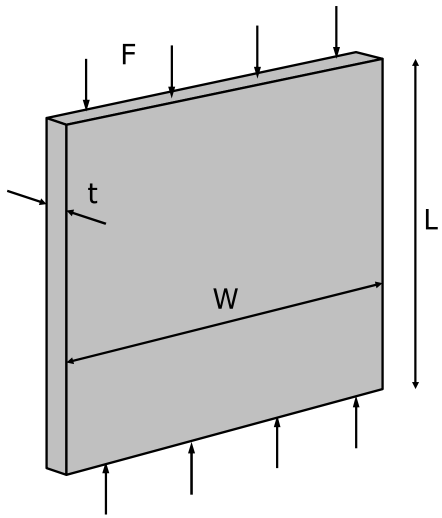
- Buckling in compression

$$\sigma_{cr} \simeq \frac{Et^2}{Lb}$$

- Keeping the buckling load of both panels identical

$$F_{\max} = \sigma_{cr,7475}\, b\, t_{7475} = \sigma_{cr,steel}\, b\, t_{steel} \Rightarrow \frac{t_{7475}}{t_{steel}} = \frac{\sqrt[3]{E_{steel}}}{\sqrt[3]{E_{7475}}} = 1.4$$

$\Rightarrow$ Steel is thinner than aluminium…



Selecting the best criterion

Buckling stability

- …but the aluminium panel weights less!

$$\frac{W_{7475}}{W_{steel}} = \frac{Lbt_{7475}\rho_{7475}}{Lbt_{steel}\rho_{steel}} = \frac{\sqrt[3]{E_{steel}}/\rho_{steel}}{\sqrt[3]{E_{7475}}/\rho_{7475}} = 0.51$$

- Thus a large $\sqrt[3]{E}/\rho$ is preferred

Material	$\sqrt[3]{E}/\rho$
Aluminium	1.472
Steel	0.762
Titanium	1.065
Isotropic carbon fibre composite	2.456
Isotropic glass fibre composite	1.07
Isotropic aramid fibre composite	2.0

Selecting the best criterion

Characteristic material values

- Specific material strength: $\dfrac{\sigma_u}{\rho}$
- Specific bending deformation: $\dfrac{\sqrt[3]{\sigma_y^2}}{\rho}$
- Column stability: $\dfrac{\sqrt{E}}{\rho}$
- Sheet stability: $\dfrac{\sqrt[3]{E}}{\rho}$

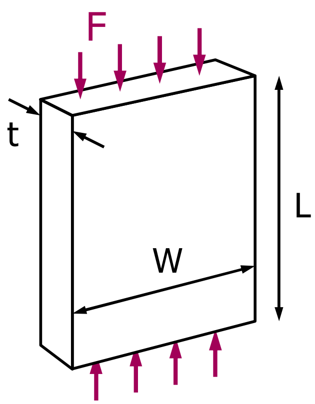
Assuming the same dimensions (geometry) !

Selecting the best criterion

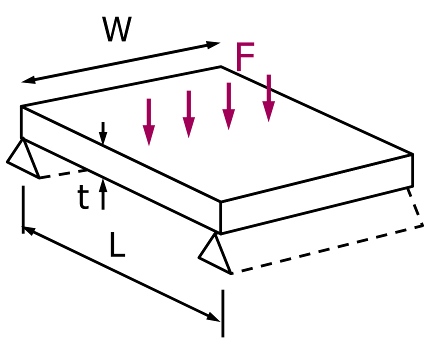
Characteristic material values

Minimize weight for given

• Loading mode	Stiffness	Strength



Stiffness: $$\frac{\sqrt[3]{E}}{\rho}$$



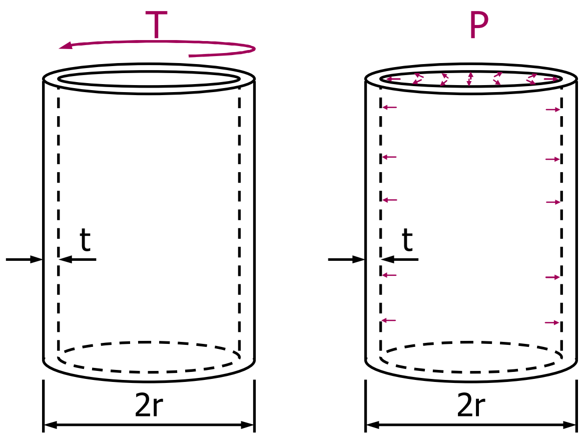
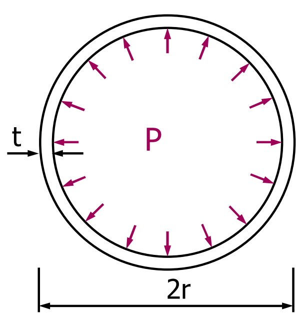
Stiffness: $$\frac{\sqrt[3]{E}}{\rho}$$

Strength: $$\frac{\sqrt{\sigma}}{\rho}$$

Assuming the same dimensions (geometry) !

Selecting the best criterion

Characteristic material values

Loading mode	Minimize weight for given Stiffness	Strength
	$\frac{E}{\rho}$	$\frac{\sigma}{\rho}$
	$\frac{E}{(1-\nu)\rho}$	Assuming the same dimensions (geometry) !

Selecting the best criterion

Characteristic material values

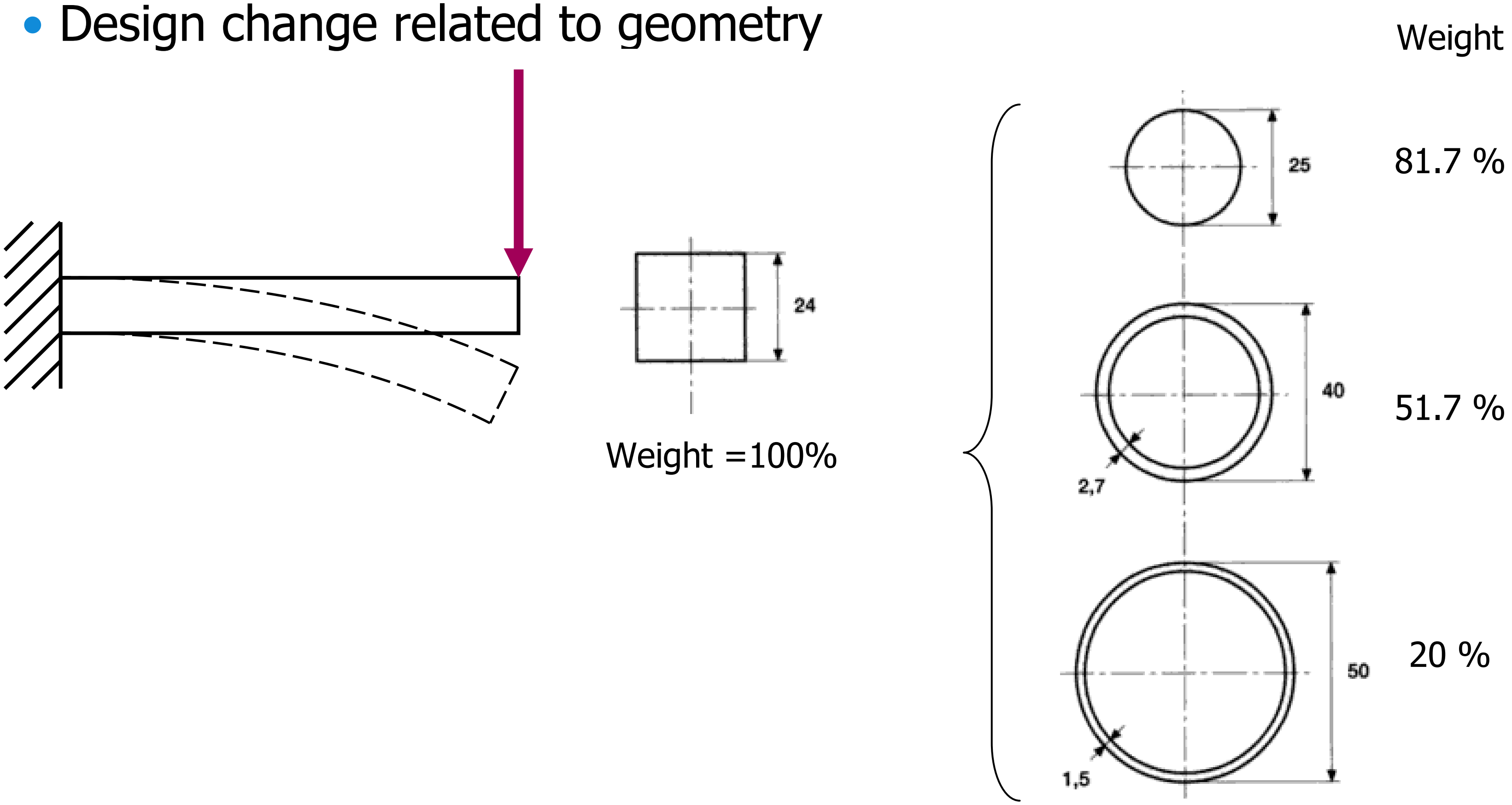
	Specific modulus		Column stability		Sheet stability	
Material	E/γ	% [1]	$\sqrt{E}/\gamma$	% [1]	$\sqrt[3]{E}/\gamma$	% [1]
Aluminium	2500	108	9.5	62	1.5	52
Steel	2692	100	5.9	100	0.8	100
Spruce	2340	115	**22.3**	**26**	4.7	16
Birch	2538	106	19.8	30	**3.9**	**19**
Bone	1500	179	9.0	65	1.6	47
Titanium	2622	103	7.8	76	1.1	73
Isotropic carbon fibre composite	**3333**	**81**	14.9	40	2.5	32
Isotropic E-glass fibre composite	536	502	5.1	116	1.1	73
Isotropic aramid fibre composite	1760	153	11.4	52	2.1	38

[1] Represents weight % of similar loaded structure compared to steel

Selecting the best criterion

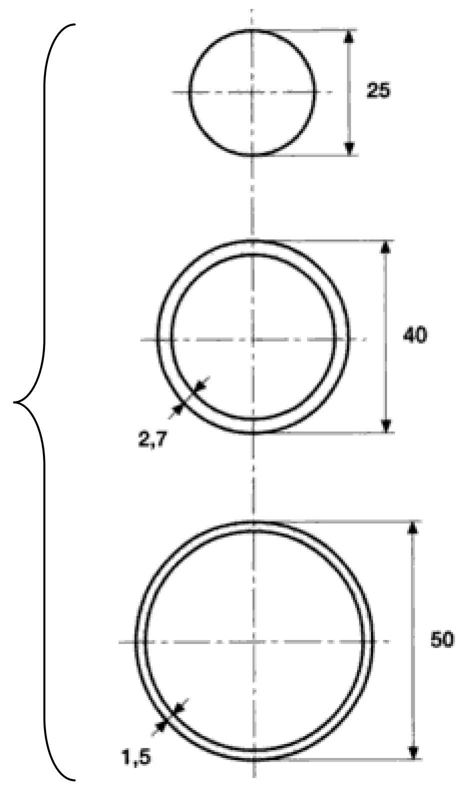
Structural design

- Design change related to geometry



Selecting the best criterion

Structural design



Weight

81.7 %

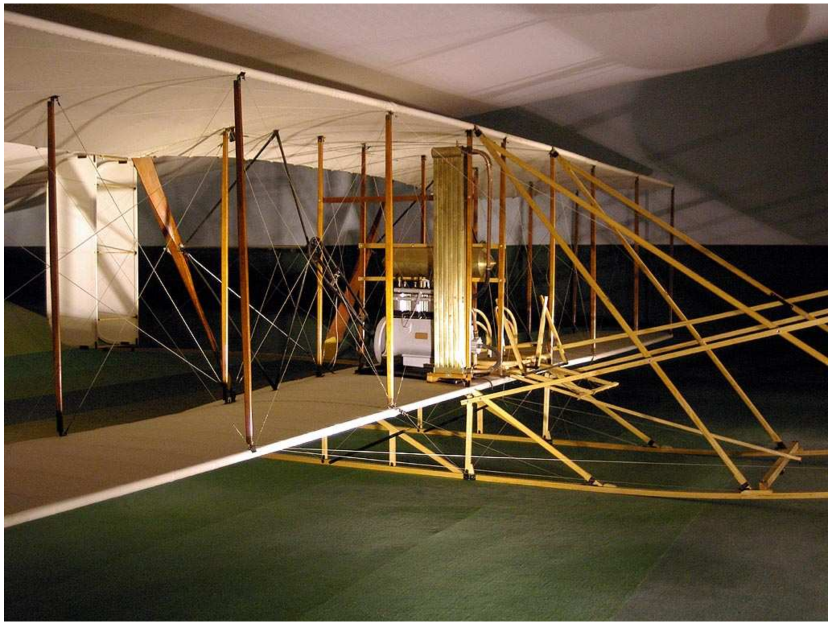
51.7 %

20 %

Selecting the best criterion

Structural design

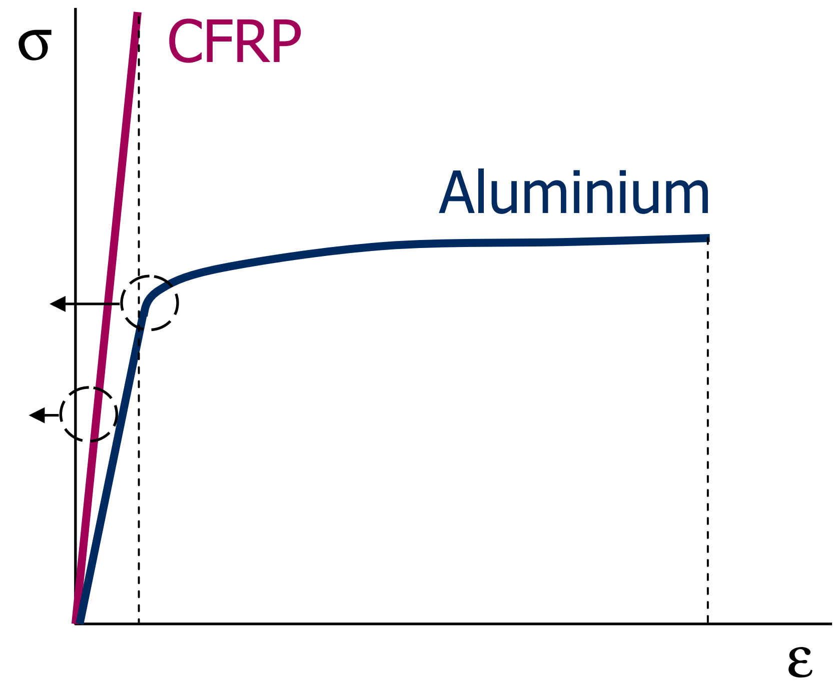
- Design change related to improved materials
  - Wood, fabric, steel tube truss → load bearing aluminium skin structure



Selecting the best criterion

Structural design

- Relate design change to realistic aircraft design !
  - Load bearing aluminium skin ⟹ load bearing composite skin
- What strength?
  - Aluminium structures: Limit load $\Rightarrow \sigma_y$
  - Composite structures: Ultimate load $\Rightarrow$ 0.35% σ_{ult}

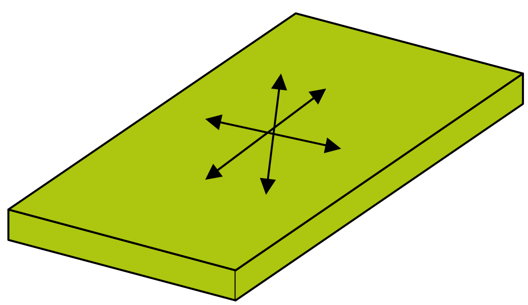


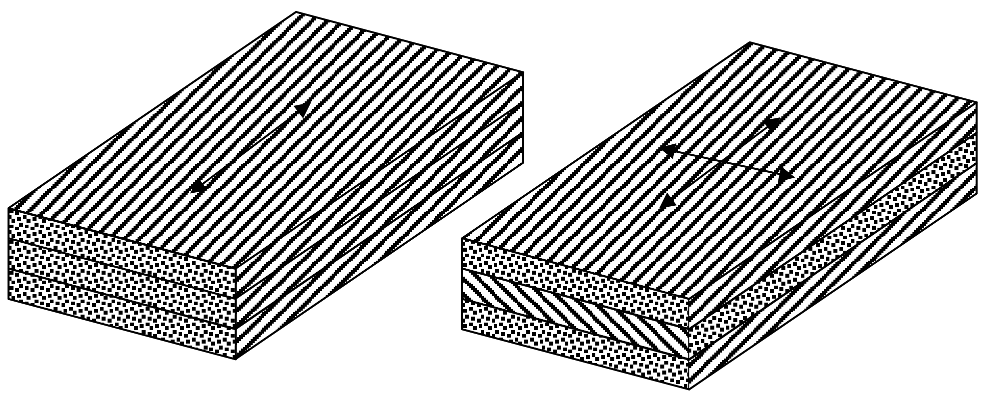
Selecting the best criterion

Structural design

- Relate design change to realistic aircraft design !
  - Load bearing aluminium skin → load bearing composite skin

- What material?
  - Aluminium sheet: isotropic   Composite sheet: highly anisotropic

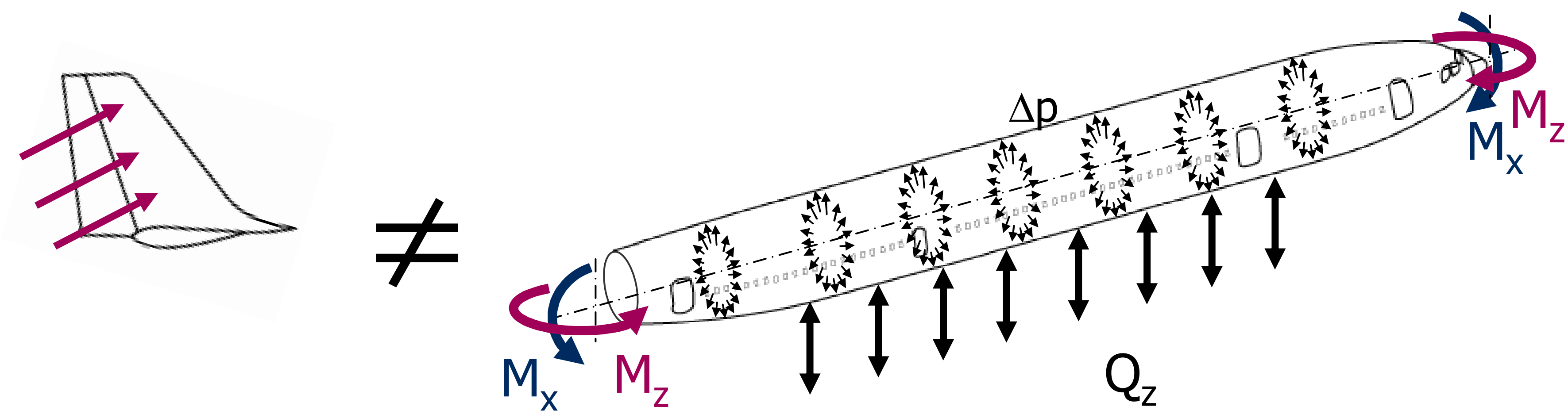




Selecting the best criterion

Structural design

- Relate design change to realistic aircraft design !
  - Load bearing aluminium skin → load bearing composite skin
- A fuselage differs in more than one way from a tail plane



Selecting the best criterion

Structural design

- Relate design change to realistic aircraft design !
  - Load bearing aluminium skin → load bearing composite skin

Material	Lay-up	E	E/ρ	σ_{max}	σ_{max}/ρ	Comment
	% 0°/±45°/90°	GPa	MPa m³/kg	MPa	MPa m³/kg	
CFRP (T800S)	60 / 30 / 10	103	64	360 [1]	0.225	Tail plane shells
CFRP (T800S)	40 / 50 / 10	77	48	270 [1]	0.170	
CFRP (T800S)	20 / 70 / 10	50	31	175 [1]	0.110	Fuselage side shell
2xxx Al-alloy		72	26	440 [2]	0.160	
7xxx Al-alloy		72	26	565 [2]	0.205	
Al-Li alloy		77	29	515 [2]	0.195	

[1] σ_{max} is based on σ_{ult} limited to 0.35% design strain

[2] σ_{max} is taken from σ_{ult} (Mil-Hdbk) including notch factor 0.9

Selecting the best criterion

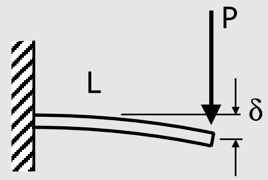
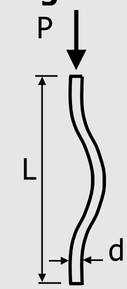
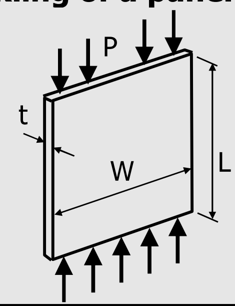
Structural design

CFRP tail plane (A400M)

CFRP fuselage (B787)

Summary

Material selection criterion

Case	Deflection of a beam 	Buckling of a strut 	Buckling of a panel 
Characteristic equation	$\delta = \frac{PL^3}{3EI} \quad I = \frac{wt^3}{12}$	$P_c = \frac{\pi^2 EI}{L^2} \quad I = \frac{\pi d^4}{64}$	$P = const \frac{E}{1-\nu^2}\left(\frac{t}{W}\right)^2 tW$
Weight	$F = LWt\rho$	$F = \frac{\pi d^2}{4} t\rho$	$F = LWt\rho$
Structural efficiency =load/weight	$\frac{P}{F} = const\left(\frac{\delta t^2}{L^4}\right)\frac{E}{\rho}$	$\frac{P}{F} = const\sqrt{\frac{P_c}{L^4}}\frac{\sqrt{E}}{\rho}$	$\frac{P}{F} = const\left(\frac{P_c}{L^2}\right)^{2/3}\frac{\sqrt[3]{E}}{\rho}$
Structure loading coefficient	$\left(\frac{\delta t^2}{L^4}\right)$	$\sqrt{\frac{P_c}{L^4}}$	$\left(\frac{P_c}{L^2}\right)^{2/3}$
Material efficiency criterion	$\frac{E}{\rho}$	$\frac{\sqrt{E}}{\rho}$	$\frac{\sqrt[3]{E}}{\rho}$