Engineering Part IB

P8 – Elective (2)

Engineering for Renewable Energy Systems

Wind Turbines - Blade Structure and Materials

Dr Michael Sutcliffe

Aims of this course

- To understand materials issues for wind turbines, including effects of scale
- To introduce composites manufacturing routes for turbine blades
- To detail a fatigue design methodology for turbine blades

Selected bibliography

Guidelines for Design of Wind Turbines, DNV/Risoe Publication, ISBN 8755028705
http://www.sandia.gov/wind/
http://www.owenscorning.com/

1 Introduction
- Concepts and Materials
- Scaling effects
- Costs

2 Material Selection
- Performance indices
- Multiple constraints

3 Shape Optimisation

4 Composite Blades
- Composite materials
- Manufacture

5 Design against Failure
- Static analysis
- Fatigue analysis

1 Introduction

Wide range of materials used in blades and towers - why?

What are the critical factors affecting material choice?

1.1 Blade materials

www.reuk.co.uk

NEG Micon NM82 1.5MW turbine. 40m blades, vacuum infusion

LM Glasfiber: A 61.5 m blade on its way to an installation 25 kms off Scotland.

www.otherpower.com

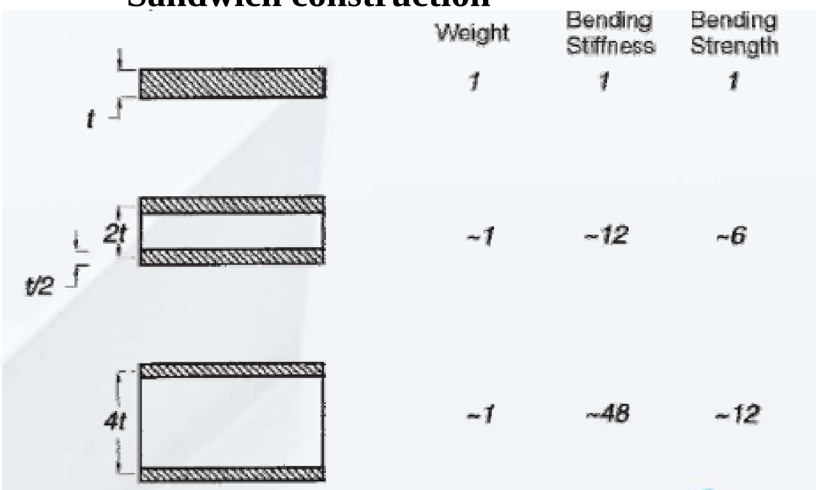
1.2 Tower construction

Tubular steel tower | Tubular concrete tower | Lattice tower | Three-legged tower | Guy-wired pole tower

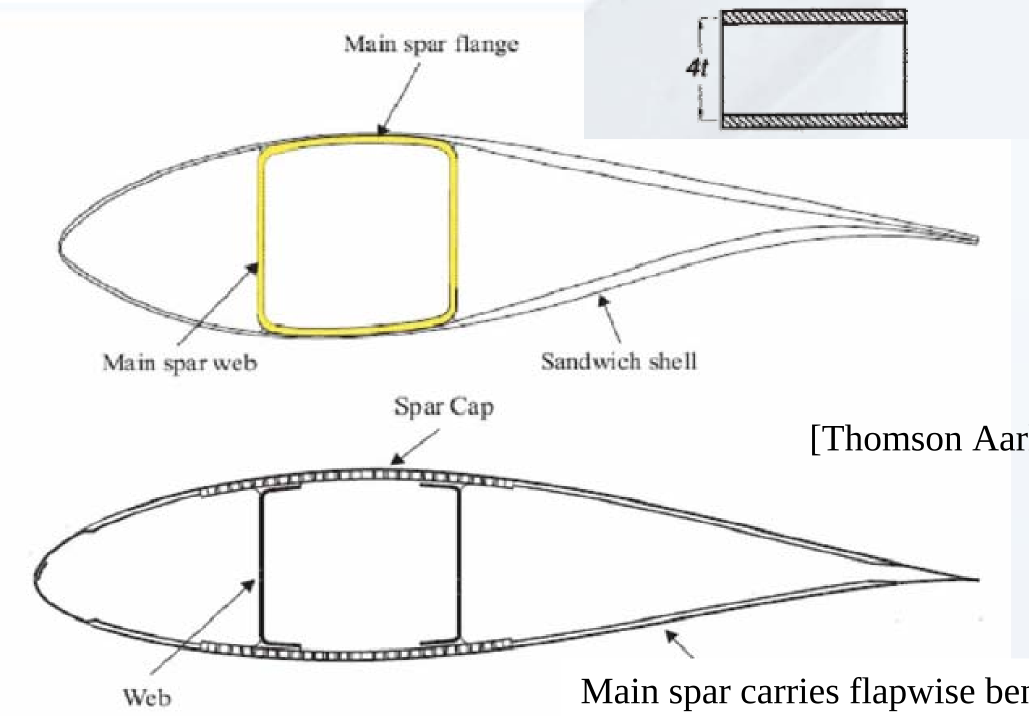
Figure 7-1. Various tower structures. From www.windpower.org, © Danish Wind Turbine Manufacturers Association.

[Risoe/DNV]

Sandwich construction



1.3 Blade structural concepts



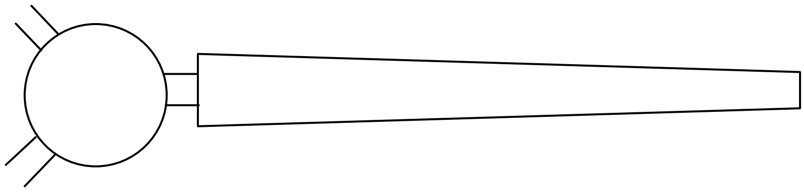
[Thomson Aarlborg]

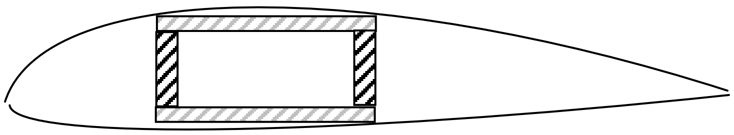
Main spar carries flapwise bending moments

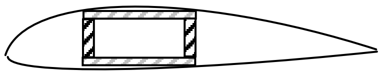
Leading and trailing edge carry edgewise bending

1.4 Scaling

Assume self-similar **planform** and **cross section** both of which scale with blade radius *R.*





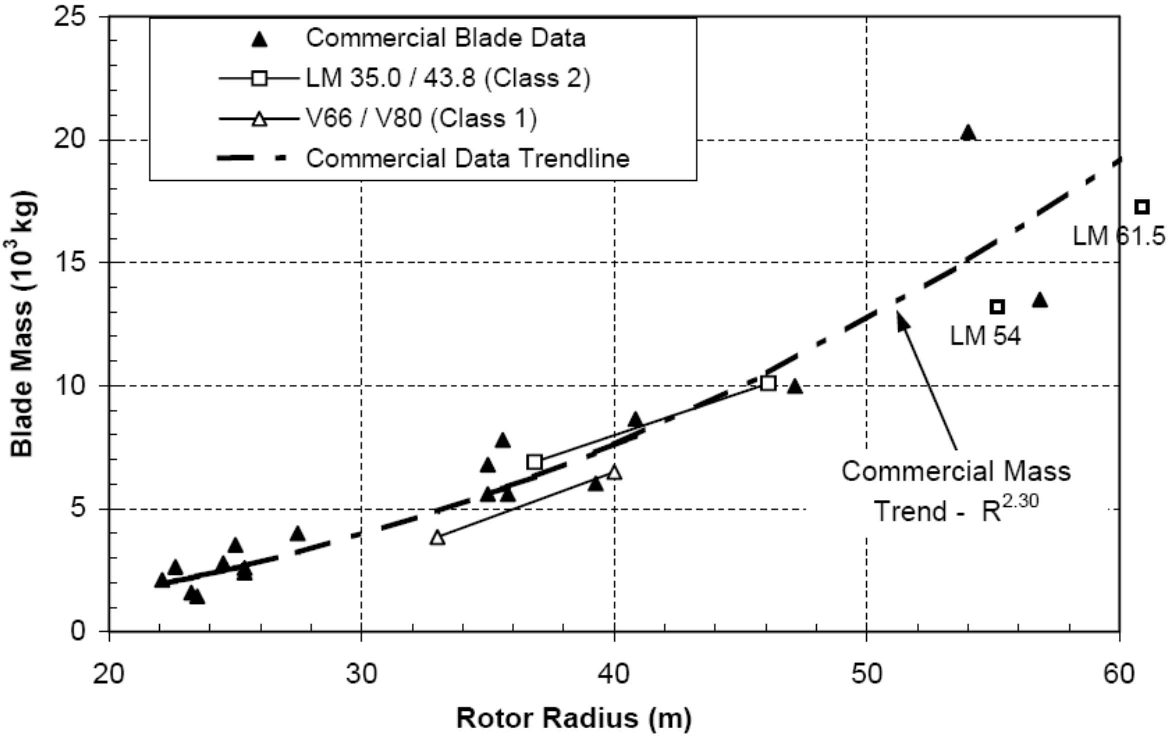


Parameter	Growth exponent n (R^n)
Tip speed ratio $\lambda = \omega R / V_0$	0
Angular velocity ω	-1
Power P	2
Weight $\int mgdr$	3
Second moment of area I	4
Aerodynamic loading intensity F_N	1
Total aerodynamic load $\int F_N dr$	2
Aerodynamic root bending moment $M_N \approx \int F_N rdr$	3
Aerodynamic stress $\sigma_{\max,aero} \approx \frac{M_N}{I_{TT}} d_o$	0
Tip flap-wise deflection	1
Self-weight root bending moment $M_{SW} \approx \int mgrdr$	4
Self weight stress $\sigma_{\max,sw} = \frac{M_{sw}}{I_{NN}} \frac{b_0}{2}$	1

- Weight reflects cost (but manufacturing and labour costs may not scale directly with weight)

- Changes in critical   with increase in size:
  – Self weight more critical for larger designs (include CFRP at tip)
  – Tip deflection scales with size - may be critical

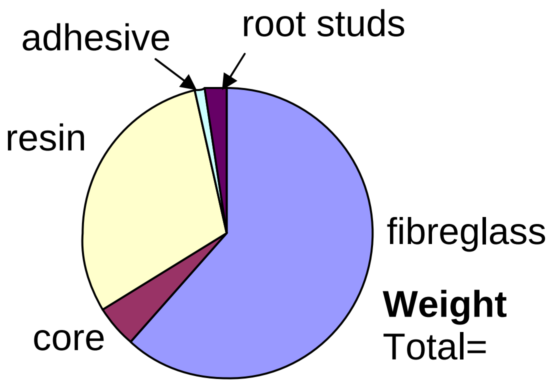
- Need to develop more efficient designs for large blades
  – Better use of materials
  – Cheaper manufacture



Glass fibre blades [Sandia 2004-0073, Owens Corning/Hartman 2006]

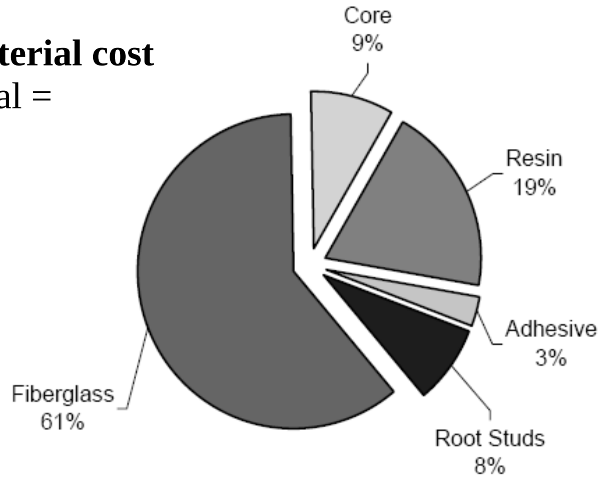
1.5 Blade Costs

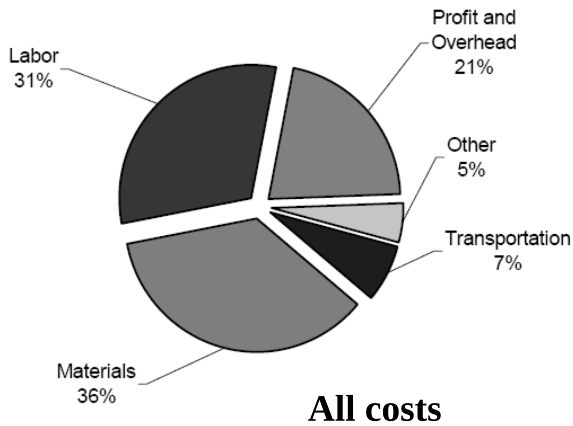
50m blade breakdown:
[Sandia 2003-1428]



Weight
Total=

Material cost
Total =



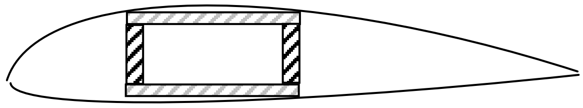


All costs
Total =

- Majority of weight taken by **fibre and resin**
- Weight proportions reflect typical fibre volume fractions (in the range 50-60%)
- Significant **labour and material costs**

Blade Costs 10-15% of installed capital cost (Sandia 2004-0073)

2 Materials Selection - Spar design



Concept

Blade length L	Beam depth $2d$ with spar caps width b, thickness t
Storm loading	Uniformly distributed load W

Example data: L = 35 m, W = 140 kN, b = 0.5m, d = 0.25m, δ = 3.5m

Constraints		
	STIFFNESS	Tip deflection
	SIZE	Maximum thickness $t = d/5$
Fixed	Depth d, width b	
Free	Thickness t	
Mass		**2nd Moment of Area**

2.1 Merit Index based on deflection constraint

Eliminate free variable thickness t

$$\delta = \frac{WL^3}{8EI}$$

$$m_\delta = 2tbL\rho = 2\frac{WL^3}{16Ebd^2\delta}bL\rho$$

Minimise mass, maximise

Minimise cost, maximise

	Aluminium	**CFRP**	**GFRP**	**Wood**
Cost C_m (£/kg)	4*	20	8	4
E (GPa)	70	140	45	20
σ_f (MPa)	100	800	100	20
ρ (kg/m^3)	2700	1500	1900	700
E/ρ $(\times 10^6)$	26	93	24	29
$E/\rho C_m$ $(\times 10^6)$	6.5	4.7	3.0	7.1
m_δ (kg)	4600	1300	5100	4200
m_σ (kg)	9300	640	6500	12000

*Aluminium costs underestimate manufacturing complexity?

2.2 Thickness constraint

$\delta = \dfrac{WL^3}{8EI} \Rightarrow E = \dfrac{WL^3}{8I\delta} = \dfrac{WL^3}{16tbd^2\delta}$ Include constraint on t=d/5:

$$E = \frac{5WL^3}{16\delta bd^3} = \frac{5 \times 140{,}000 \times 35^3}{16 \times 3.5 \times 0.5 \times 0.25^3} =$$

Sensitive to **length and depth**

Longer blades may be impractical for wood and GFRP - include

2.3 Multiple constraints

Include stiffness **and** fatigue limit $\sigma_f = \dfrac{Md}{I} = \dfrac{WLd}{2I} = \dfrac{WLd}{4tbd^2}$

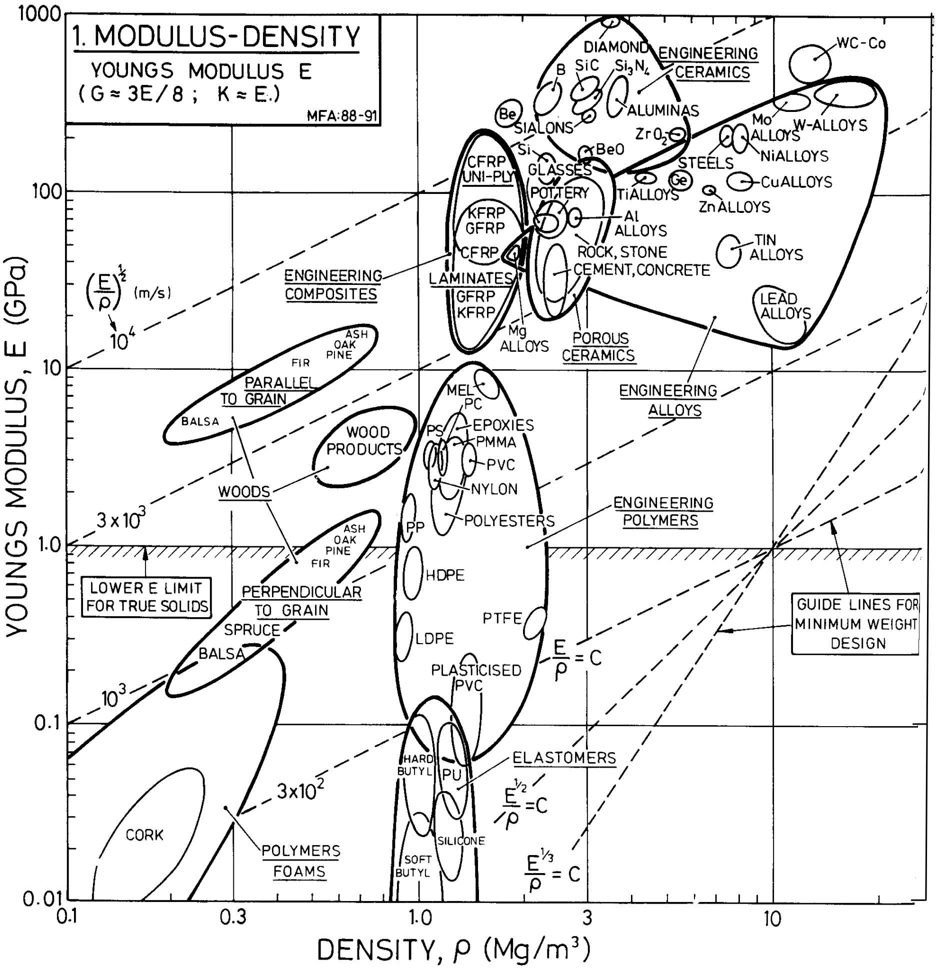
Use **tabular** approach

$t = \dfrac{WL}{4bd\sigma_f}$ and therefore $m_\sigma = 2tbL\rho = \dfrac{\rho WL^2}{2\sigma_f d} =$

Choose material which meets both constraints at minimum **mass**

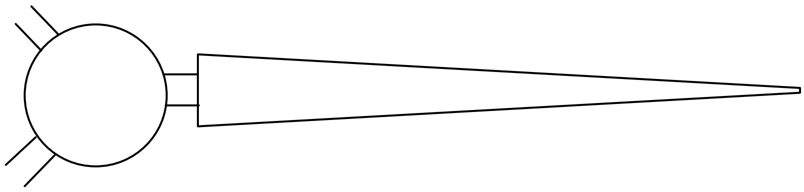
Cost is critical - need to model this accurately and include manufacturing costs

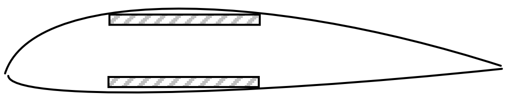
between blade cost and weight (lower weight reduces other costs)


1. MODULUS-DENSITY
YOUNGS MODULUS E
(G ≈ 3E/8 ; K ≈ E.)
MFA:88-91
YOUNGS MODULUS, E (GPa)
DENSITY, ρ (Mg/m³)
ENGINEERING CERAMICS
DIAMOND
WC-Co
ALUMINAS
SIALONS
W-ALLOYS
Mo ALLOYS
NiALLOYS
STEELS
CuALLOYS
TiALLOYS
ZnALLOYS
Al ALLOYS
TIN ALLOYS
LEAD ALLOYS
ENGINEERING ALLOYS
CFRP UNI-PLY
KFRP GFRP
LAMINATES
GFRP KFRP
ENGINEERING COMPOSITES
GLASSES
POTTERY
ROCK, STONE
CEMENT, CONCRETE
POROUS CERAMICS
Mg ALLOYS
PARALLEL TO GRAIN
PERPENDICULAR TO GRAIN
WOODS
WOOD PRODUCTS
BALSA
SPRUCE
ENGINEERING POLYMERS
EPOXIES
PMMA
PVC
NYLON
POLYESTERS
HDPE
LDPE
PTFE
PLASTICISED PVC
ELASTOMERS
HARD BUTYL
PU
SILICONE
SOFT BUTYL
POLYMERS FOAMS
CORK
LOWER E LIMIT FOR TRUE SOLIDS
GUIDE LINES FOR MINIMUM WEIGHT DESIGN
E/ρ = C
E^½/ρ = C
E^⅓/ρ = C
(E/ρ)^½ (m/s)

3 Shape Optimisation

- Can use ad hoc method to put material where it is needed.
- Analysis for spar design but also relevant for tower design.





Concept

Assume a triangular plan form and depth profile $d(x)$

Note that the spar breadth b does not need to be the same as the blade width.

Consider a storm loading situation with the turbine not rotating. A total wind load W is distributed as a uniform pressure over the blade.

How should we optimise the spar by changing the spar thickness t and breadth b as a function of position ?

Tapering options

We will assume that the spar thickness t is much less than the depth $2d$, so that the relevant geometric change is the spar

Consider three options for spar area as a function of position x from tip:

Constant area (e.g. constant spar width and thickness – not practical at tip?) $A = A_0$

Linear tapered area (e.g. linearly tapering width, constant thickness) $A = A_0 \dfrac{x}{L}$

Quadratical tapered area (linearly taper width and thickness) $A = A_0 \left(\dfrac{x}{L}\right)^2$

In general with n = 0, 1 and 2 for constant, linear and quadratic tapers.

A_0 is a free variable chosen to match the materials and constraints.

Structural analysis

$$\text{Mass } m = \rho \int_0^L A dx = \frac{\rho A_0}{L^n} \int_0^L x^n dx = \frac{\rho A_0}{n+1} \frac{L^{n+1}}{L^n} = \frac{\rho A_0 L}{n+1}$$

Bending moment

$$M(x) = \frac{WL}{3}\left(\frac{x}{L}\right)^3$$

2nd moment of area

$$I(x) = 2\frac{A}{2}d^2 = Ad^2 = A_0\left(\frac{x}{L}\right)^n d_0^2\left(\frac{x}{L}\right)^2 = A_0 d_0^2\left(\frac{x}{L}\right)^{n+2}$$

Stress

$$\sigma(x) = \frac{Md}{I} = \frac{WL}{3}\left(\frac{x}{L}\right)^3 \frac{d}{Ad^2} = \frac{WL}{3A_0 d_0}\left(\frac{x}{L}\right)^3\left(\frac{x}{L}\right)^{-n}\left(\frac{x}{L}\right)^{-1} = \frac{WL}{3A_0 d_0}\left(\frac{x}{L}\right)^{2-n}$$

Strength constraint:

Note that, for $n =$, the stress is constant in the spar along the length of the blade.

For $n = 0$ or 1 the stress is a maximum at the blade root ($x = L$).

Putting $\sigma_{\max} = \sigma_f$ and eliminating the free variable A_0, the mass m_σ can be obtained:

$$\sigma_f = \frac{WL}{3A_0 d_0} \Rightarrow A_0 = \frac{WL}{3d_0\sigma_f}$$

Hence $m_\sigma = \dfrac{\rho A_0 L}{n+1} = \dfrac{\rho W L^2}{3d_0\sigma_f(n+1)}$

Minimum mass is obtained with $n =$ (note that this is the constant stress case).

Deflection:

$$\kappa = \frac{d^2 y}{dx^2} = \frac{M}{EI}$$: integrate twice to find tip deflection

$$\frac{d^2 y}{dx^2} = \frac{M}{EI} = \frac{\frac{WL}{3}\left(\frac{x}{L}\right)^3}{EA_0 d_0^2 \left(\frac{x}{L}\right)^{n+2}} = \frac{WL}{3EA_0 d_0^2}\left(\frac{x}{L}\right)^{1-n} = C\left(\frac{x}{L}\right)^{1-n} \quad \text{with } C = \frac{WL}{3EA_0 d_0^2}$$

For $n = 0$ $\quad \frac{d^2 y}{dx^2} = C\left(\frac{x}{L}\right)$

integrating twice and putting in appropriate boundary conditions at $x = L$:

$$\frac{dy}{dx} = 0 \ , y = 0$$

therefore $\frac{dy}{dx} = \frac{C}{L}\left(\frac{x^2}{2} - \frac{L^2}{2}\right)$ and $y = \frac{C}{2L}\left(\frac{x^3}{3} - L^2 x + \frac{2}{3}L^3\right)$

so at $x = 0$ the tip deflection $\quad \delta = \frac{CL^2}{3} = \frac{WL^3}{9EA_0 d_0^2}$

For $n = 1$ $\quad \frac{d^2 y}{dx^2} = C$

therefore $\frac{dy}{dx} = C(x - L)$ and $y = C\left(\frac{x^2}{2} - Lx + \frac{L^2}{2}\right)$

and the tip deflection $\quad \delta = \frac{CL^2}{2} = \frac{WL^3}{6EA_0 d_0^2}$

For $n = 2$ $\quad \frac{d^2 y}{dx^2} = C\left(\frac{x}{L}\right)^{-1}$

therefore $\frac{dy}{dx} = CL(\ln x - \ln L)$ and $y = CL(x\ln x - x - x\ln L + L)$

so at $x = 0$ the tip deflection $\quad \delta = CL^2 = \frac{WL^3}{3EA_0 d_0^2}$

Stiffness constraint

The tip deflection constraint gives a constraint on mass, again by eliminating A_0

for n = 0 $\quad \delta = \dfrac{WL^3}{9EA_0 d_0^2} \Rightarrow A_0 = \dfrac{WL^3}{9Ed_0^2\delta}$ and $m_\delta = \dfrac{\rho A_0 L}{1} \Rightarrow m_\delta = \dfrac{\rho WL^4}{9Ed_0^2\delta}$

for n = 1 $\quad \delta = \dfrac{WL^3}{6EA_0 d_0^2} \Rightarrow A_0 = \dfrac{WL^3}{6Ed_0^2\delta}$ and $m_\delta = \dfrac{\rho A_0 L}{2} \Rightarrow m_\delta = \dfrac{\rho WL^4}{12Ed_0^2\delta}$

for n = 2 $\quad \delta = \dfrac{WL^3}{3EA_0 d_0^2} \Rightarrow A_0 = \dfrac{WL^3}{3Ed_0^2\delta}$ and $m_\delta = \dfrac{\rho A_0 L}{3} \Rightarrow m_\delta = \dfrac{\rho WL^4}{9Ed_0^2\delta}$

Summary of results

Shape parameter	n	0	1	2	
Strength constraint	m_σ		1/6	1/9	$\times \dfrac{\rho WL^2}{d_0 \sigma_f}$
Stiffness constraint	m_δ		1/12	1/9	$\times \dfrac{\rho WL^4}{Ed_0^2\delta}$
Mass ratio	$\dfrac{m_\delta}{m_\sigma}$		1/2	1	$\times \dfrac{\sigma_f L^2}{Ed_0\delta}$

Choose n which minimises the mass.

For strength, this corresponds to n = , for stiffness the best choice is n =

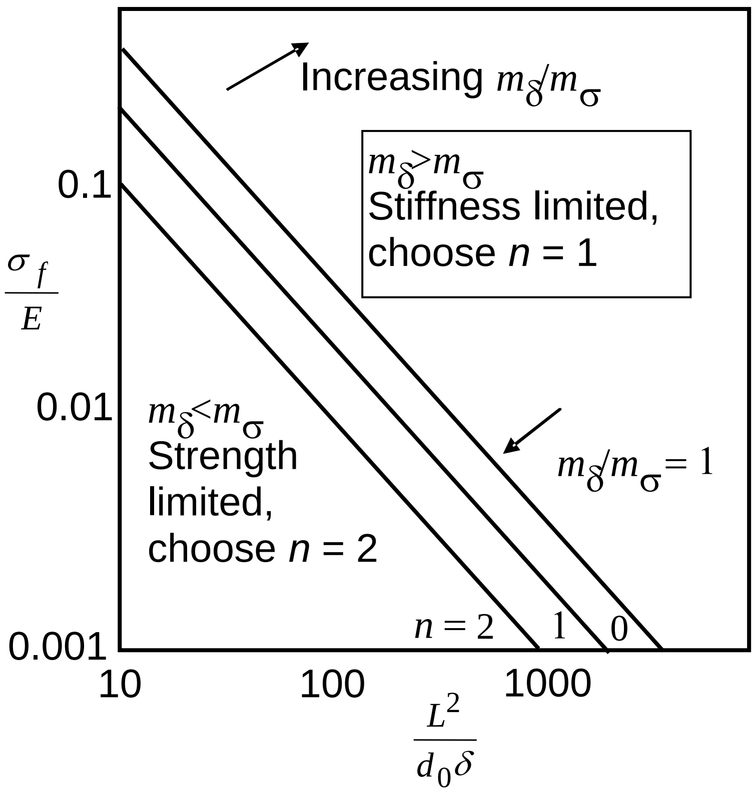
For the multiple constraint problem, which constraint is critical depends on the ratio of the masses required to meet each of the constraints and hence on $\dfrac{\sigma_f L^2}{Ed_0\delta}$

For $\frac{\sigma_f L^2}{E d_0 \delta} > 3$, $\frac{m_\delta}{m_\sigma} > 1$ for n = 0, 1 & 2 so STIFFNESS is critical – choose $n = 1$

For $\frac{\sigma_f L^2}{E d_0 \delta} < 1$, $\frac{m_\delta}{m_\sigma} < 1$ for n = 0, 1 & 2 so STRENGTH is critical - choose $n = 2$

For $1 < \frac{\sigma_f L^2}{E d_0 \delta} < 3$ both constraints may be active

e.g. for the example blade using Aluminium $\frac{\sigma_f L^2}{E d_0 \delta} = \frac{100 \times 35^2}{70000 \times 0.25 \times 3.5} =$



4 Composite Blade Design

- specific stiffness and strength
- shapes viable
- resistance
- surface
- maintenance

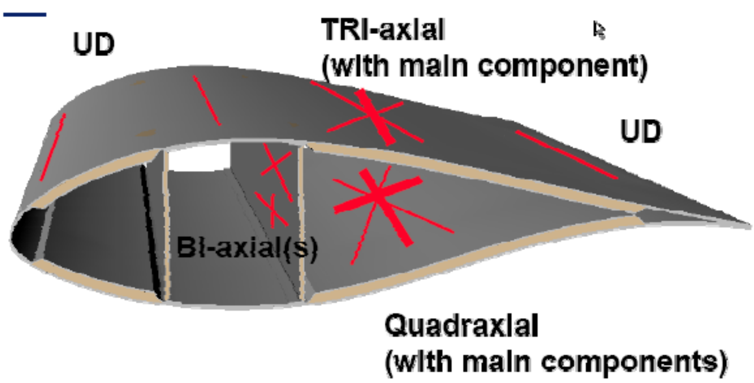
4.1 Materials

Fibres
– unidirectional material
– multidirectional laminates
– random mat
– carbon, glass, wood

Matrix:
– infusion
– pre-impregnation
– e.g. epoxy, polyester

Composites
Glass fibre reinforced plastic – GFRP
Carbon fibre reinforced plastic –CFRP
Wood laminate, e.g. birch, Douglas fir
Hybrids (zebrawood = GFRP + CFRP + wood)
CFRP and wood are well matched in failure
GFRP and CFRP are not well matched

Sandwich panels



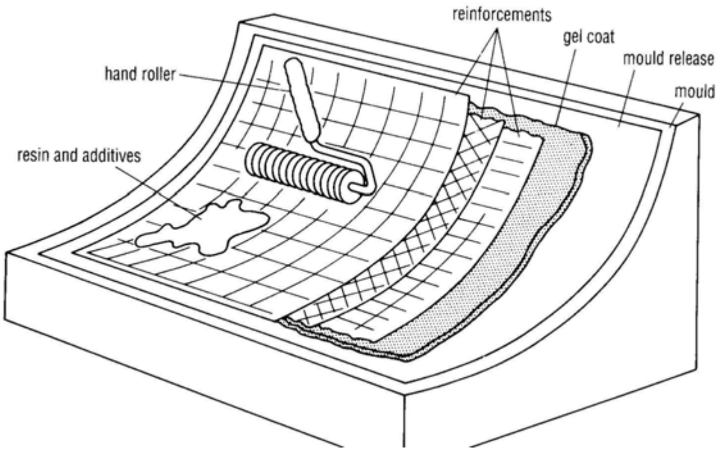
Fibre orientations:
Owens Corning
2006/DeMint

Align fibres with
loading direction

4.2 Processes

Wet hand lay-up

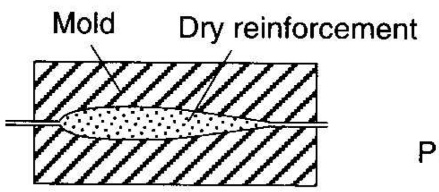
Layup on mould
Dry or pre-preg material
Vacuum bag to consolidate
Curing - room temperature, radiant heaters



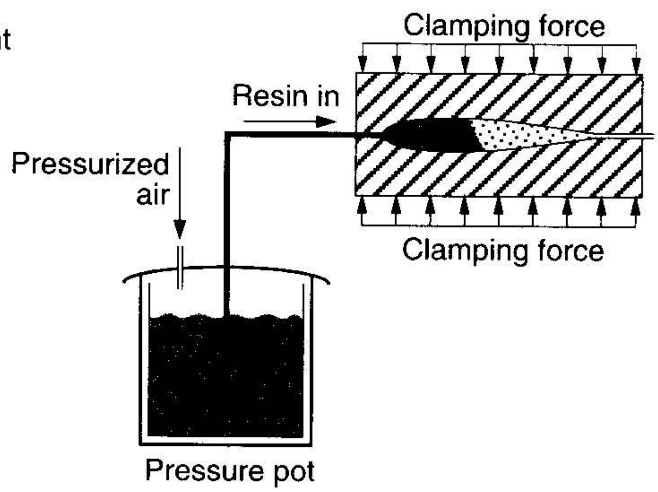
[Mayer, 1992]

Resin transfer moulding

Closed mould process
Charge mould with dry fabric
Inject thermoset resin at relatively low pressure



[Astrom, 1997]

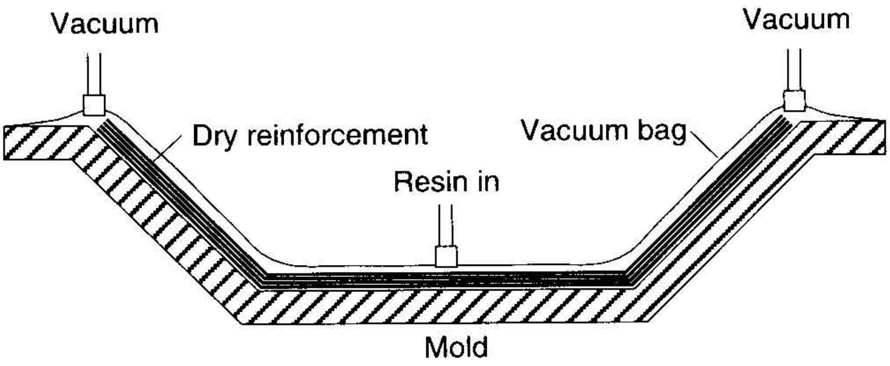


Vacuum injection moulding

Open or closed mould
Use vacuum bag with open mould
Vacuum forces resin through reinforcement

LM Glasfiber

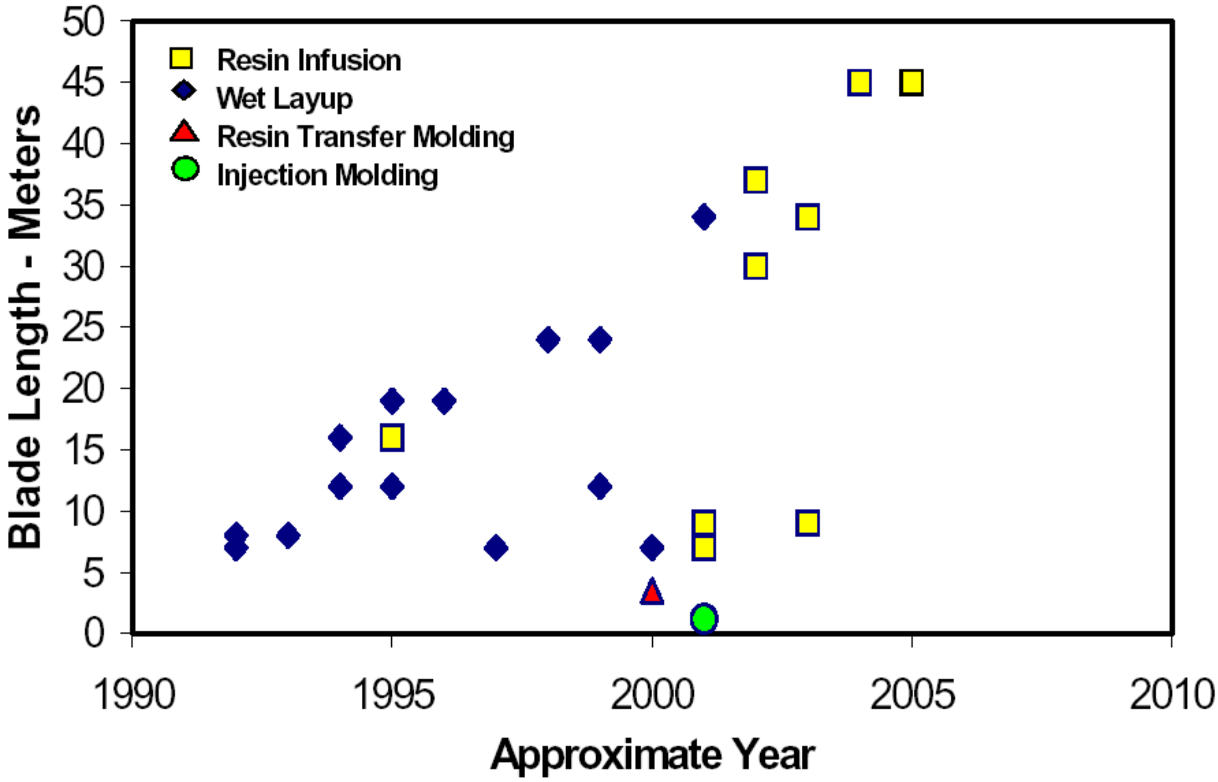
Astrom, 1997



LM Glasfiber

polyworx.com

Blade production routes

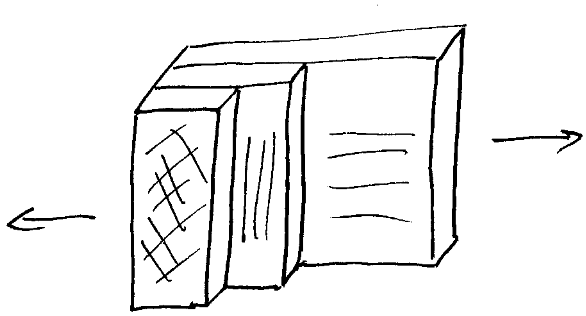


[Owens Corning 2006/DeMint et al]

4.3 Stiffness

Overall laminate stiffness made up by contributions from each ply

Carpet plot [Bader] gives Young's modulus as a function of percentage of plies in plies (assume only these directions)



e.g. Unidirectional material (100% : 0°): E =

Stiffest, but suffers from cracks along fibres.

Include 'off-axis material'

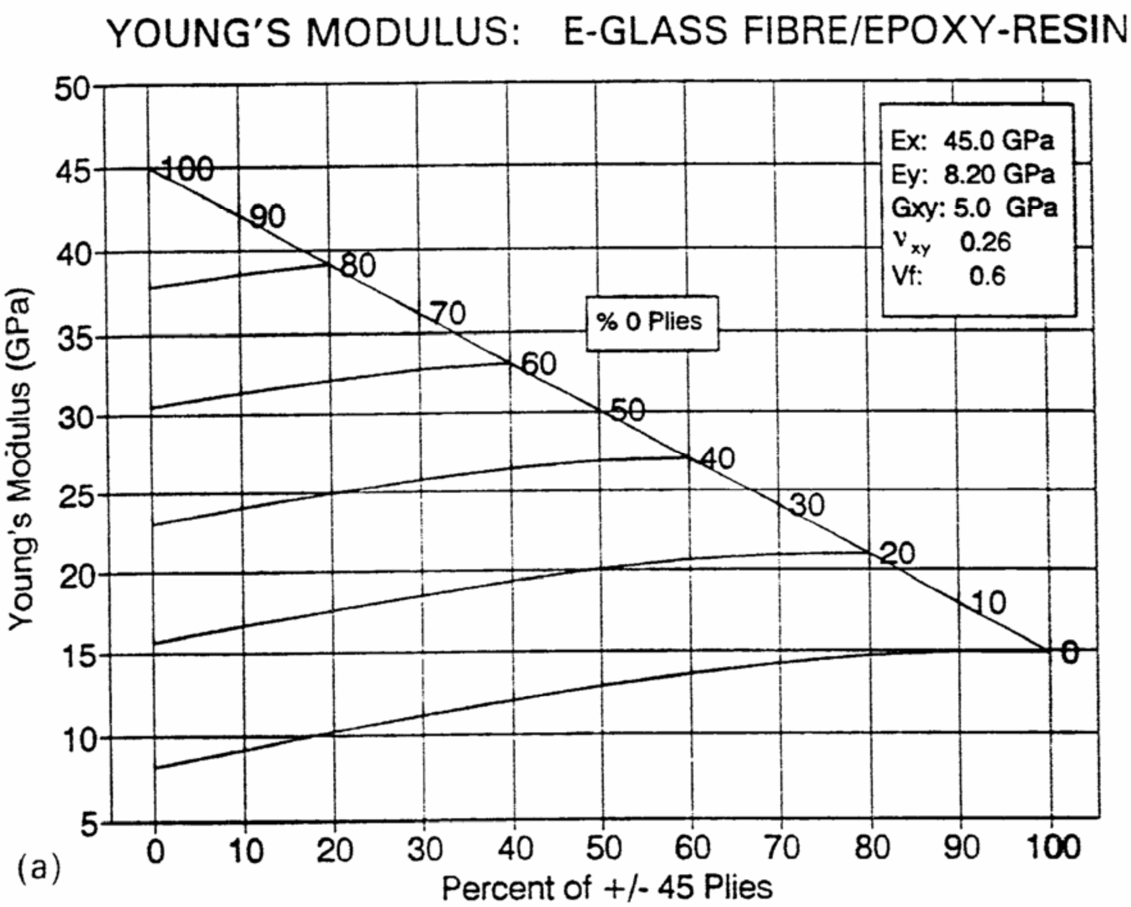
e.g. (50% 0°, 50% ±45°): E =

Same ply, now in transverse direction

(50% ±45°, 50% 90°): E =

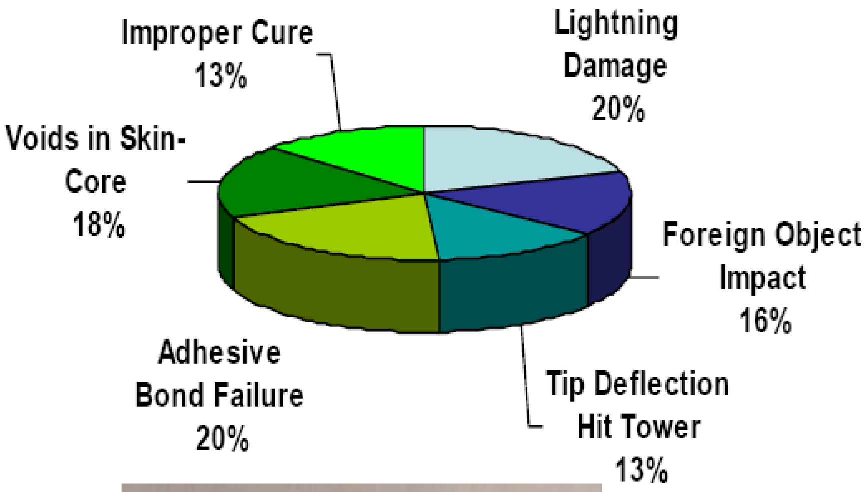
All three ply directions

(40% 0°, 40% ±45°, 20% 90°,): E =



5 Design against failure

Blade field failures
[Owens Corning/Hartman 2006)



Study of 45 blades:
NA Windpower P34 V1 N12
Jan 2005

[SNL/Corning 2006]

Testing

LM Glasfiber test bed.

5.1 Static failure

Unidirectional laminate

Use failure stress or strain, which depends on direction of loading

	CFRP	**GFRP**
σ^+ (MPa)	1500	1100
σ^- (MPa)	1200	600
e^+ (%)	1.1	2.8
e^- (%)	0.9	1.5

Failure for loading along fibre direction of typical unidirectional laminate

Multidirectional laminate

Can calculate individual ply stresses and compare failure modes
Easier, though less accurate, to use a laminate failure strain "**allowable**".
The failure strain corresponds to failure of the ply with the smallest strain to failure.

	CFRP	**GFRP**
e^+ (%)	0.4	0.3
e^- (%)	0.5	0.7

Multidirectional laminates

e.g. Strength of unidirectional GFRP in tension = 1100 MPa
Strength of (50% 0°, 50% $\pm$45°) GFRP laminate = $E\, e^+$ =

Knock-down factors

Need to include many knock-down factors (e.g. up to factor of

- manufacturing
- ply drops
- holes
- joints

5.2 Fatigue failure

S-N curve for unnotched strength

Increasing applied stress range S decreases lifetime (note whether **range** or **amplitude** is quoted)

$N = \left(\frac{S}{S_0}\right)^{-M}$ N – number of cycles to failure, M, S_0 – material constants

Can take the tensile strength σ_{ts} as the stress amplitude S_0 or $S_0/2$ (for S = amplitude and range, respectively) for one cycle from the S-N data, since failure on the first cycle corresponds to static failure.

Effect of fluctuating stress levels - Miner's rule

The component fails when the proportion of the life time used by each block adds up to one

$$\text{i.e. } \sum_i \frac{N_i}{N_{fi}} = 1 \text{ (Data Book)} \qquad (10)$$

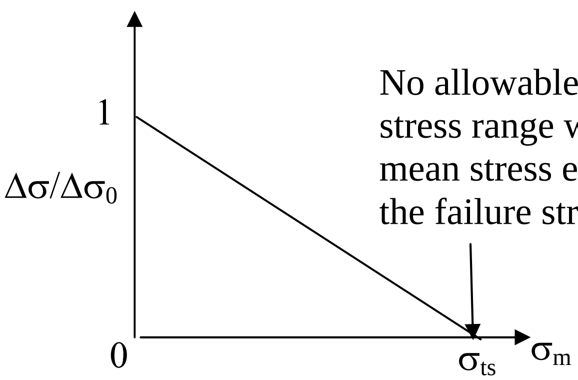
N_{fi} is the number of cycles that you would need for failure with the stress range and mean stress of the ith block.

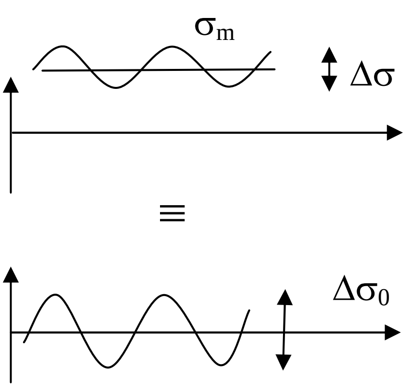
Effect of mean stress – Goodman's rule

For the same fatigue life, the stress range $\Delta\sigma$ operating with a mean stress σ_m is equivalent to a stress range $\Delta\sigma_0$ and zero mean stress, according to the relationship

$$\Delta\sigma = \Delta\sigma_0\left(1 - \frac{\sigma_m}{\sigma_{ts}}\right) \text{ (Data Book)} \qquad (11)$$

where σ_{ts} is the tensile strength (i.e the mean stress giving no fatigue life)



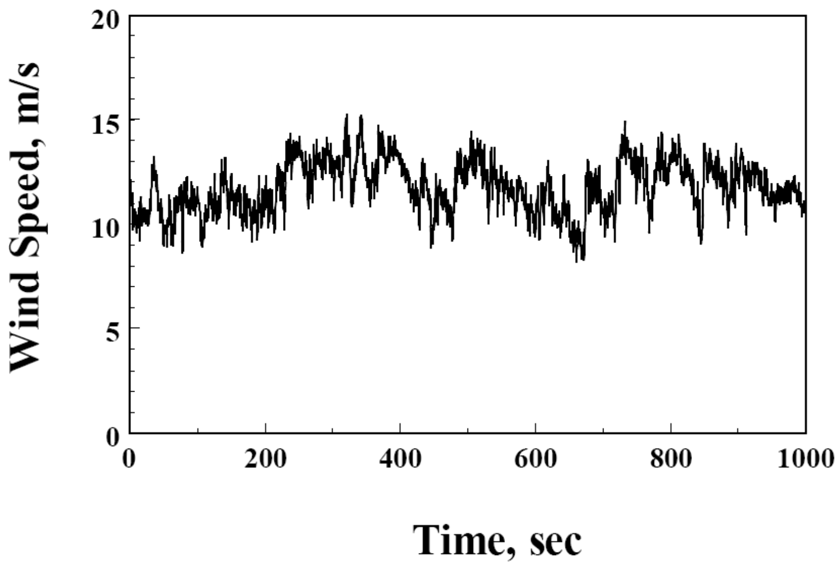


Load cycle assessment

Need statistics to model loading and failure with random wind loading

e.g. WISPER spectrum widely used in Europe (Wind SPEctrum Reference)

Convert wind and self-weight load to stress cycle via structural model

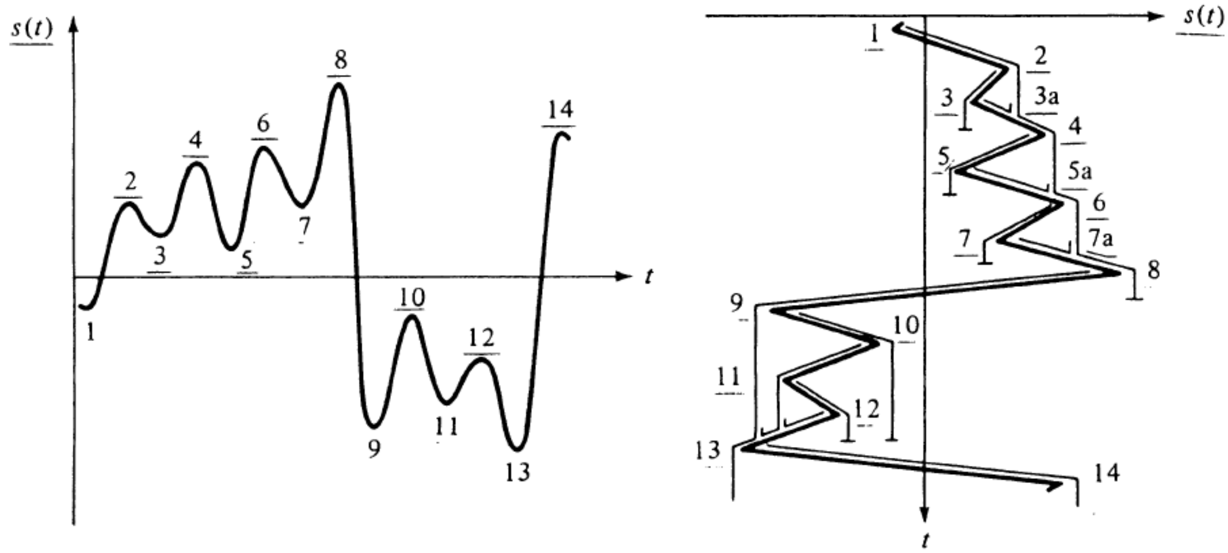


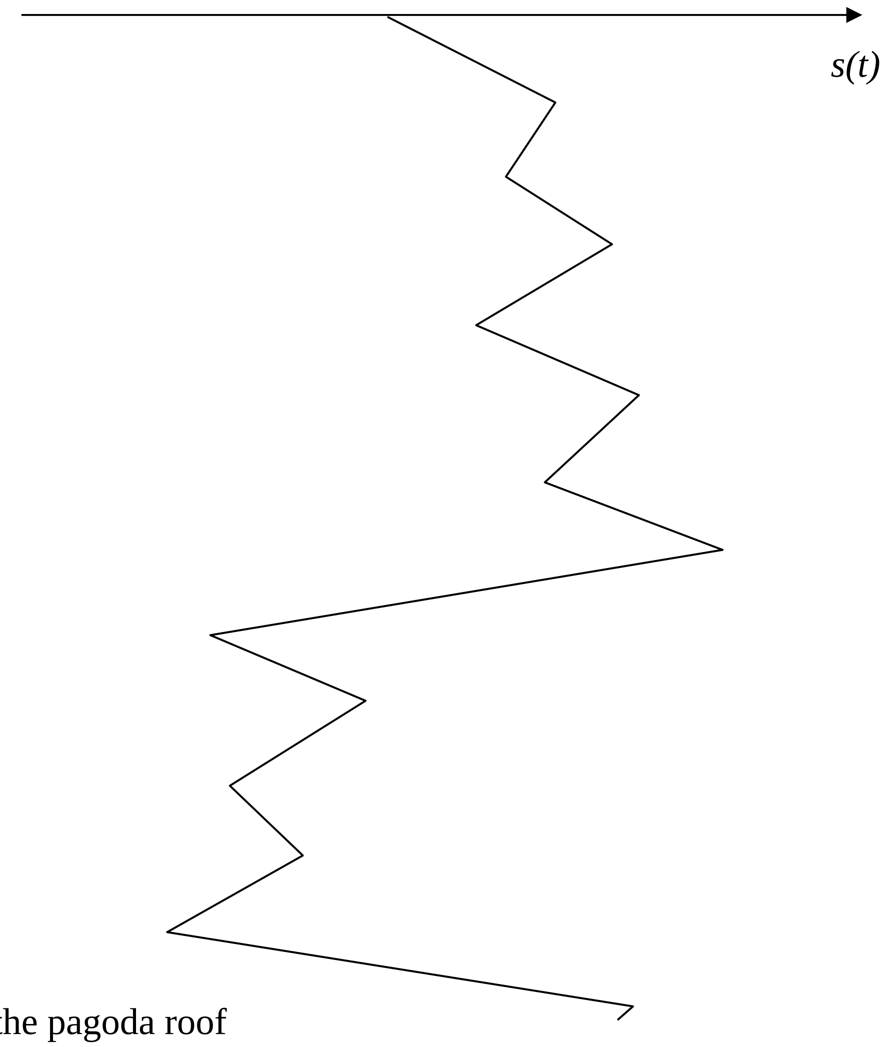
Typical wind speed data, Texas [Sutherland and Veers 1995]

Rainflow counting

Need to identify cycles of load within random signal

[Wirshing and Shehata/DNV Risoe]





- Imagine rain **flowing down** the pagoda roof

- Rainflow **initiates** at each **peak** and **trough** and drips down

- When a flow-path **started** at a **trough** comes to the **tip** of the roof, the **flow stops** if the **opposite trough** is **more negative** than that at the **start** of the **path** under **consideration** [(1-8], [9-10]. A path started at a peak is stopped by a peak which is more positive than the peak at the start of the path [2-3], [4-5].

- If **rain** flowing down a roof **intercepts** a **previous path**, the **present path** is **stopped** [3-3a], [5-5a]

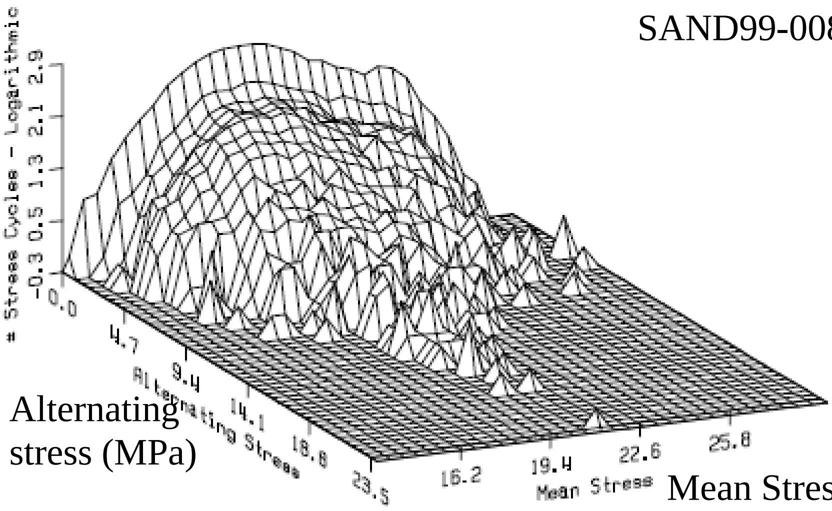
- A new path is not started until the path under consideration is stopped

- **Half cycles of loading** are projected distances on the stress axis [1-8], [3-3a], [5-5a]. This is the data which is needed to construct the load history.

Each peak-originated half-cycle is followed by a trough originated half-cycle of the same range for (i) long stress histories (ii) short stress histories if the first and last peaks have same magnitude. In this case calculate peaks and assume trough half cycles are the same.

Typical load spectra

NPS 100 kW Turbine
SAND99-0089



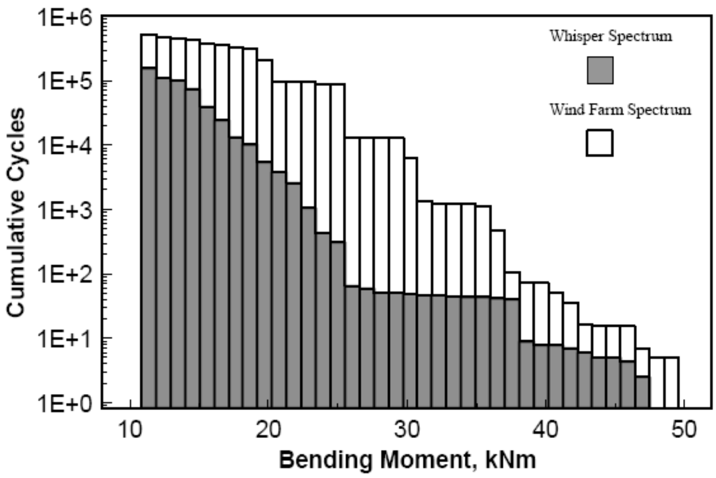


Figure 20. Cumulative 2-Month Reference Alternating Load Spectrum.

SAN99-0089 Wind farm spectrum on Micon 65kW turbine

Numerical characterisation of loading

Divide spectrum into bins (minimum 50): each bin has a different Nfi

Alternating stress amplitude (MPa)	Mean stress (MPa): 0-20	20-40	40-60
0-50			
50-100			
100-150			

Analytical characterisation of loading

Various forms available giving probability of stress amplitude S

e.g. exponential distribution of probability density function $\phi(S) = \frac{1}{\bar{S}} \exp\left(\frac{-S}{\bar{S}}\right)$

$\bar{S}$ is the mean of the stress amplitudes

No effect of mean stress on fatigue life included in characterisation

Additional parameter is the rate of loading (number of load cycles per unit time) or total number of cycles

Fatigue life - S-N data

Need to include variability in tests and material

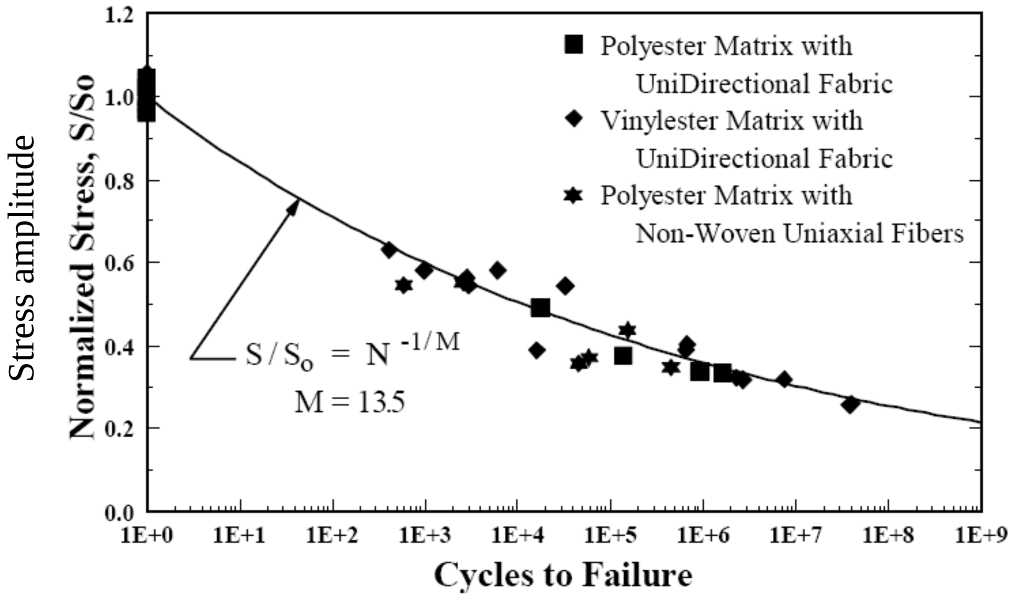
Can fit data by relationship

$$N = \left(\frac{S}{S_0}\right)^{-M}$$

	S_0 (MPa)	M	Fatigue Limit (MPa)
Glass fibre	300	10	50
CFRP	1500	40	800
Wood	50	20	20

Typical fatigue data (varies significantly within each material group)

Here S_0 is the stress amplitude



[Sandia 99-0089]

Fatigue failure prediction

Numerical

Illustrated by example, with M = 10, $S_0 = \sigma_{ts}$ = 300 MPa

Mean Stress (MPa)

Alternating stress amplitude (MPa)	0-5	5-10	10-15
0-5			
5-15	*n*		
15-25			

Number of cycles in time block *T*

For each bin

Goodman's rule: include effect of mean stress on stress amplitude

$$\frac{\Delta\sigma}{2} = \frac{\Delta\sigma_0}{2}\left(1 - \frac{\sigma_m}{\sigma_{ts}}\right) \Rightarrow \frac{\Delta\sigma_0}{2} = \frac{\Delta\sigma}{2}\left(\frac{\sigma_{ts}}{\sigma_{ts} - \sigma_m}\right)$$

S-N data: find life time N_{fi} from this load

$$N_{fi} = \left(\frac{S}{S_0}\right)^{-M} = \left(\frac{10.08}{300}\right)^{-10} = 5\times 10^{14}$$

Miner's rule: proportion of lifetime by this block of time =

Sum the effects of all the bins

Sum the proportion of the lifetime used up by all the bins - say α

Then the number of repeat blocks = $1/\alpha$ and the lifetime of the component =

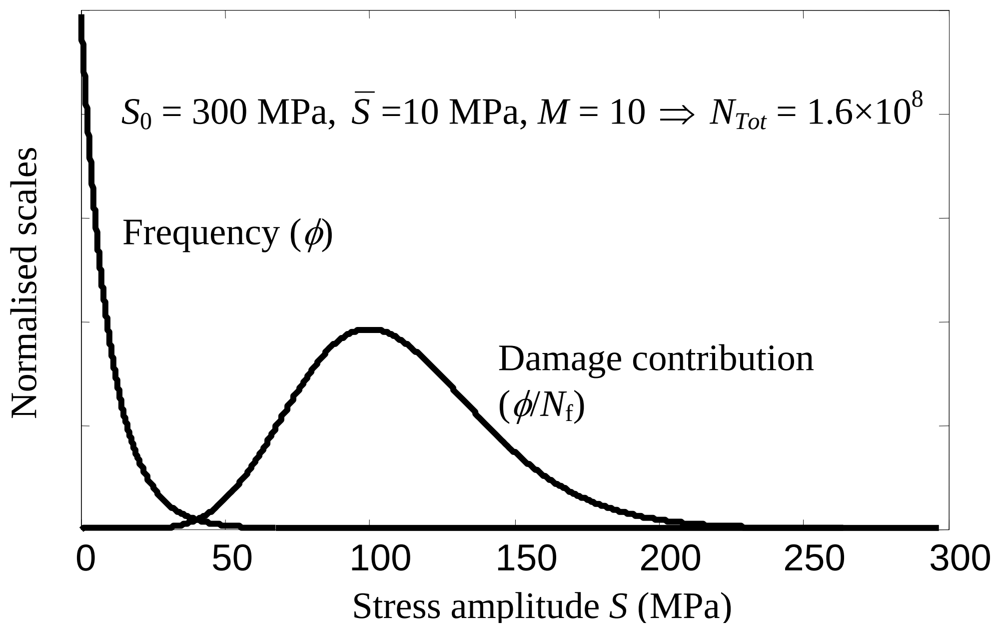
Analytical

Failure when the life used up by contributions at different stress amplitudes sums to one using Miner's rule, where N_{tot} is the total number of cycles

$N_{Tot}\phi(S)dS$ is the number of cycles over the stress interval

$$1 = \int_0^\infty \frac{N_{Tot}\phi(S)}{N_f(S)} dS = \frac{N_{Tot}}{S_0^M \bar{S}} \int_0^\infty S^M \exp\left(-S/\bar{S}\right) dS = N_{Tot}\left(\frac{\bar{S}}{S_0}\right)^M \Gamma(M+1)$$

$\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt$ is the Gamma function, equal to (z-1)! for positive integers.



Effect of **extreme loads dominates**

– need to get better estimate of loading

– very sensitive to power exponent M in damage law and to $\bar{S}/S_0$.