# Elements of structural and fatigue analysis

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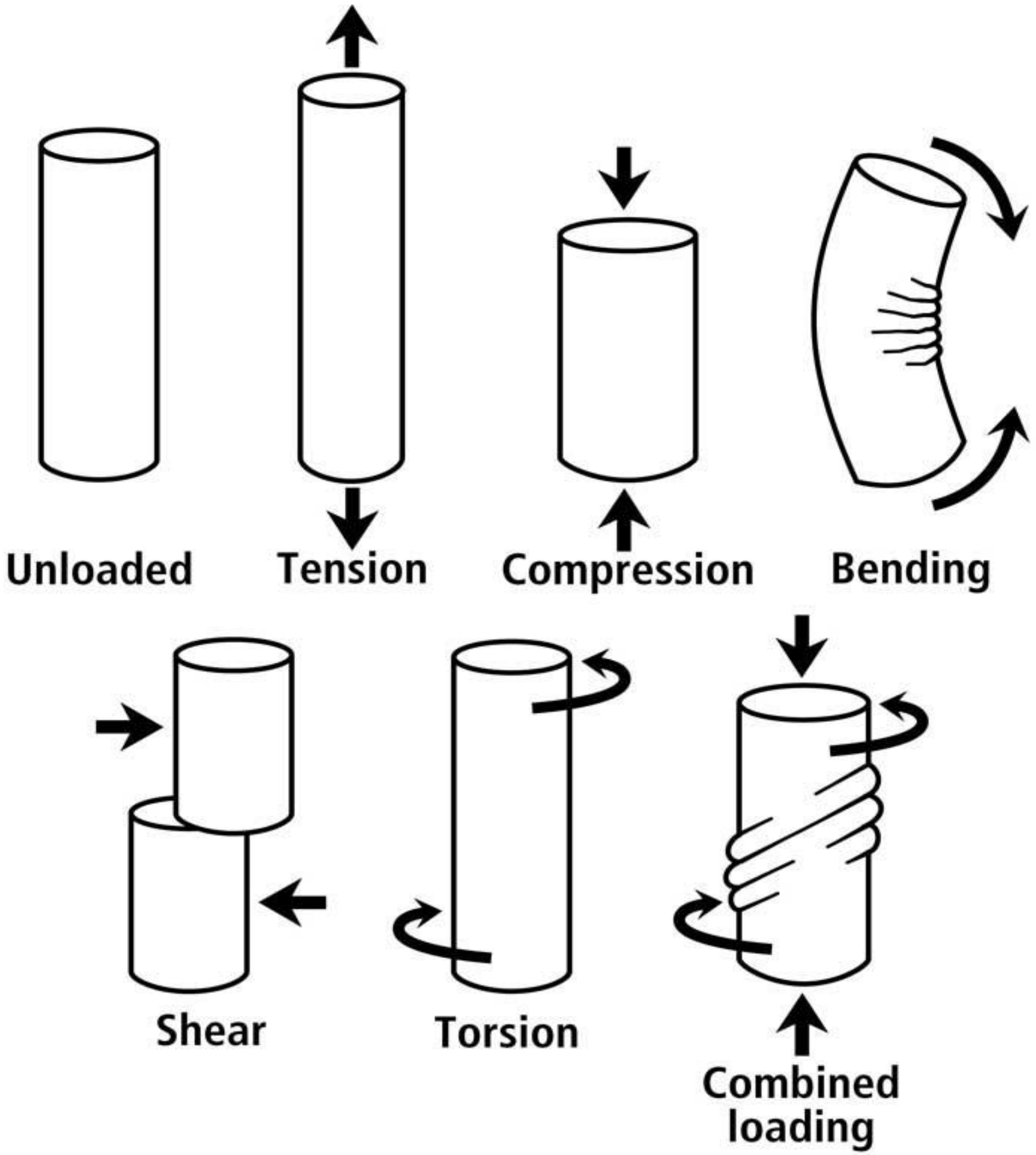
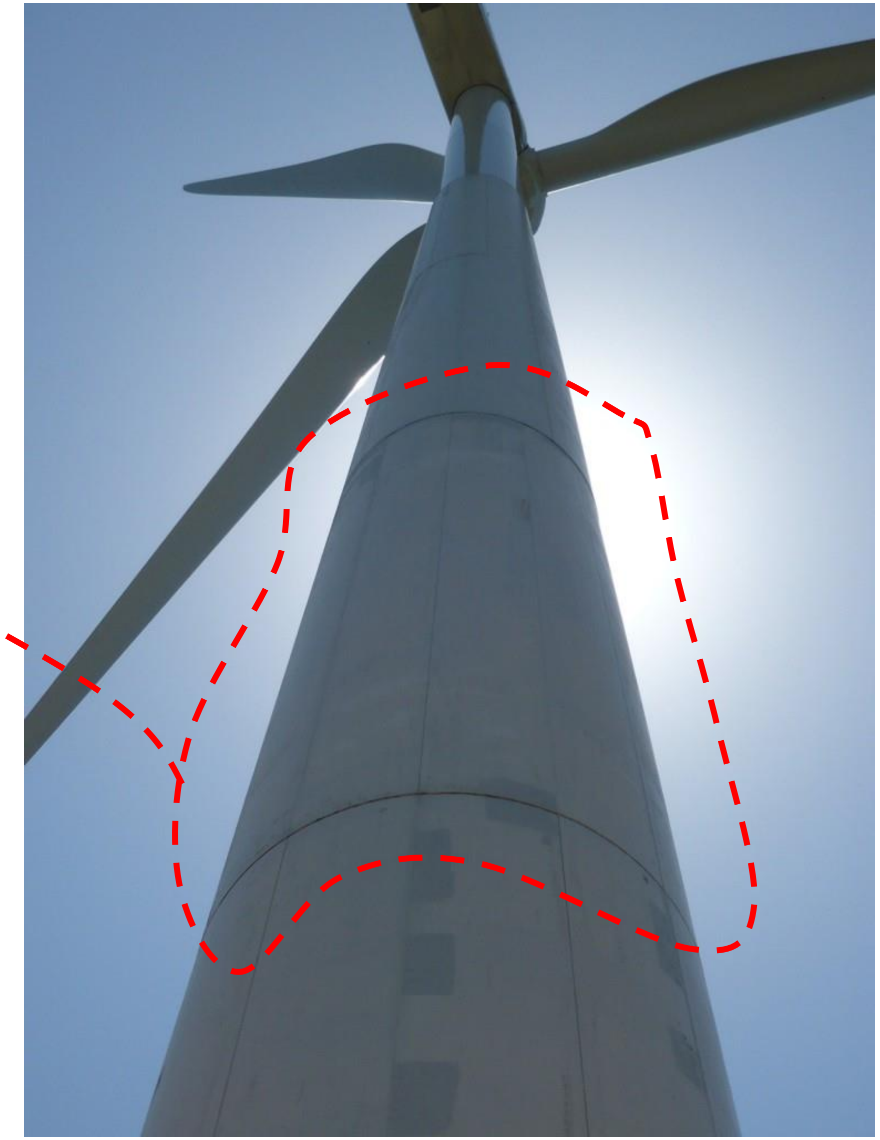
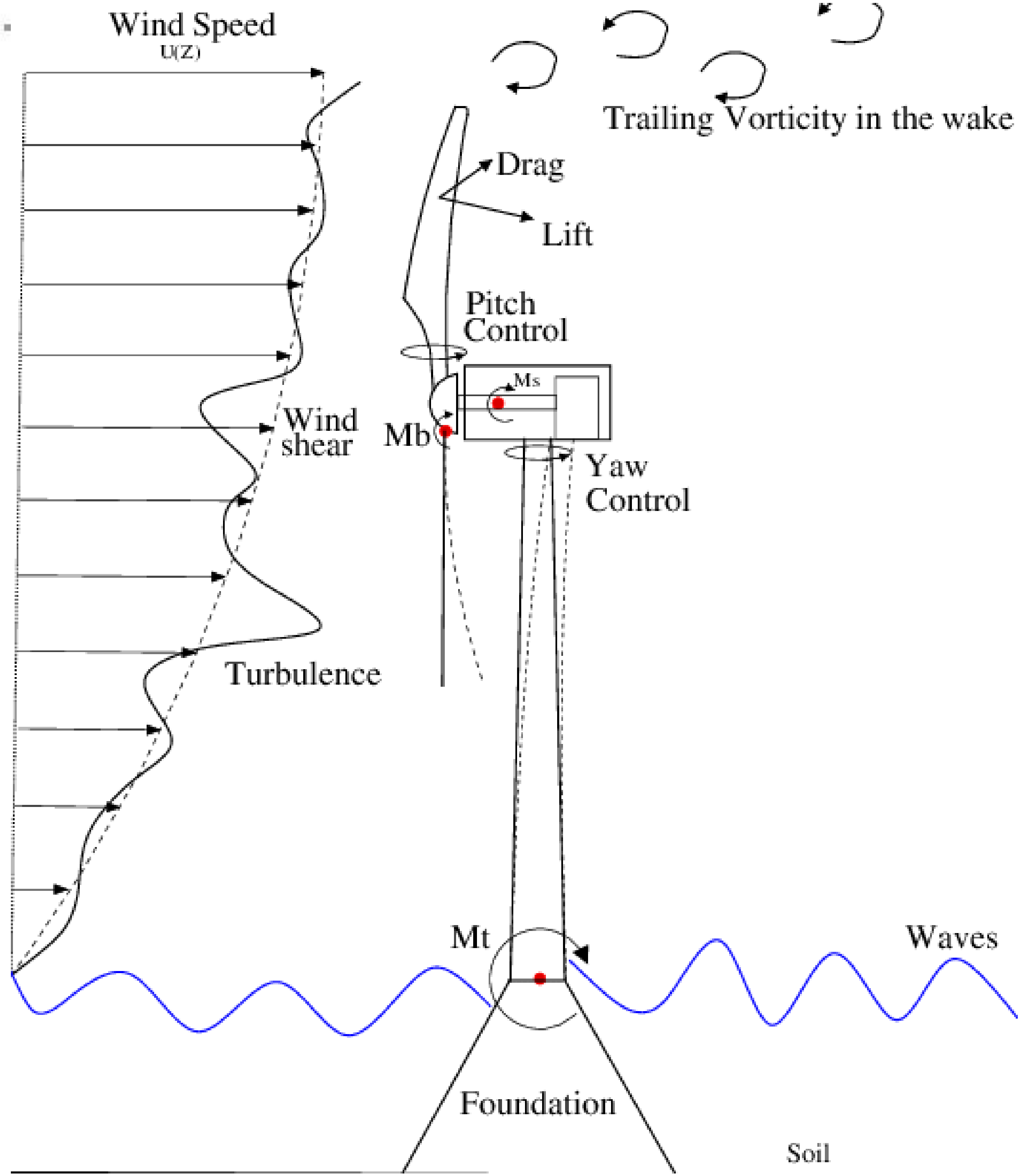
# Overview

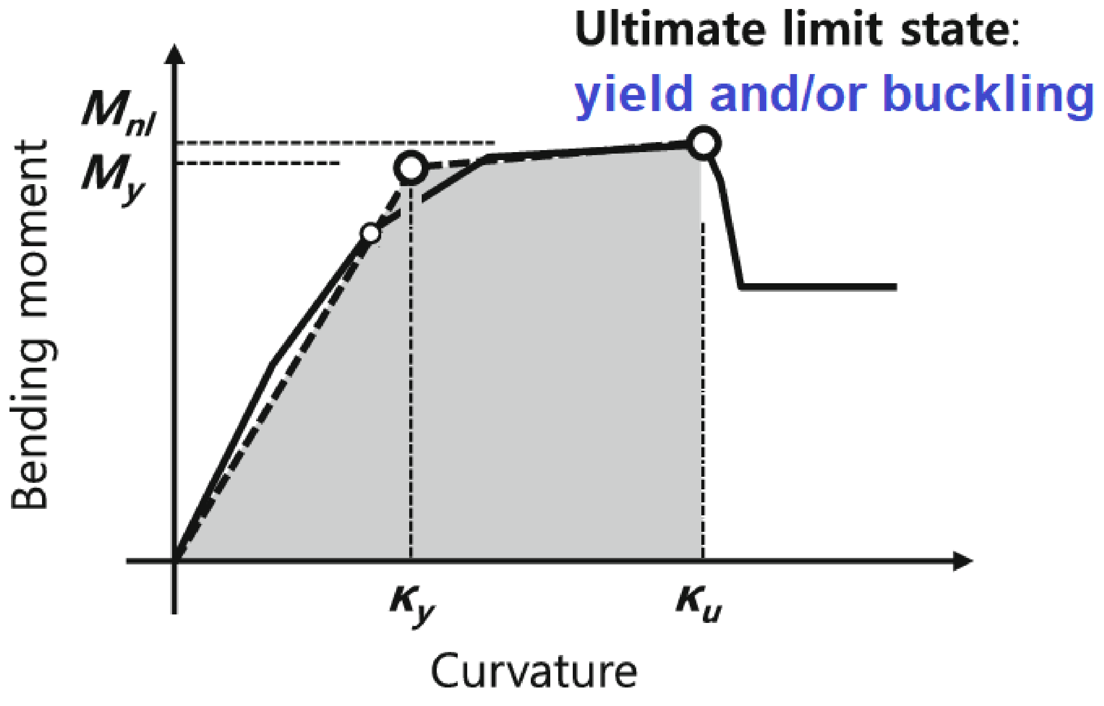
- Introduction to Structural Analysis
- Introduction to Fatigue Analysis
- Onshore and Offshore wind turbine structural analysis
- Wind turbines fatigue analysis and design
- Advanced topics

## Actions and internal forces for a part of a wind turbine tower






## ULTIMATE LIMIT STATE

**Critical bending moments**

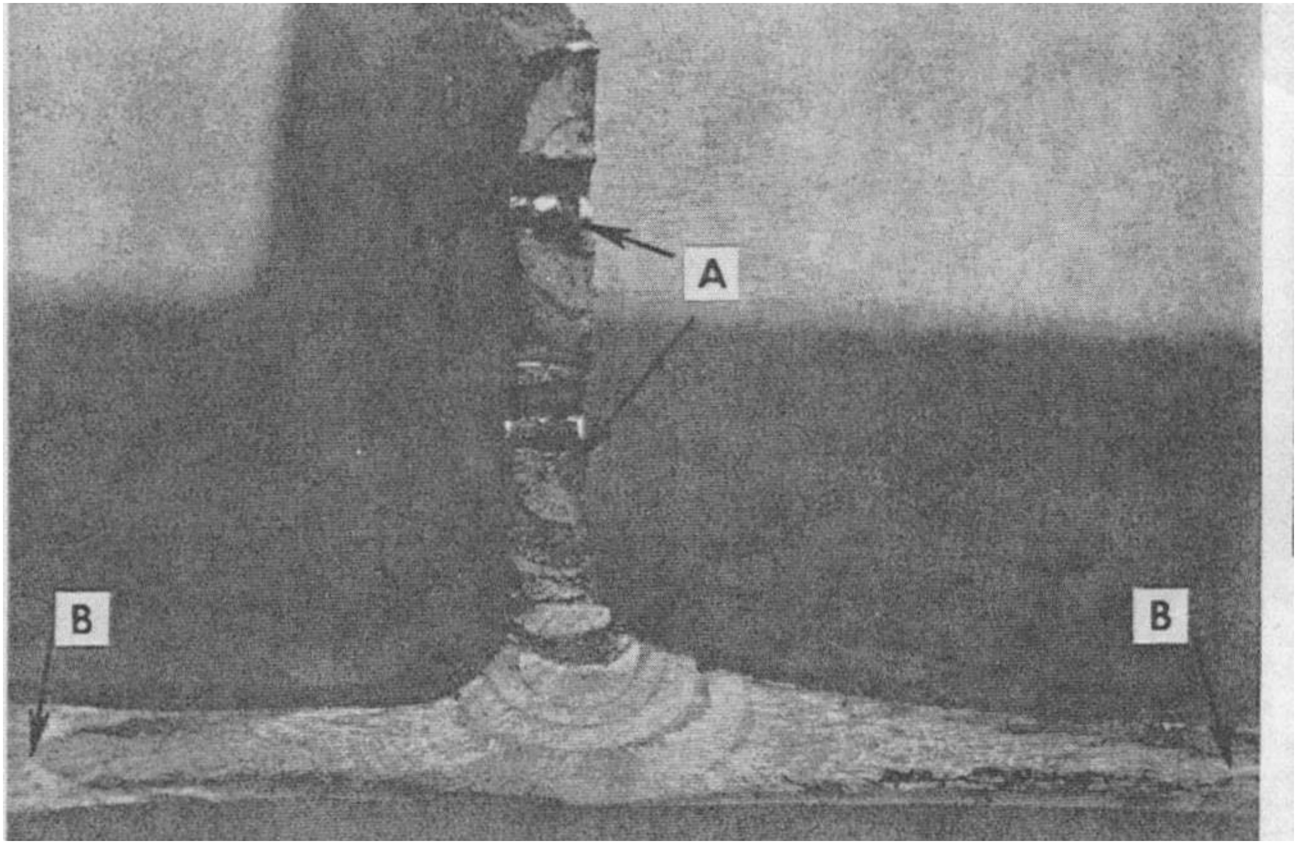
**Mt:** max. bending moment for the tower

**Ms:** max. bending moment for the shaft

**Mb:** max. bending moment for the blades

# Nature of fatigue failure

- Starts with a crack - usually at a stress concentration
- Crack propagates until the material fractures suddenly
- Fatigue failure is typically sudden and complete, and doesn't give warning




# Ultimate Loads and Fatigue Loading

| Design Driver | | |
|---|---|---|
| Component | Ultimate | Fatigue |
| Rotor | | |
| Blades and Hub | | • |
| Drive Train | | |
| Low-Speed Shaft | | • |
| Gearbox | | • |
| High-Speed Shaft | • (breaking) | |
| Nacelle | | |
| Bedplate | • (stiffness) | • |
| Yaw Drive | • (breaking) | |
| Tower | • (stiffness, stability) | |
| Foundation | • (breaking) | |

**Typical situation of design drivers for the wind turbine components**

The structural and mechanical components of the wind turbine are subject to the requirement of

Resisting the ultimate or limit loads

Resisting the fatigue loading

Meet the stiffness requirements

**Ultimate Loads:** Calculating the limit loads for the design is a matter of identifying one-time or infrequent load situations that might damage the structure or the mechanical components.

The ultimate load and stress calculation includes three types of analyses which respect to:

1. Breaking strength for example for the yaw drive and the tower/foundation at extreme wind speeds

2. Structural stability for example buckling of steel-tube towers

3. Stiffness for example critical deflections of the roto rblades with respect to rotor blade/tower clearance at extreme gusts or during fast rotor braking

**Limit strength design** of a wind turbine is normally a problem of extreme wind loading on a static structure.

**Ultimate Loads:** Calculating the limit loads for the design is a matter of identifying one-time or infrequent load situations that might damage the structure or the mechanical components.

The load cases selected for ultimate load design must cover realistic combinations of external wind conditions and machine states. The load cases for design are chosen from:

1. normal wind conditions in combination with normal machine states.

2. normal wind conditions in combination with machine fault states.

3. extreme wind conditions in combination with normal machine states.

The general format of determining the design actions on structures subjected to accidental actions are defined in EN 1990-1-1. This can be simplified for structures to the expression:

$$E_d = \{G_{k,j} + A_d + \psi_1 Q_{k,1} + \psi_2 Q_{k,2}\}$$

- $E_d$ is the effect of the combined actions
- $G_{k,j}$ is the permanent action
- $A_d$ is the action due to an accidental event
- $Q_{k,1}$ is the leading frequent variable action
- $Q_{k,2}$ is the accompanying quasi-permanent variable action
- $\psi_1$ is the factor for leading frequent value of a variable action
- $\psi_2$ is the factor for accompanying quasi-permanent value of a variable actions

# Fatigue Load Spectrum

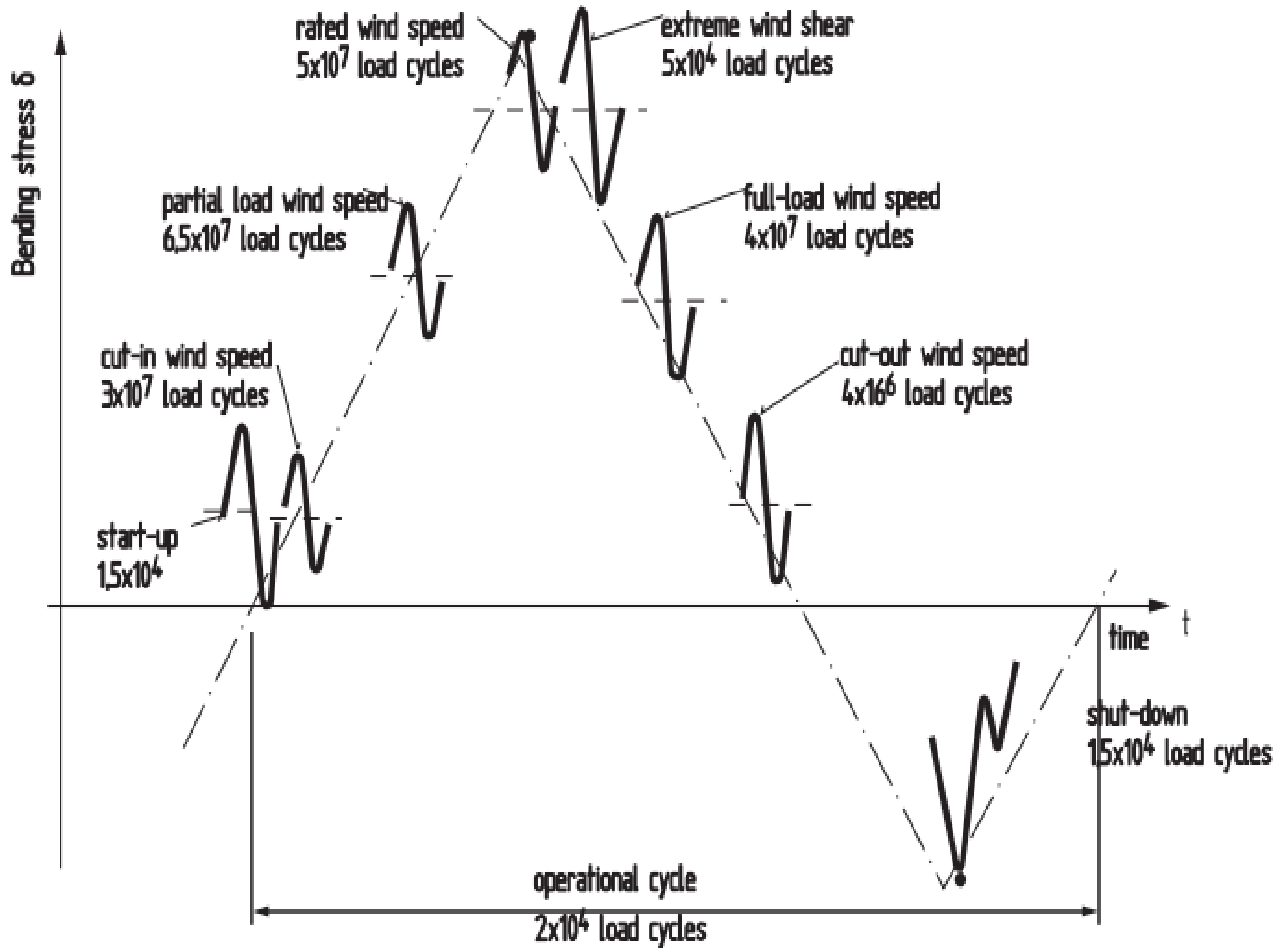
In **simple stress situations** with static loads, it is sufficient to calculate the structural strength separately for individual load situations or load cases.

If a safe **fatigue life** is required with alternating loads, elementary fatigue strength theory assumes that stress fluctuations occur with constant amplitudes within the lifetime of a component.

If the stress amplitudes are below the fatigue strength of the material, then the number of load cycles no longer plays a role, i. e. changes in load can be endured any number of times.

If the stress amplitudes are higher than the fatigue strength allows, only a certain number of load fluctuations can be sustained, i. e. the material is only “ fatigue-limited”.

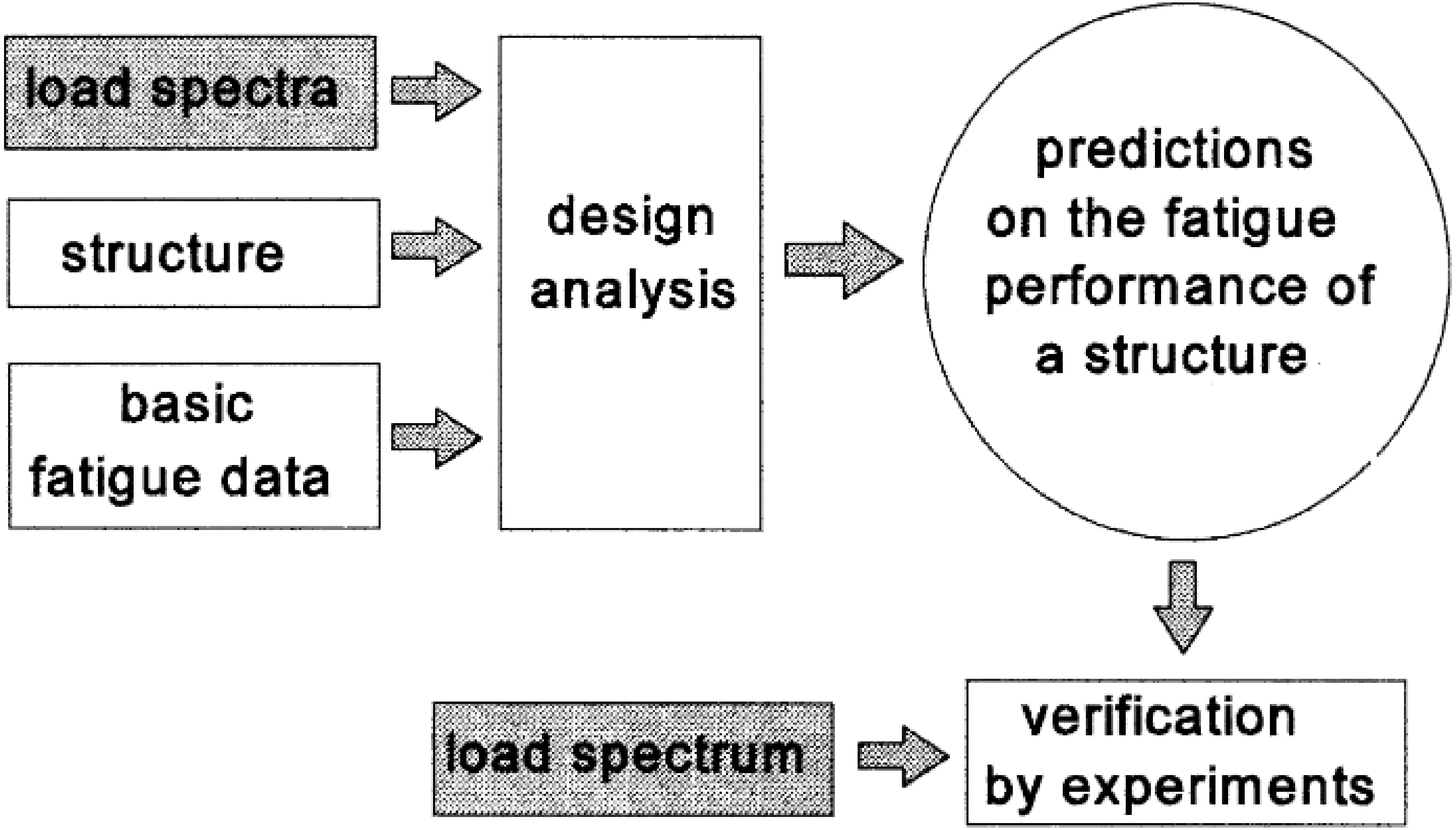
# Fatigue Load Spectrum

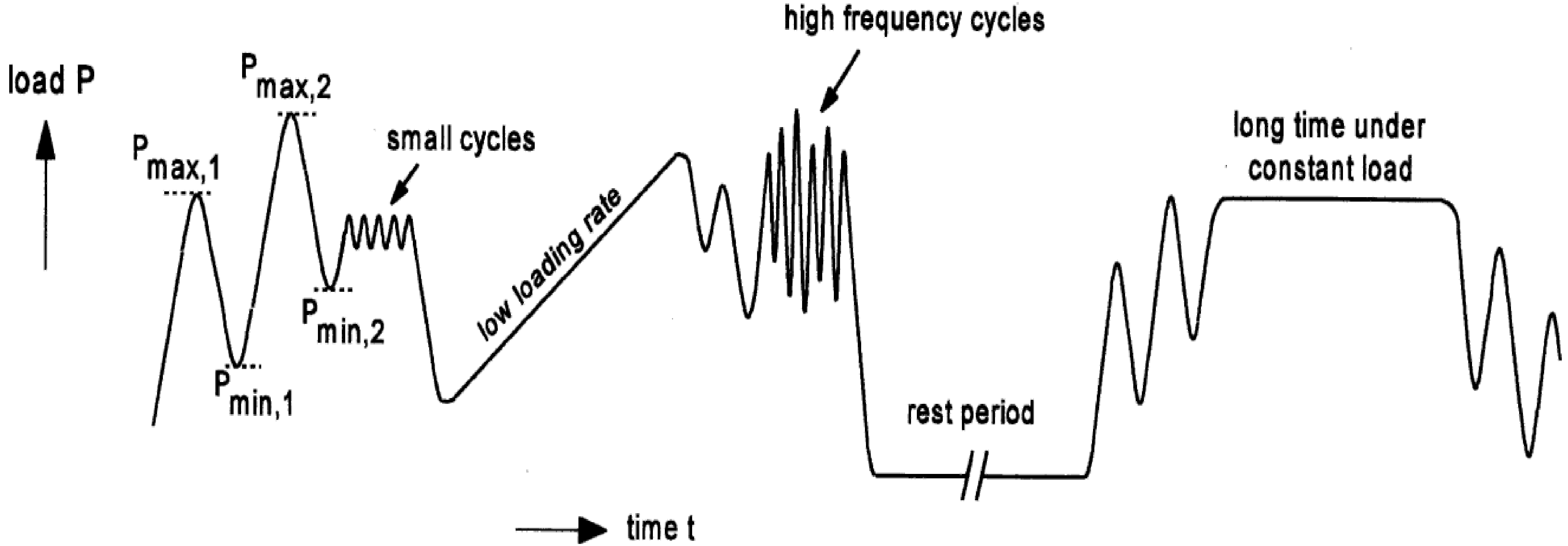


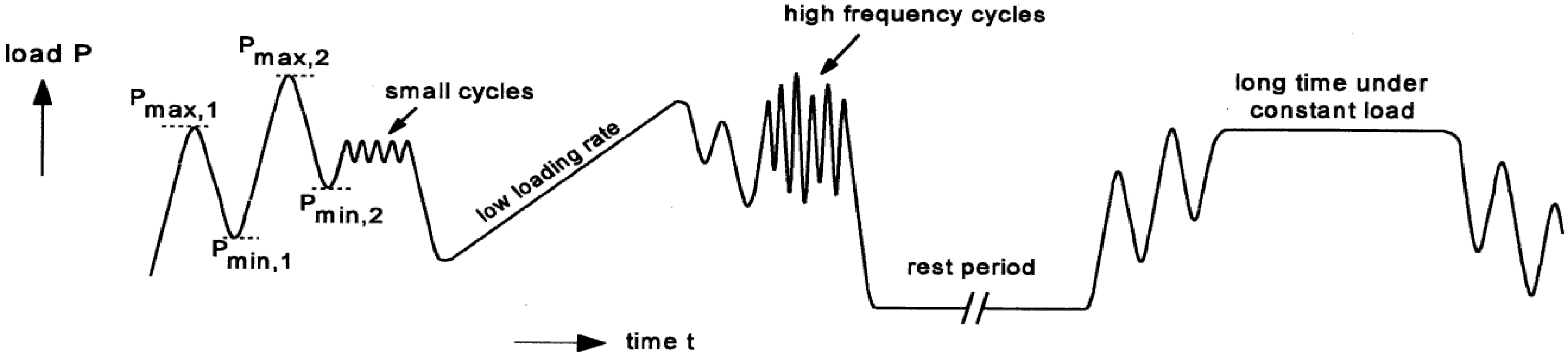

The load spectrum summarises the stress situation of a component over its entire life in an idealised form.

The load sequence within an operating cycle of the wind turbine, which the component has passed through a certain number of times within its life, forms the basis for the load spectrum

The progression of the cyclic bending moment experienced by the rotor blades of a wind turbine in the individual load cases serves as an example (see Figure).


load spectra
structure
basic fatigue data
design analysis
predictions on the fatigue performance of a structure
load spectrum
verification by experiments


load P
P max,1
P min,1
P max,2
P min,2
small cycles
low loading rate
high frequency cycles
rest period
long time under constant load
time t




1) Is it necessary to know the full sequence of all turning points of the load history?
2) Are all similar wind turbines in service subjected to the same load history, or in other words, how unique is a certain load history for a specific wind turbine?
3) Are small cycles of interest, or is the fatigue damage contribution of these cycles negligible?
4) Is it important whether loads are applied at a high or a low loading rate (wave shape)?
5) Long periods at zero load (rest periods, wind turbine not in use) or long periods at a significant load level (average load in service if dynamic loads do not occur during that period), are these periods important for the fatigue damage accumulation?

# Approach to fatigue failure in analysis and design

**Fatigue-life methods**

- Stress Life Method
- Strain Life Method
- Linear Elastic Fracture Mechanics Method

# Fatigue-life methods

**Three major methods**

Stress-life

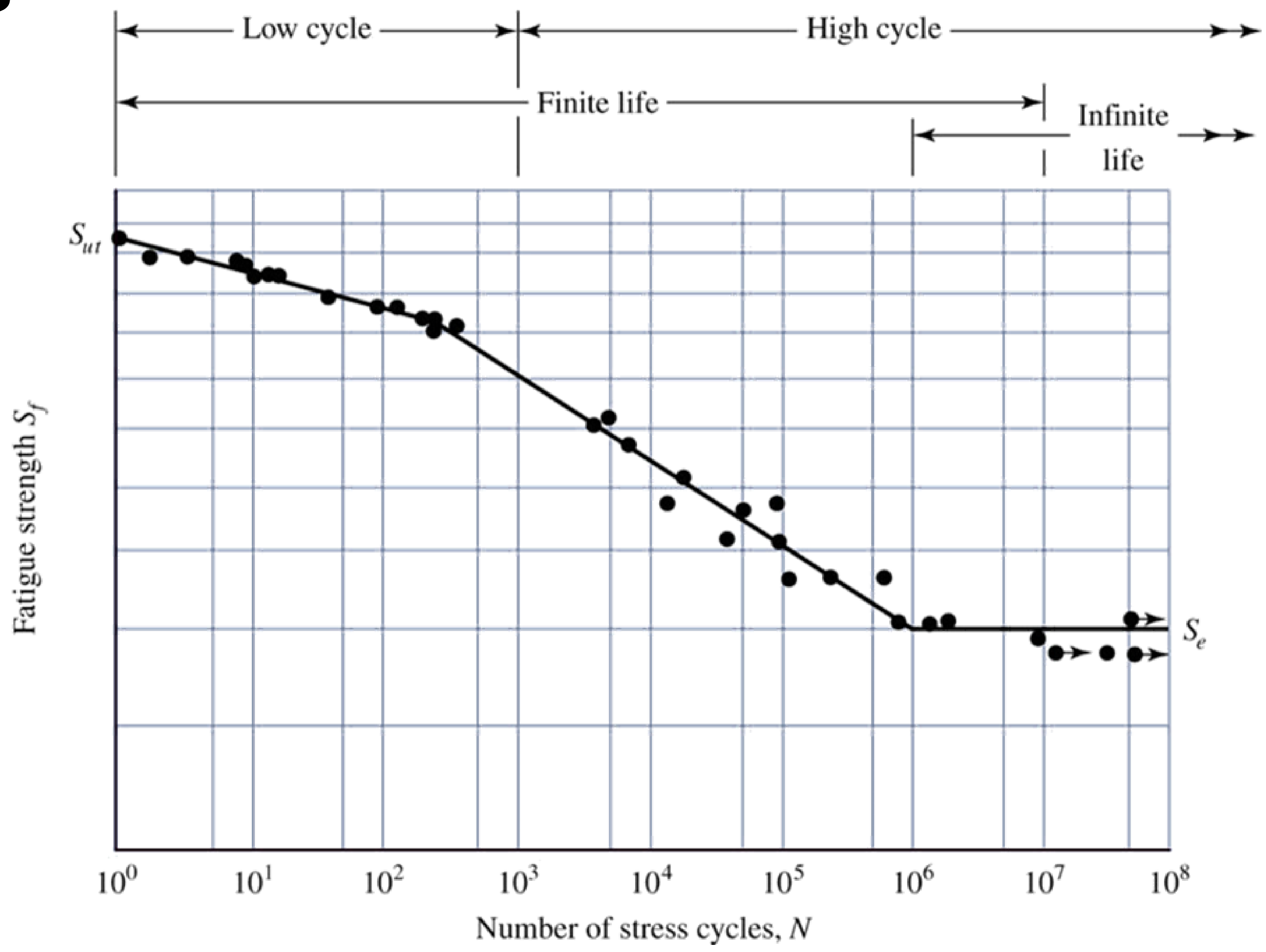
Strain-life

Linear-elastic fracture mechanics

Each predict life in number of cycles to failure, **N**, for a specified level of loading

Low-cycle fatigue: $1 \leq N \leq 10^3$ cycles

High-cycle fatigue: $N > 10^3$ cycles



# The 3 major methods

- **Stress-life**
  - Based on stress levels only
  - Least accurate for low-cycle fatigue
  - Most traditional
    - Easiest to implement
    - Ample supporting data
    - Represents high-cycle applications adequately
- **Strain-life**
  - More detailed analysis of plastic deformation at localized regions
  - Good for low-cycle fatigue applications
  - Some uncertainties exist in the results
- **Linear-elastic fracture mechanics**
  - Assumes crack is already present and detected
  - Predicts crack growth with respect to stress intensity
  - Practical when applied to large structures in conjunction with computer codes and periodic inspection

# Strain-life method

Fatigue failure almost always begins at local discontinuity

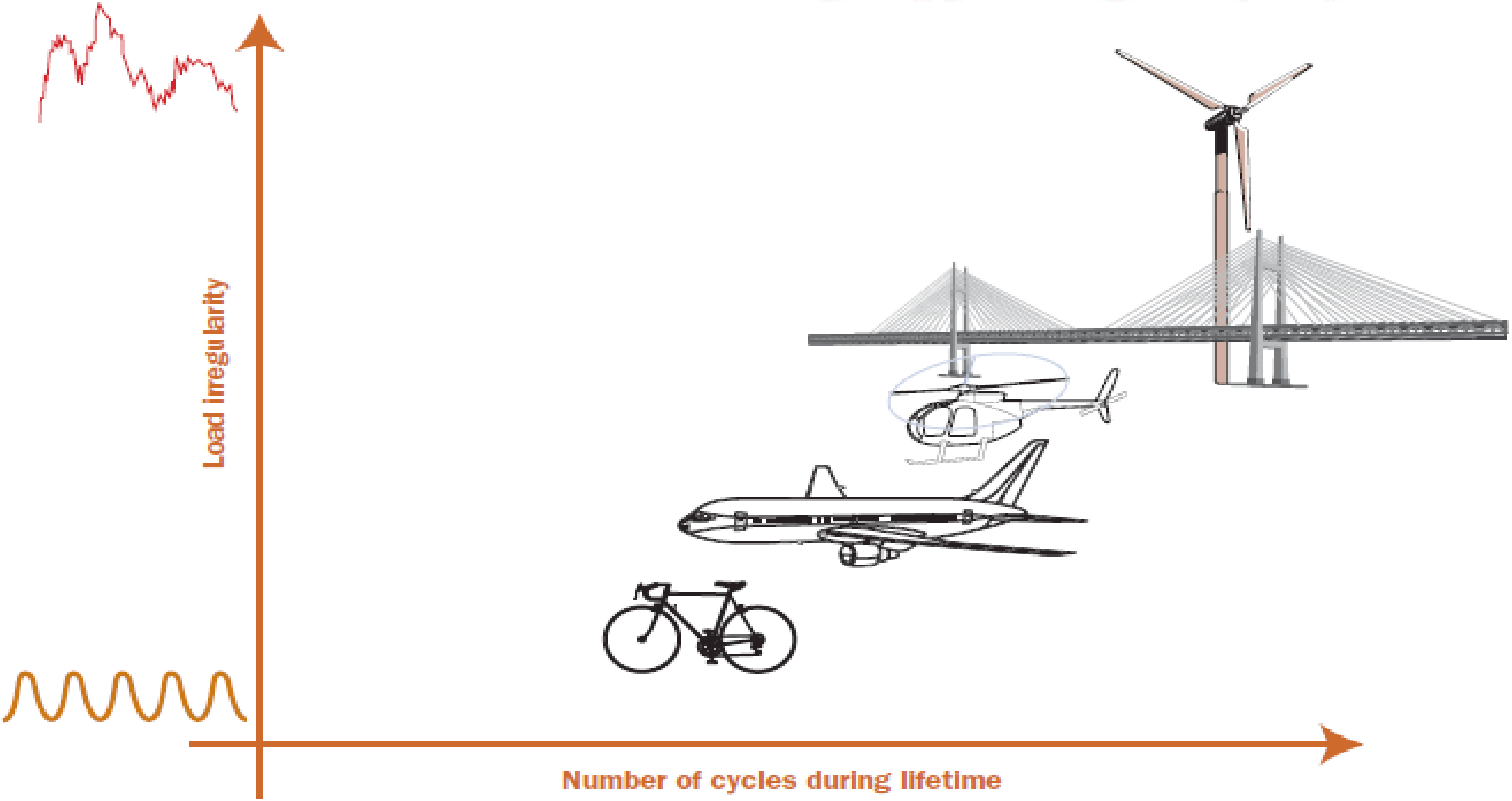
- Notch, crack or others
- When stress at discontinuity > elastic limit, plastic strain occurs
- Fatigue fracture occurs for cyclic plastic strains

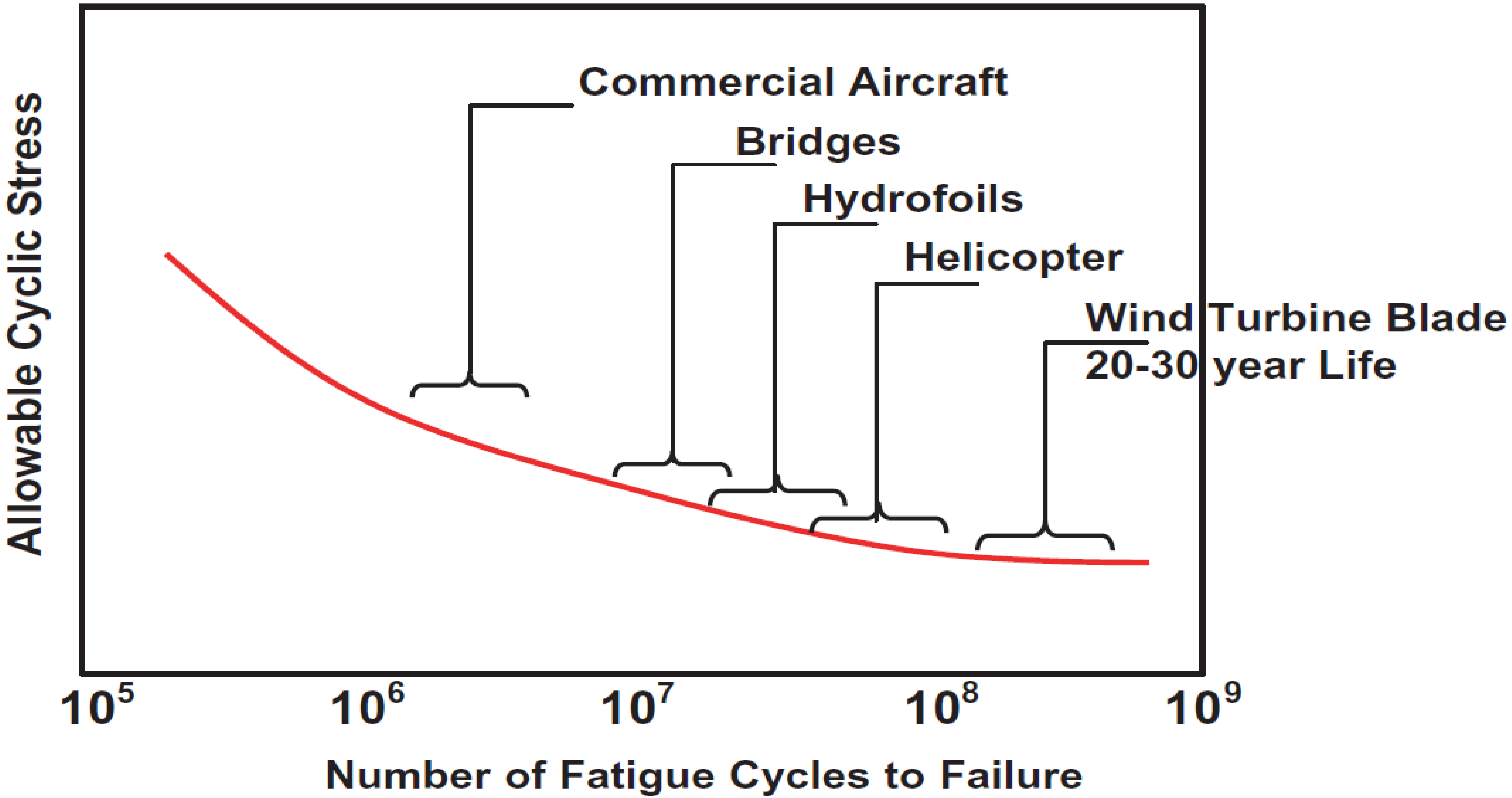
Can find fatigue life given strain and other cyclic characteristics

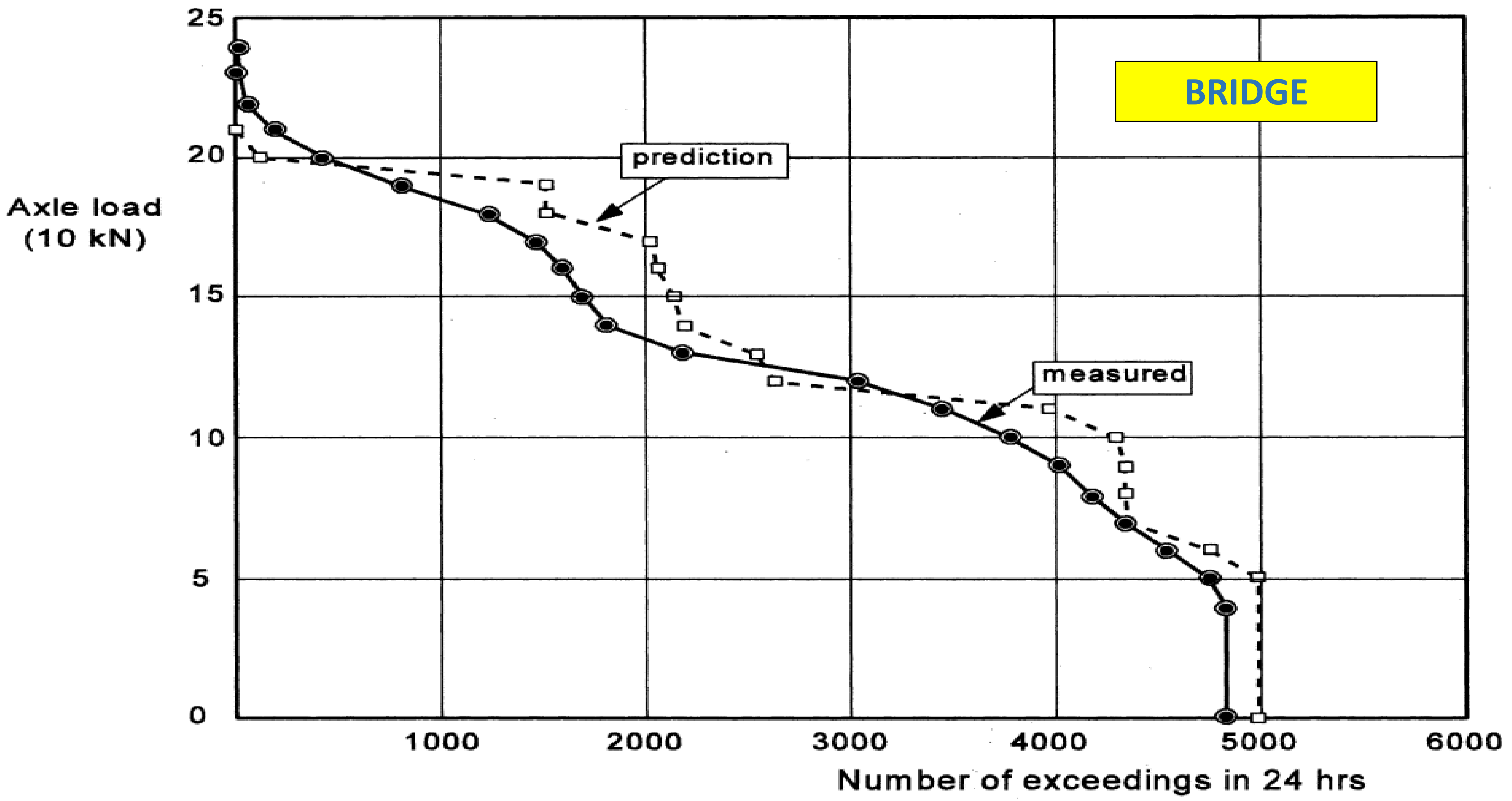
- Often the designer does not have these *a priori*

# Linear-elastic fracture mechanics method

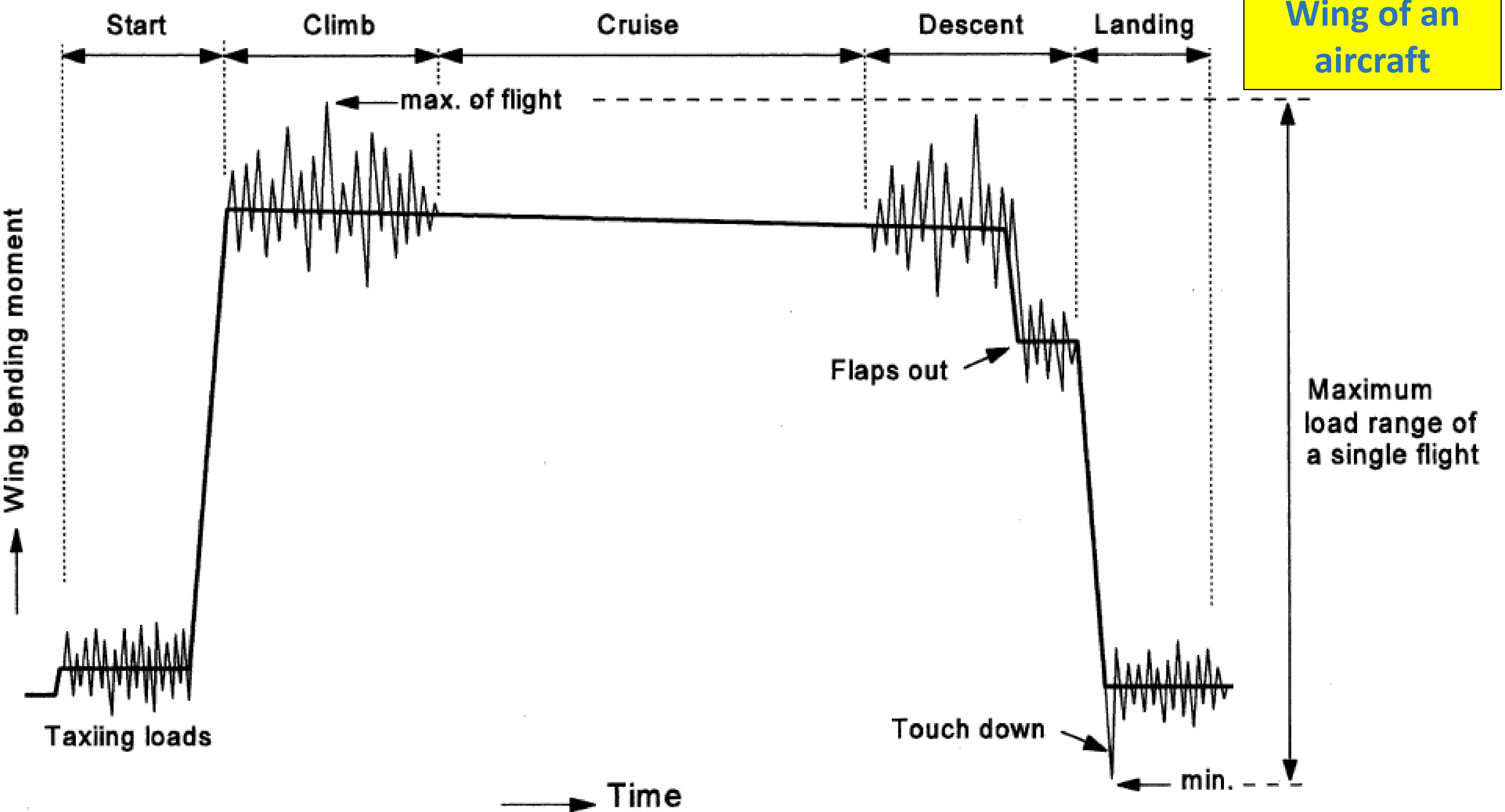
- Stage 1 – crystal slip through several contiguous grains
- Stage 2 – crack extension
- Stage 3 – fracture
- Method involves
  - Determining stress intensity as function of crack length
  - From here, determine life
- In reality, computer programs are used to calculate fatigue crack growth and therefore onset of failure


Load irregularity
Number of cycles during lifetime


Commercial Aircraft
Bridges
Hydrofoils
Helicopter
Wind Turbine Blade
20-30 year Life
Allowable Cyclic Stress
$10^5$
$10^6$
$10^7$
$10^8$
$10^9$
Number of Fatigue Cycles to Failure


BRIDGE
Axle load (10 kN)
25
20
15
10
5
0
1000
2000
3000
4000
5000
6000
Number of exceedings in 24 hrs
prediction
measured

**Wing of an aircraft**



# Fatigue analysis and Design. Type of loads

**1. Deterministic loads:** A load is considered to be deterministic if it can be defined as a specific occurrence, from which it is known that it will occur with a magnitude that can be estimated.

**2. Stochastic loads:** have an essentially statistical nature. They cannot be predicted to occur with a certain magnitude at a given moment.

## Mathematical Models and Calculation Procedure

**Aerodynamic rotor model** The calculation of aerodynamic loading, both due to the steady-state flow against the rotor as well as from wind turbulence, requires an aerodynamic rotor model.

Blade element theory is a suitable instrument for aerodynamic loads from a steady-state wind flow.

Dynamic loads caused by wind turbulence and the elastic response of the structure can be calculated by means of a simplified aerodynamic model.

A linear analytical approach for the dependence of the aerodynamic force coefficients on the angle of attack is often sufficient.

# Case study 1: Design of wind turbine blades

## Wind turbine blade

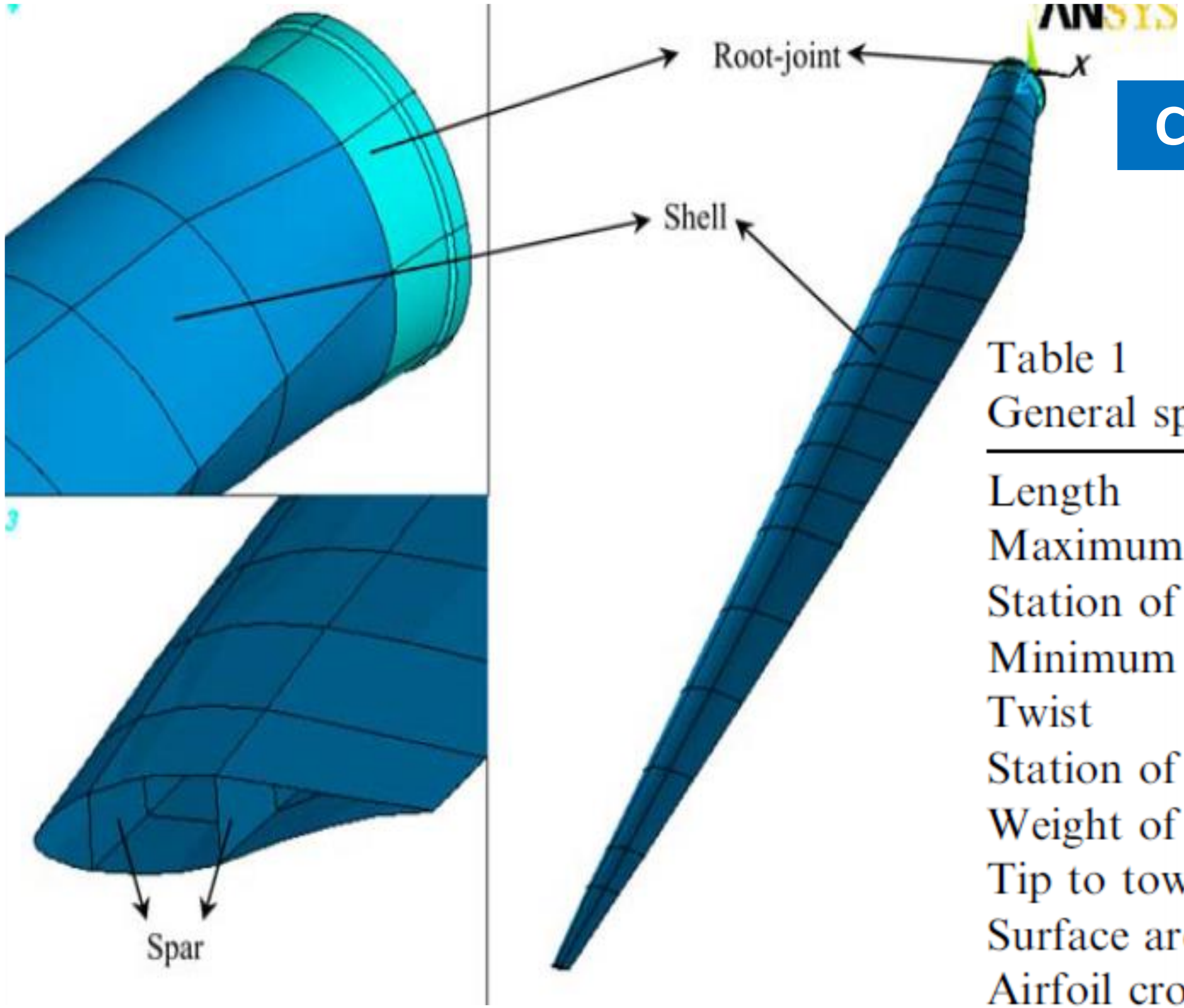
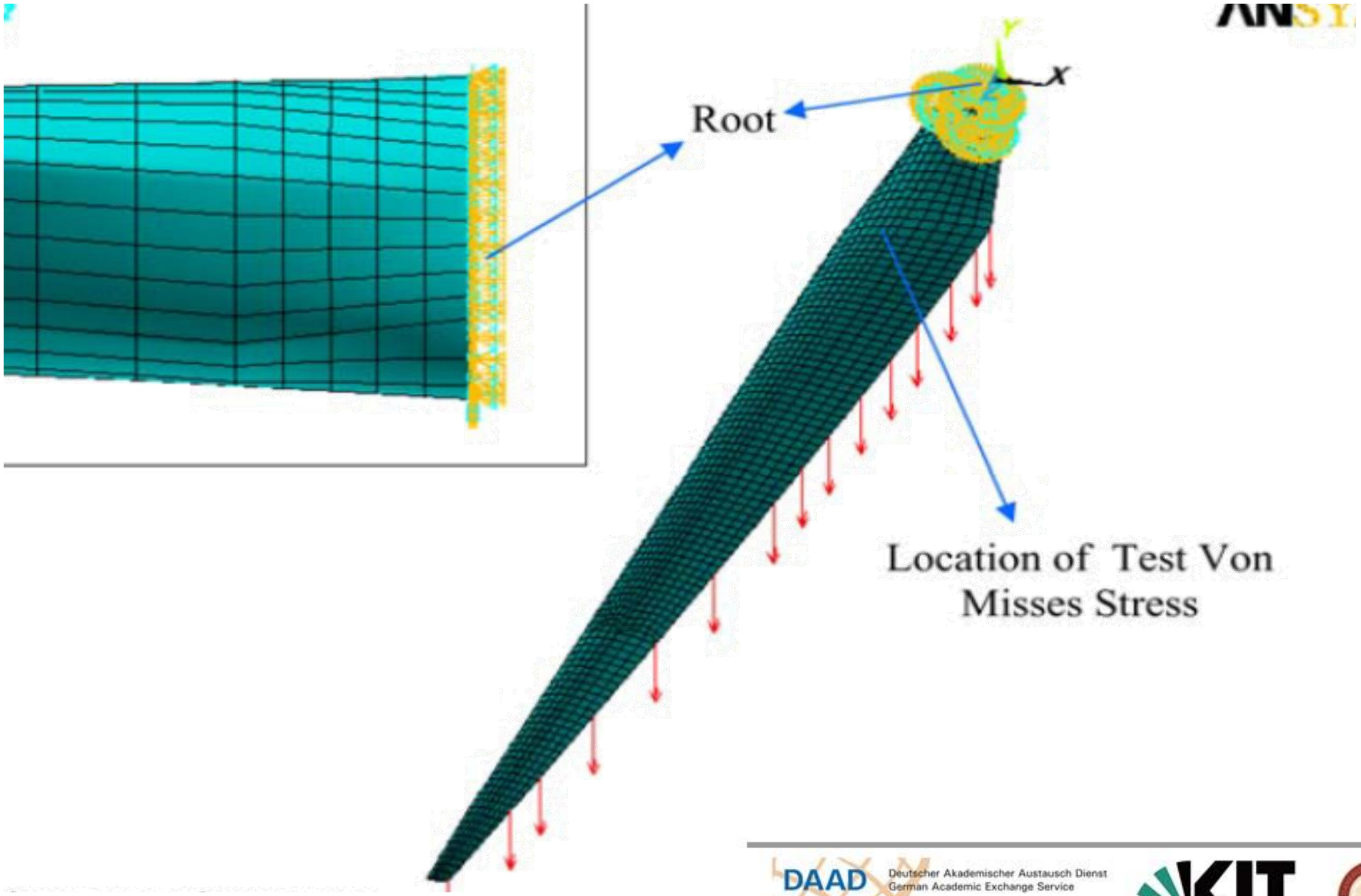


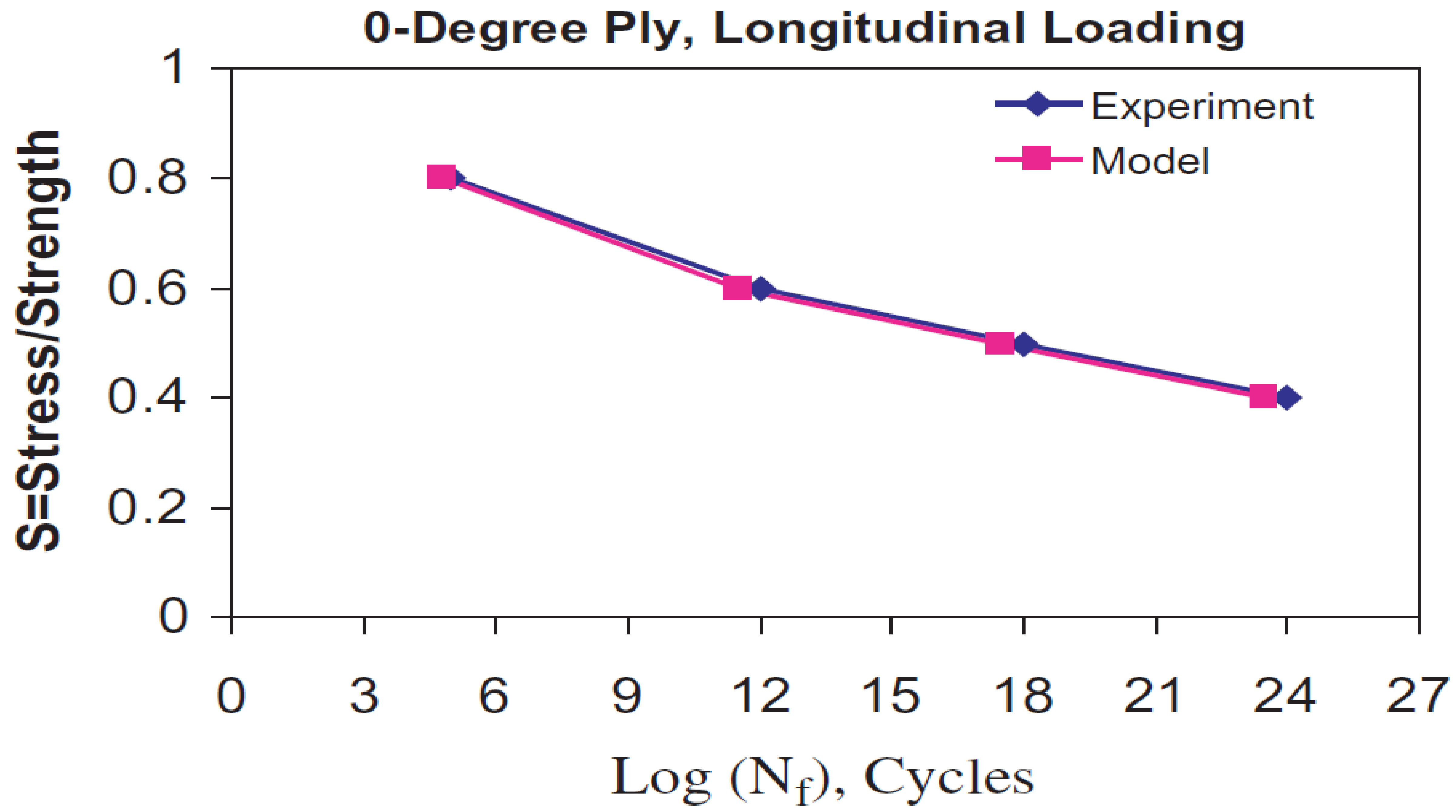

Table 1
General specifications of investigated blade

| | |
|---|---|
| Length | 22,900 mm |
| Maximum chord | 2087 mm |
| Station of maximum chord | R4500 |
| Minimum chord | 282.5 mm |
| Twist | 15.17° |
| Station of CG | R8100 |
| Weight of blade | 1250 kg |
| Tip to tower distance | 4.5 m |
| Surface area | 28 $m^2$ |
| Airfoil cross-section types | FFA-W3, NACA-63-xxx, MIX |

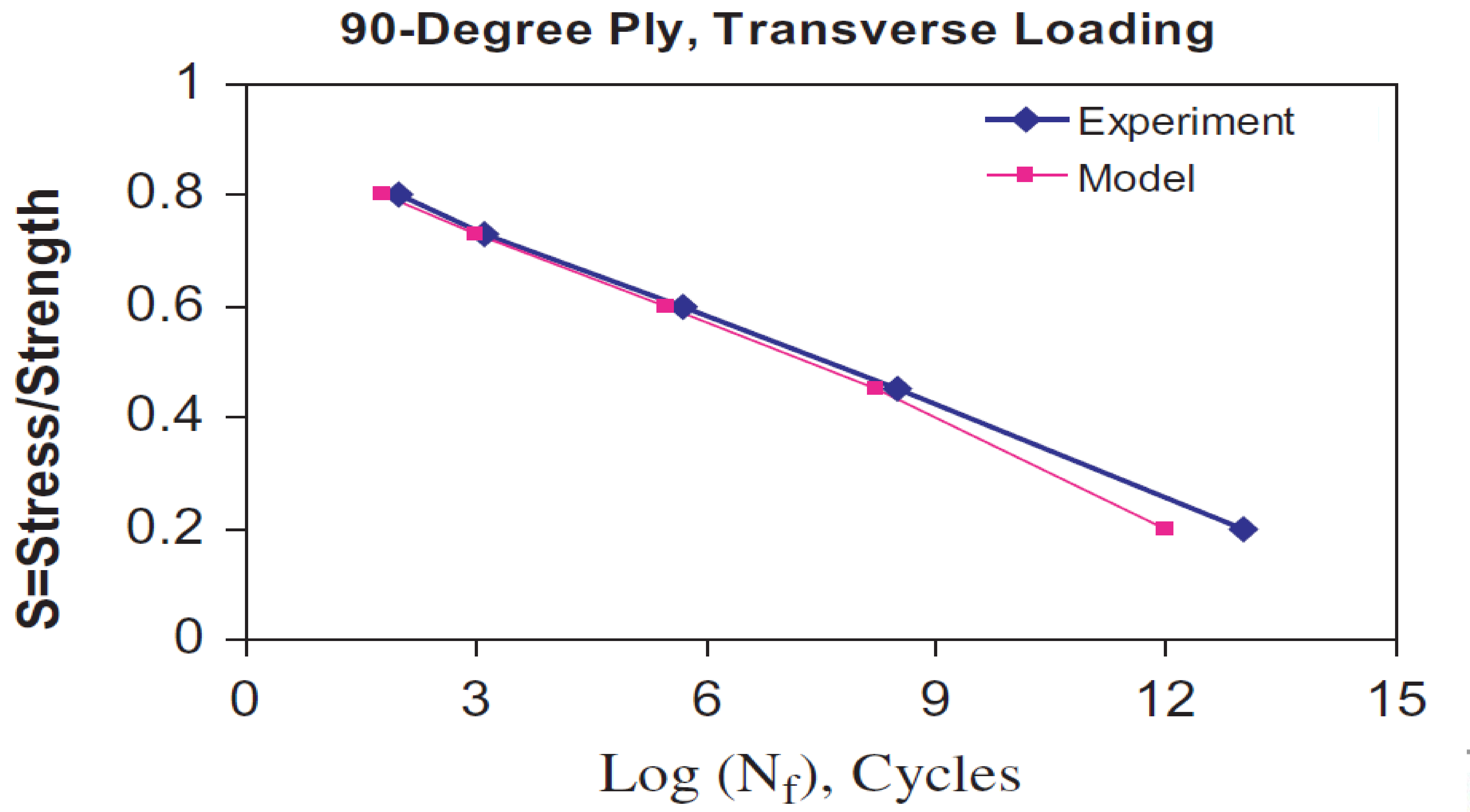

Root
Y
X
Location of Test Von
Misses Stress

## Loads

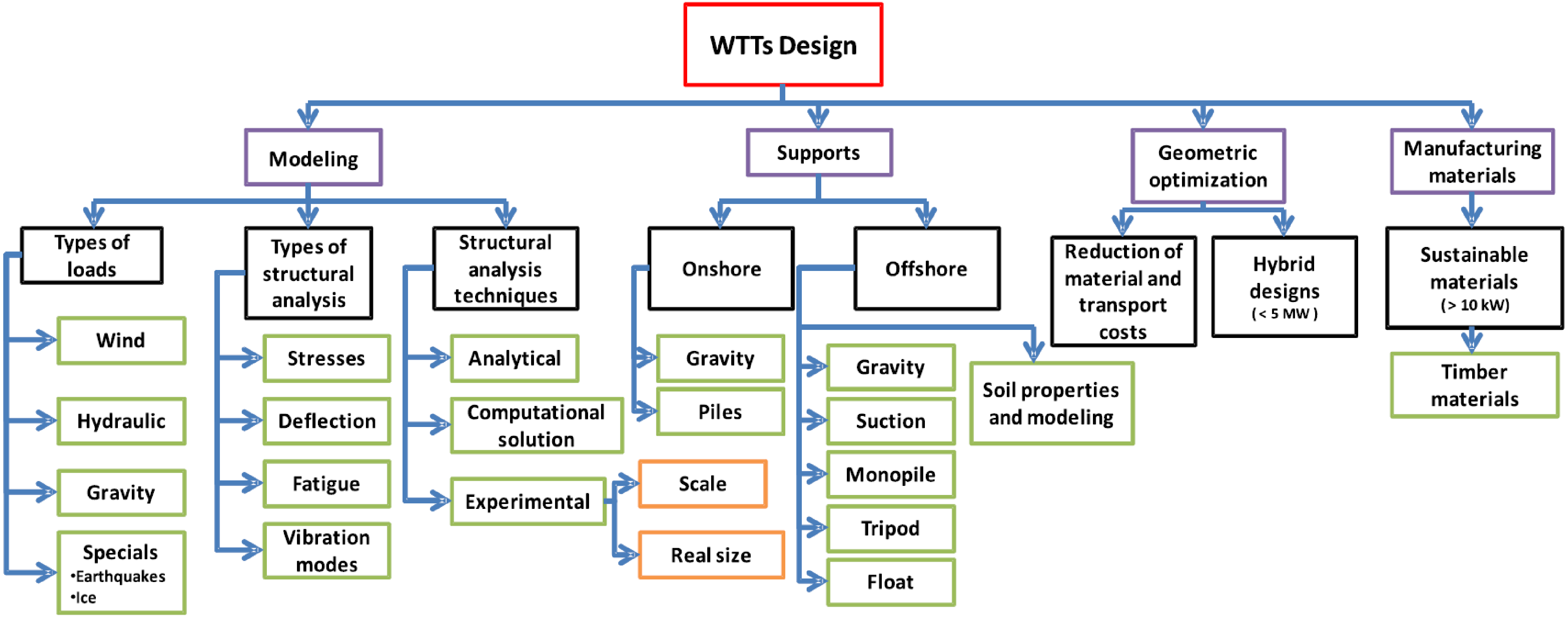
1. Aerodynamic loads on the blade
2. Weight of the blade
3. Annual gust
4. Changes in the wind direction
5. Centrifugal force
6. Force that arise from start/stop angular acceleration
7. Gyroscopic forces due to yaw movements
8. Activation of mechanical brake
9. Thermal effect

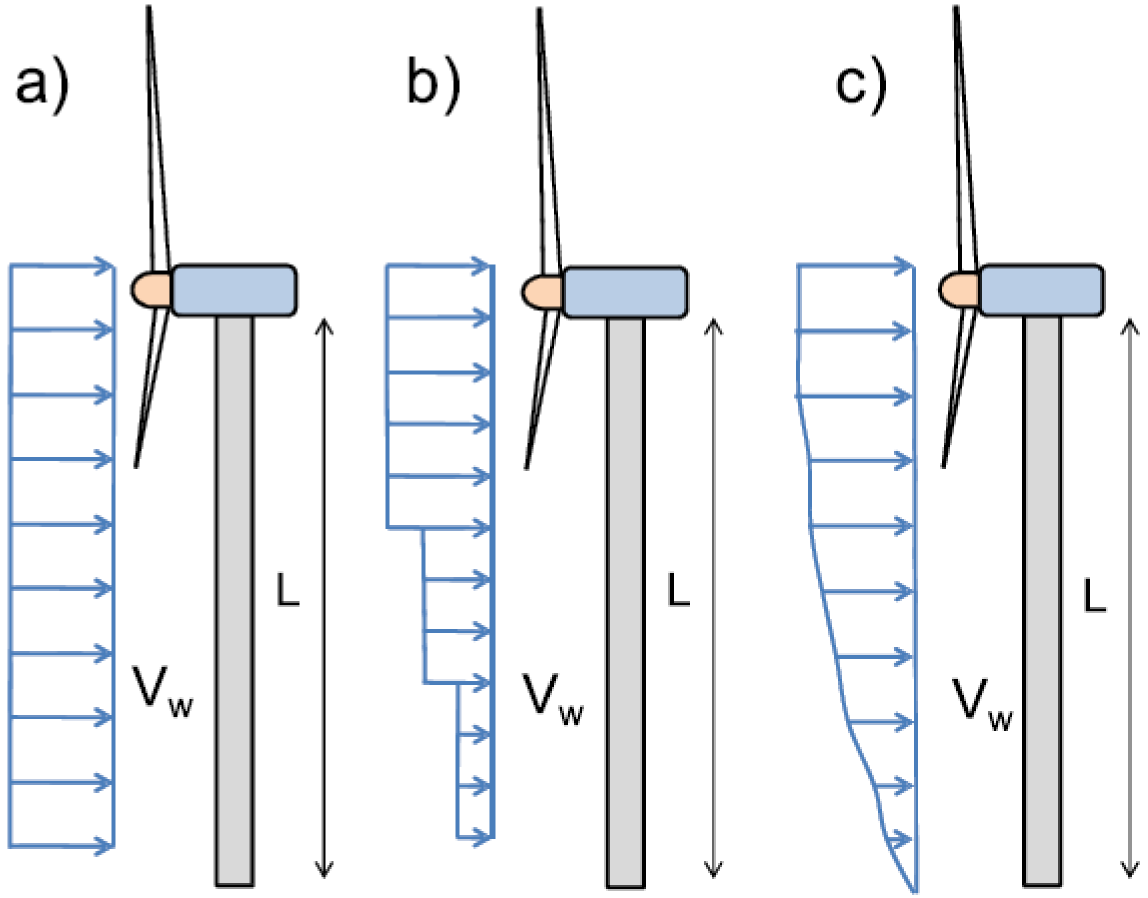


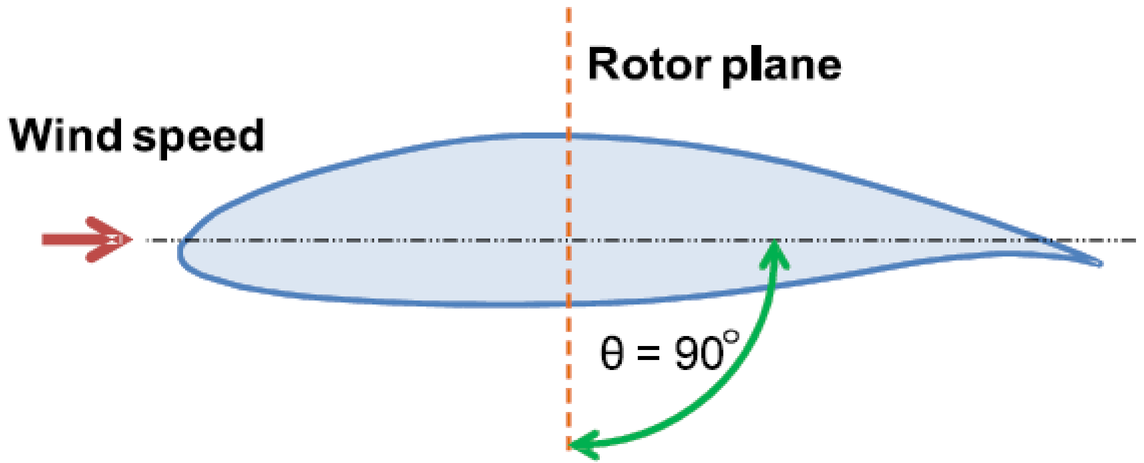
0-Degree Ply, Longitudinal Loading
Experiment
Model
S=Stress/Strength
1
0.8
0.6
0.4
0.2
0
0
3
6
9
12
15
18
21
24
27
Log (Nf), Cycles

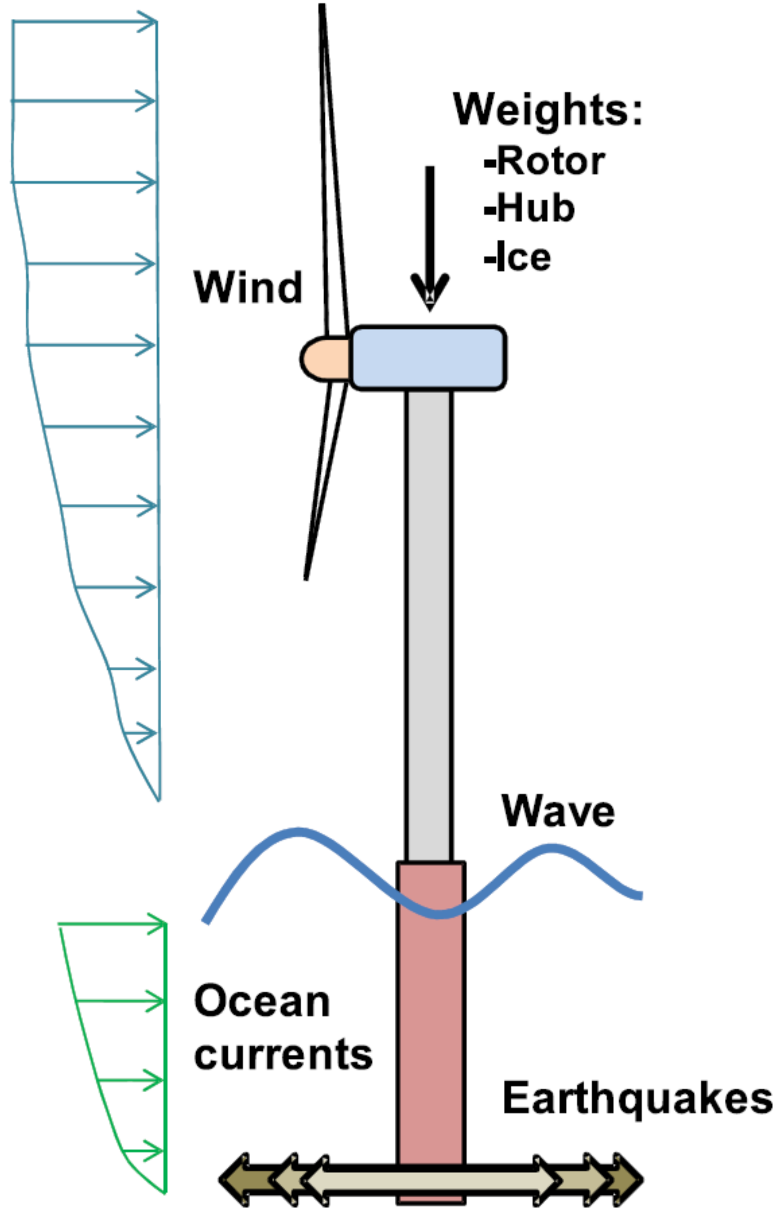

90-Degree Ply, Transverse Loading
S=Stress/Strength
1
0.8
0.6
0.4
0.2
0
0
3
6
9
12
15
Log (N_f), Cycles
Experiment
Model

# Case study 2: Design of wind turbine tower (WTT)

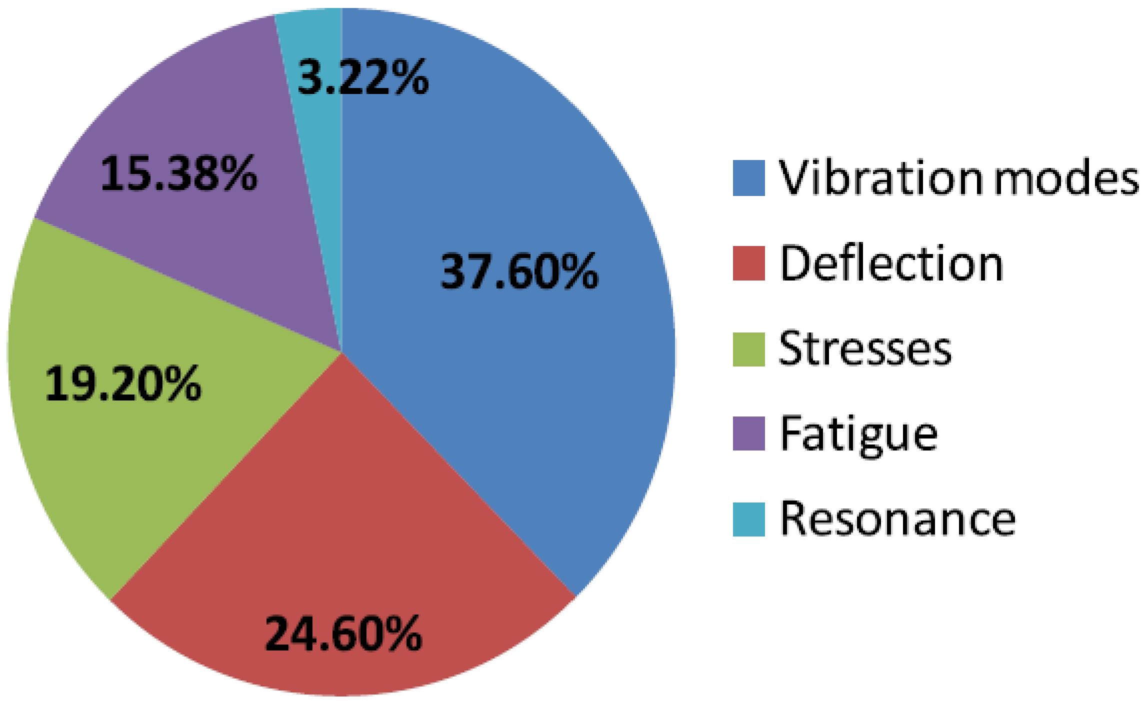



a)
b)
c)
L
L
L
$V_w$
$V_w$
$V_w$


Rotor plane
Wind speed
θ = 90°




## Type of analysis most used for WTTs



# Thank you for your attention