## Reliability Of Wind Turbine Blades


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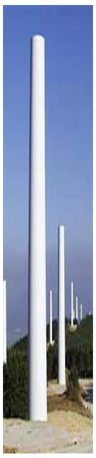
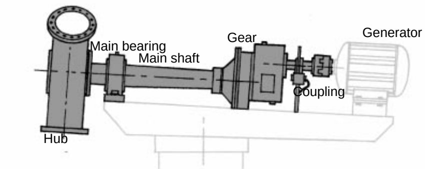
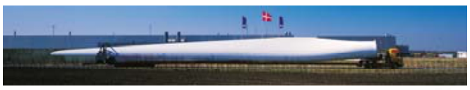
## The Wind Turbine - Components

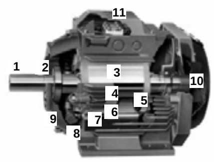


http://www.windpower.org/en/kids/

http://www.windmission.dk/workshop/BonusTurbine.pdf



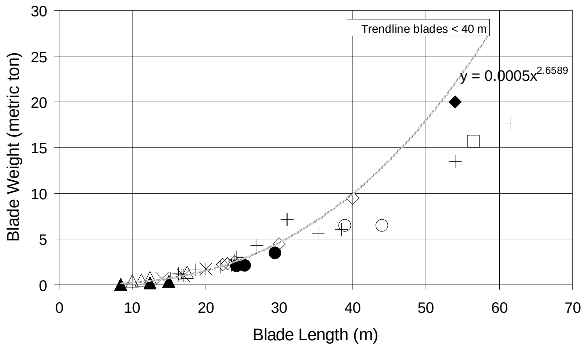






1. Generator shaft
2. Rolling bearings
3. Rotor
4. Rotor aluminium bar
5. Rotor aluminium ring
6. Stator
7. Coil
8. Stator plates
9. Coil heads
10. Ventilator
11. Connection box

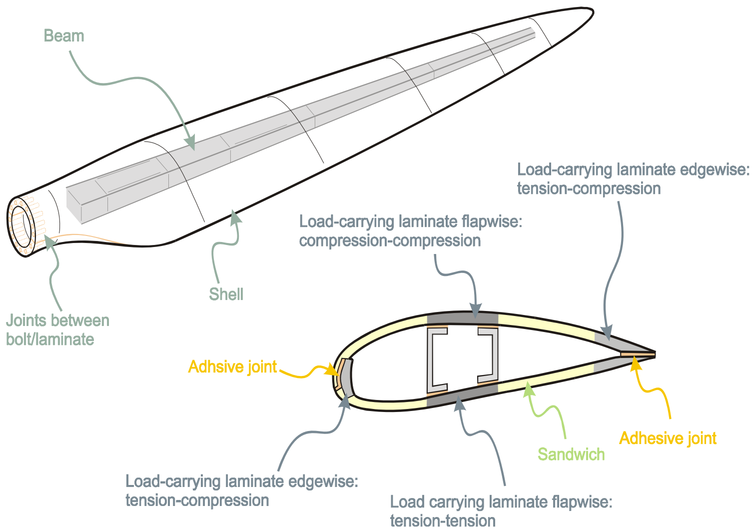
## The Wind Turbine Blade

LM 61.5 m (17.7 tons)



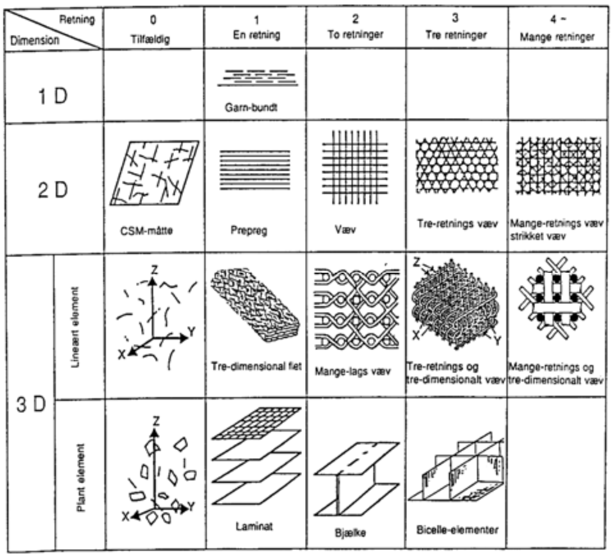

## Blade construction

- an aerodynamic shell and a load-carrying beam

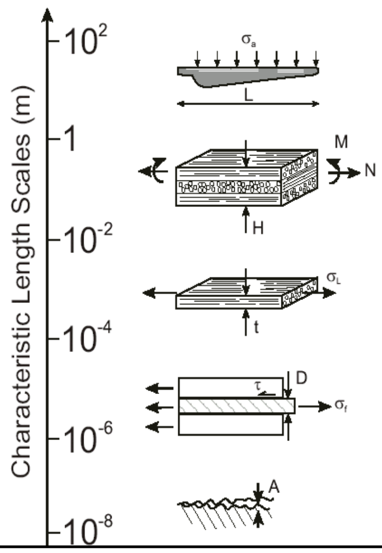


## Composite materials

- Fibre-orientation
  - unidirectional
  - weaves/patterns
  - random orientation
- Boundary fibre/matrix:
  - interface
  - interphase (zone)




## Composite Length Scales



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## Blade test - quality control

LM 61.5 m

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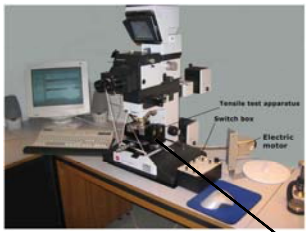
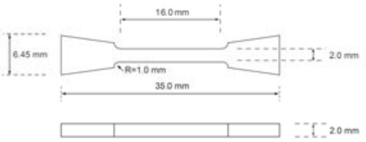
Single fibre fragmentation set-up




Specimen’s geometry

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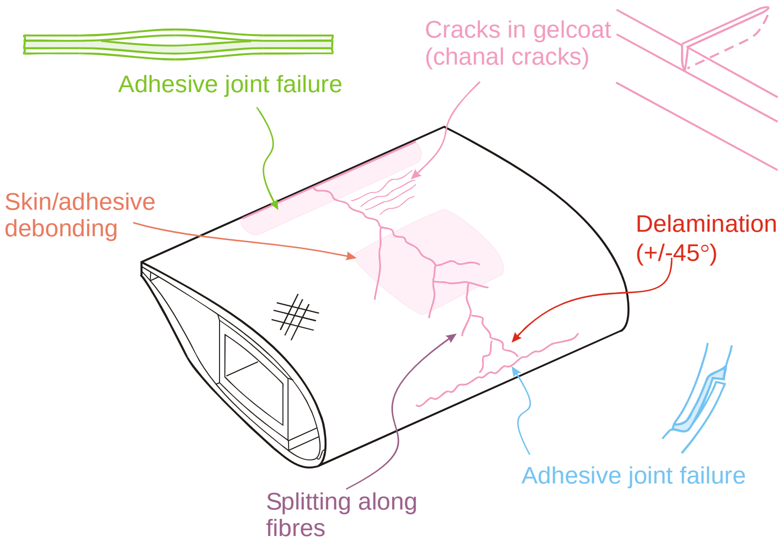
## Fracture modes - example: a wind turbine blade

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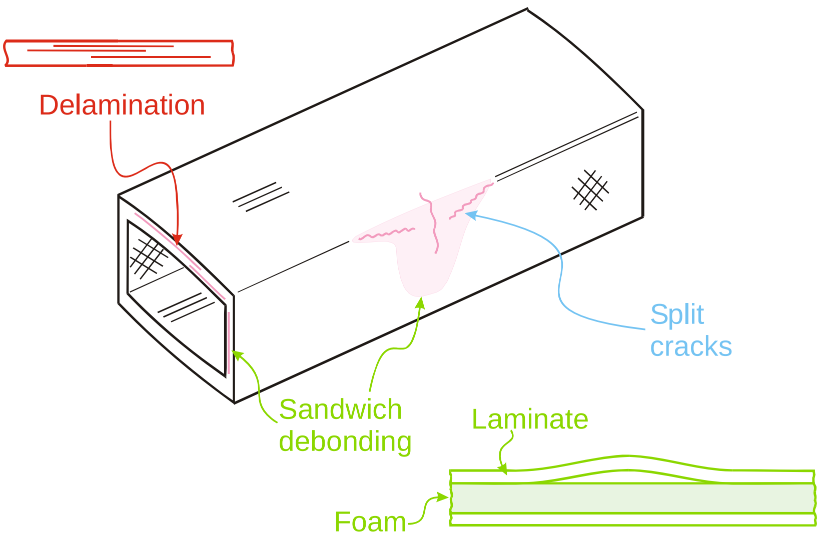
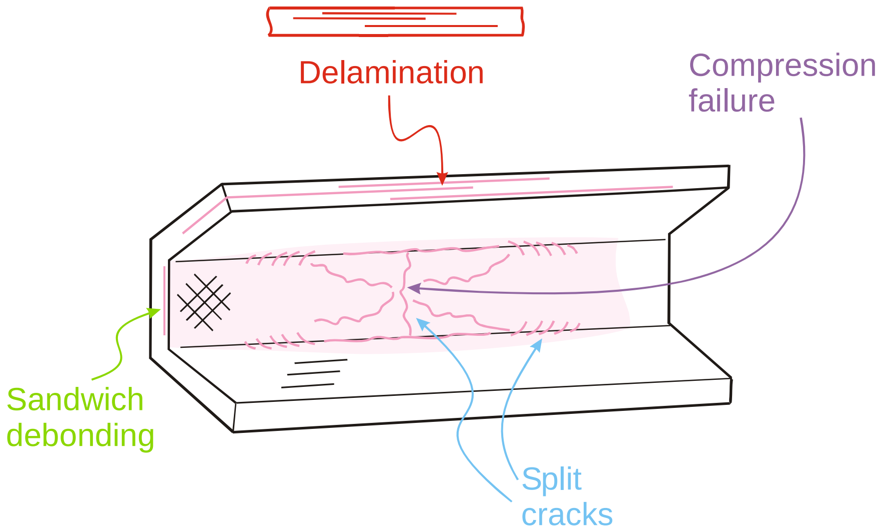
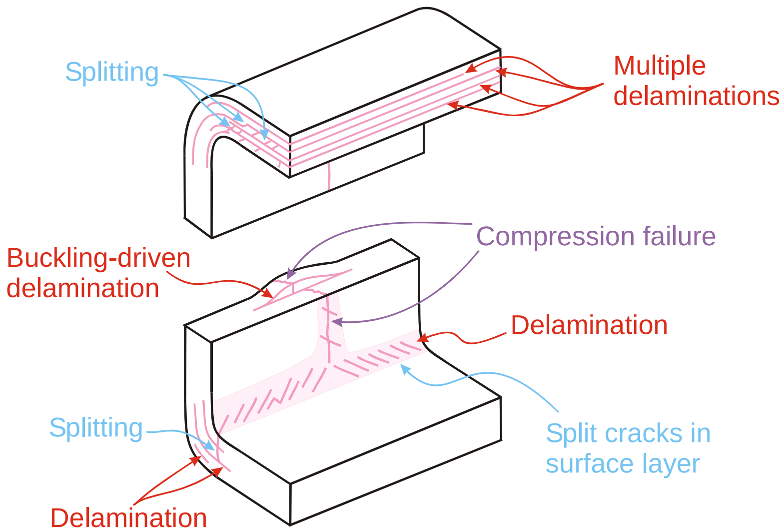
## Fracture modes - example: a wind turbine blade



## Fracture modes - example: a wind turbine blade




## Fracture modes - example: a wind turbine blade



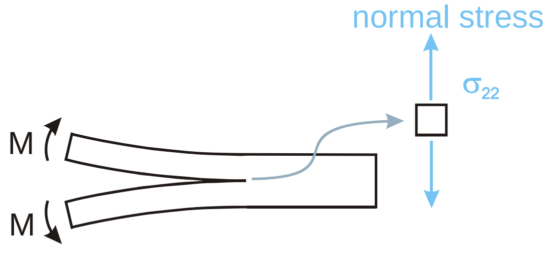
## Damage modes in composite structures - summary

- Failure of adhesive joints (leading - and trailing edges)
  - cracking inside adhesive layer
  - cracking along adhesive/laminate interface
- Sandwich delamination
- - cracking along cor
- Laminat-
  - delamina
  - tensile & compression failure (fibre fracture)
  - splitting (cracking parallel with the fibre direction)

**Design against crack propagation: use fracture mechanics**

## Fracture mechanics concepts - 1

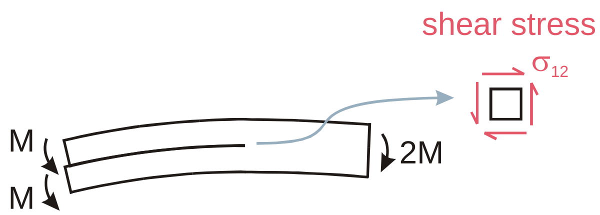
**Mode I**




crack opening normal to crack plane, $\delta_n$

## Fracture mechanics concepts - 2

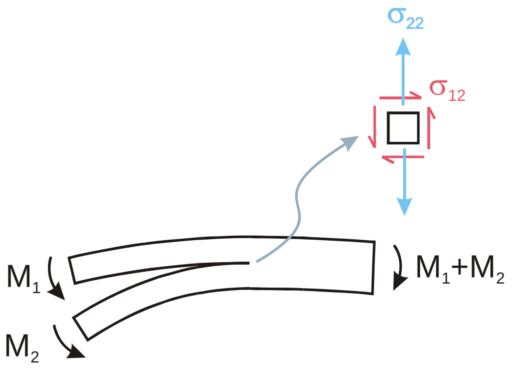
**Mode II**




tangential crack opening displacement, $\delta_t$

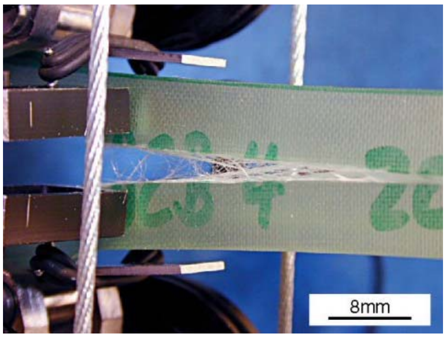
## Fracture mechanics concepts - 3

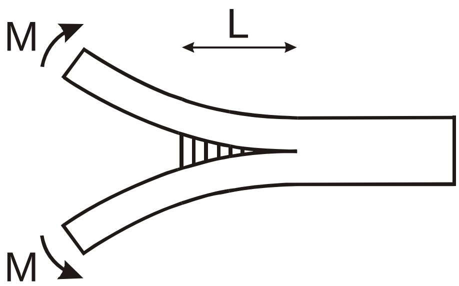
**Mixed mode**




crack opening displacements:
normal $\delta_n$ and tangential $\delta_t$

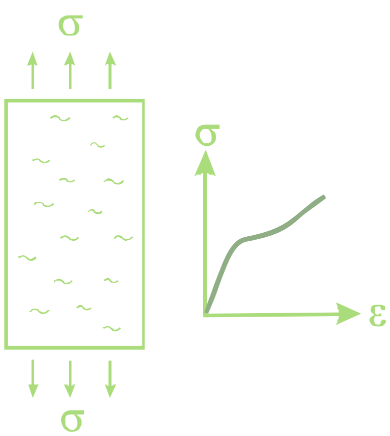
## Fracture mechanics concepts - 4



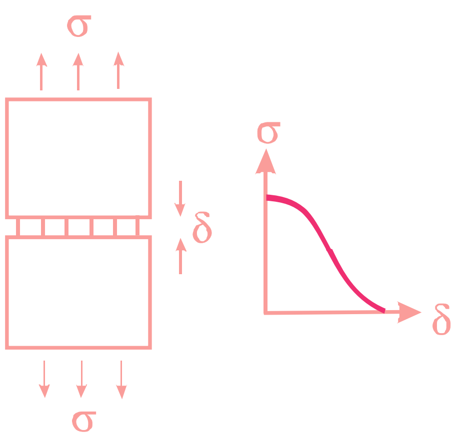




Large-scale bridging

## What is a cohesive law? - distributed and localized phenomena




Stress-strain law




Stress-separation law

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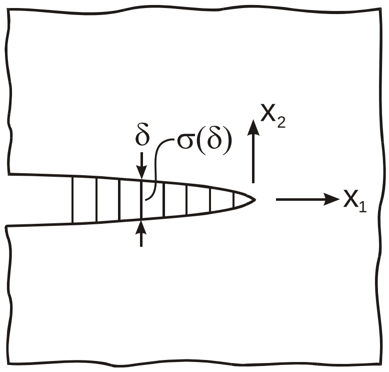
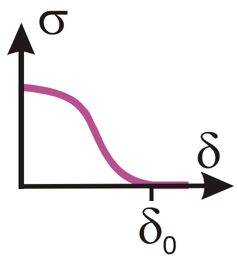
## Cohesive law - the mechanical response of the failure process zone

$$\sigma = \sigma(\delta)$$

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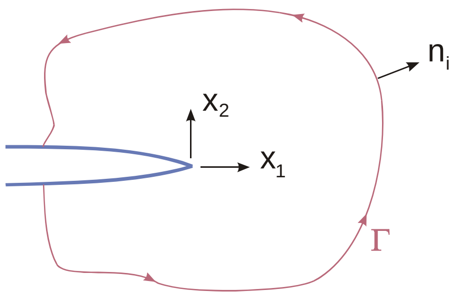
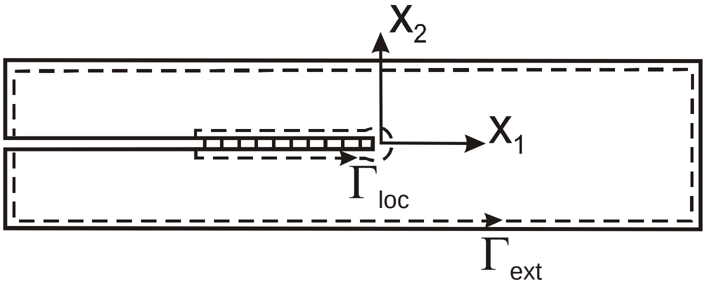
## J integral - a useful mathematical tool




$$J = \int_{\Gamma} \Phi dx_2 - \sigma_{ij} n_i \frac{\partial u_j}{\partial x_1} dS$$

## The J integral is path-independent

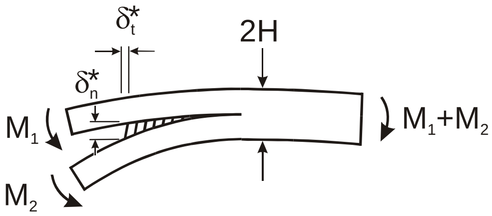



$$J_{ext} = J_{loc}$$

## A new test method - demands for a test method using the J integral approach

- Allows **stable crack growth** for all mode mixities
- Allows the **full range of mode mixity** for same geometry
  ⇒ same specimen geometry can be used for all mode mixities
  ⇒ eliminates uncertainties regarding processing differences
- Use specimen configuration for which the **J integral is given in analytical form** under large scale bridging
  ⇒ eases the determination of cohesive laws

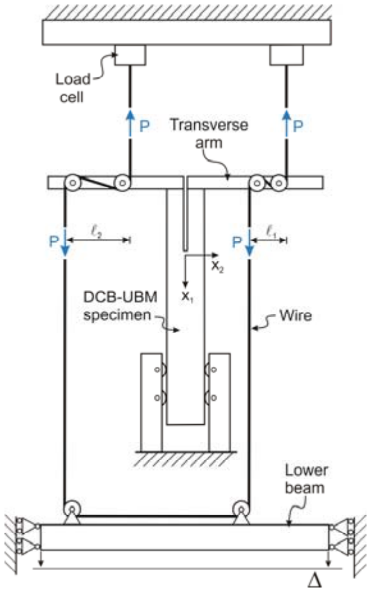
## Determination of mixed mode cohesive laws - summary




$$J = \frac{21\left(M_1^2 + M_2^2\right) - 6M_1M_2}{4B^2H^3E_{11}}$$

$$\sigma_{22}\left(\delta_n^*, \delta_t^*\right) = \frac{\partial J_R}{\partial \delta_n^*} \qquad \sigma_{12}\left(\delta_n^*, \delta_t^*\right) = \frac{\partial J_R}{\partial \delta_t^*}$$

## Loading Principle



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## The test fixture

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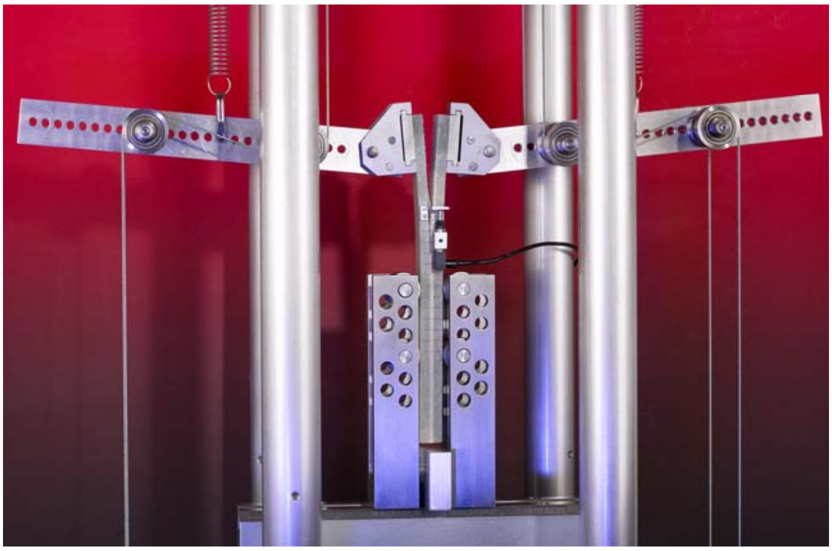
## Test fixture - applying uneven bending moments to the DCB-UBM



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## Evaluation of approach

### Manufacturing
- coupon test specimens
- medium-size specimens

### Characterisation
- measurement of material properties
  - stress/strain
  - fracture toughness (cohesive laws)

### Component testing
- test of medium size specimen
  - measurement of deformation
  - measurement of maximum load

### Model prediction
- model of component
  - prediction of deformation
  - predicting of load carrying capacity

### Comparison
- predicted maximum load
- experimental maximum load

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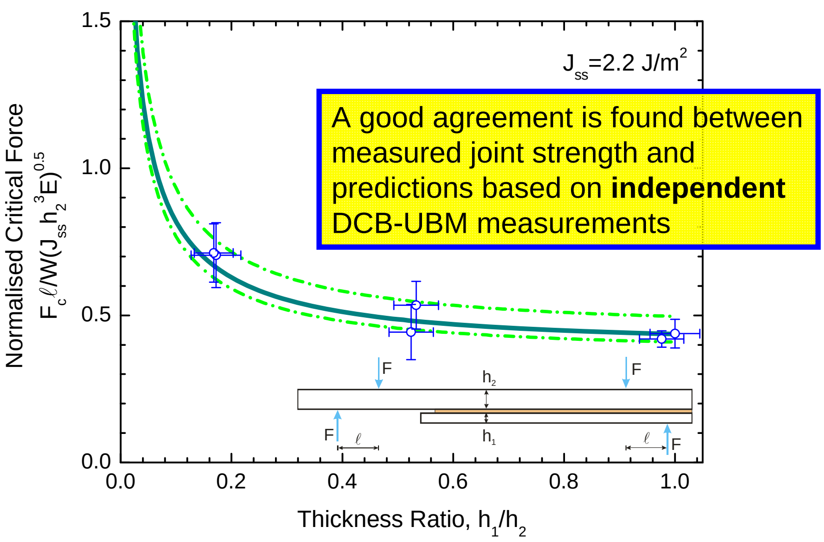
## Test set-up - medium size specimens

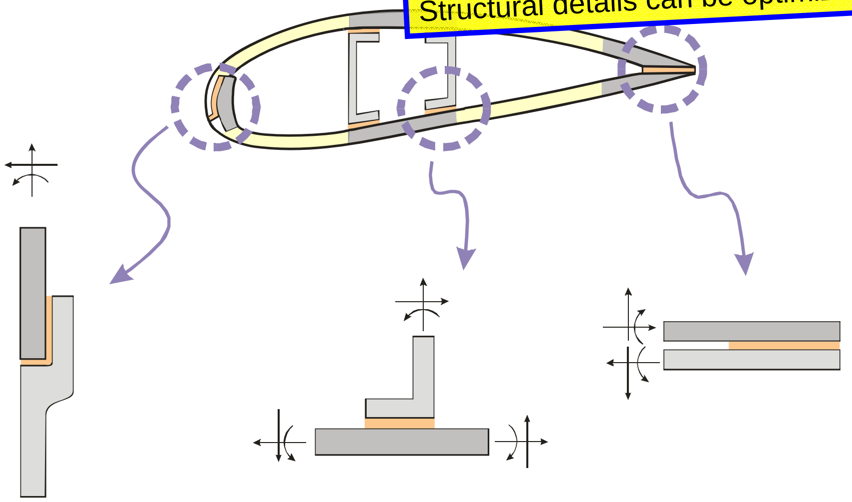
## Predicted and measured strength




## Adhesive joints in wind turbine blades

Failure can be modelled by fracture mechanics

Structural details can be optimized



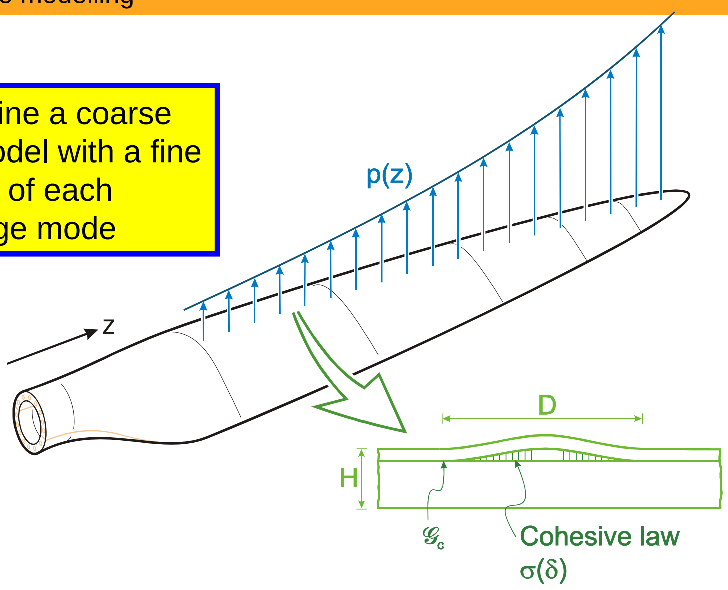
## Perspectives

Capabilities of characterising and modelling damage growth in wind turbine blades offers **challenges** and **possibilities**:

- multiscale modelling ⇒ **combine models**, coarse and fine
- understanding failure mechanisms ⇒ **optimize materials**
- understanding structural failure
  ⇒ optimize **repair** (understanding when to repair)
  ⇒ enables proper use of **structural health monitoring**

## Multiscale modelling

Combine a coarse 3D model with a fine model of each damage mode



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## Concluding remarks

- ❑Material mechanics and the continuum damage mechanics approach is used to account for the basic behaviour of the materials and to characterize the damage evolution in long fiber laminated composites.
- ❑Fracture mechanics and cohesive laws are used for analysing construction details and joints
- ❑The experimentally determined behaviour are based on both component and full scale tests
- ❑Larger structures necessitates analyses and tests of scaled components.
- ❑The relationships between component behaviour and full scale can be analysed using models and mechanical laws based on the fundamentals in materials mechanics

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## How large can they grow?




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## Large Wind Turbines – 55 m rotor blades

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## 5M Wind Power Turbine, Brunsbüttel, Germany, 61.5 m blades

**(Courtesy of LM Glasfiber A/S)**