Crack growth in adhesive joints in polymer matrix composites:
- numerical modelling and experiments

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Motivation

- test accuracy of predictions from CZM

Strategic aim:

Use cohesive zone modelling (CZM) in modelling of wind turbine blades

LM Glasfiber A/S

Example: LM 61.5 m long blades deflects 17 meters during certification test

Motivation

- test accuracy of predictions from CZM

Strategic aim:

Use cohesive zone modelling (CZM) in modelling of wind turbine blades

Short term aim:

Demonstrate the capability of CZM - test accuracy of strength predictions, in particular

- investigate sensitivity to **cohesive law parameters**

Outline

– problem in focus: adhesive joint specimens

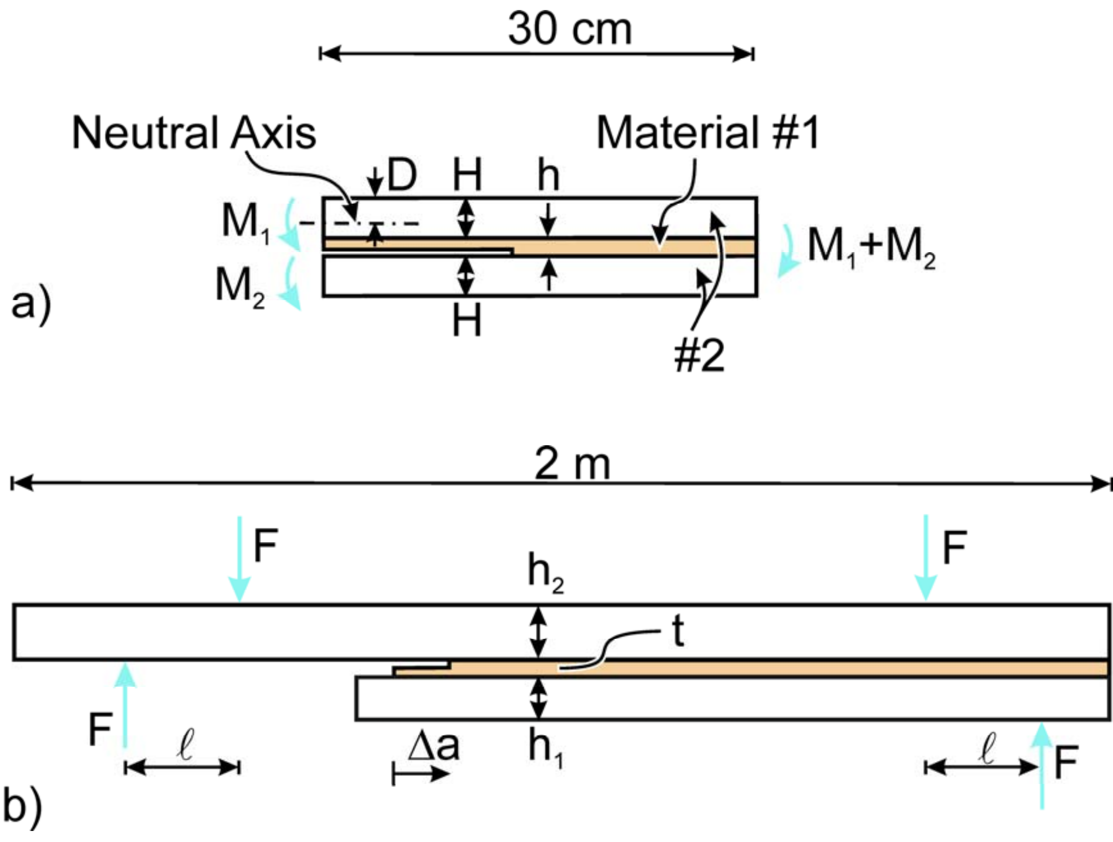
- 1) Determine mode I and mode II cohesive lows (DCB-UBM)

⇓

- 2) Predict joint strength - finite element simulations

⇓

- 3) Compare with experimental results



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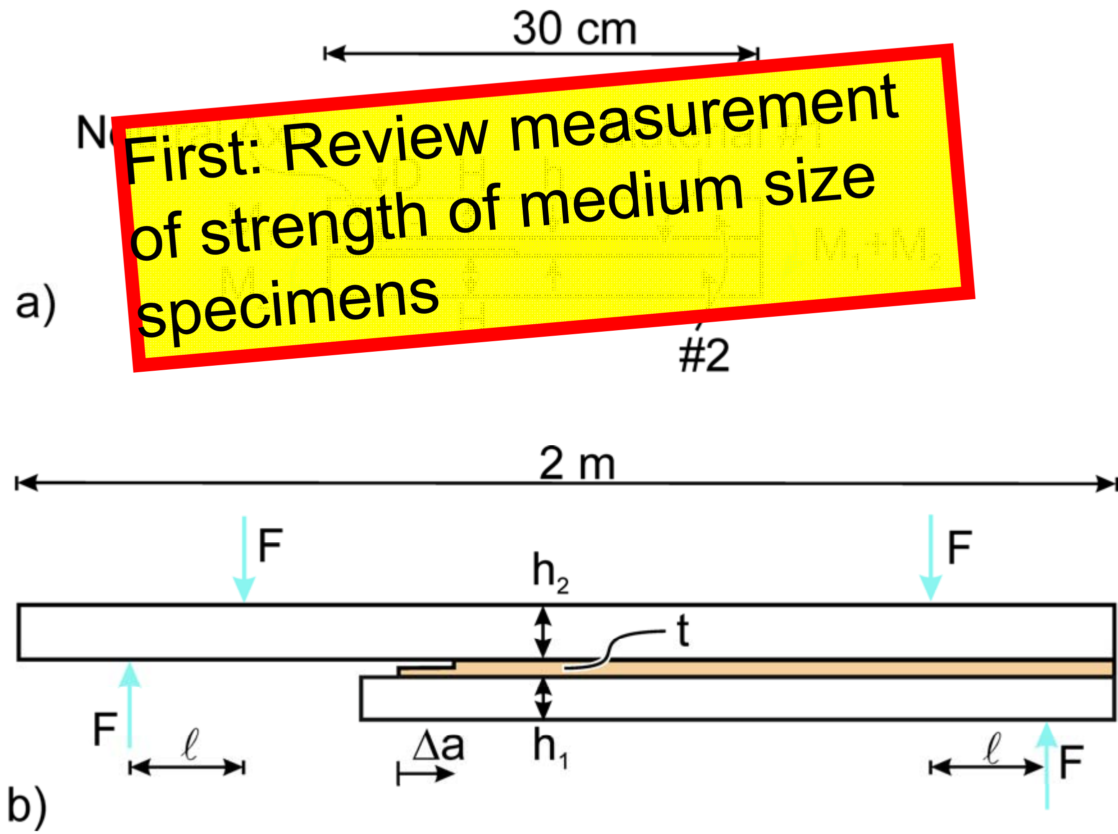
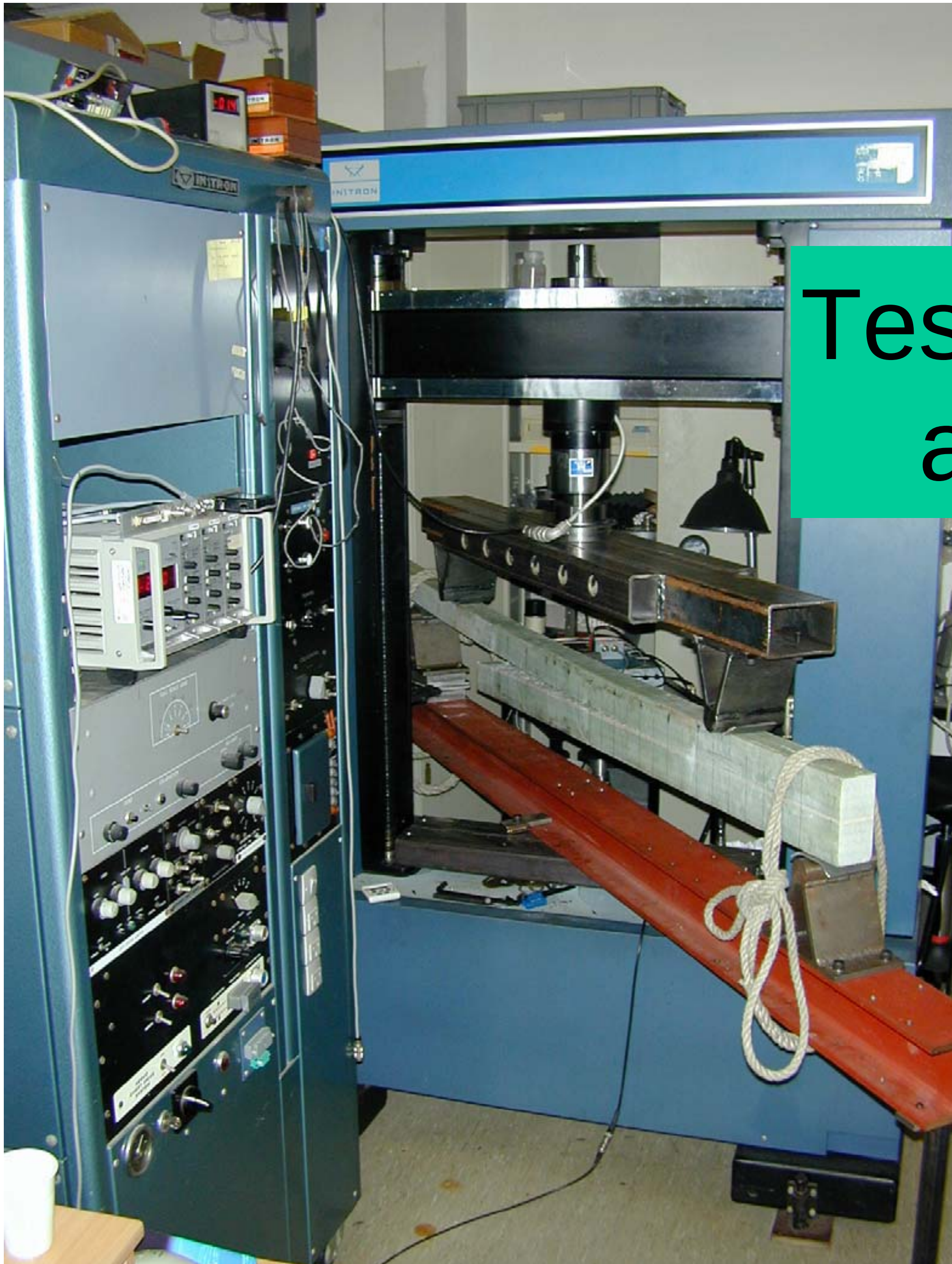


First: Review measurement of strength of medium size specimens

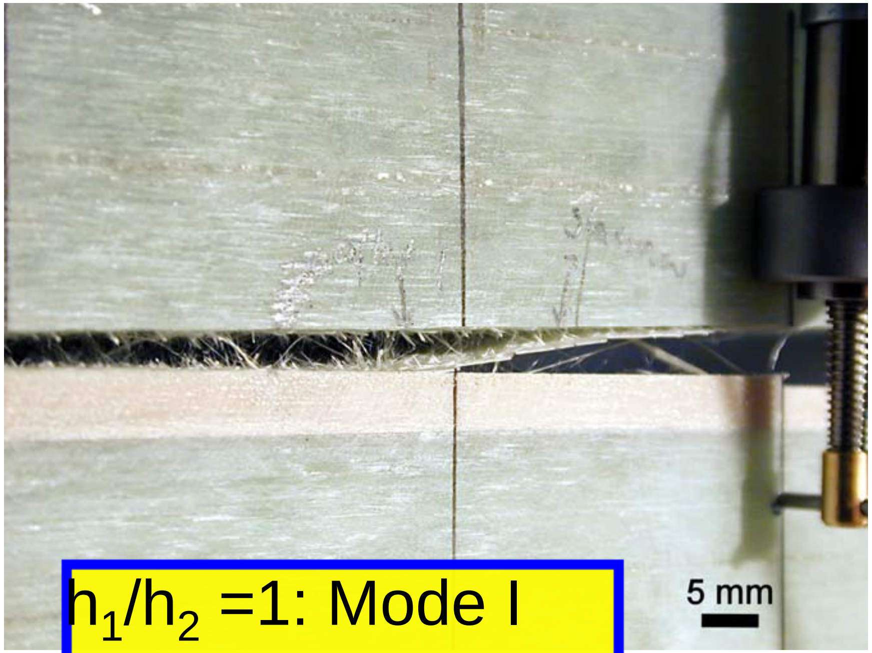
DTU



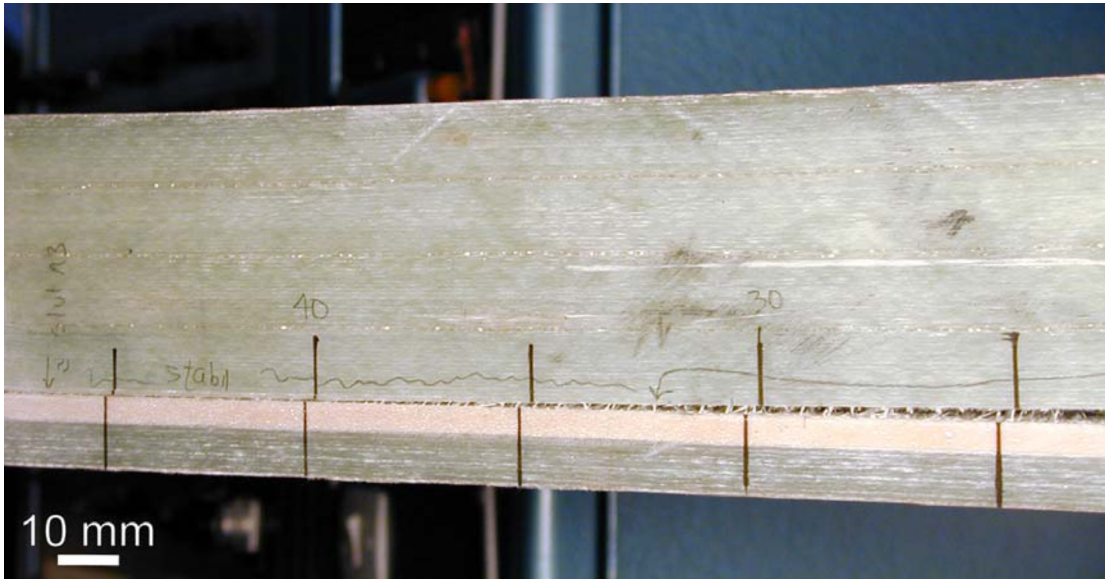
Test of medium size adhesive joints

- polymer matrix composite
- polymer adhesive
- 3 different h_1/h_2 (thickness) ratios

Crack growth
- openings



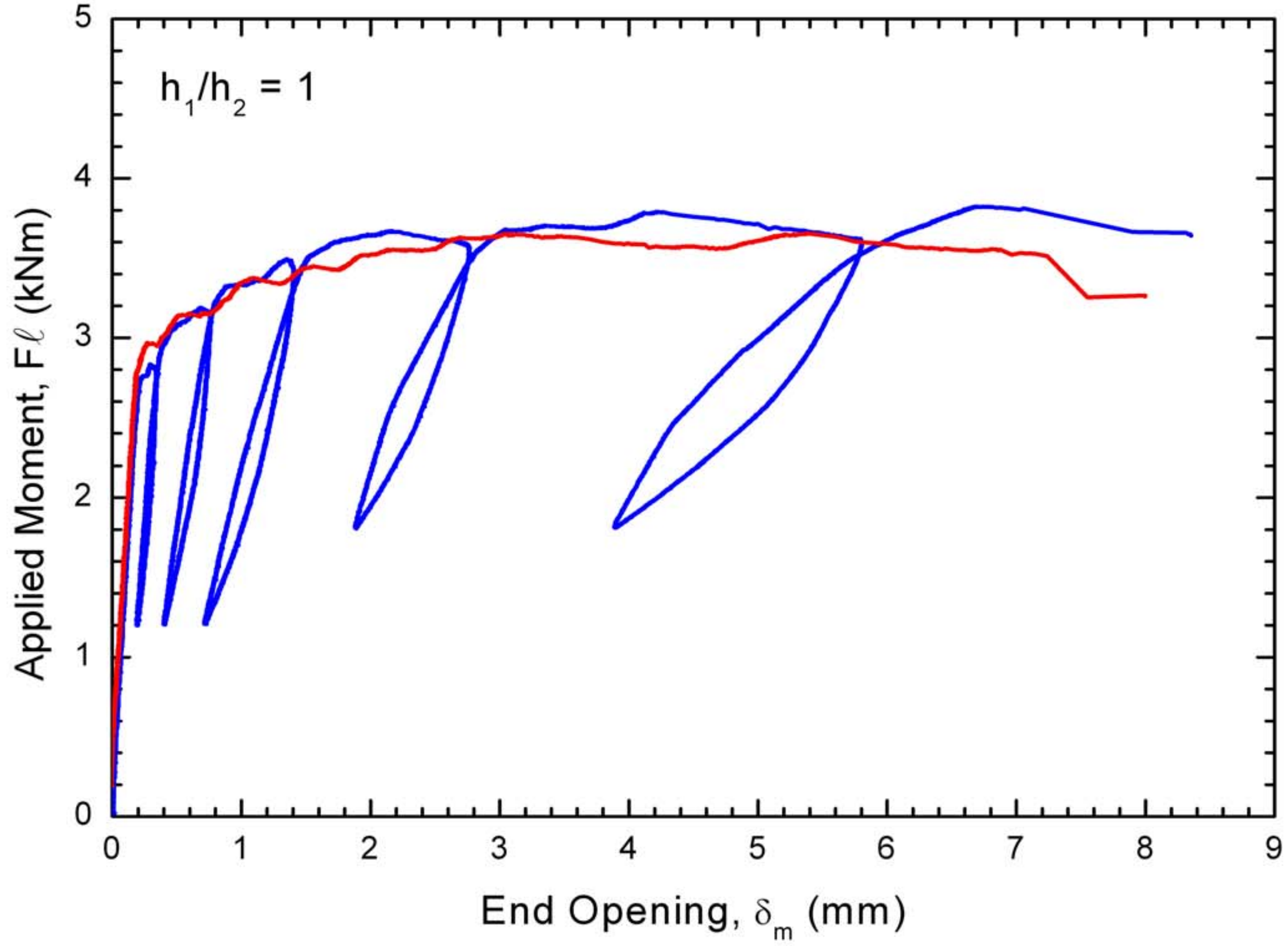
h_1/h_2 =1: Mode I dominated opening



h_1/h_2 =0.17: Mode II dominated opening

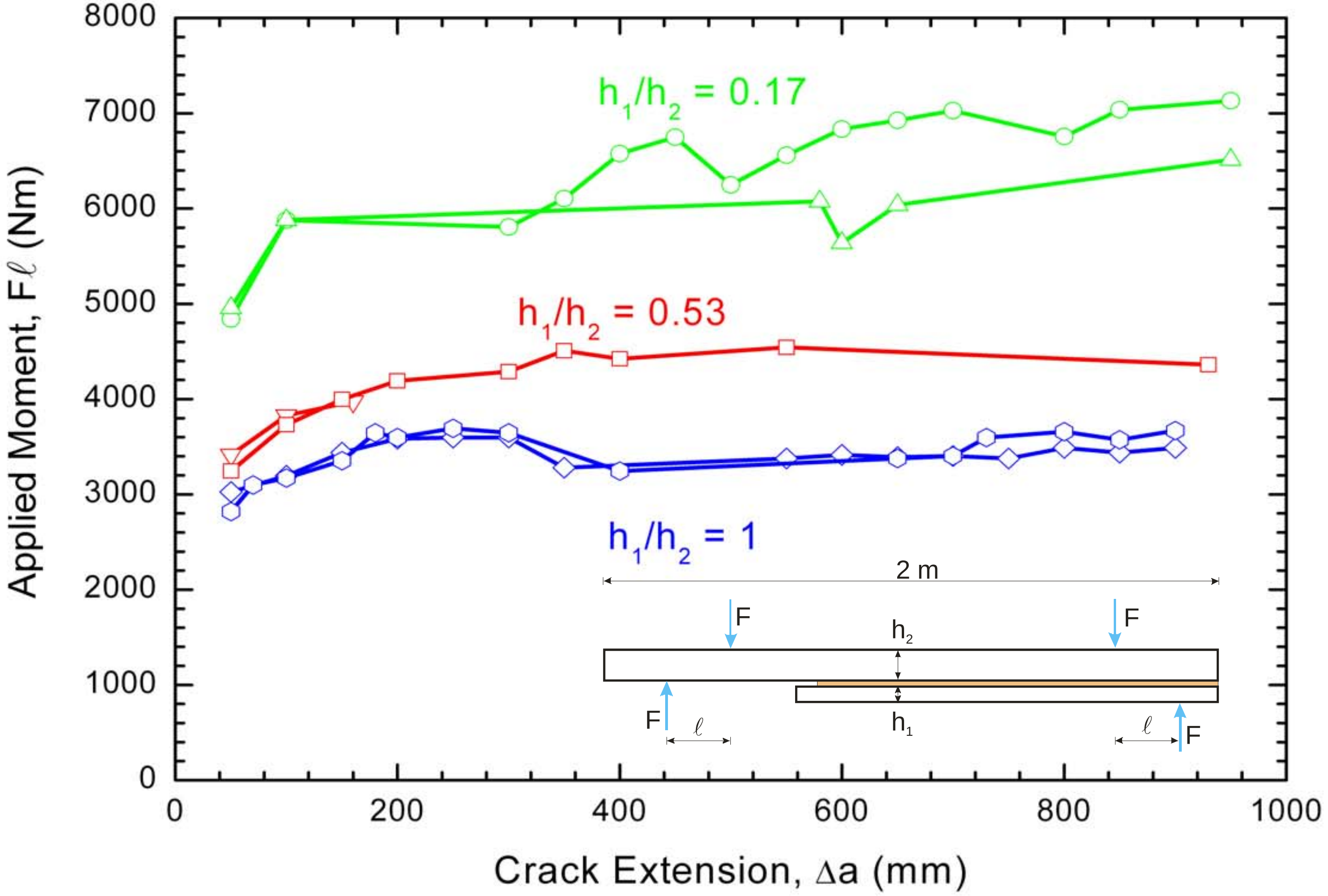
Typical results

- measured moment-opening relationship



Effect of thickness ratio h_1/h_2

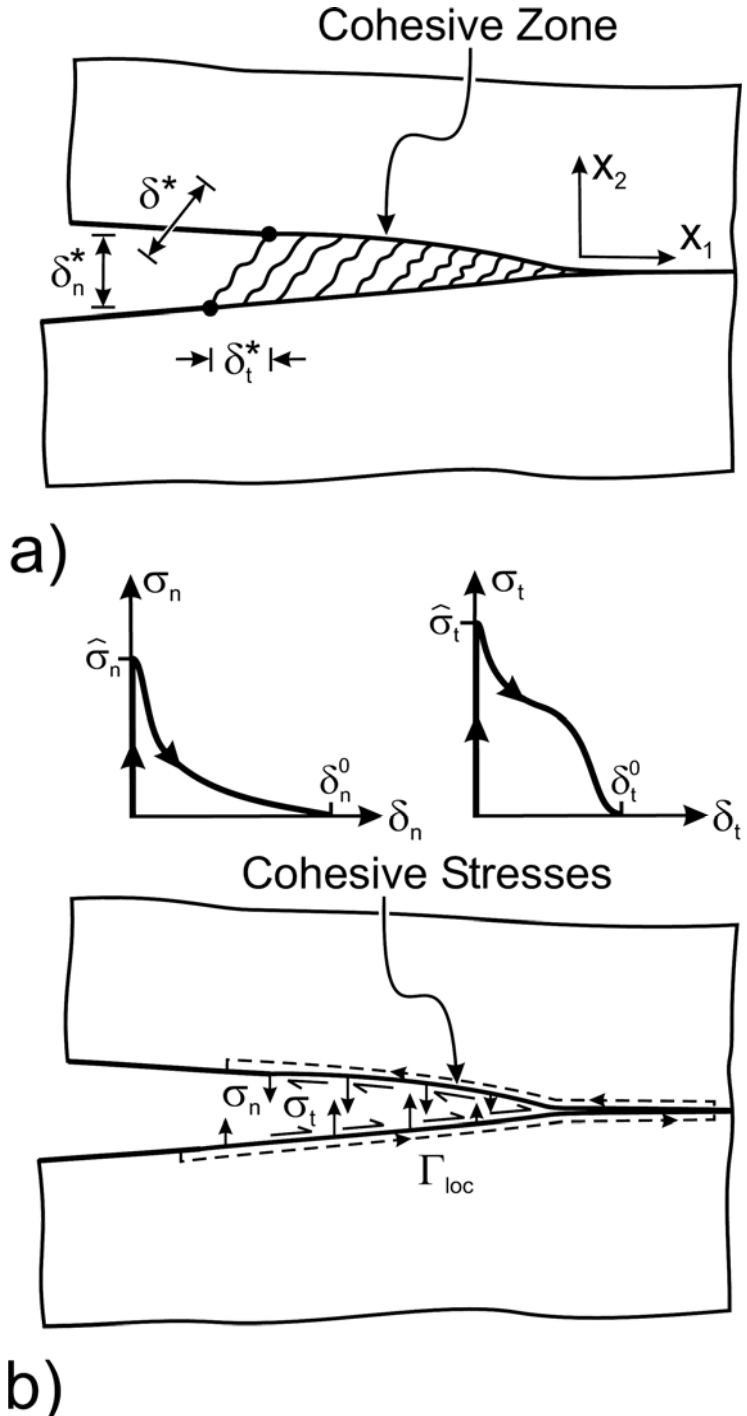
- moment as a function of crack extension



Part 1: Cohesive laws

- measurements

- Part 1: Measurements of cohesive laws
- Part 2: FE Modelling
- Part 3: Comparison with experiments (medium size specimens)



Cohesive laws

- stress-separation laws

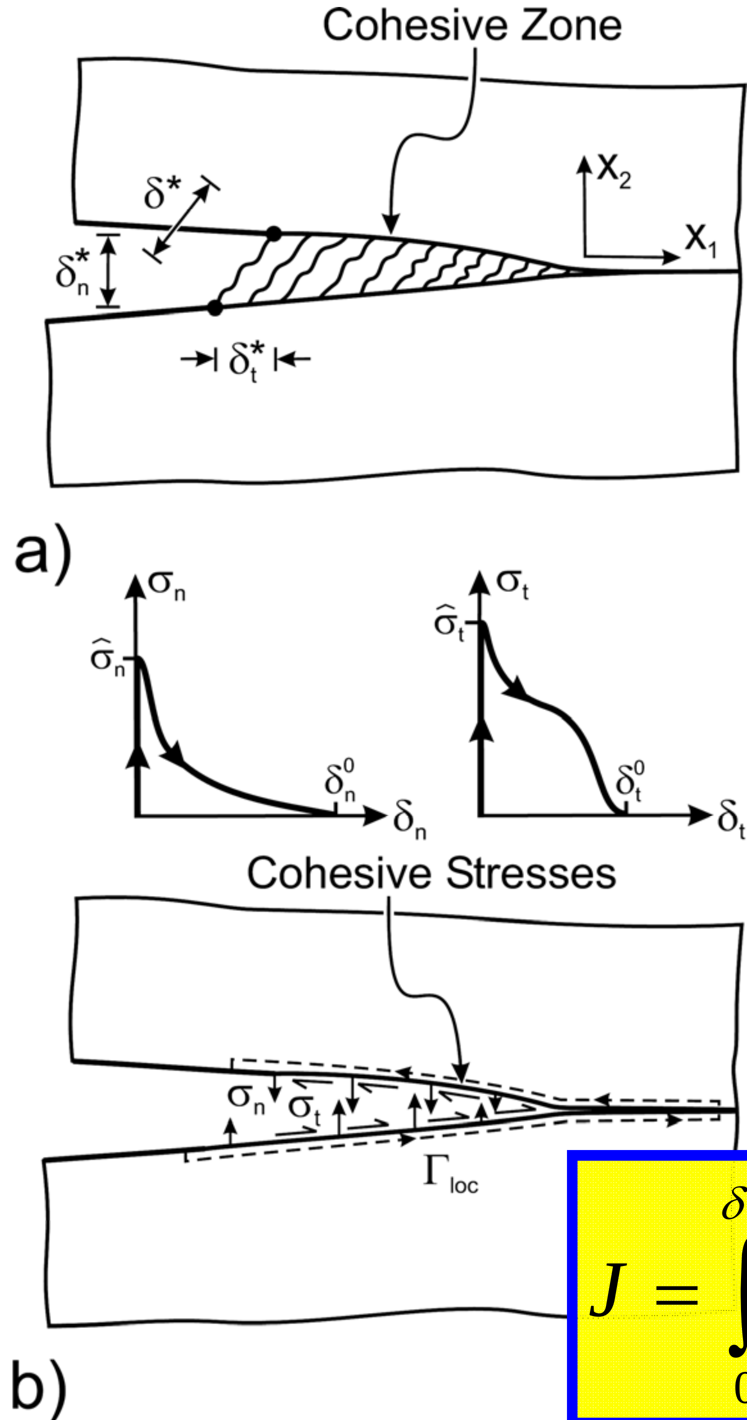
Stresses depend on separations:

$$\sigma_n = \sigma_n(\delta_n, \delta_t)$$

$$\sigma_t = \sigma_t(\delta_n, \delta_t)$$

Cohesive laws

- stress-separation laws



Stresses depend on separations:

$$\sigma_n = \sigma_n(\delta_n, \delta_t)$$

$$\sigma_t = \sigma_t(\delta_n, \delta_t)$$

$$J = \int_0^{\delta_n^*} \sigma_n(\delta_n, \delta_t) d\delta_n + \int_0^{\delta_t^*} \sigma_t(\delta_n, \delta_t) d\delta_t$$

Determination of cohesive laws

- a J integral approach

Under pure normal opening

("mode I")

$$\frac{dJ_R}{d\delta_n^*} = \sigma_n\left(\delta_n^*\right)$$

where δ^*_n is the end-opening

Under pure tangential opening

("mode II")

$$\frac{dJ_R}{d\delta_t^*} = \sigma_t\left(\delta_t^*\right)$$

where δ^*_t is the end-sliding

Determination of cohesive laws

- a J integral approach

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$$\frac{dJ_R}{d\delta_t^*} = \sigma_t\left(\delta_t^*\right)$$

where δ^*_t is the end-sliding

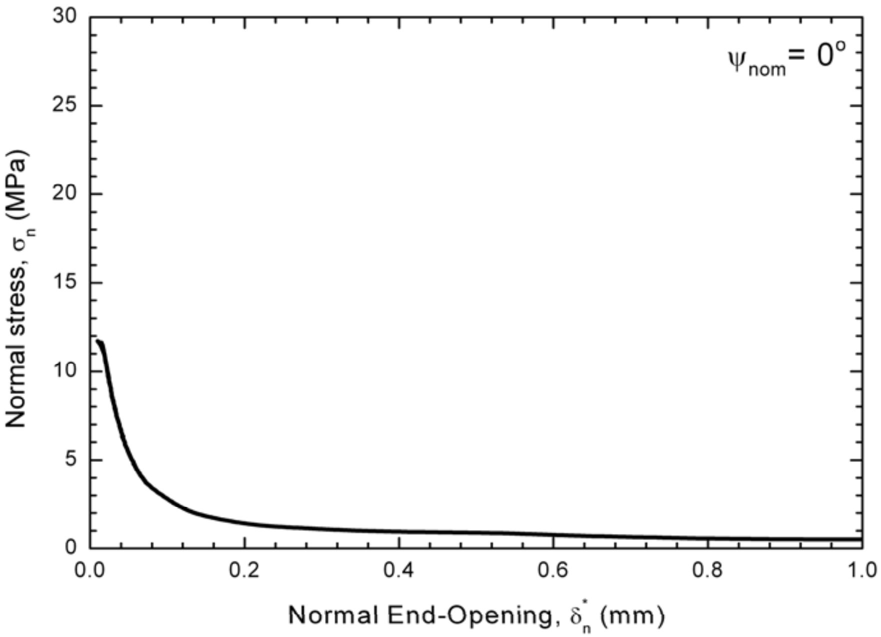
Idea:

a) measure fracture resistance, J_R, end-opening, δ^*_n and end-sliding δ^*_t, during experiments - DCB specimens loaded with uneven bening moments (DCB-UBM)

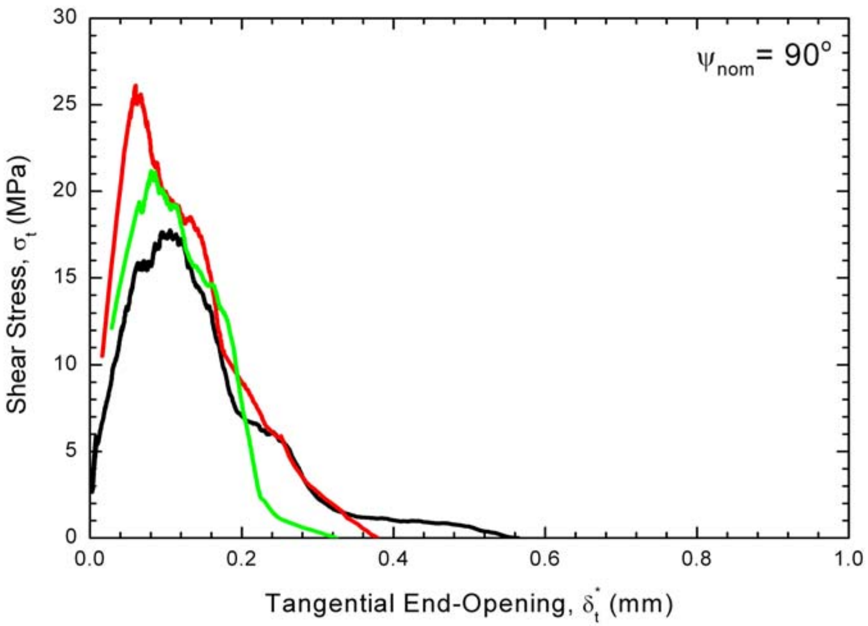
b) determine pure mode cohesive laws by differentiation

Measured cohesive laws
- pure modes

"Mode I"

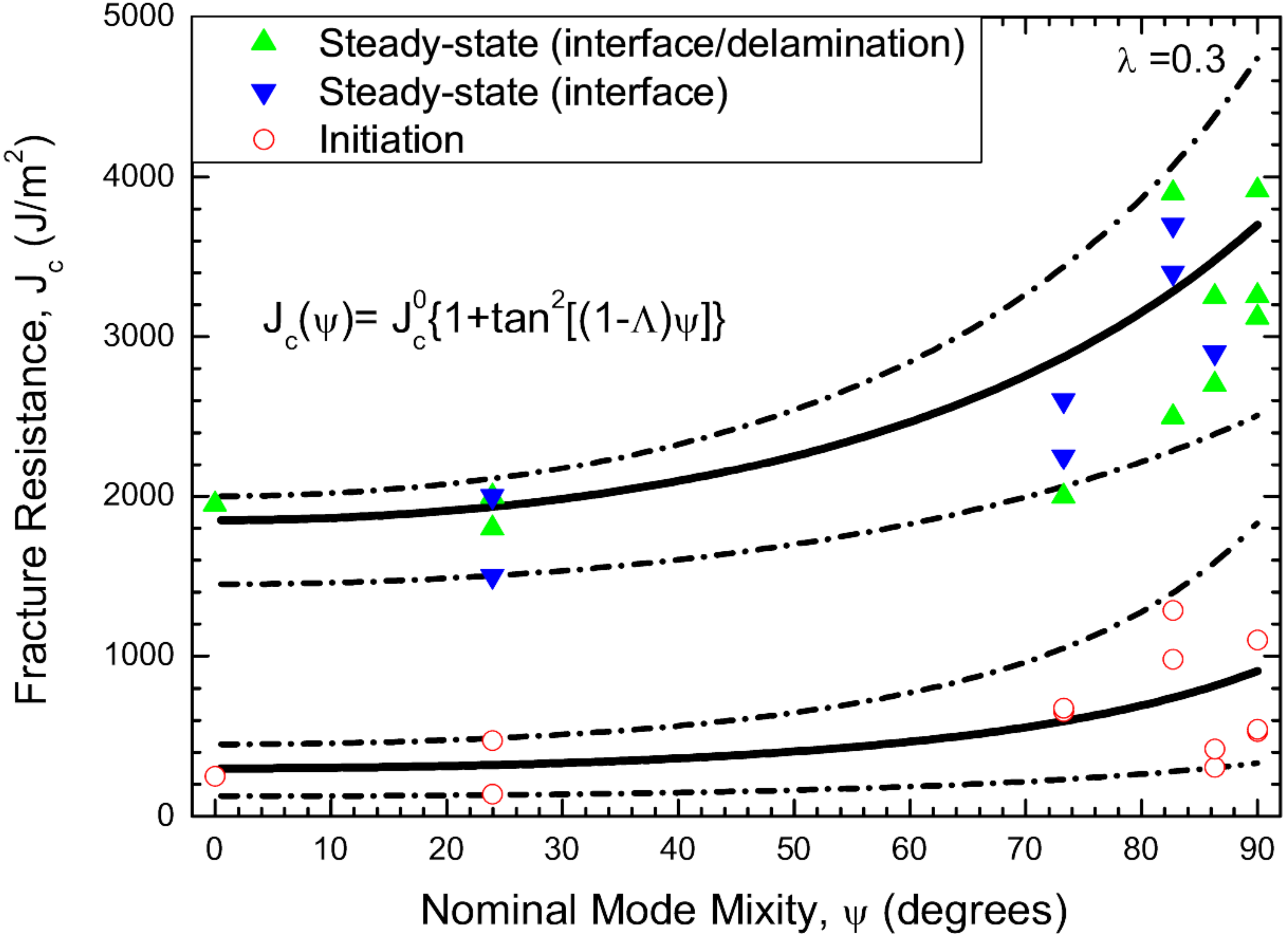


"Mode II"



Measured fracture resistance

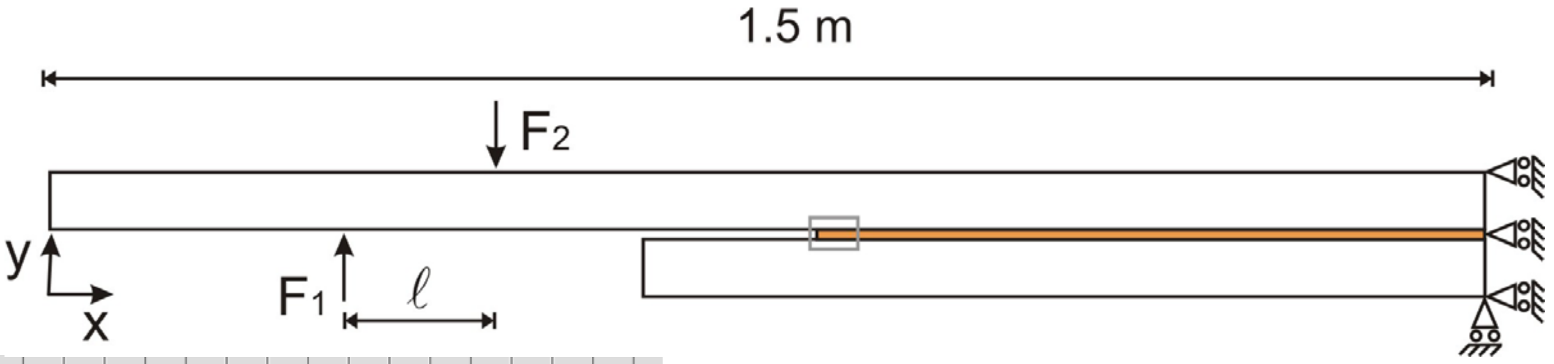
- steady-state value higher than initiation value

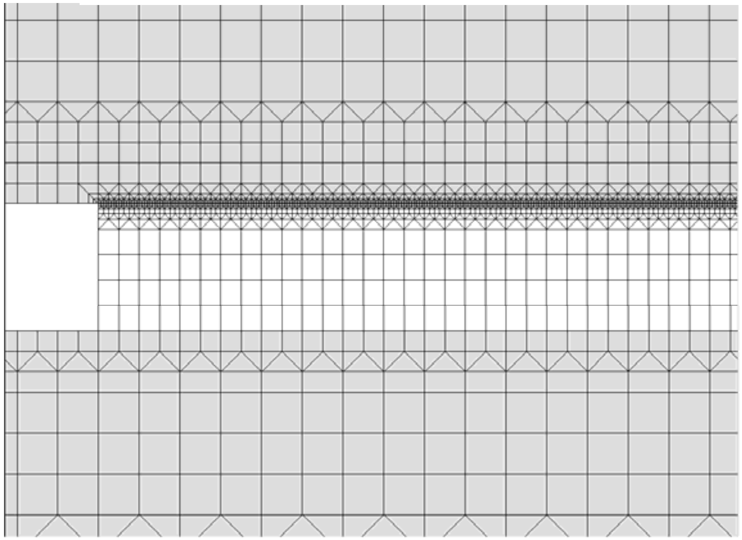


Part 2: Modelling

- Part 1: Measurements of cohesive laws
- Part 2: FE Modelling
- Part 3: Comparison with experiments (medium size specimens)

Finite Element (FE) formulation
- 2D plane problem

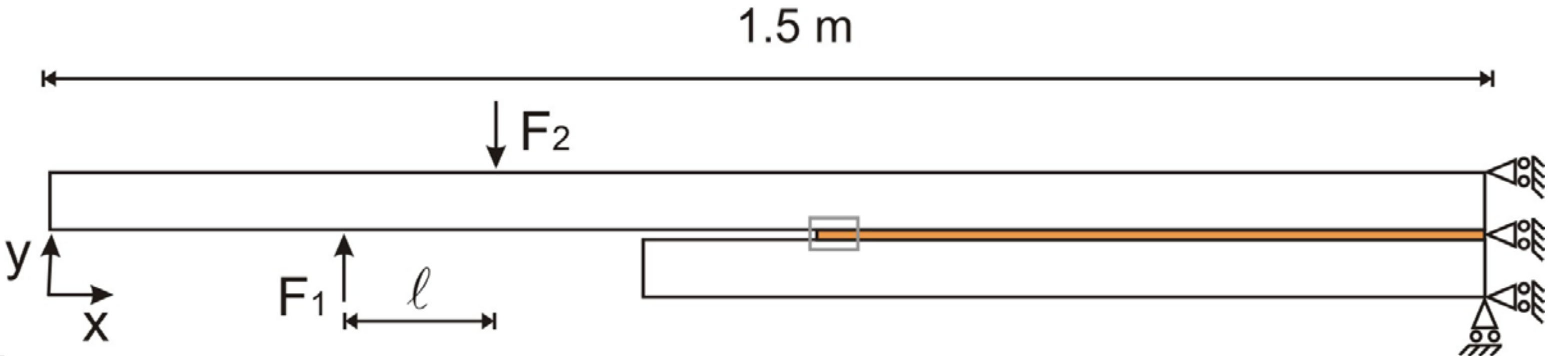


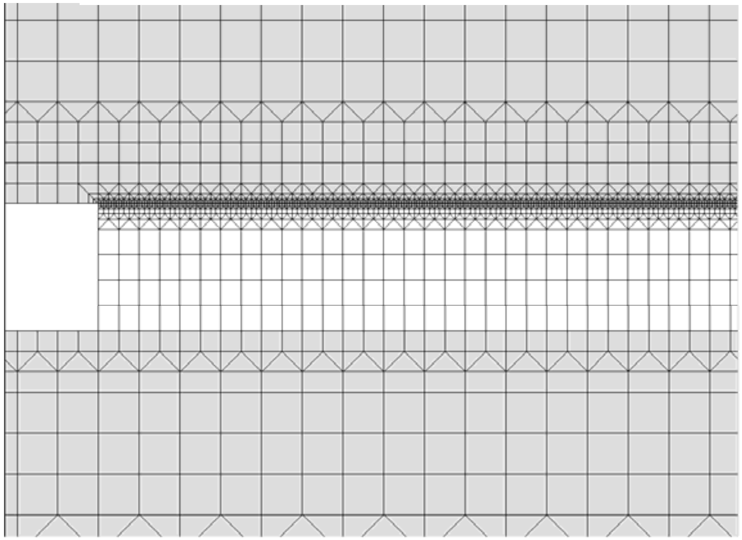


Abaqus Explicit commercial code used to solve the problem under quasi-static conditions (prescribed displacements)

Finite Element (FE) formulation

- 2D plane problem





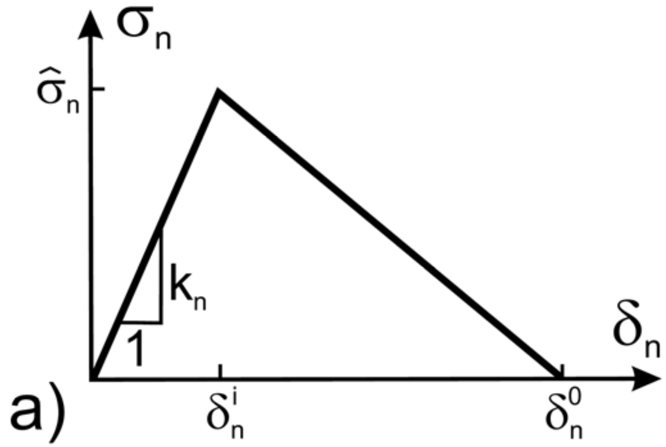
←Cohesive zone

Abaqus Explicit commercial code used to solve the problem under quasi-static conditions (prescribed displacements)

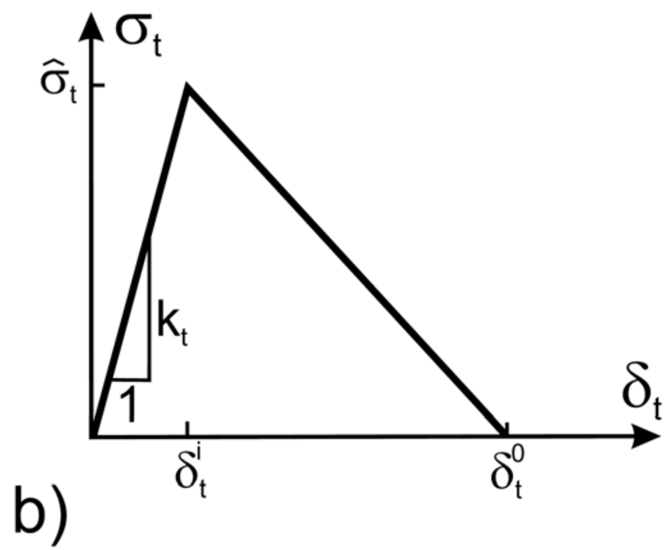
Pure mode cohesive laws

- build in cohesive laws in Abaqus

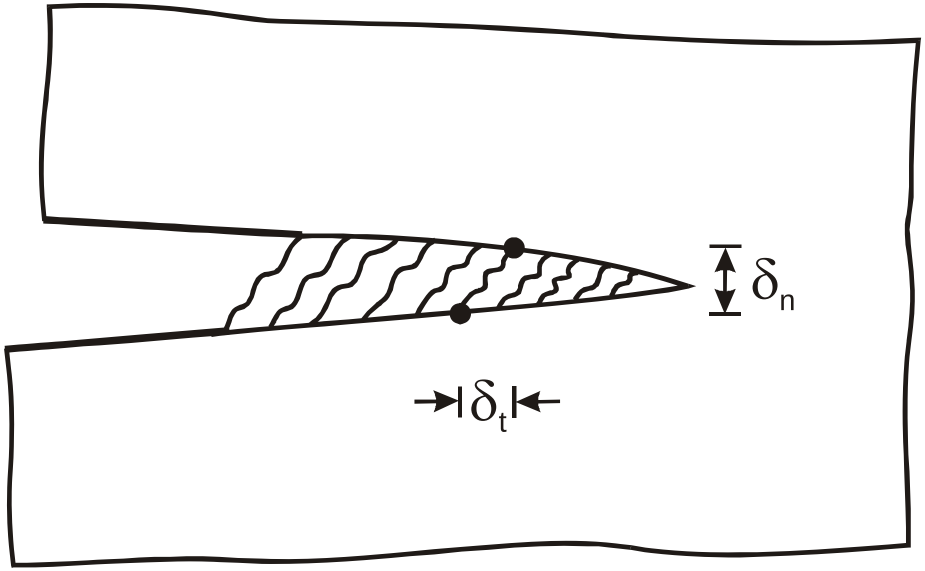
Normal stress

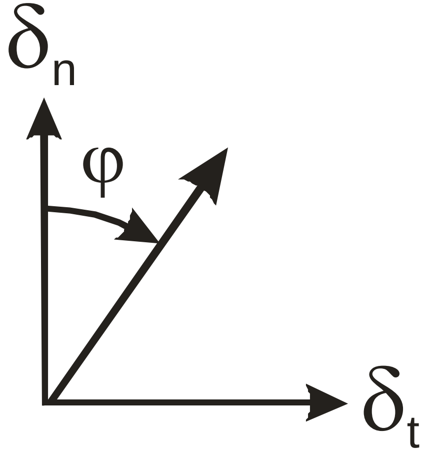


Shear stress



Phase angle of opening, φ





$$\varphi = \tan^{-1}(\delta_t/\delta_n)$$

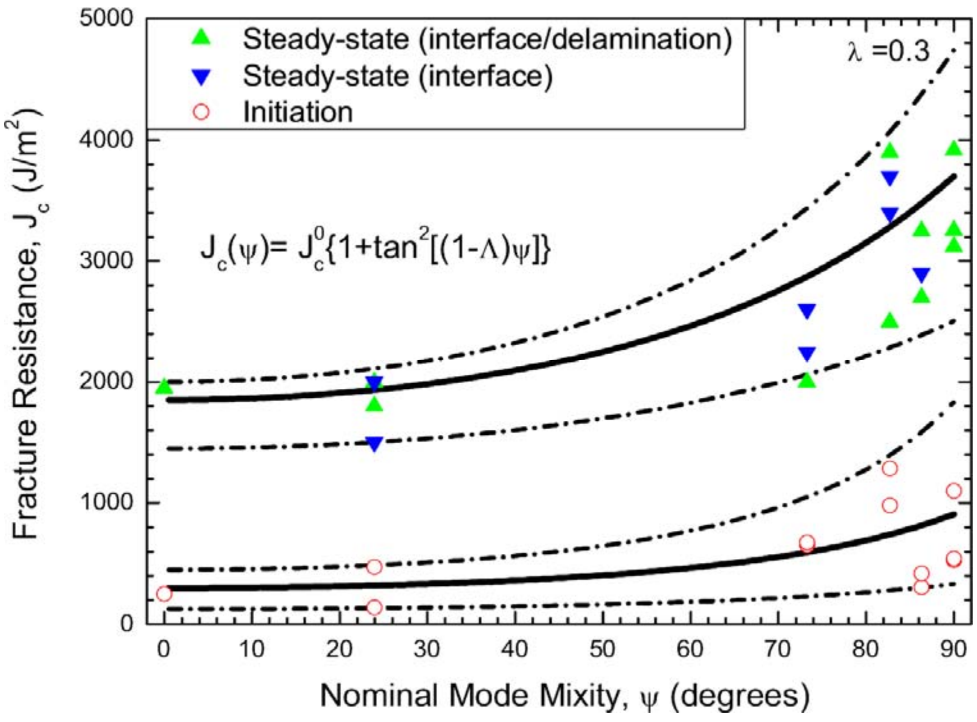
Mixed mode cohesive stresses

- ensuring correct mixed mode fracture energy

Assume φ = ψ (phase angle of openings φ equal to nominal mode mixity ψ)

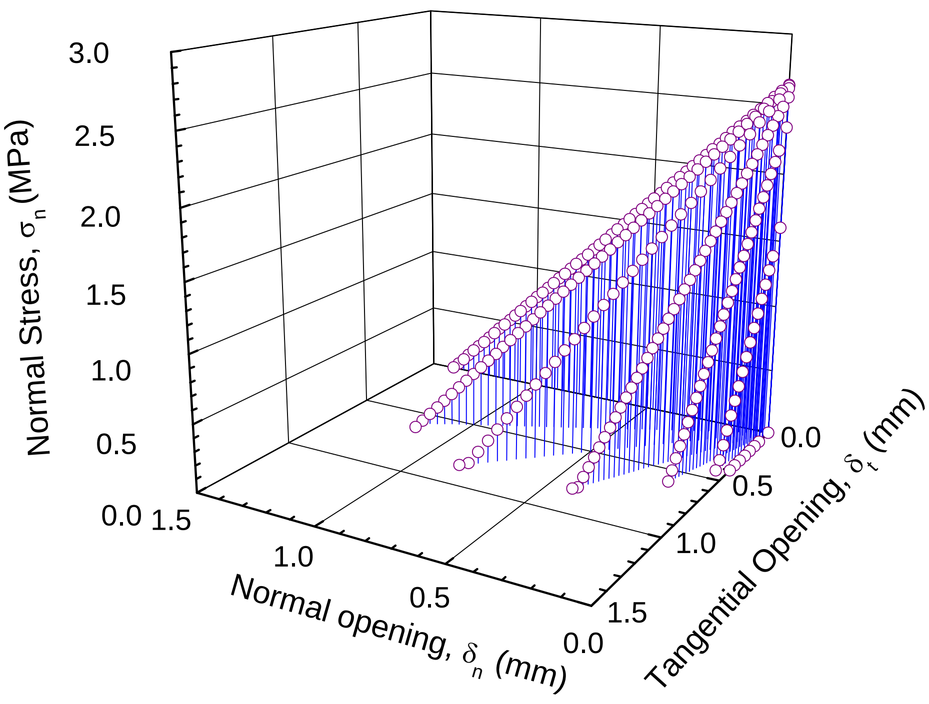
Decreasing peak stresses $\hat{\sigma}_n(\varphi)$ and $\hat{\sigma}_t(\varphi)$ to ensure correct mixed mode fracture energy, $J_c = J_c(\psi)$

$$\left(\frac{\hat{\sigma}_n(\varphi)}{\hat{\sigma}_n(\varphi = 0^\circ)}\right)^2 + \left(\frac{\hat{\sigma}_t(\varphi)}{\hat{\sigma}_t(\varphi = 90^\circ)}\right)^2 = 1$$

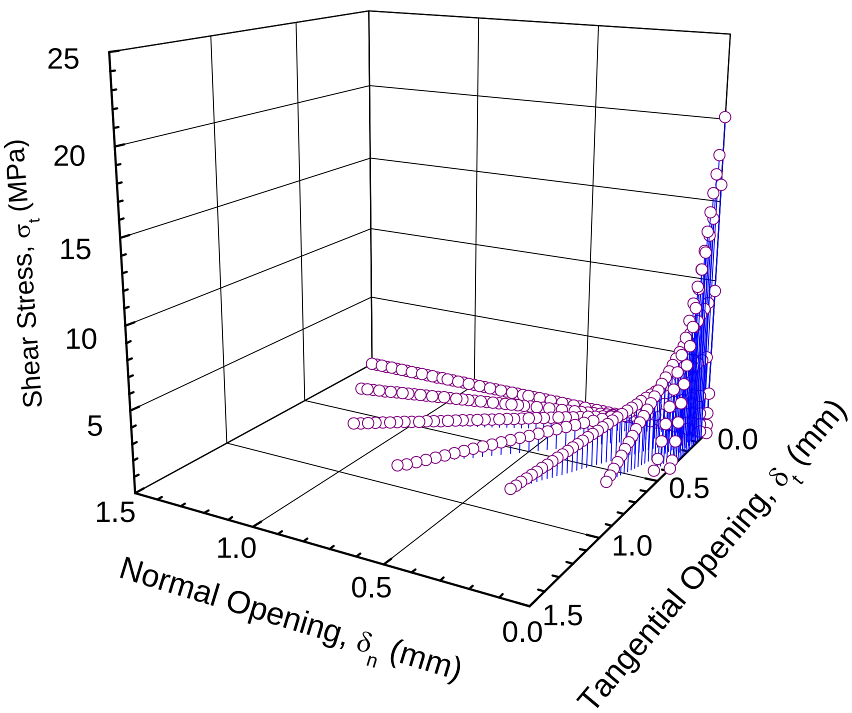


Mixed mode cohesive stresses
- as a function of normal and tangential openings

Normal stress



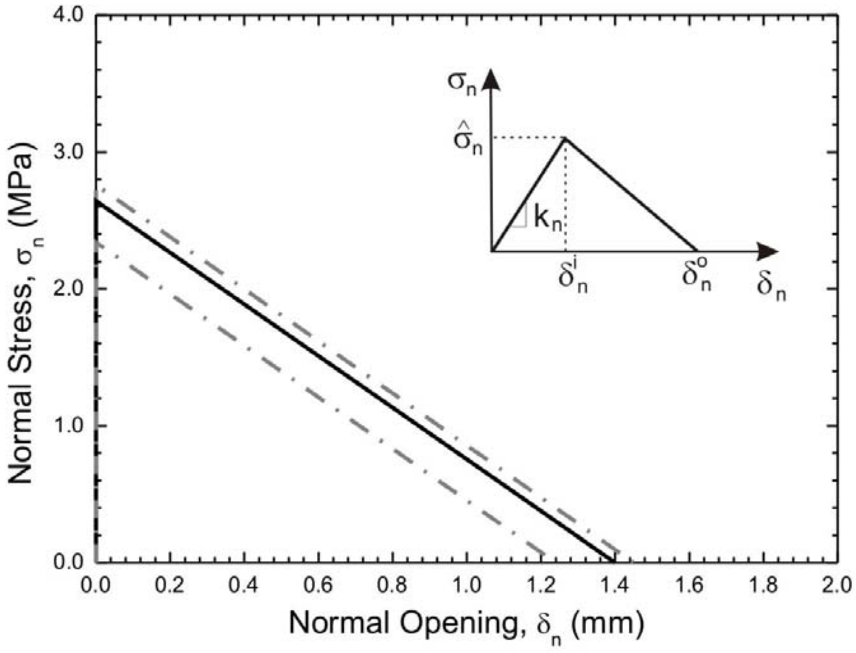
Shear stress



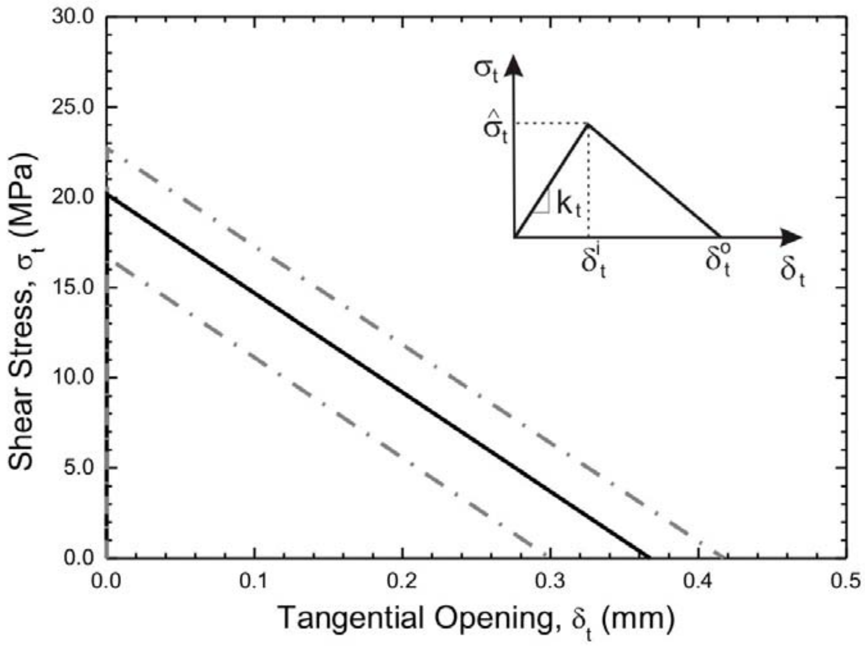
Cohesive law parameters

- average, upper and lower bounds of fracture energy

<u>Normal stress</u>

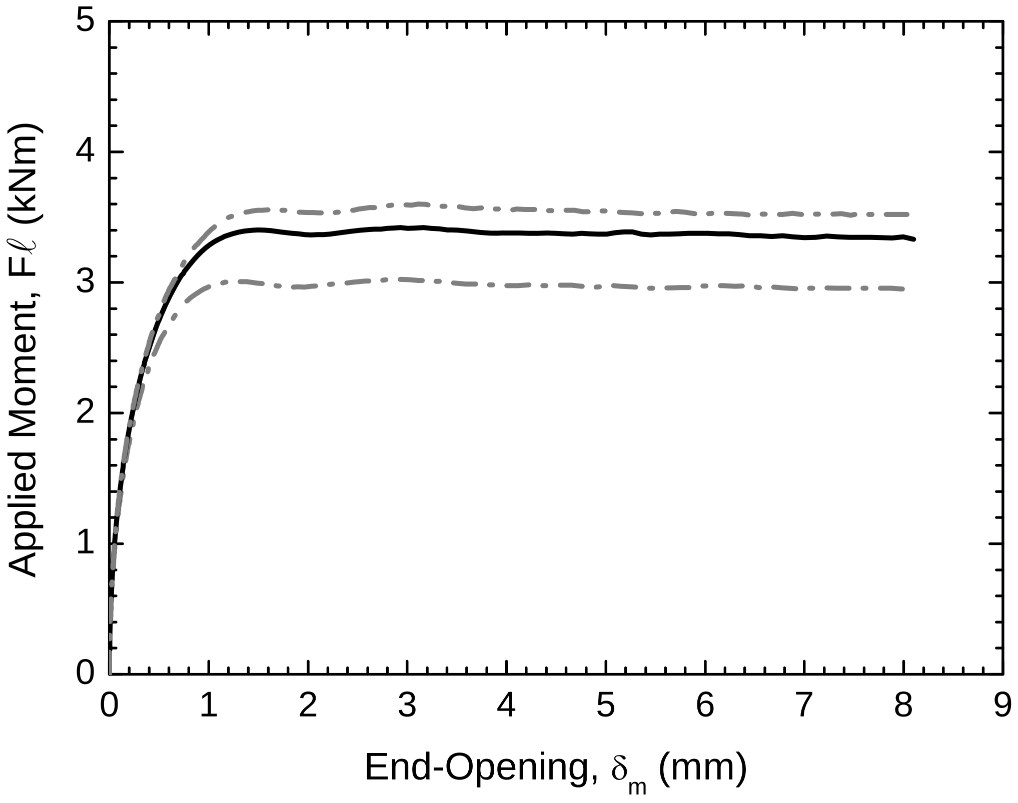


<u>Shear stress</u>



Example of prediction

- moment as a function of end opening

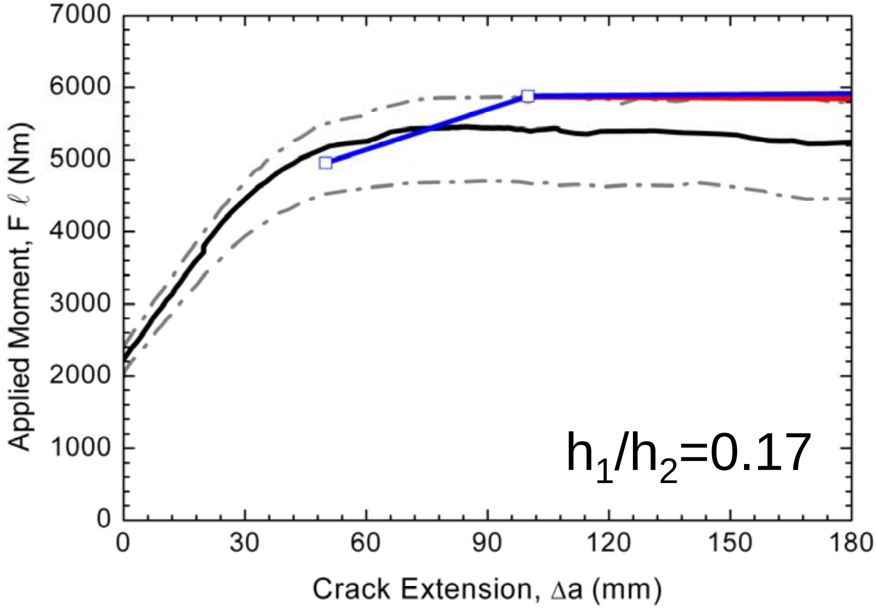


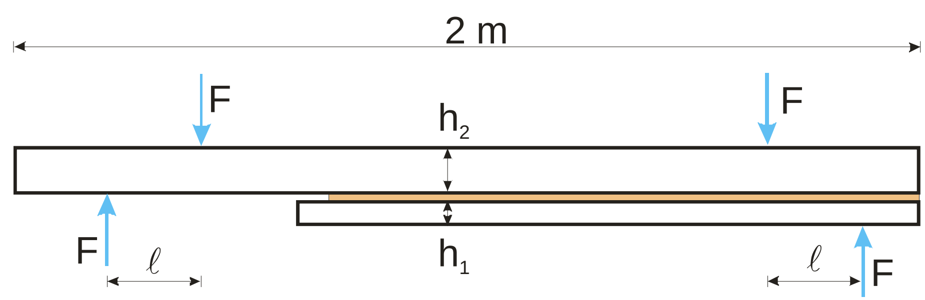
Part 3: Comparison with experiments

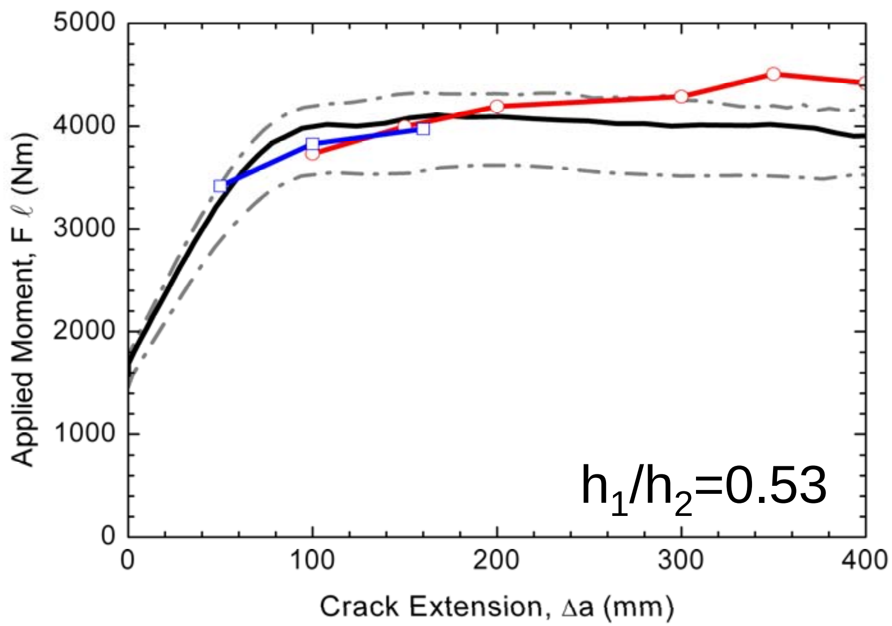
- Part 1: Measurements of cohesive laws
- Part 2: FE Modelling
- Part 3: Comparison with experiments (medium size specimens)

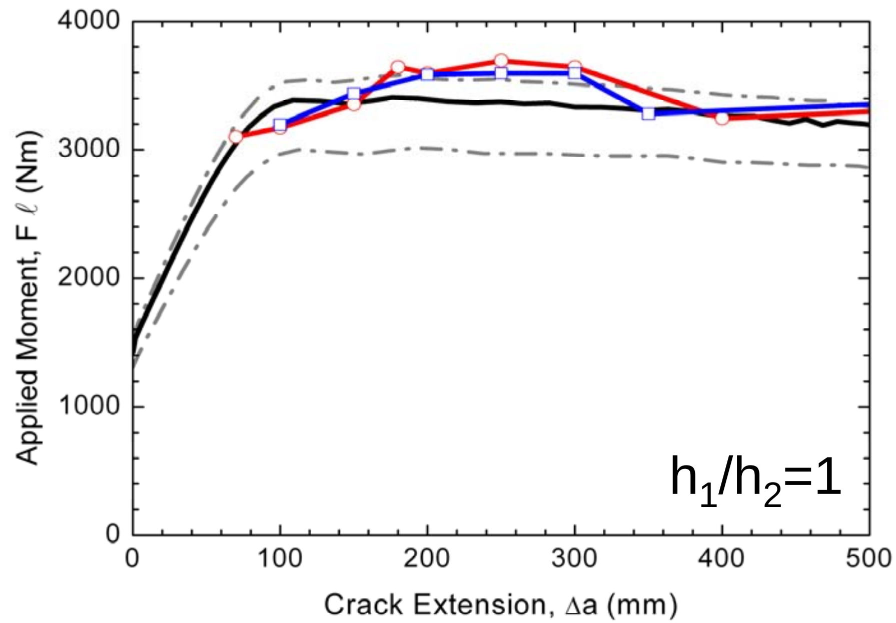
Comparison

- effect of crack length and beam thickness ratio, h_1/h_2





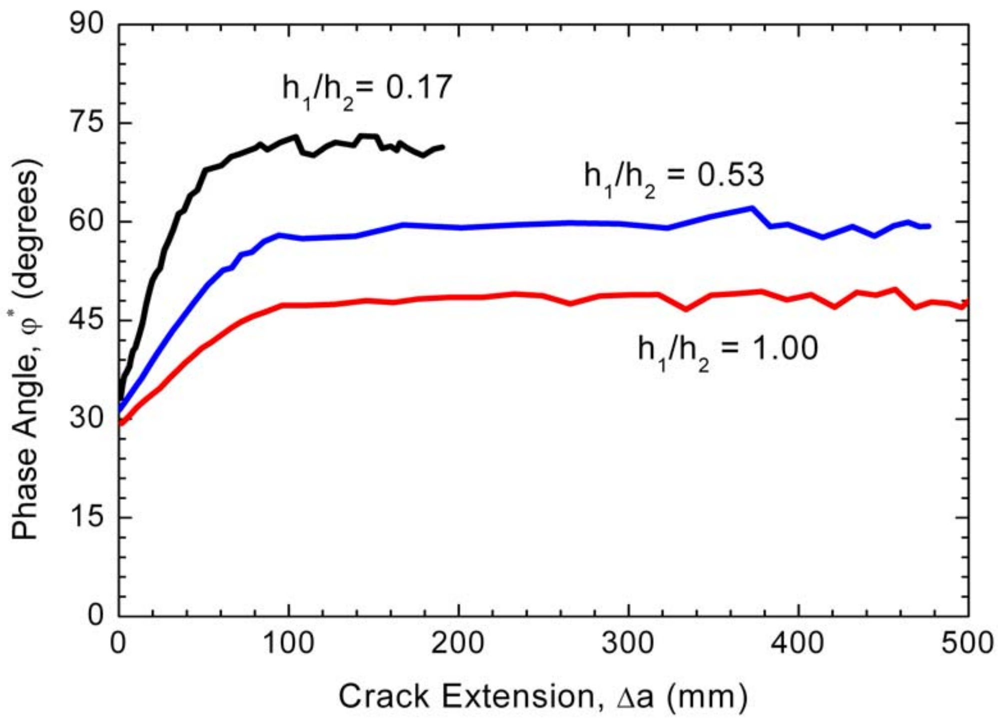


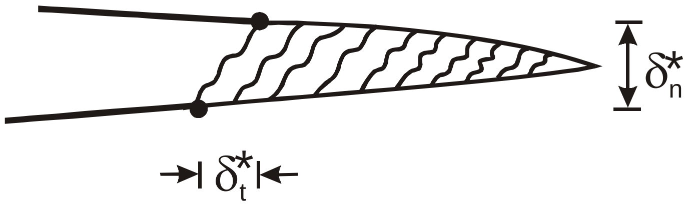


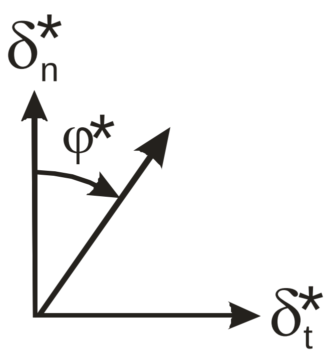
Effect of beam thickness ratio

- phase angle of end-opening, φ*

Phase angle of end-opening, φ*, increases with decreasing h_1/h_2 (thickness ratio) ... i.e. more Mode II





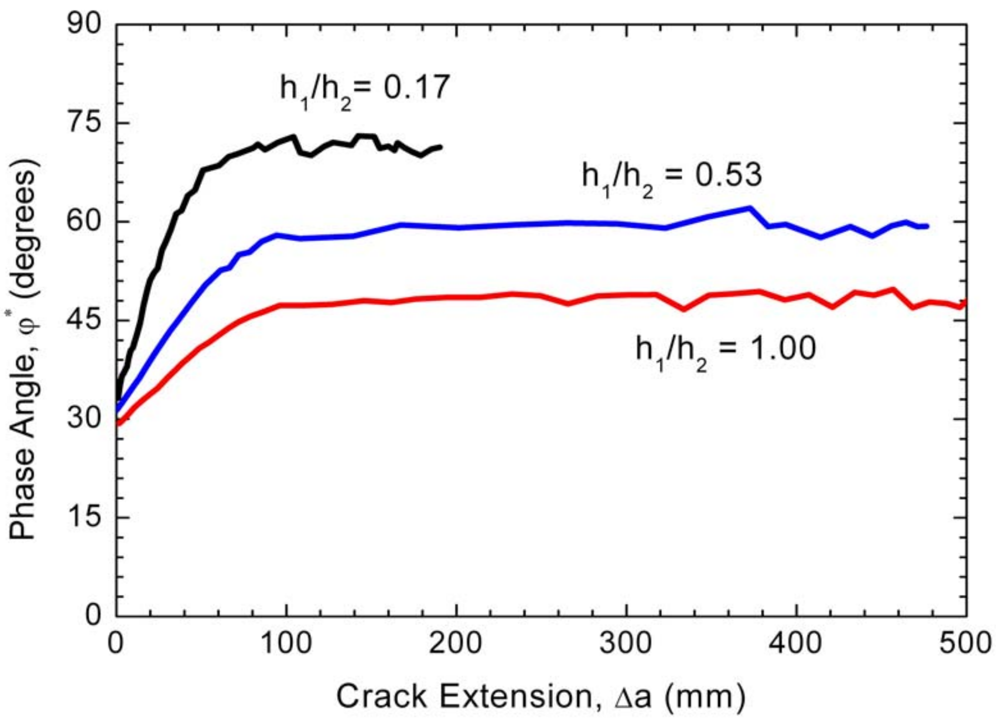


Effect of beam thickness ratio

- phase angle of end-opening, φ*

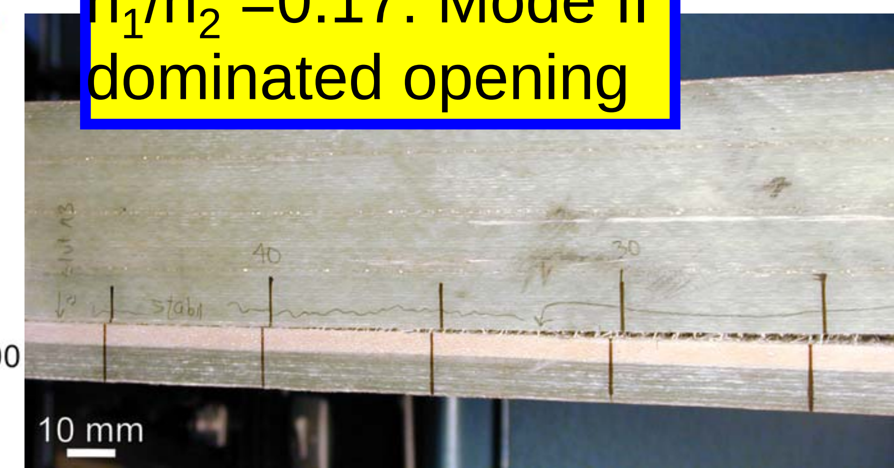
... same trend as

found experimentally



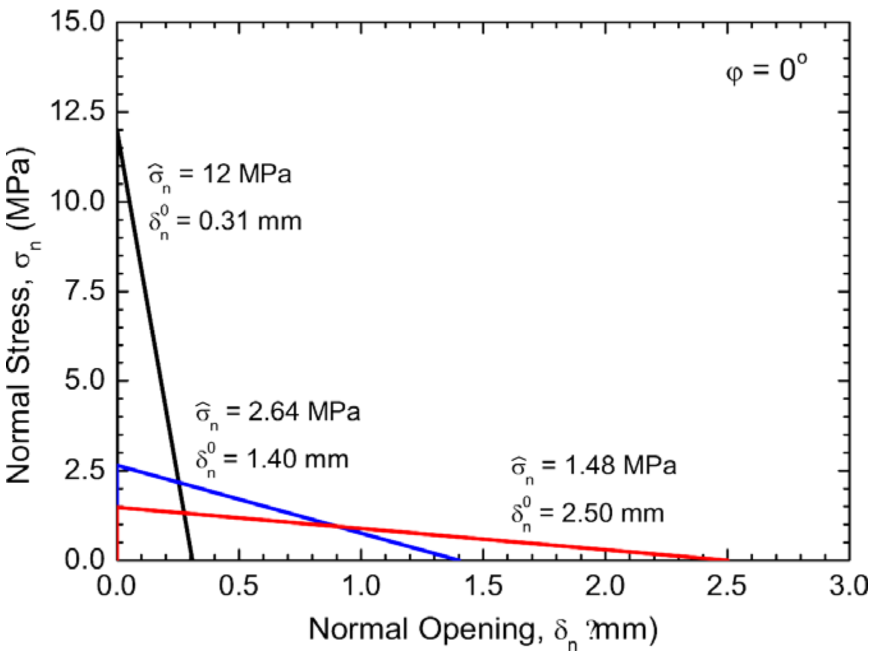
h_1/h_2 =1: Mode I dominated opening

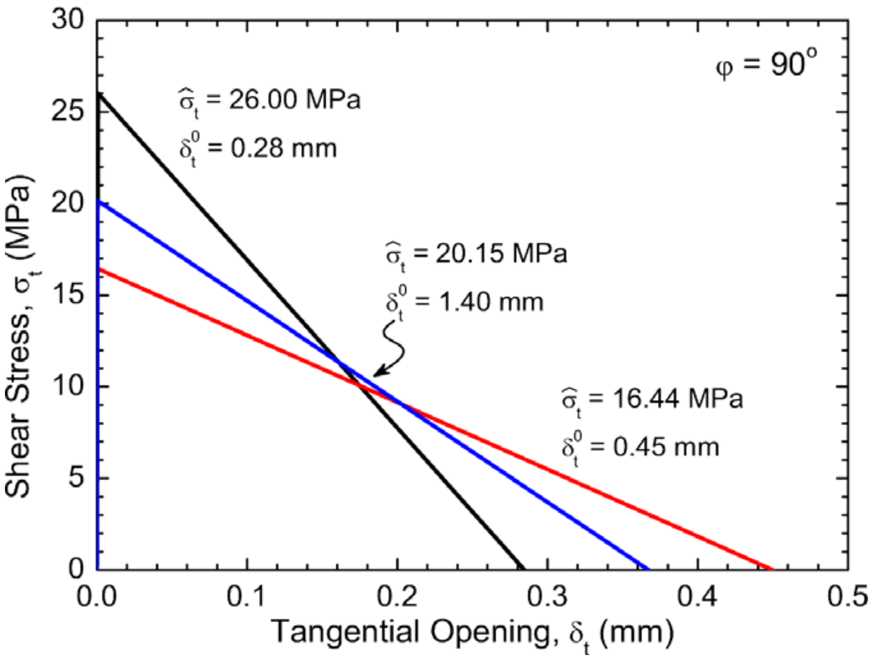
h_1/h_2 =0.17: Mode II dominated opening



Effect of cohesive law parameters
- same Mode I and Mode II fracture energy

- explore the effect of peak stress and critical separation





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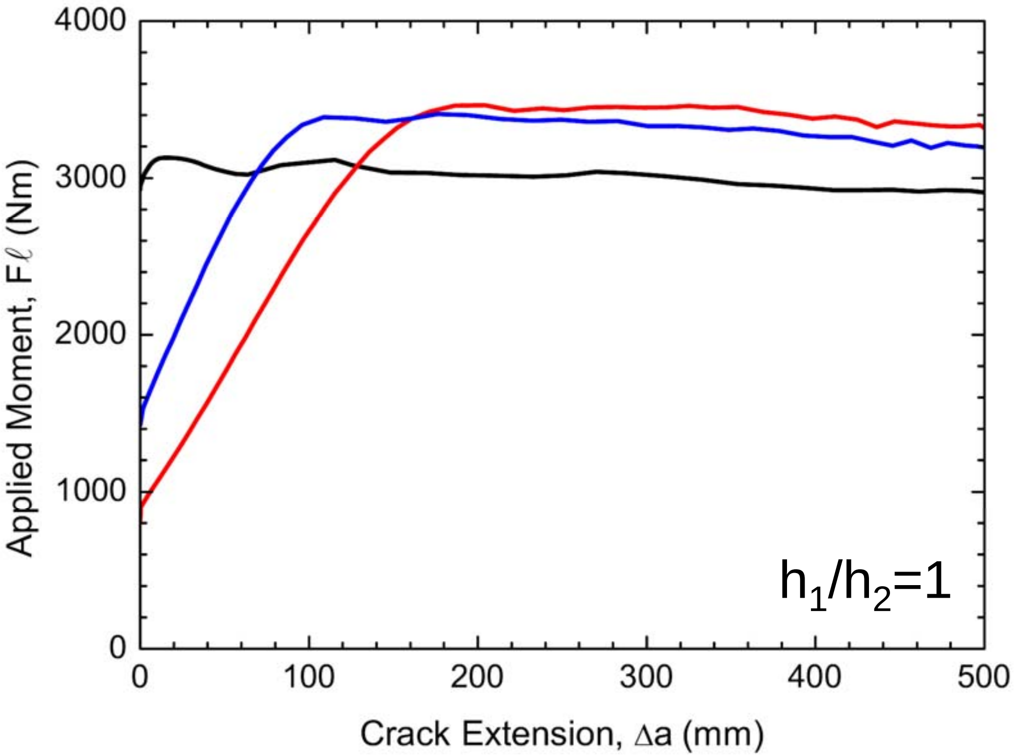


<u>Cohesive law parameters:</u>

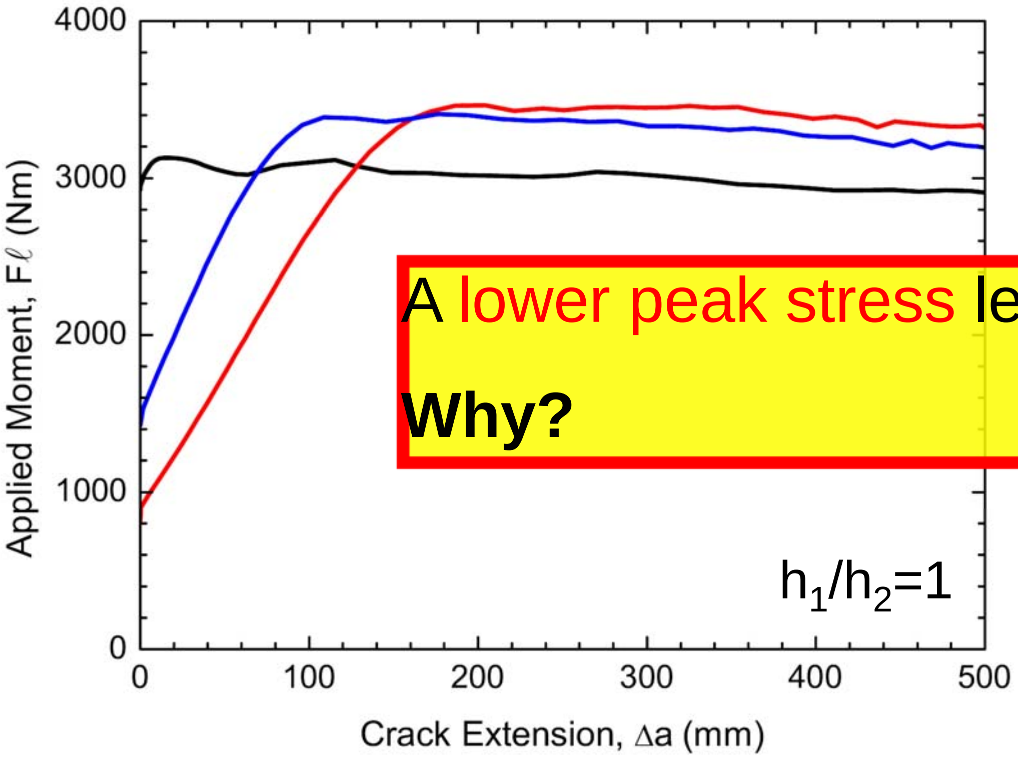
high peak stress
low critical opening

medium peak stress,
medium critical opening

low peak stress
high critical opening

Effect of cohesive law parameters

- same Mode I and Mode II fracture energy



<u>Cohesive law parameters:</u>

high peak stress
low critical opening

medium peak stress,
medium critical opening

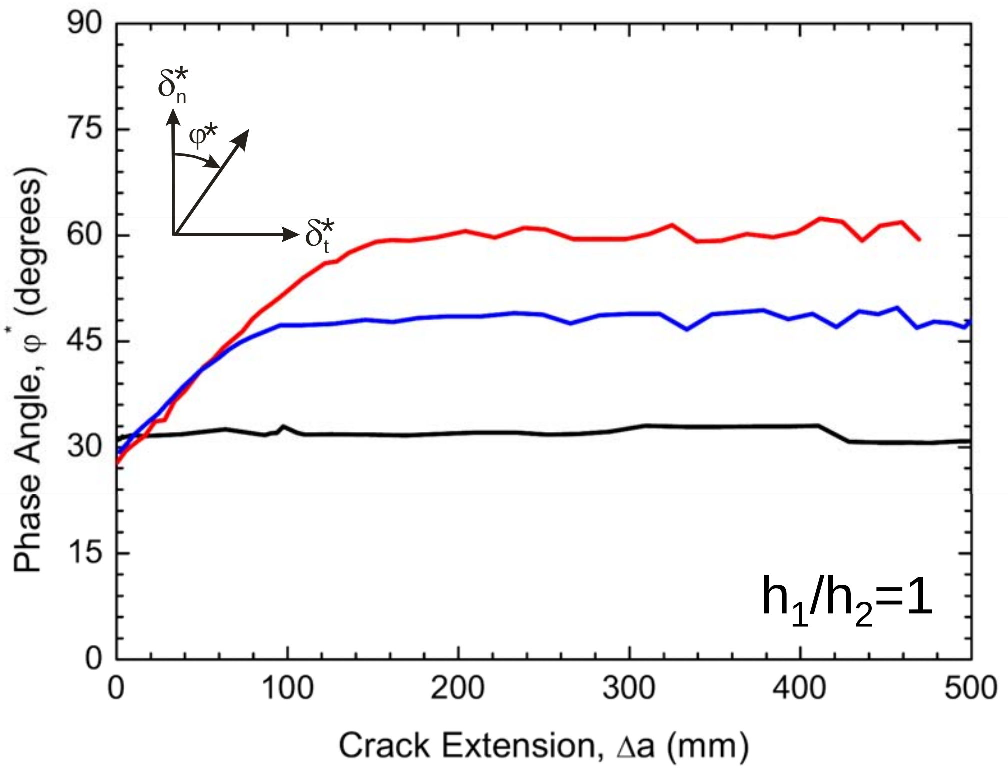
low peak stress
high critical opening

A lower peak stress leads to higher fracture load

Why?

Effect of cohesive law parameters

- same Mode I and Mode II fracture energy



<u>Cohesive law parameters:</u>

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Effect of cohesive law parameters

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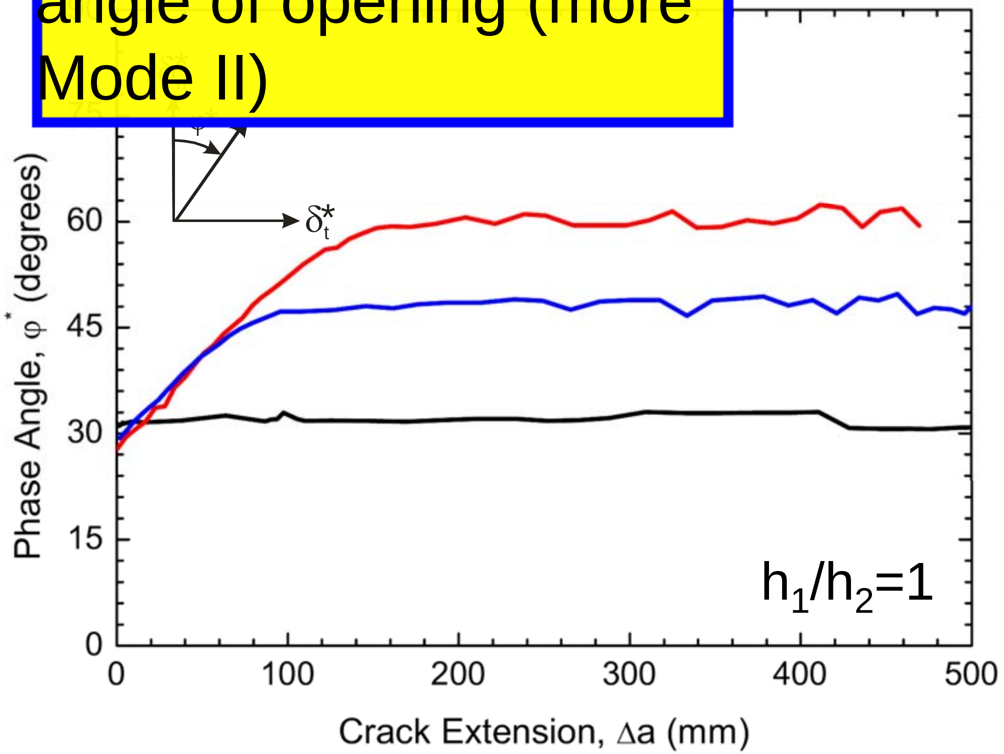
Higher peak stresses results in higher phase angle of opening (more Mode II)



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Effect of cohesive law parameters

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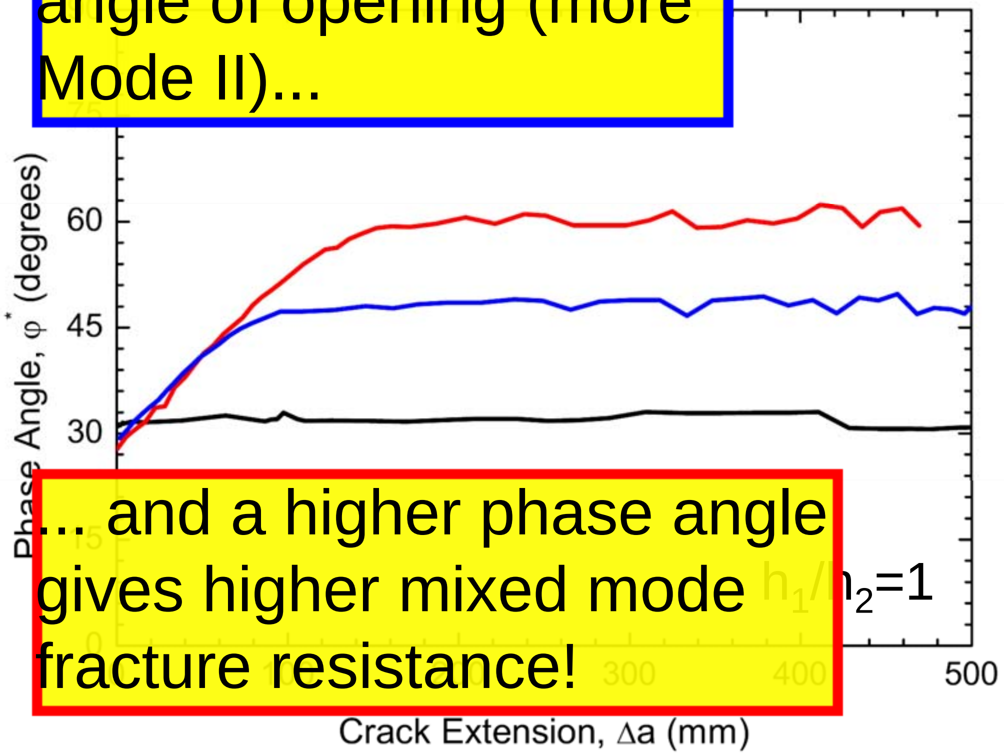


... and a higher phase angle gives higher mixed mode fracture resistance!

<u>Cohesive law parameters:</u>

high peak stress
low critical opening

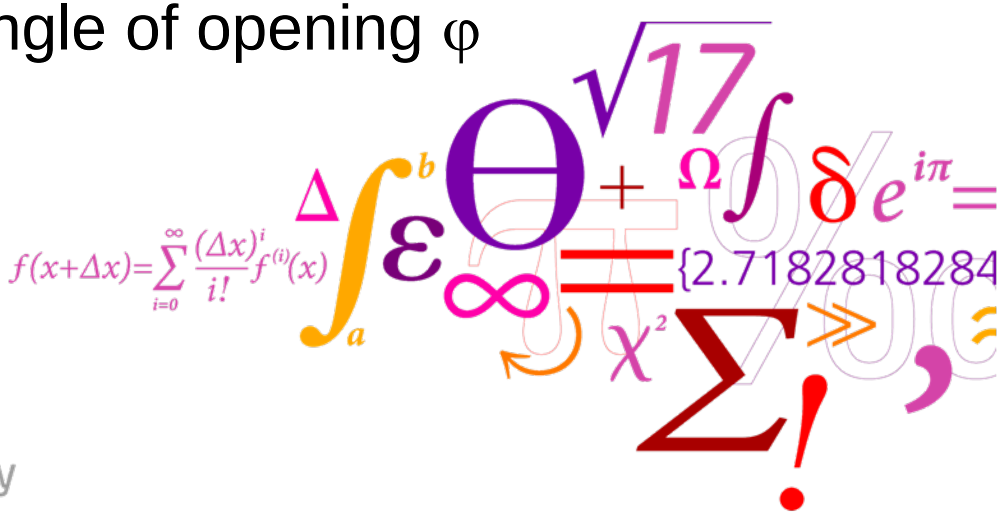
medium peak stress,
medium critical opening

low peak stress
high critical opening

Conclusions
- cohesive zone modelling

- Even quite approximate cohesive laws give results that are in fair agreement with experiments

- Mixed mode results are sensitive to pure mode parameters through changes in phase angle of opening φ



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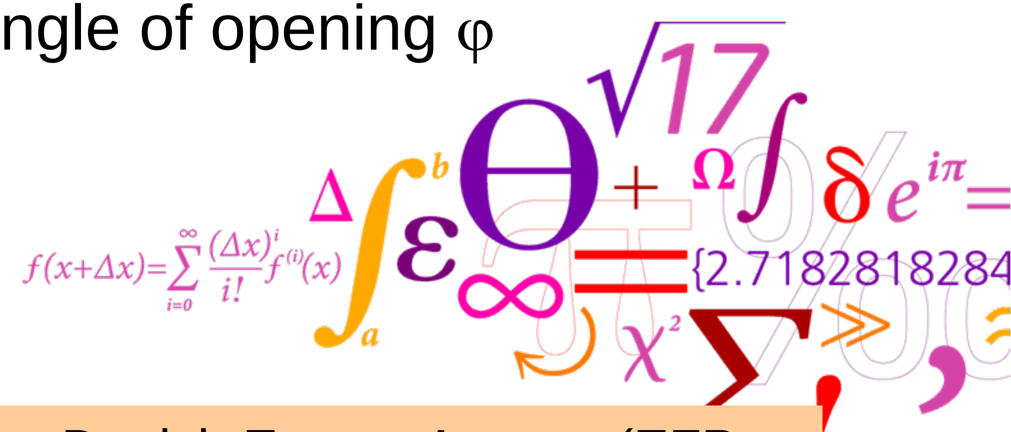

Research partially supported by the Danish Energy Agency (EFP grant no. 33033-0267).

Conclusions
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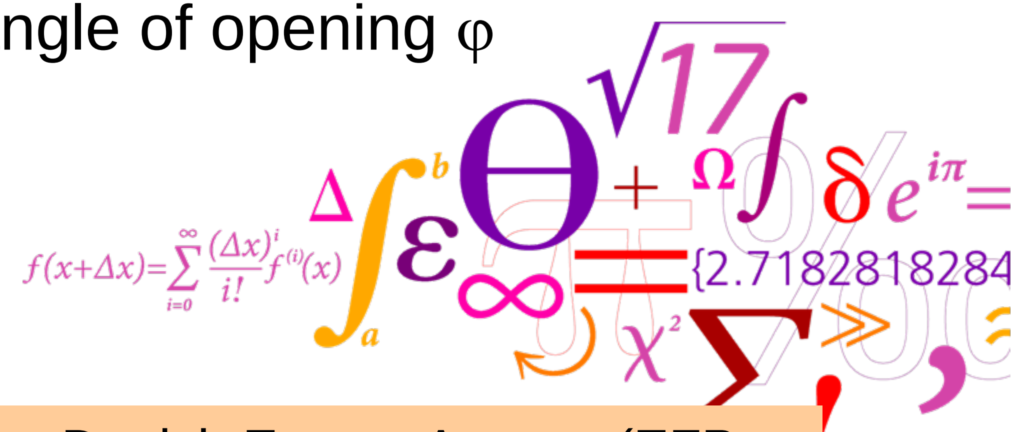
Thanks for your attention!

Any questions?



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