UNIVERSITY OF SKÖVDE

Measurement of Cohesive Laws for Delamination of Composites

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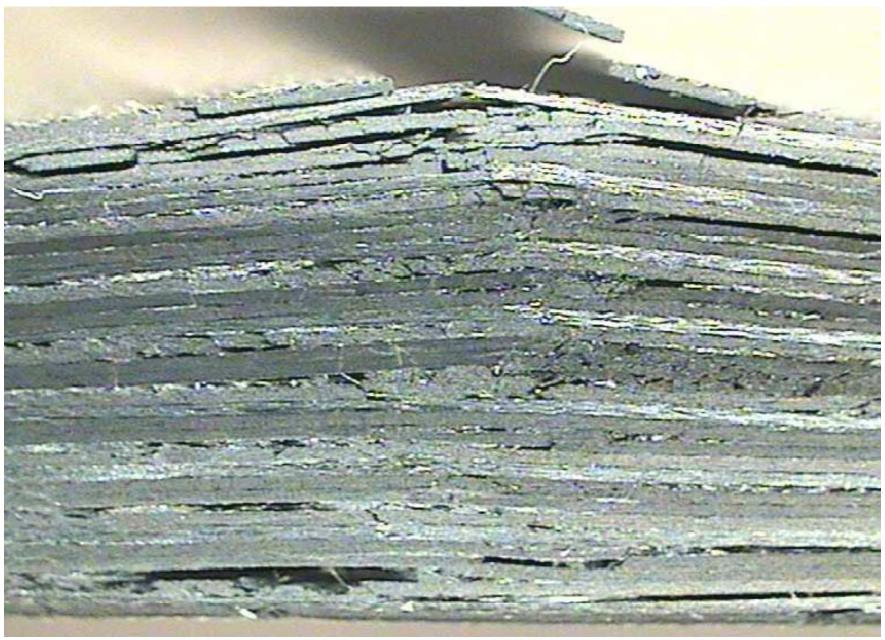
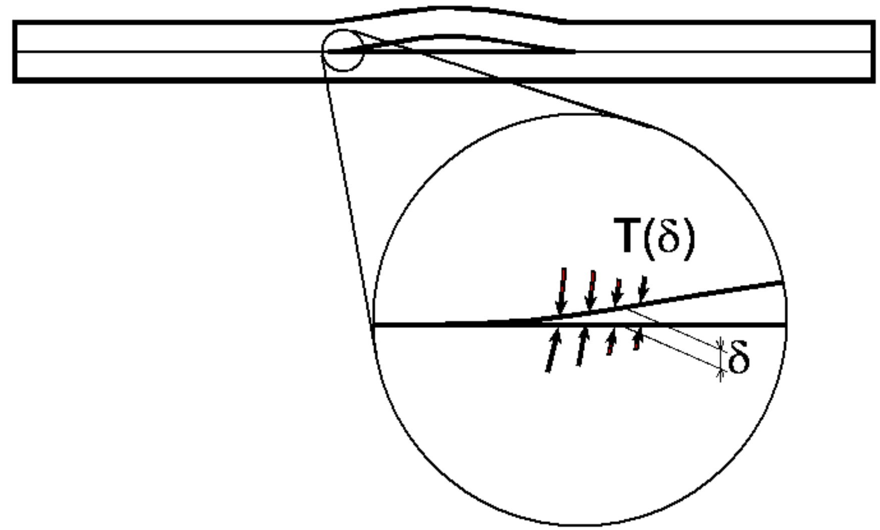
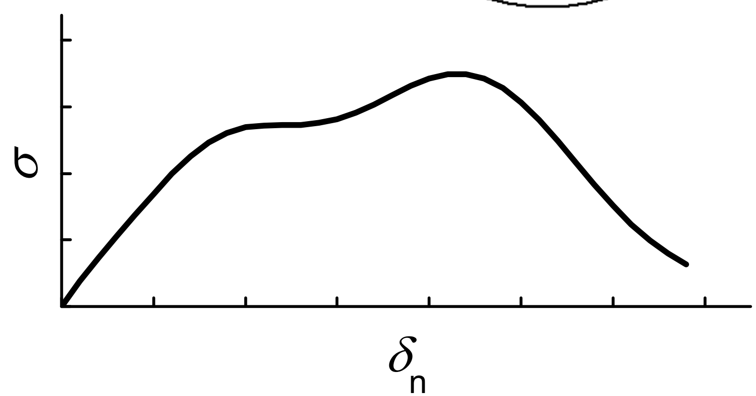
Outline

- Delamination & Cohesive laws
- Methods to deduce/measure cohesive laws
- Experimental techniques
- Results
- Conclusions

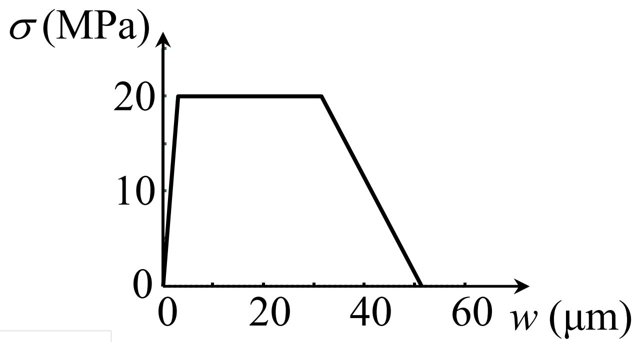
Delamination

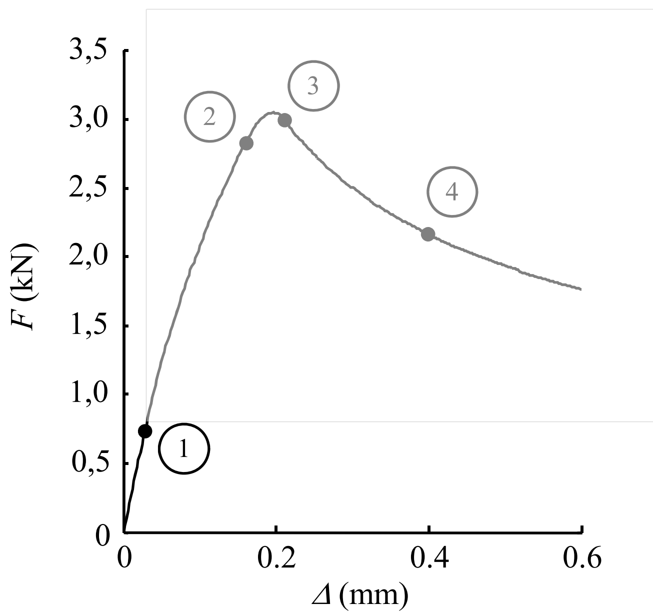


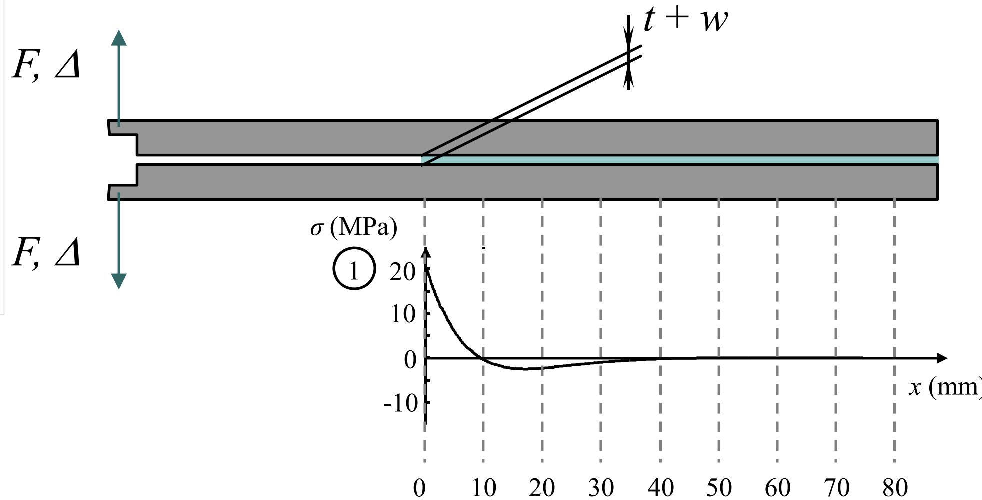




Cohesive laws

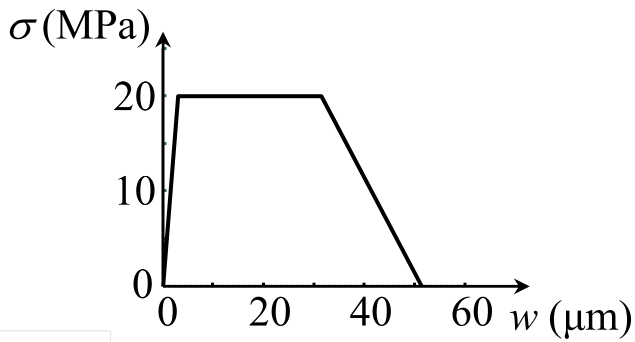


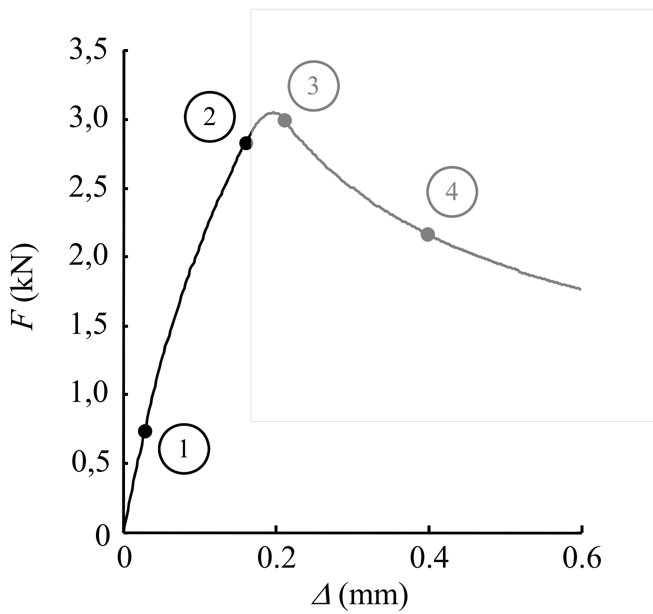


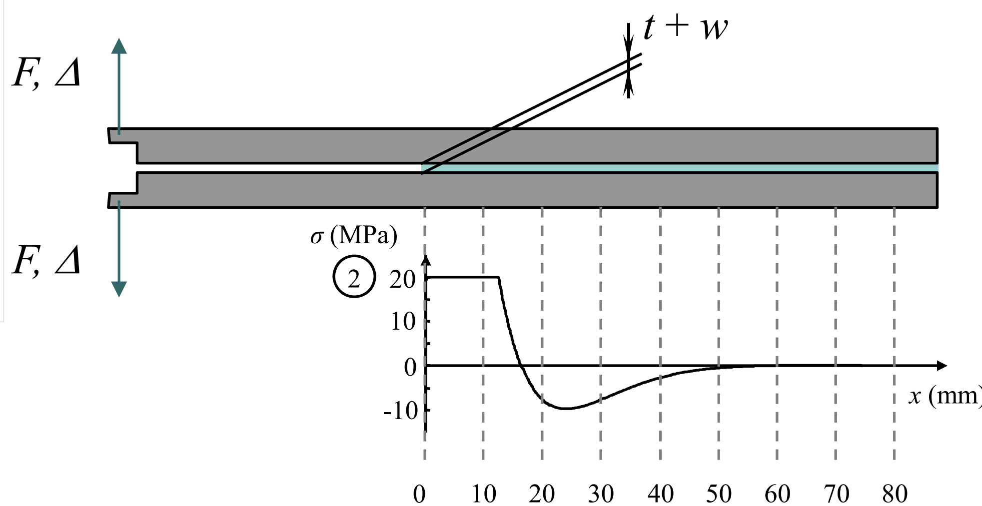


Visualization by Anders Biel

Cohesive laws







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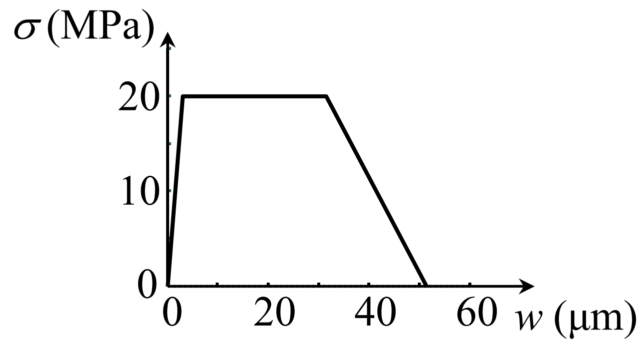
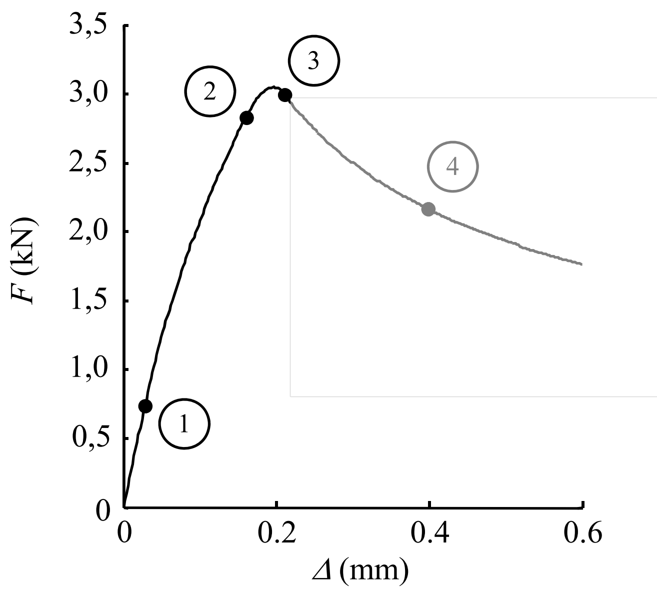
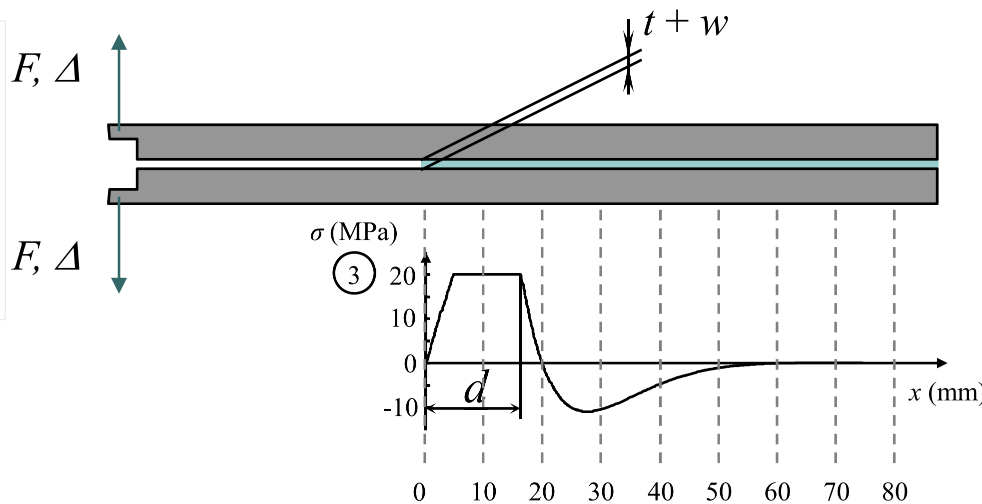
Cohesive laws

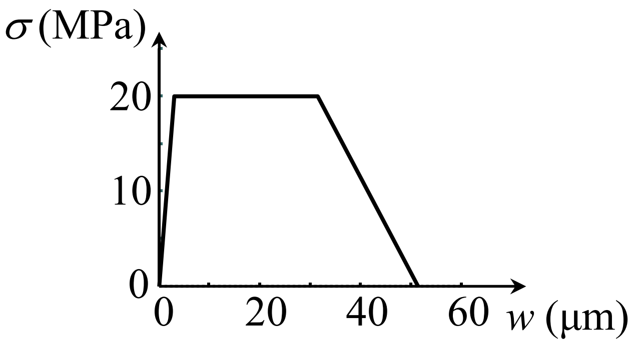


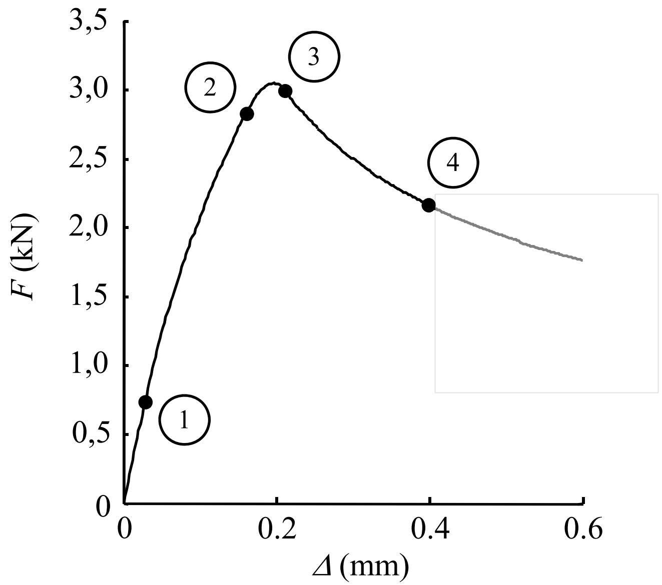


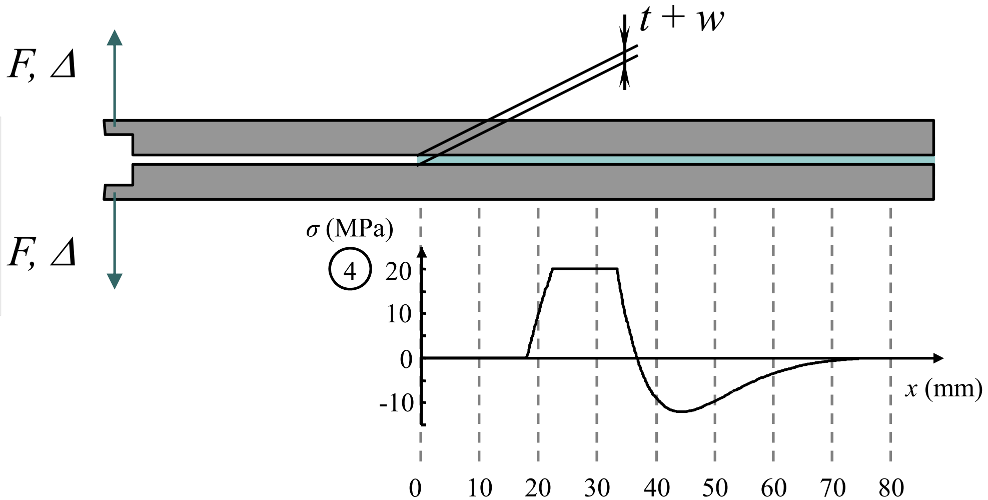


Visualization by Anders Biel

Cohesive laws

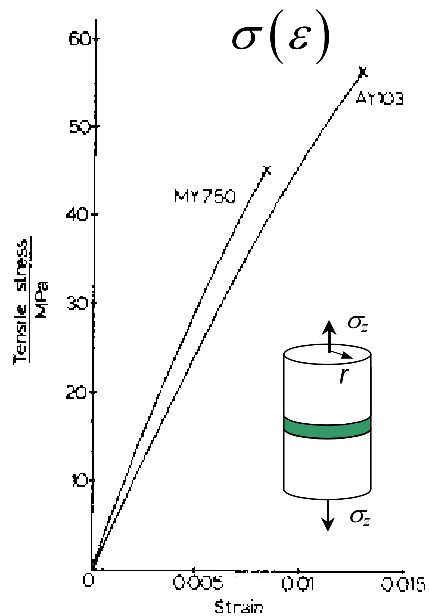




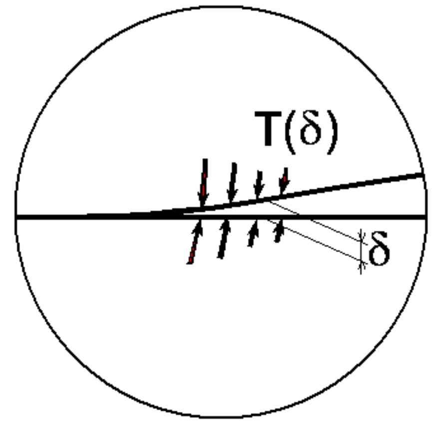


Visualization by Anders Biel

Measure/Deduce Cohesive laws



First method
- Loses stability when softening
- Difficult to capture complete cohesive law

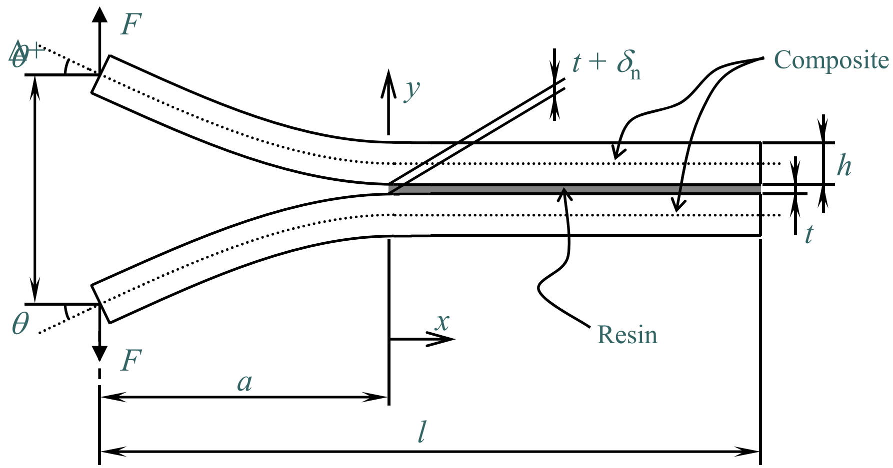


Second method, idea:

1. Measure $\delta(x)$,
2. Compare with analysis based on assumed cohesive law
3. Adapt cohesive law to get good correspondence

- Often insensitive to details of cohesive law

Measure/Deduce Cohesive laws



Third method, idea:

1. Measure load vs. displacement
2. Compare with analysis based on assumed cohesive law
3. Adapt cohesive law to get good correspondence

- Sometime insensitive to details of cohesive law

Forth method, idea:

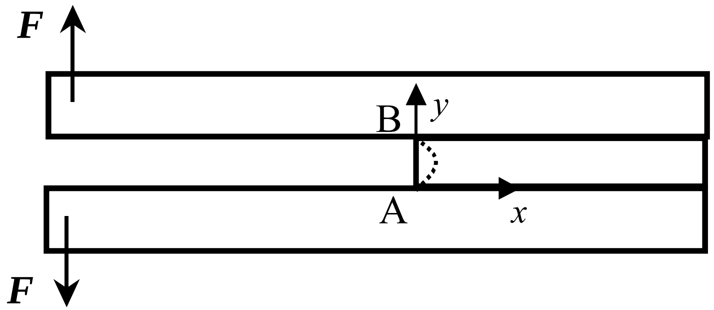
1. Use J-integral
2. Measure J from applied load using an exterior integration path
3. Use an interior integration path to get J ~ cohesive law
4. Use path independence of J to get cohesive law

- Not so intuitive – difficult to understand?

Cohesive laws

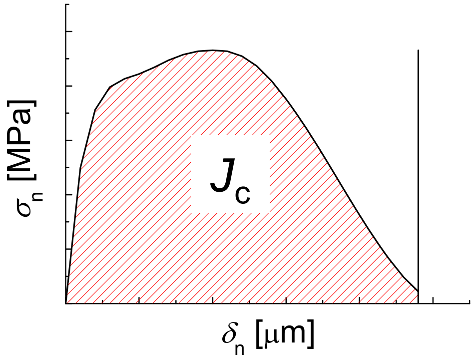
The J-integral

$$J \equiv \int_S \left(W \mathrm{d}y - T_i u_{i,x} \mathrm{d}S \right)$$

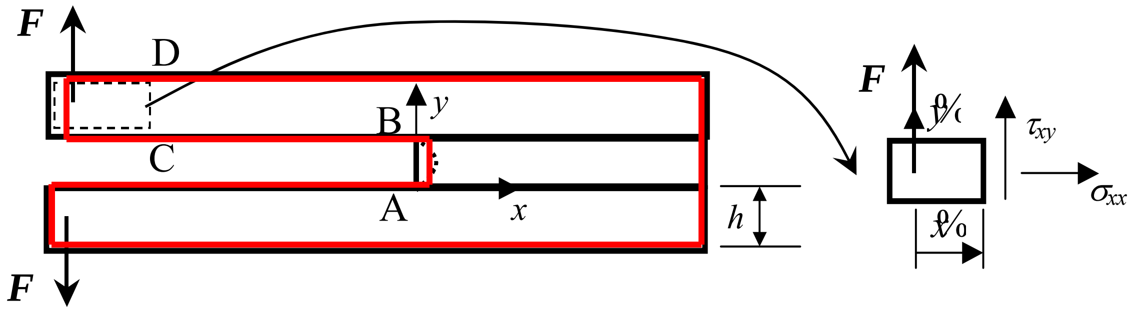


Chose path A to B:

$$J \equiv \int_0^t W \mathrm{d}y = \int_0^t \left(\int_0^{\delta_n} \sigma(\widehat{\delta}_n) \frac{\mathrm{d}\widehat{\delta}_n}{t} \right) = \int_0^{\delta_n} \sigma(\widehat{\delta}_n) \mathrm{d}\widehat{\delta}_n$$



Inverse method



$$J_{\mathrm{CD}} = -F\theta/b$$

If J is evaluated along the closed red path S we get $J_{\mathrm{closed}} = 0$

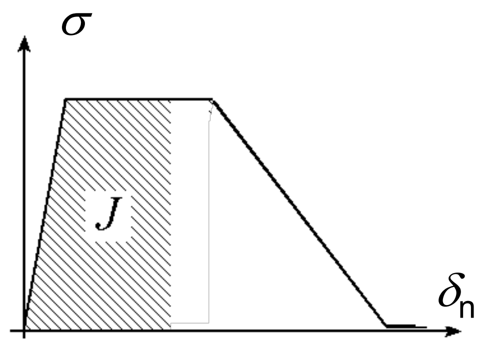
$$J_{\mathrm{closed}} = J_{\mathrm{AB}} + 2J_{\mathrm{CD}} = 0$$

$$J_{\mathrm{AB}} = \int_0^{\delta_n} \sigma(\hat{\delta}_n)\mathrm{d}\hat{\delta}_n$$

$$\Rightarrow \boxed{\sigma(\delta_n) = \frac{2}{b}\frac{\mathrm{d}(F\theta)}{\mathrm{d}\delta_n}}$$

Olsson and Stigh, 1989, IJF

Method to measure cohesive law



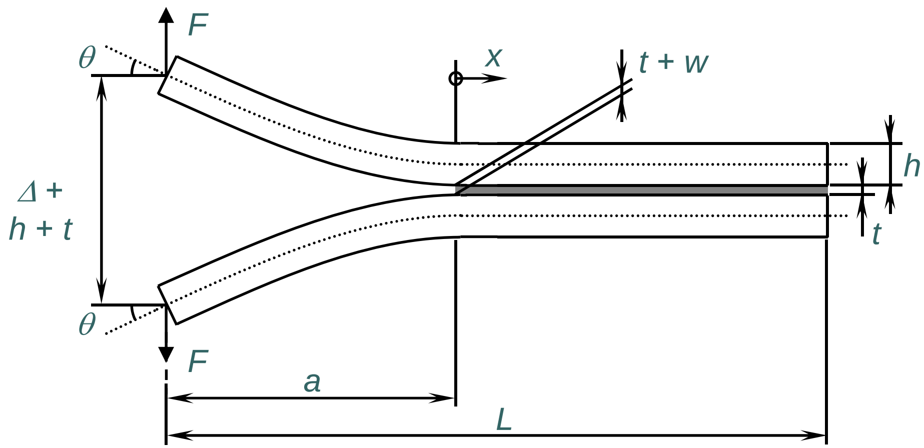
$$J(\delta_n) = \int_0^{\delta_n} \sigma(\hat{\delta}_n)\mathrm{d}\hat{\delta}_n$$

$$\sigma(\delta_n) = \frac{\mathrm{d}J(\delta_n)}{\mathrm{d}\delta_n}$$

Experimental method

Visualization by Svante Alfredsson

Using concept of energetic forces

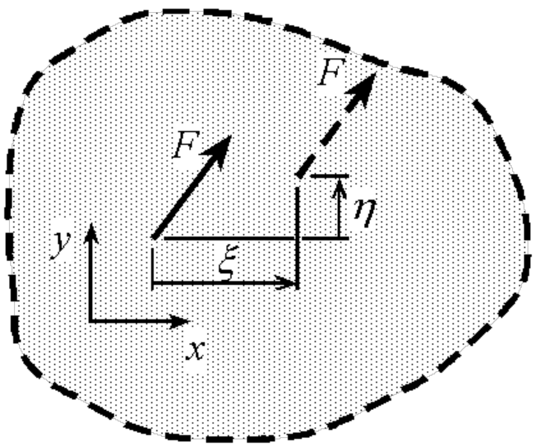


J = energetic force acting on an object in an elastic field (Eshelby)

$$J_i \delta\xi_i \equiv -\frac{1}{b}\frac{\partial\Pi}{\partial\xi_i}\delta\xi_i$$

Three objects identified for the DCB-specimen: the crack tip and the two acting loads

J for a point load



Kelvin's problem – singularity

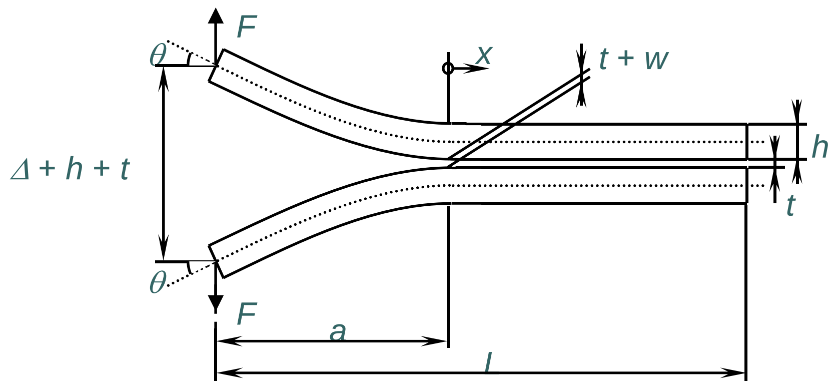
$$\Pi = -F_i \left(u_i^{\mathsf{s}} + u_i^{\mathsf{a}} \right)$$

Infinite geometry

Finite geometry

$$J_j^{\text{point load}} = -\frac{1}{b}\frac{\partial \Pi}{\partial \xi_j} = \frac{1}{b} F_i u_{i,j}^{\mathsf{a}}$$

Equilibrium of energetic forces



Imagine a sequence of events:

1. Move crack tip $\Delta\xi$ to the right $\rightarrow \Delta\Pi_1$

$$J^{\text{crack tip}} = \int_0^w \sigma(\hat{w})\,\mathrm{d}\hat{w}$$

2. Move forces $\Delta\xi$ to the right $\rightarrow \Delta\Pi_2$

$$J^{\text{forces}} = \frac{2}{b}F\theta$$

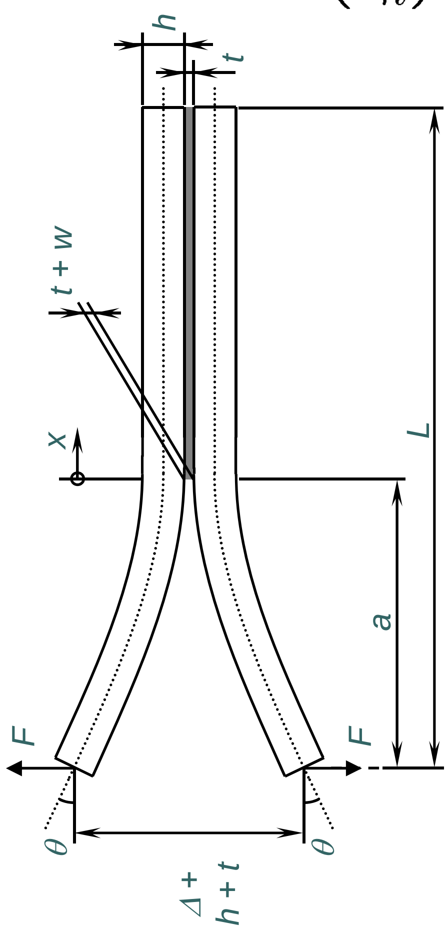
3. Back to original configuration $\rightarrow \Delta\Pi_1 = \Delta\Pi_2$

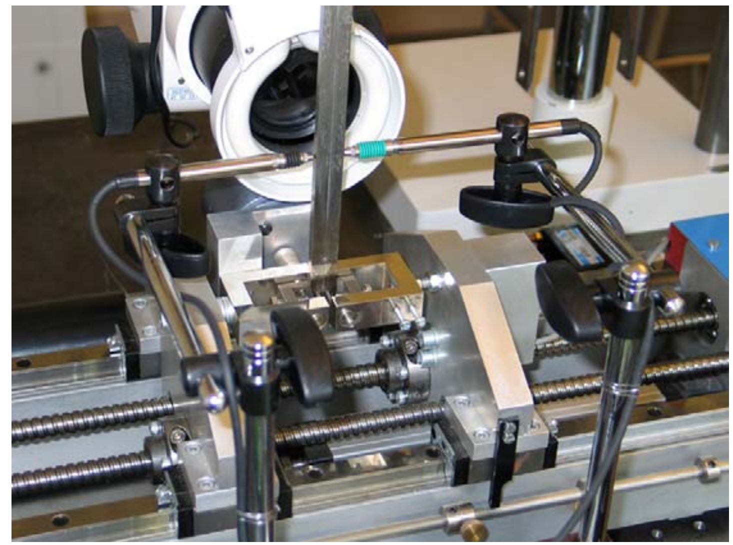
$$J^{\text{crack tip}} = J^{\text{forces}}$$

$$\int_0^w \sigma(\hat{w})\,\mathrm{d}\hat{w} = \frac{2}{b}F\theta \qquad \sigma(w) = \frac{2}{b}\frac{\mathrm{d}(F\theta)}{\mathrm{d}w}$$

Experimental technique

$$\sigma(\delta_n) = \frac{2}{b}\frac{\mathrm{d}(F\theta)}{\mathrm{d}\delta_n}$$



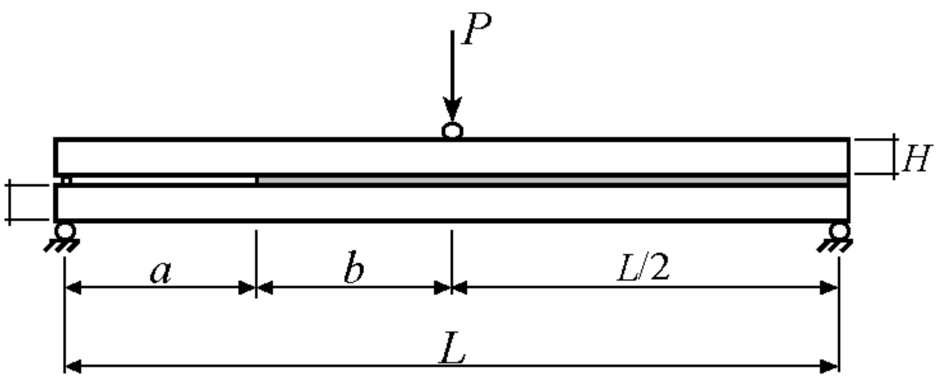


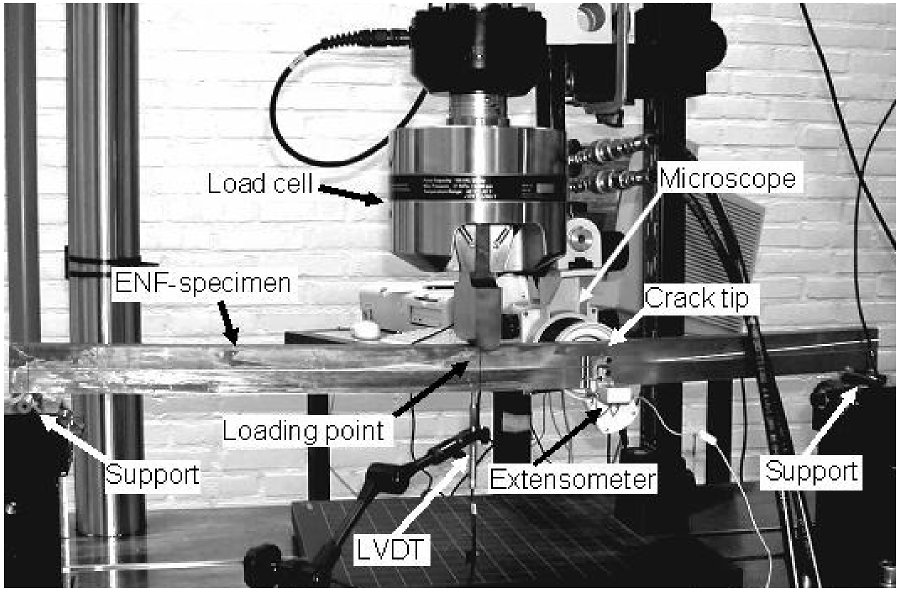
Measured:

1. Force F
2. Rotation θ
3. Elongation of adhesive δ_n

Andersson and Biel, IJSS, 2006

Cohesive laws in shear





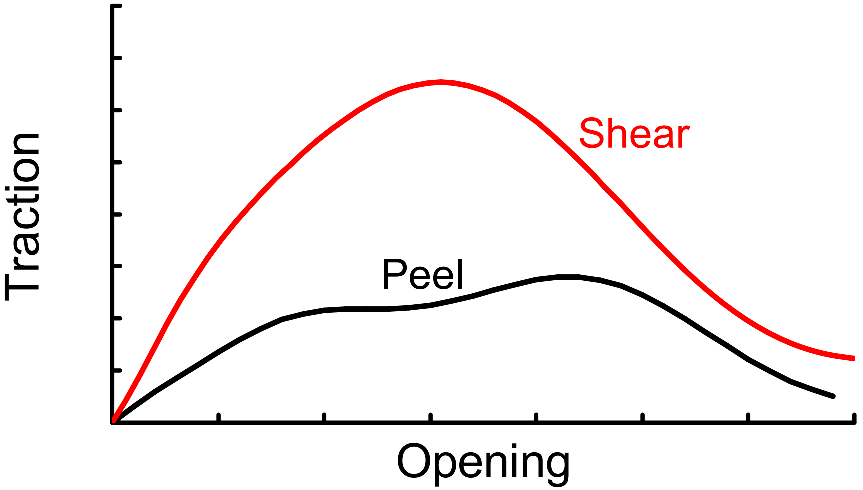
$$\tau(\delta_t) = \frac{\mathrm{d}}{\mathrm{d}\delta_t}\left[\frac{9}{16}\frac{P^2a^2}{EW^2H^3} + \frac{3}{8}\frac{P\delta_t}{WH}\right]$$

Measured:

1. Force P
2. Shear deformation δ_t

Alfredsson, IJSS, 2004; Leffler et al. IJSS, 2007

Results CFRP



Conclusions

- Cohesive laws provide convenient methods to calculate the behaviour of structures using the FE-method
- Experimentally
  - *J* is viewed as a function of the opening of the cohesive zone at the tip of a blunted crack
  - *J* is measured continuously during an experiment
  - Path independence gives evolution of cohesive law during experiment
- Cohesive law gives fracture energy – in “small scale damage” fracture energy determines structural behaviour
- Fracture energy for resin ~ 1/10 of fracture energy of modern epoxy adhesives