A practical approach for the peel stress prediction in the trailing-edge adhesive joint of wind turbine blades

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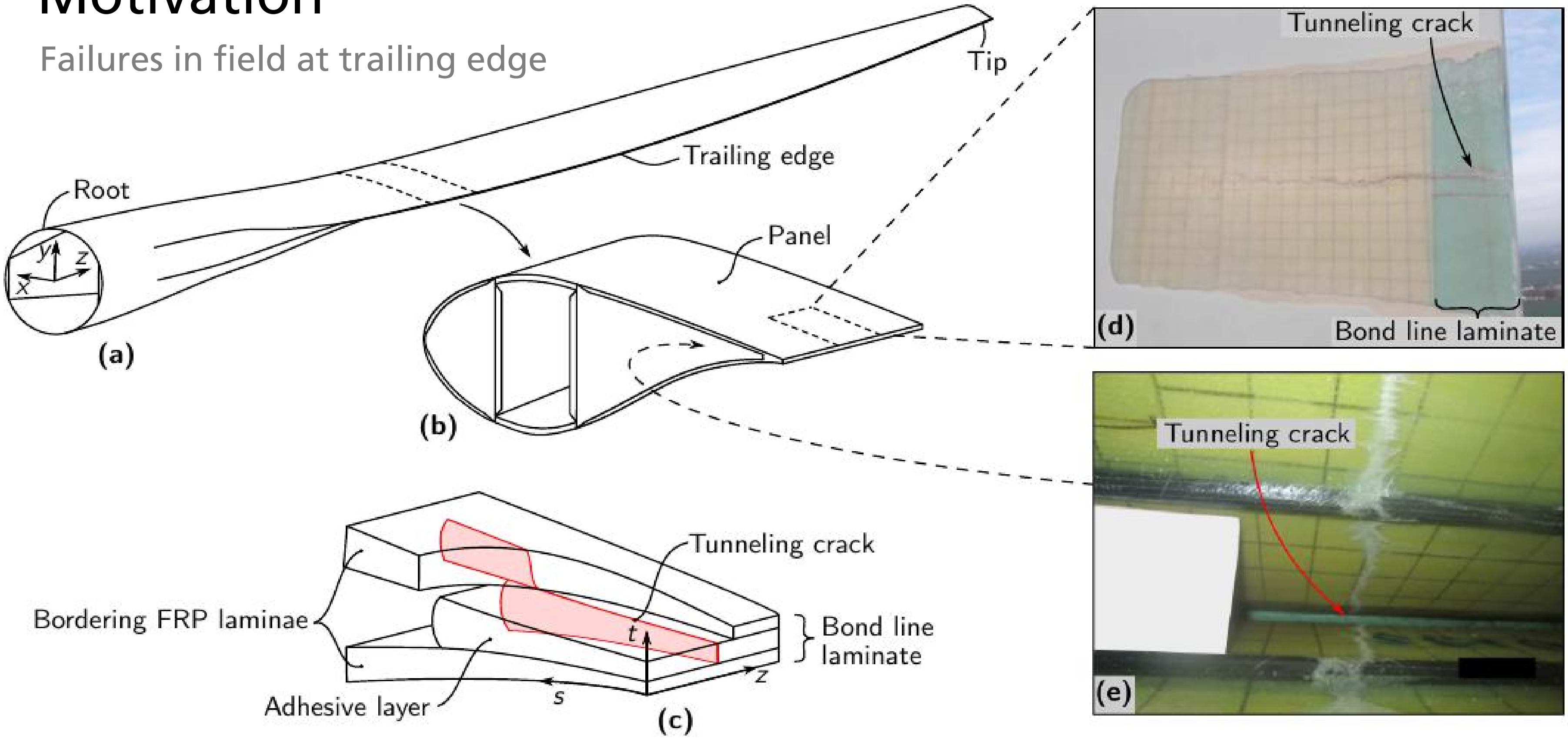
Motivation

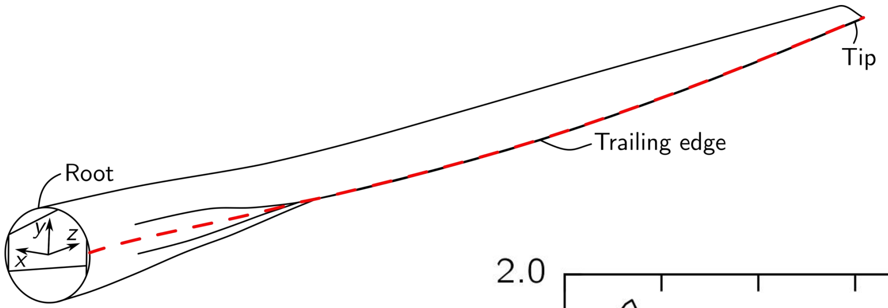
Failures in field at trailing edge

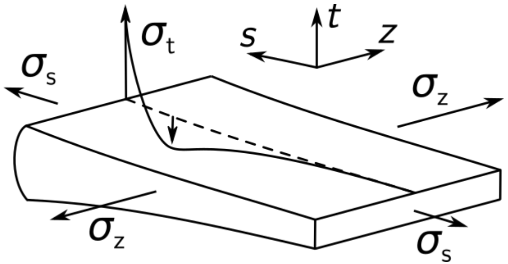


Rosemeier et al., 2019

Motivation

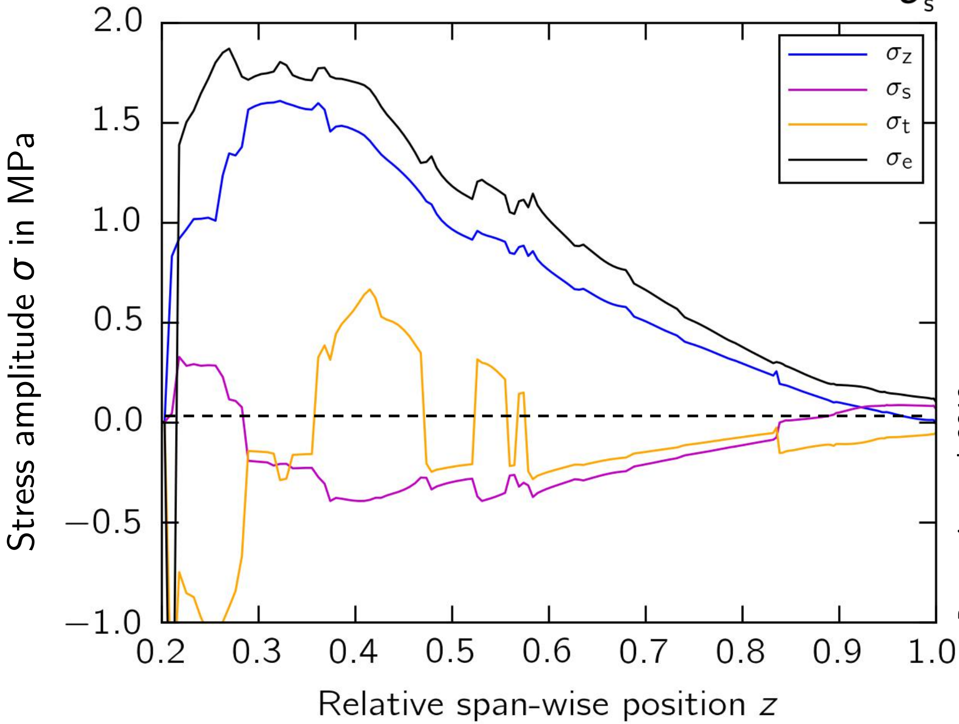
Why peel stresses?





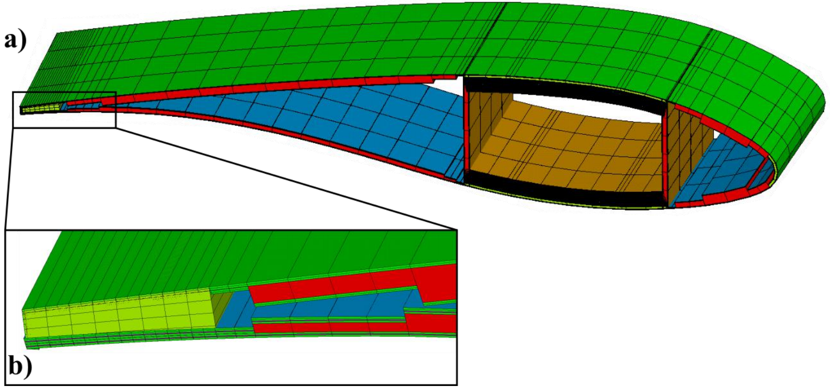
- A recent study showed:
  A finite element model subjected to field loads revealed that besides longitudinal stresses, peel stresses make a significant contribution to fatigue, i.e., crack initiation

- IEC standard and DNV GL guideline encourage to include peel stresses in analysis of adhesive joints



Rosemeier et al. 2019

Fatigue analysis approach



- Full-scale blade finite element simulation yields multi-axial stress state

- Equivalent stress (Beltrami) takes all stress components into account

$$\sigma_e = \sqrt{\sigma_z^2 + \sigma_s^2 + \sigma_t^2 - 2\nu(\sigma_z\sigma_s + \sigma_s\sigma_t + \sigma_z\sigma_t) + 2(1+\nu)(\tau_{zs}^2 + \tau_{st}^2 + \tau_{zt}^2)}$$

- Stress exposure (Puck) as a damage criterion

$$e = \frac{\sigma}{R^t}$$

- Stress-life curve (Basquin) in combination with constant-life diagram (modified Goodmann) yield cycles toward crack initiation in the adhesive layer

$$N_i = \left(\frac{1 - e_i^m}{e_i^a}\right)^m \qquad D = \sum_i D_i = \sum_i \frac{n_i}{N_i}$$

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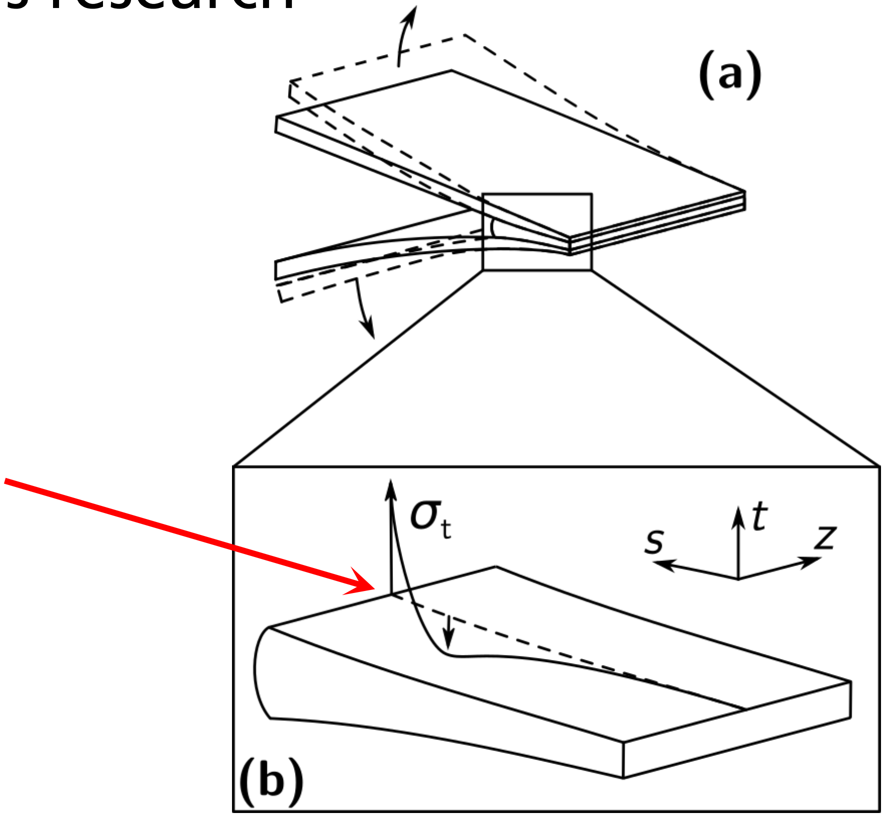
Problem statement for this research

- “Pumping” induces peel stress in the adhesive layer of the trailing edge joint
- To take account of this peel stress in the design phase, adequate models are required
- **Problem: singularity at inner edge, where is peel stress peak of interest**
- Modeling approach should be:
  - applicable to state-of-the-art finite element implementation
  - computationally efficient (no computer cluster)
  - reliable (be conservative)



Methods

Spies' analytical model

- Double cantilevered beam
- Symmetric
- Peel stress distribution in adhesive:

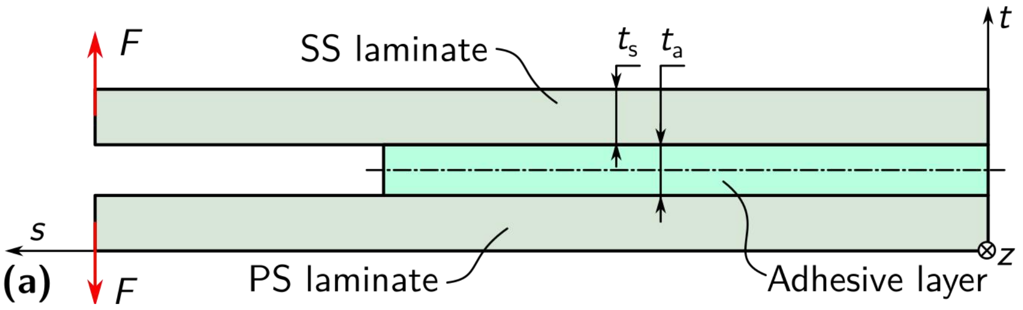
$$\sigma_\mathrm{t} = \sigma_\mathrm{t}^0 \, e^{-\frac{x}{c}} \left(\cos\frac{x}{c} - \frac{M}{M+Fc} \sin\frac{x}{c} \right)$$

$$\sigma_\mathrm{t}^0 = \frac{M+Fc}{b\,c^2}$$

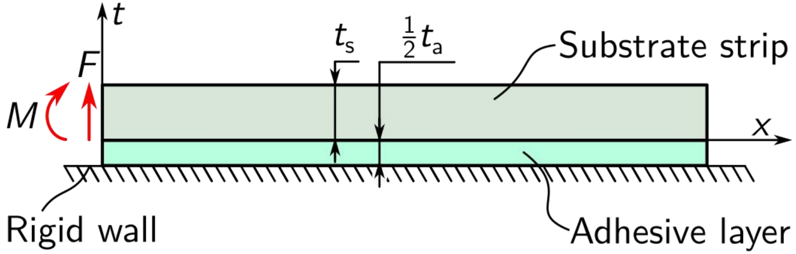
- Substrate <u>anisotropic:</u> <u>isotropic:</u>

$$c = \sqrt[4]{\frac{t_\mathrm{a} B}{2E_\mathrm{a}}} \qquad c = t_\mathrm{s} \sqrt[4]{\frac{1}{6} \frac{\frac{E_\mathrm{s}}{E_\mathrm{a}}}{\frac{t_\mathrm{s}}{t_\mathrm{a}}}}$$

(a)

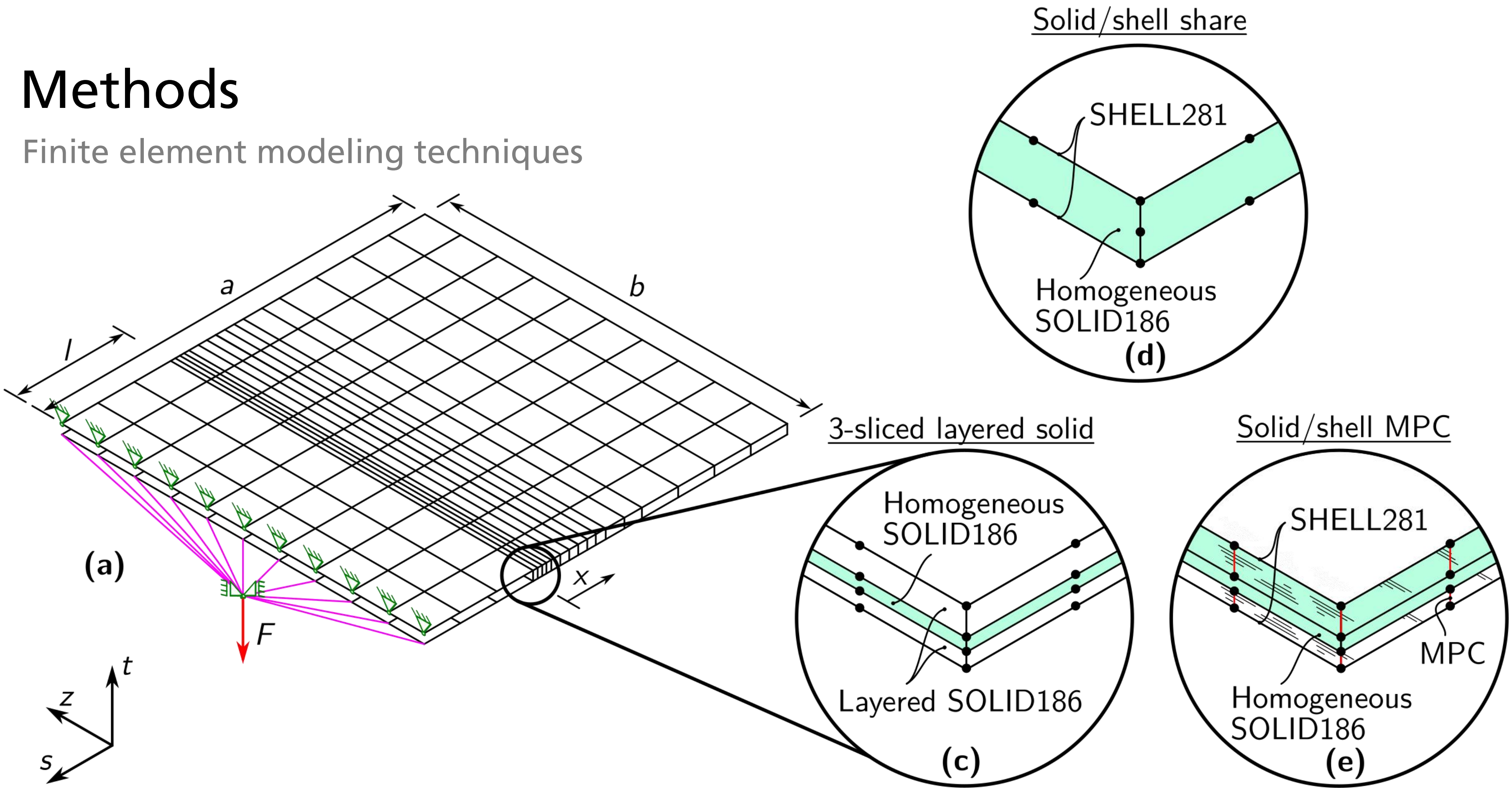


(b)



Methods

Finite element modeling techniques



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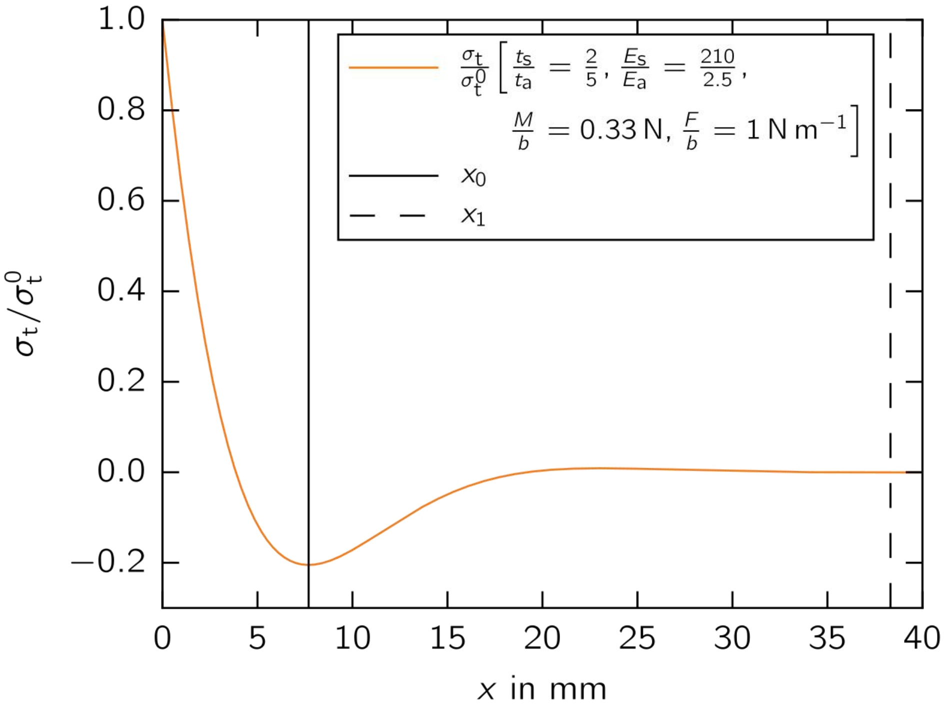
Methods

Mesh density

- Typical peel stress distribution according to Spies
- Extrema found via first derivative of
  - x_0 = valley
  - x_1 = beginning of flat plateau

$$x_n = 2c\left(n\,\pi + \arctan\frac{1-\frac{M}{M+Fc}+\sqrt{2\left(1+\frac{M}{M+Fc}^{2}\right)}}{1+\frac{M}{M+Fc}}\right)$$

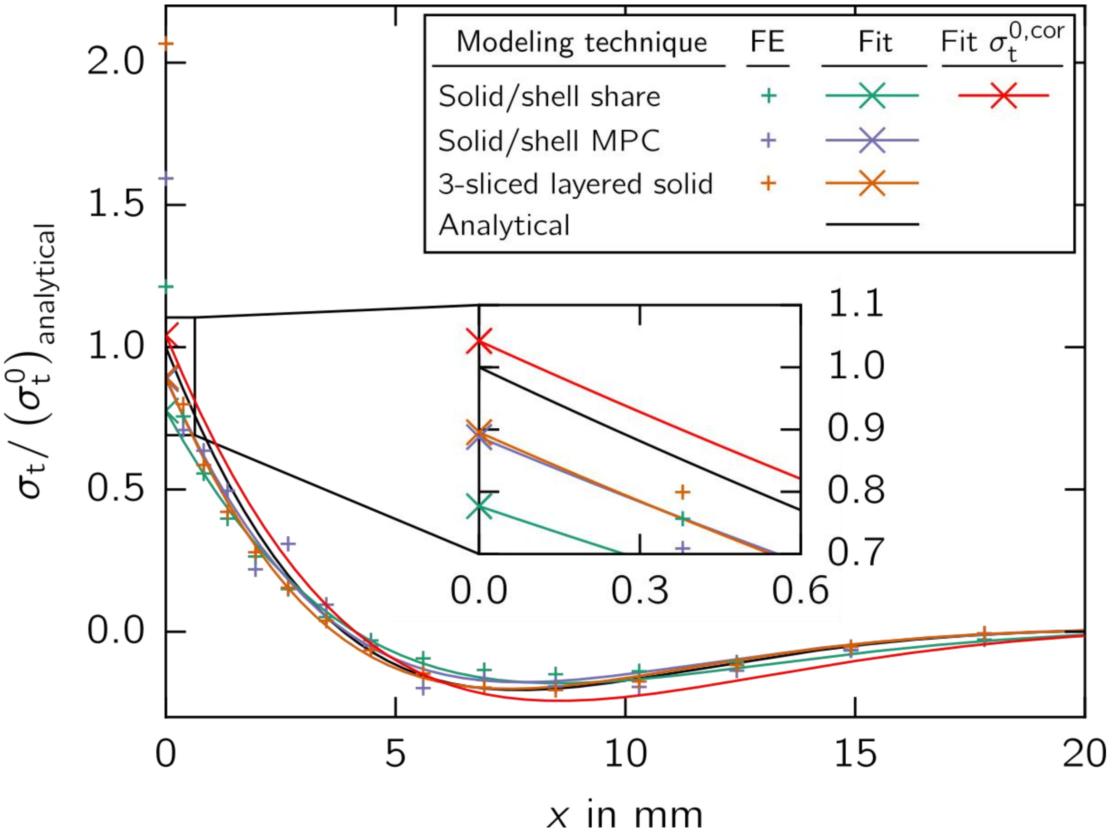
- Used to estimate mesh density at the edge in finite element model



Results

Effect of modeling techniques

- Reference: steel-adhesive joint
- Least-squares fit varied parameters: *F*, *M*, and *b* in Spies' model to fit nodal results
- First value neglected because of singularity
- "solid/shell MPC" and "3-sliced layered solid" are closest to analytical
- After corrections "solid/shell share" is closest to analytical



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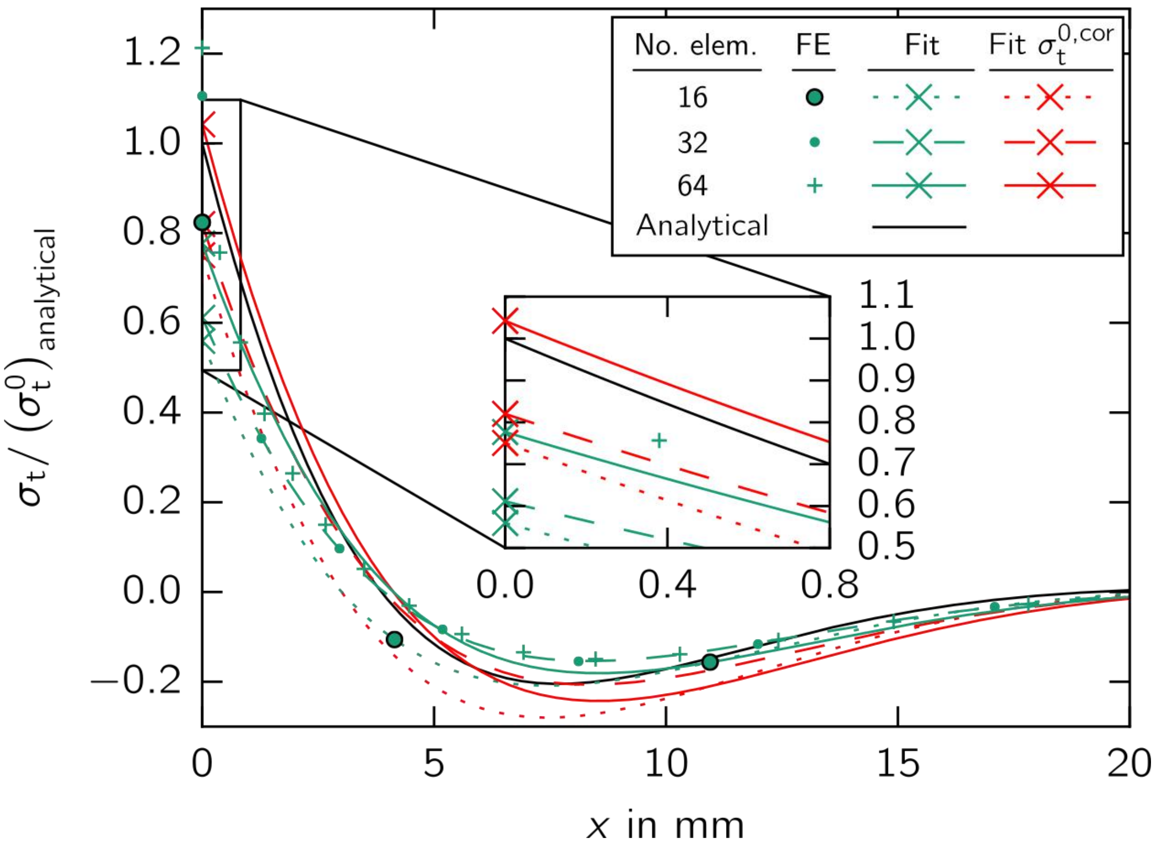
Results

Effect of mesh density

- Chosen model: “solid/shell share”
- At least 3 nodal results within distance $2x_0$ required to capture stress peak close to analytical solution
- The higher the mesh density the better the match between analytical and FE fit



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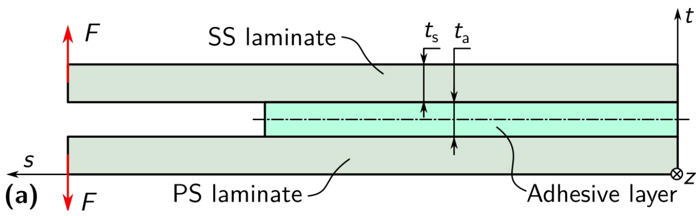
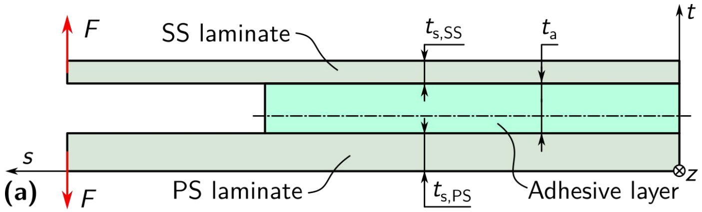
Conclusions and future work

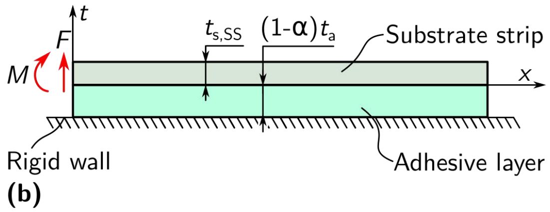
- Proposed practical approach to estimate peel stress peak with help of analytical model which approximates and extrapolates nodal stress results
- Approach circumvents dilemma that stress peak coincides with singularity
- "solid/shell share" technique can be implemented with least effort into state-of-the-art FE model
- Future:
  - Asymmetric joints
  - Other loading situations, e.g., in-plane normal or shear stressing

Symmetric



Asymmetric





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Thank you for your attention!
Any questions?

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Corrections for “solid/shell share” model

- First, adhesive thickness corrected in analytical model

$$t_{\mathrm{a}}^{\mathrm{cor}} = \frac{1}{2} t_{\mathrm{a}} + t_{\mathrm{s}}$$

- Second, after approximation FE results, peal stress peak is again corrected in order to obtain comparable results to analytical

$$\sigma_{\mathrm{t}}^{0,\mathrm{cor}} = \sigma_{\mathrm{t}}^{0} \sqrt{\frac{t_{\mathrm{a}} + 2t_{\mathrm{s}}}{t_{\mathrm{a}}}}$$