A mixed-dimensional delamination structural model for general laminated composites including REBCO coated conductors

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Introduction: REBCO mechanics

- REBCO CC is very strong longitudinally & well understood
- Delamination (interlaminar shear) failure remains a poorly-understood challenge
  - Noteably challenging in epoxy-impregnated coils
  - Broad range of experimental experience, but limited experimental data
  - Most data is post-mortem imaging, not functional data
  - Most failures are either transverse REBCO failures or mixed-mode debonding at the buffer-layer/REBCO interface
  - Pin-pull transverse tests, pull tests & other small-scale experiments give results consistent with coil observations
  - No experimental data at the layer-scale
- Conductor slitting during manufacturing can affect performance
- Modeling and simulation allow evolutional, *in-situ* insights into all constituent layers

REBCO modeling … challenges and solution

- REBCO coated conductor consists of multiple, laminated, high aspect ratio (HAR) thin films sandwiched between a thick stabilizer and substrate
- Modeling laminated composites with HAR thin films in 3D is very challenging
  - Enormous number of degrees of freedom results from thickness-dependent fine meshing of each HAR layer
  - Smaller meshing leads to smaller time steps in time-dependent models
- Over past decade we have developed high-fidelity 3D/2D mixed-dimensional models of quench behavior of REBCO coils and of (GR)NI magnets; these have proven to be quite effective
- Here we look to use the same conceptual approach to delamination modeling

A ***General*** 3D/2D Modeling Methodology for Laminated Composites

- Key ideas:
  - Model all HAR thin film layers with 2D surfaces and physics
    - Solves thickness-dependent meshing and computational problems
  - Model thick layers (substrate, stabilizer) in 3D for accuracy
  - Consequences: degrees of freedom and time steps are independent of thicknesses
- Key techniques:
  - Represent each HAR layer as a separate 2D geometrical layer
    - Adjacent laminated layers can be overlapped on the same geometrical location
  - Each 2D layer has its own 2D physics with distinct dependent variables
  - Use “paired interfacial equation” to couple two in-contact surfaces
    - An in-contact surface can be a 2D HAR layer or a boundary of a 3D layer
    - The key mechanism that couples 2D physics and 3D physics

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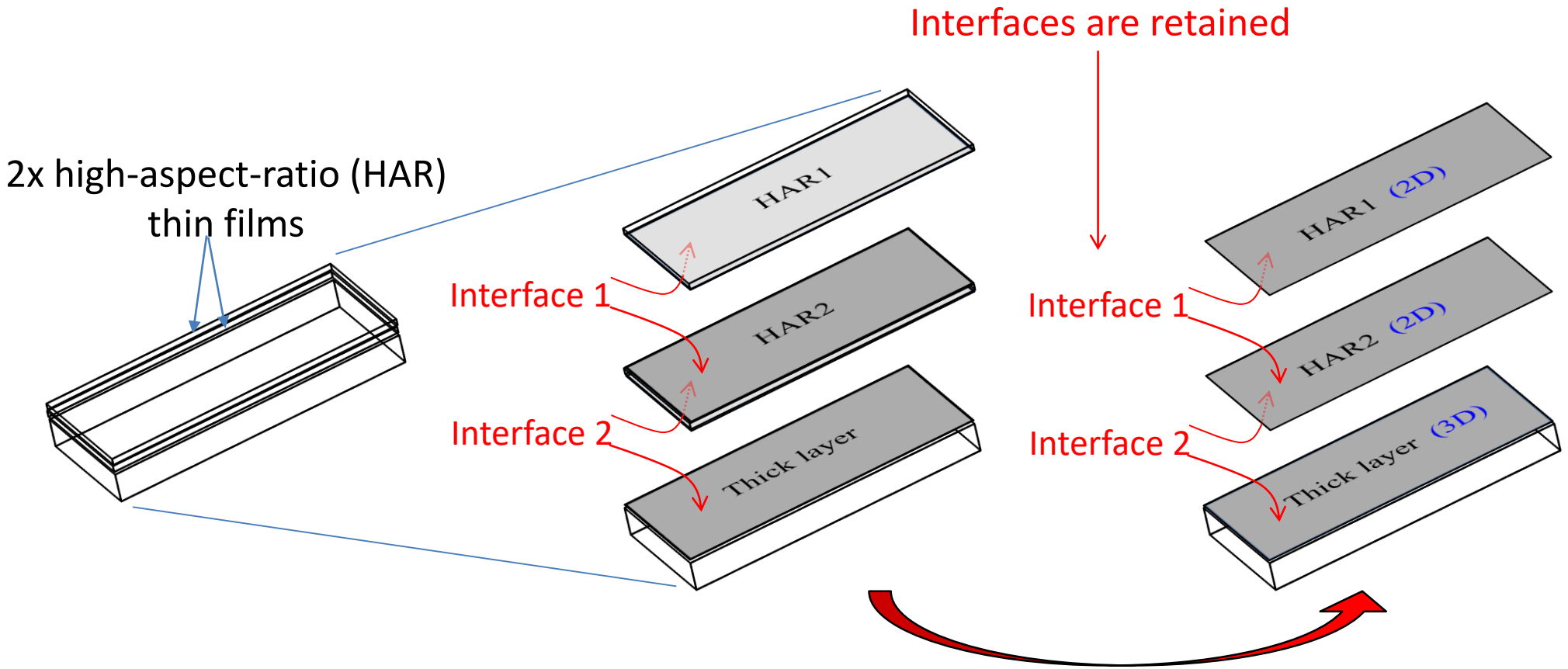
Step 1: Build 3D/2D Geometrical Structure



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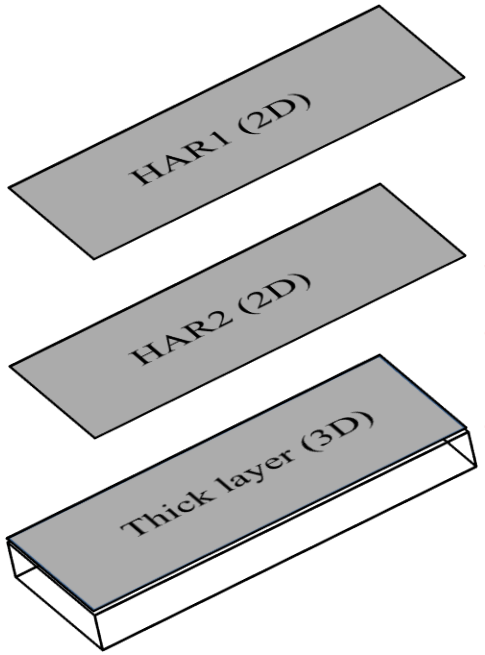
Step 2: Add 3D/2D Physics



2D tangential gradient operator

Mechanical	Thermal	Electrical
$\boldsymbol{\sigma} = \mathbf{C}\boldsymbol{\varepsilon}$ (On **2D** shell or membrane element)	$dC\frac{\partial T}{\partial t} - d\nabla_t(\kappa\nabla_t T) = dQ_h + \text{normal flux}$	$-d\nabla_t(\sigma\nabla_t V) = dQ_J + \text{normal flux}$
$\boldsymbol{\sigma} = \mathbf{C}\boldsymbol{\varepsilon}$ (On **3D** domain element)	$C\frac{\partial T}{\partial t} - d\nabla(K\nabla T) = dQ_h$	$-\nabla(\sigma\nabla V) = Q_J$

3D gradient operator

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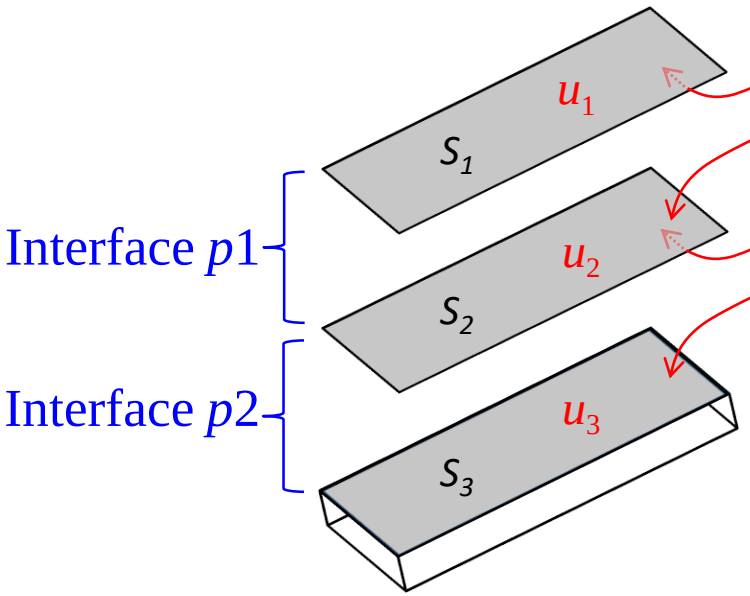
Step 3: Couple 3D/2D Physics from Different Layers on Interfaces

1. Define "pairing" on interface k to pair two in-contact surfaces (S_k as source and S_{k+1} as destination)
2. Use "pairing" operator $src2dst\_pk(u_k)$ and $dst2src\_pk(u_{k+1})$ to extract variables u_k on surface S_k and u_{k+1} on S_{k+1}

source to destination



Mechanics – **interfacial spring connection**

$$\sigma = K_{12}(src2dst\_p1(u_1) - dst2src\_p1(u_2))$$
$$\sigma = -K_{12}(src2dst\_p1(u_1) - dst2src\_p1(u_2))$$
$$\sigma = K_{23}(src2dst\_p2(u_2) - dst2src\_p2(u_3))$$
$$\sigma = -K_{23}(src2dst\_p1(u_2) - dst2src\_p1(u_3))$$

Spring constant [N/m^3]

Heat – interfacial normal heat flux

$$-\nabla_t T \cdot n = \frac{\kappa_{12}}{d_{12}}(src2dst\_p1(T_1) - dst2src\_p1(T_2))$$

...

Thickness, thermal conductivity

Electric – interfacial normal current flux

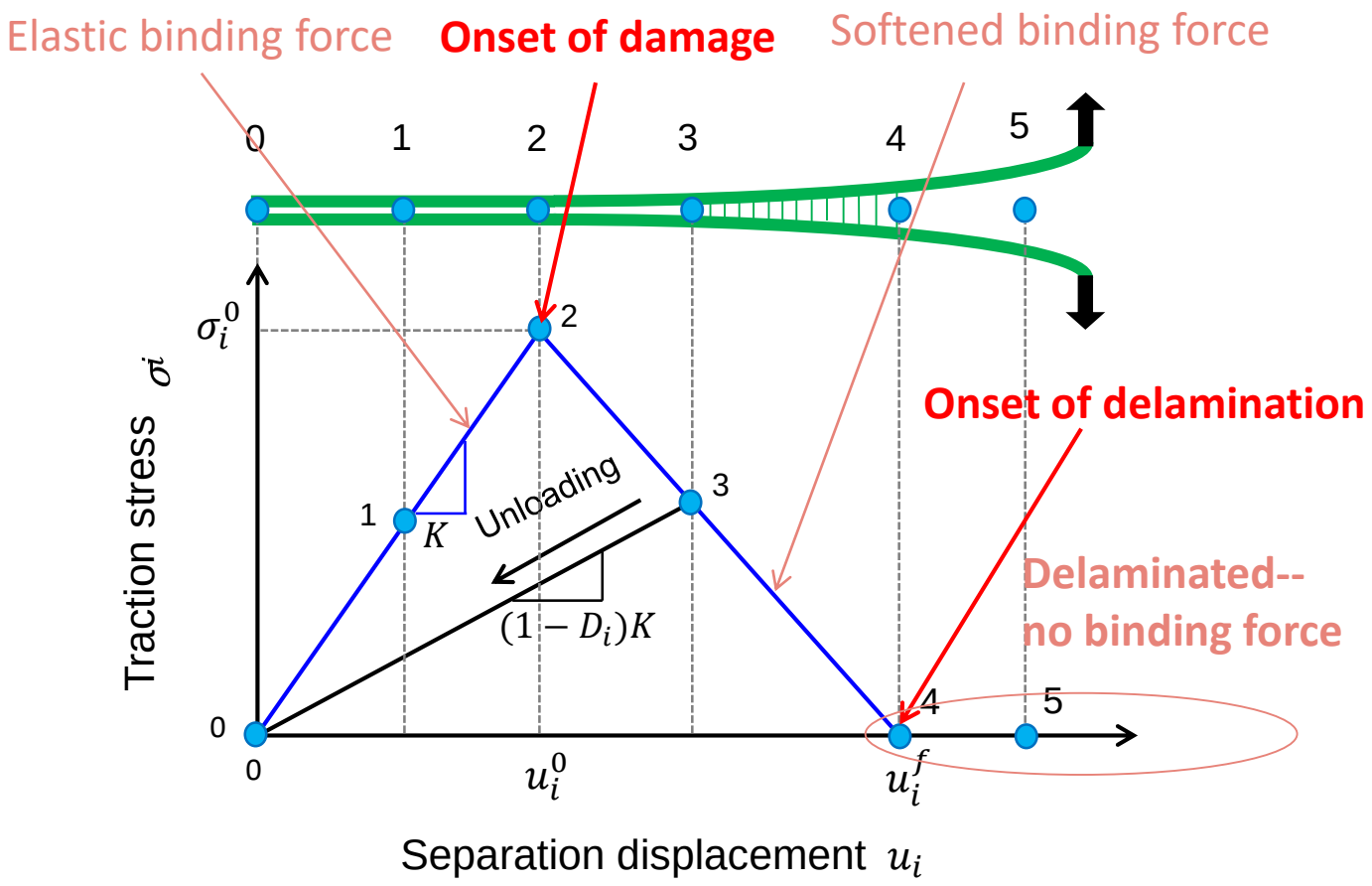
$$-\nabla_t V \cdot n = \frac{\sigma_{12}}{d_{12}}(src2dst\_p1(V_1) - dst2src\_p1(V_2))$$

...

Thickness, electrical conductivity

Cohesive Zone Model (CZM) for Delamination

- Bilinear traction-separation law describes weakening of interfacial binding stress σ_i ($i = n, s$ for normal or shear mode) on a delaminating interface between two in-contact surfaces
  - σ_i decreases when the separation displacement u_i passes the damage initiation separation, u_i^0
  - σ_i vanishes when u_i is greater than the ultimate failure separation u_i^f



CZM Spring Connection for Mixed-mode Delamination

K' is called the penalty stiffness in CZM. It's like a bilinear spring constant with softening and complete debonding

Note that model supports normal, shear, and mixed-mode loadings in compression and tension

On interface k, $u_{i,k} = src2dst\_pk(u_{i,k}) - dst2src\_pk(u_{i,k+1}),\quad i = n, s$

Spring connection on interface k

$$\boldsymbol{\sigma}_{m,k} = K'_{m,k}\,\mathbf{u}_{m,k}$$

mixed-mode u

$$u_{m,k} = \sqrt{u_{n,k}^2 + u_{s,k}^2}$$

normal-mode u shear-mode u

$$u_{m,k}^{\max} = \max\left\{u_{m,k,\text{old}}^{\max}, u\right\}$$

For tensile u

$$K'_{m,k} = \begin{cases} K, & u_{m,k}^{\max} \le u_{m,k}^0 \quad \text{(Elastic binding)} \\ (1 - D_{m,k})K, & u_{m,k}^0 < u_{m,k}^{\max} < u_{m,k}^f, \quad \text{for } u_{n,k} \ge 0 \quad \text{(Softened binding)} \\ 0, & u_{m,k}^{\max} \ge u_{m,k}^f \quad \text{(Delaminated, no binding)} \end{cases}$$

$$D_{m,k} = \begin{cases} 0 & u_{m,k}^{\max} \le u_{m,k}^0 \\ \dfrac{u_{m,k}^f (u_{m,k}^{\max} - u_{m,k}^0)}{u_{m,k}^{\max} (u_{m,k}^f - u_{m,k}^0)} & u_{m,k}^0 < u_{m,k}^{\max} < u_{m,k}^f \\ 1 & u_{m,k}^{\max} \ge u_{m,k}^f \end{cases}$$

For compressive u

$$K'_{m,k} = K, \quad \text{for } u_n < 0$$

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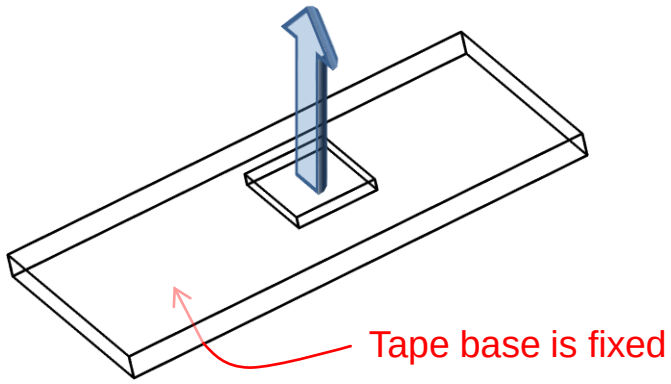
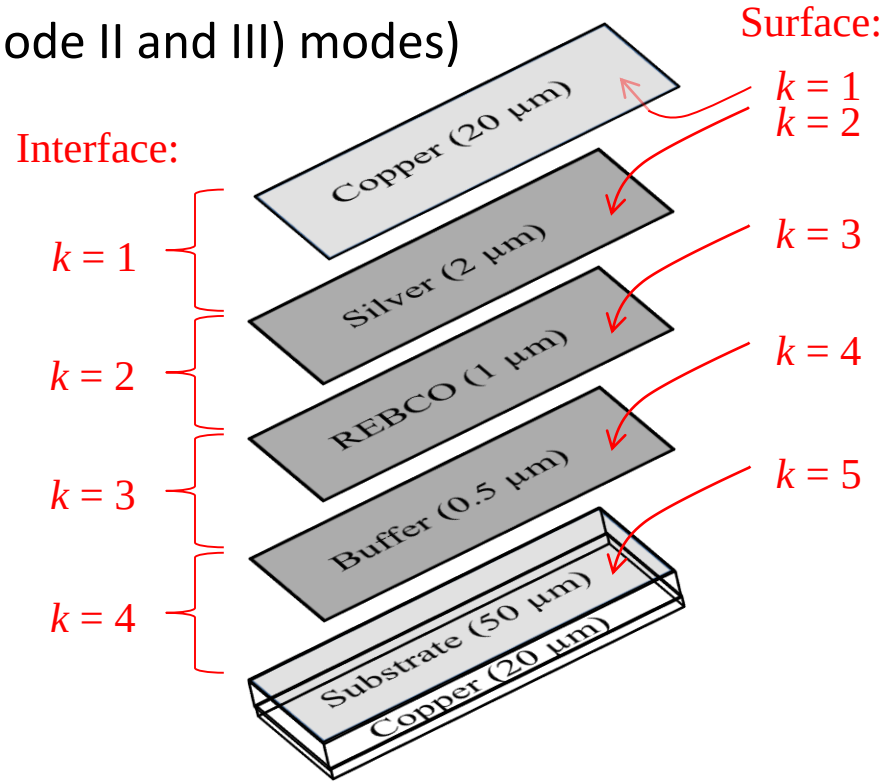
REBCO Coated Conductor Delamination Modeling

- All layers included in real dimensions; all materials include plasticity, some unknown parameters
- 2D Membrane element with plasticity (but no bending stiffness) is used on 2D surfaces
  - In COMSOL, 2D shell element has no plasticity yet (but with bending stiffness)
- Use CZM-based spring connections on delaminating interface
  - C-axis transverse anvil pull loading
  - Induces mixed-mode delamination (normal (mode I) + shear (mode II and III) modes)



Delamination “experiment”



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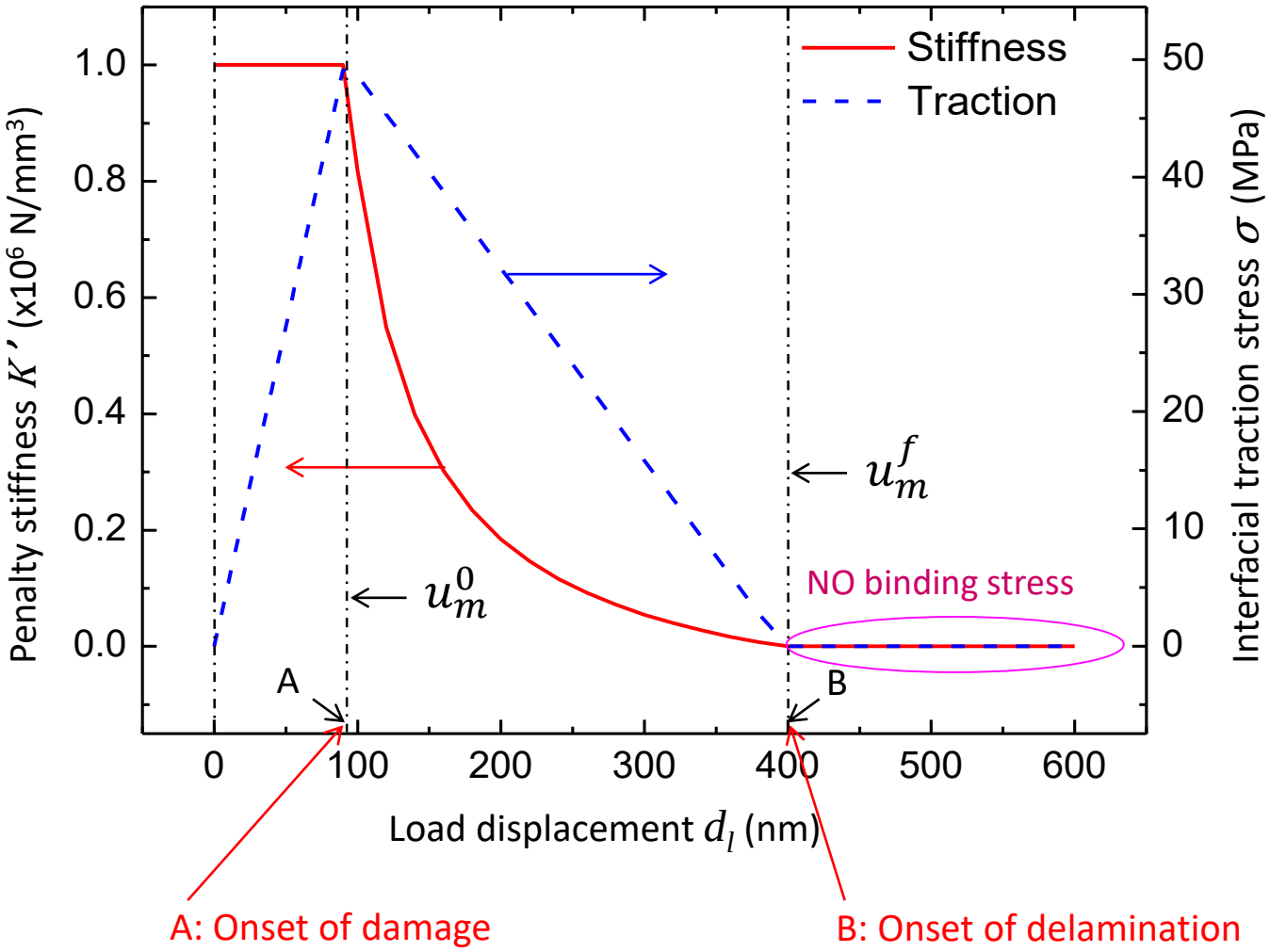
Evolution of Stiffness and Stress during Delamination

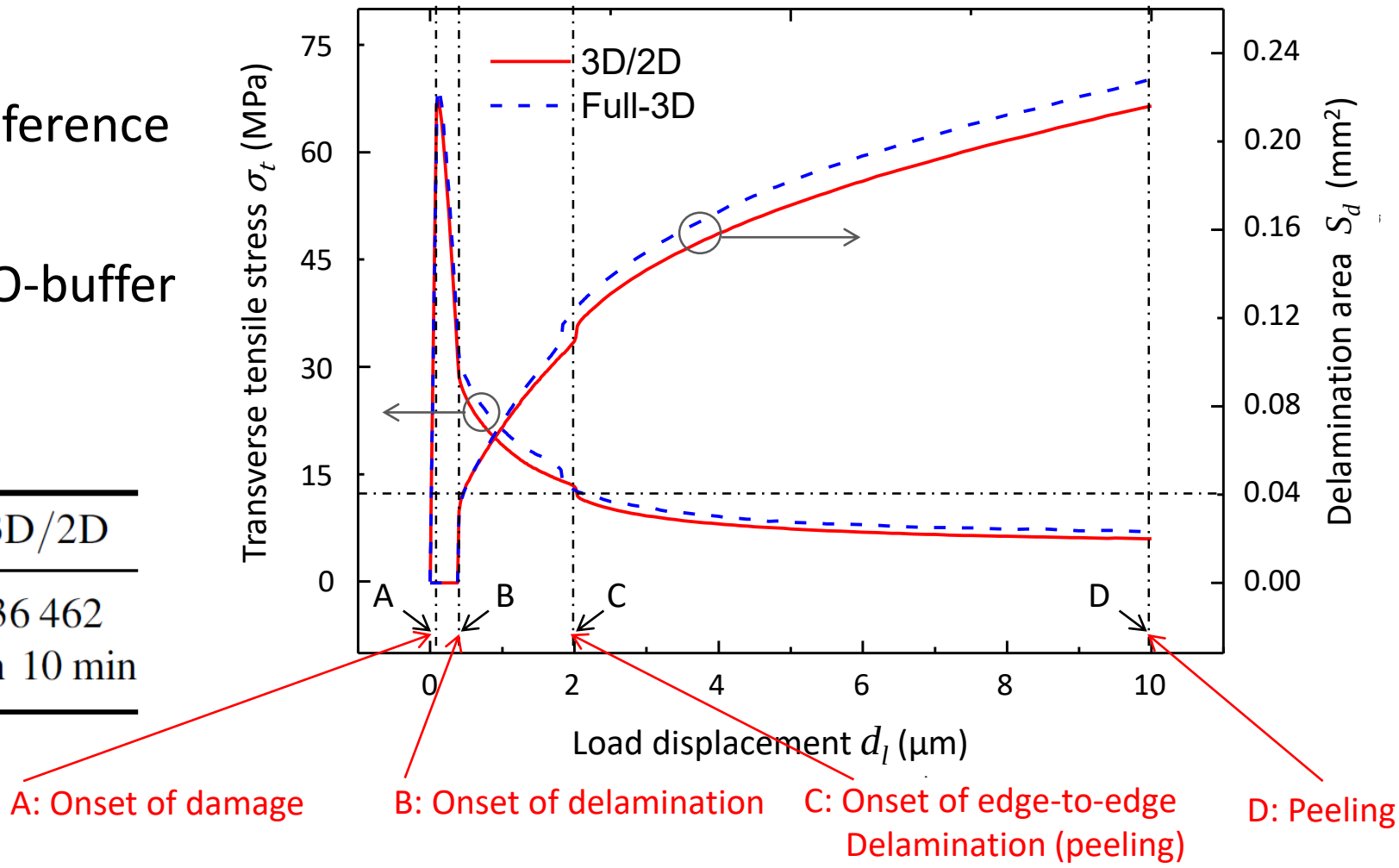


Computational Validation by Full-3D Model- Conductor

- No way to validate 3D/2D layer-level details
- Use full-3D for comparative reference
  - accuracy & speed
- Delamination occurs on REBCO-buffer interface
- <5% error

	3D	3D/2D
DoFs	198 871	36 462
Computational time	22 h 56 min	1 h 10 min

Inflection points occur when edge-to-edge delamination begins



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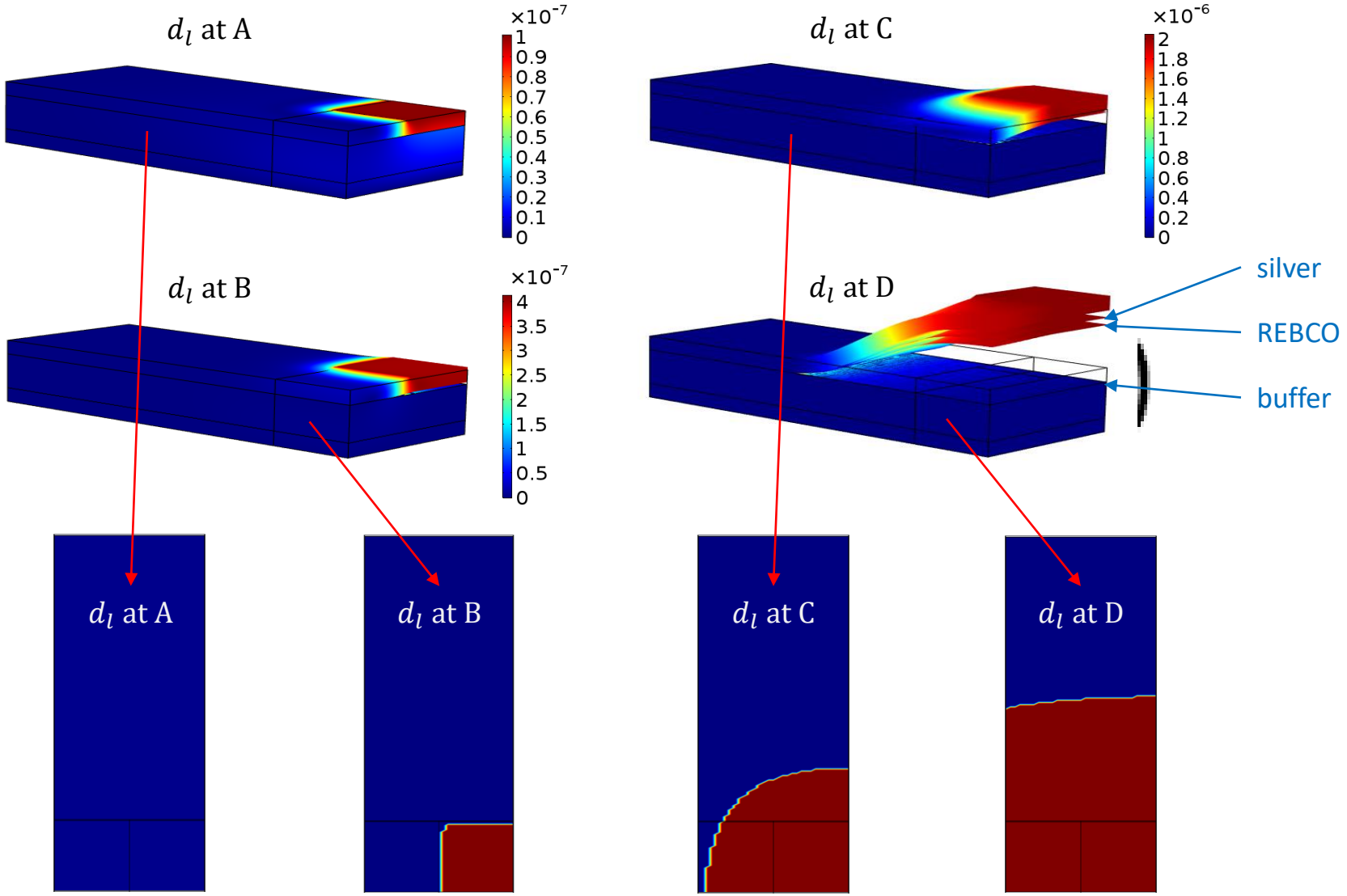
Visualization of delamination process



Onset of damage | Onset of delamination | Onset of edge-to-edge delamination | Peeling

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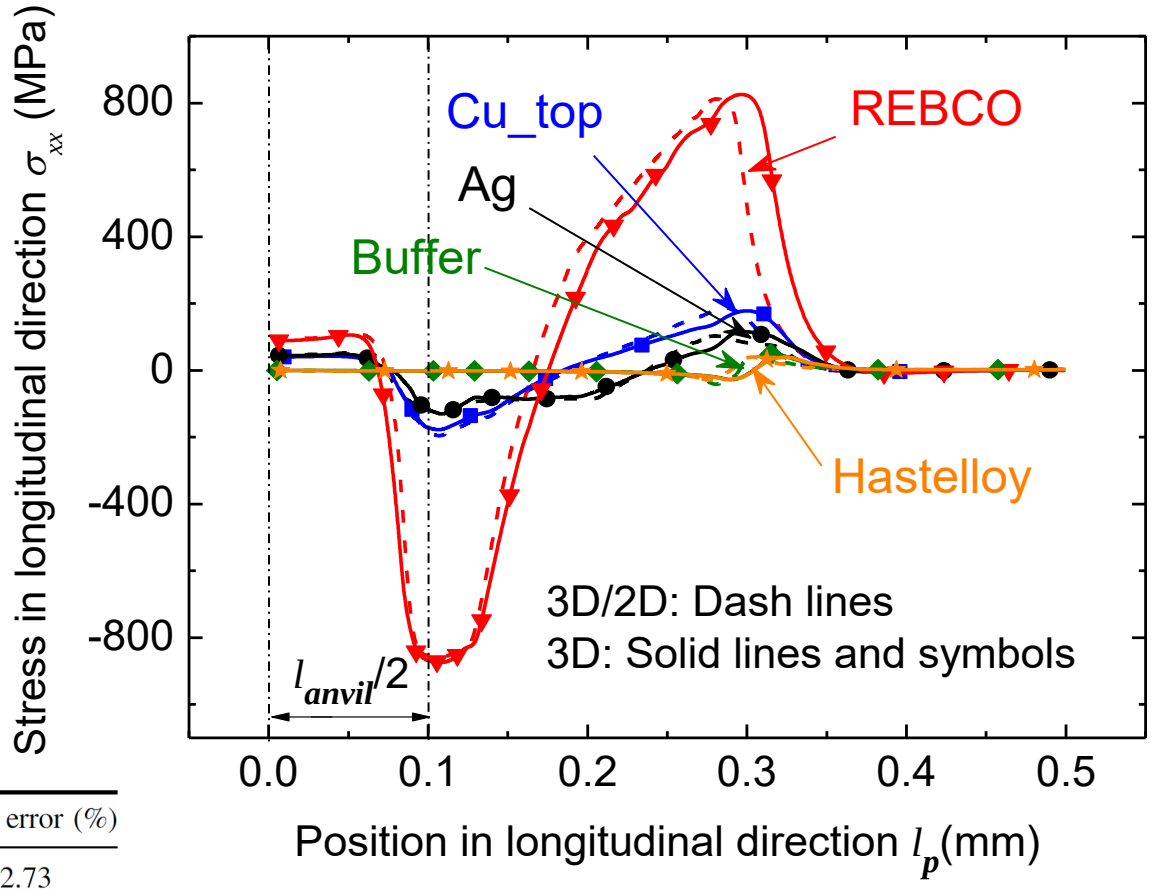
Computational Validation by Full-3D Model: Layer-Level

- Delamination occurs on REBCO-buffer interface
- In 3D/2D model (dashed lines), the lack of bending stiffness in membrane element causes delamination on the REBCO-buffer interface to be slower



	Layer	3D	3D/2D	Absolute error (MPa or mm)	Relative error (%)
Stress at crack front (MPa)	Cu_top	183	188	5	2.73
	Ag	115	103	−12	−10.43
	YBCO	827	812	−15	−1.81
	Buffer	47	46	−1	−2.13
	Hastelloy	39	40	1	−2.5
Crack front position (mm)		0.300	0.285	−0.015	−5.00

* CZM implemented on REBCO-buffer interface only

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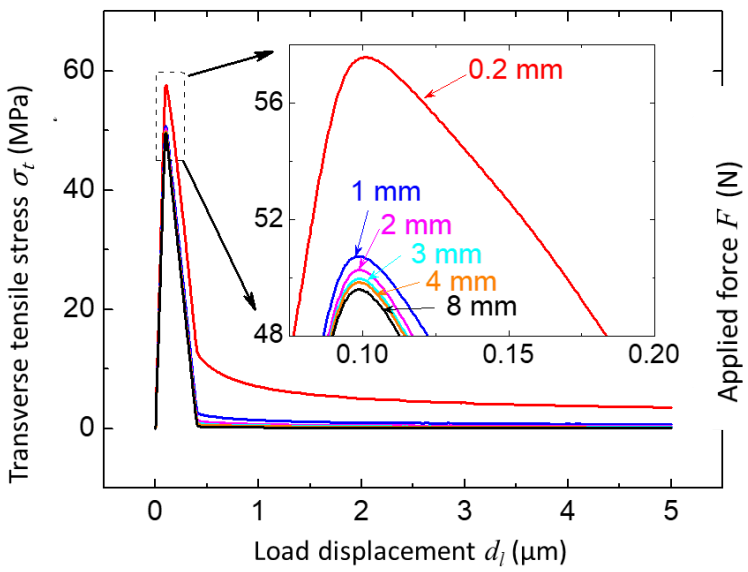
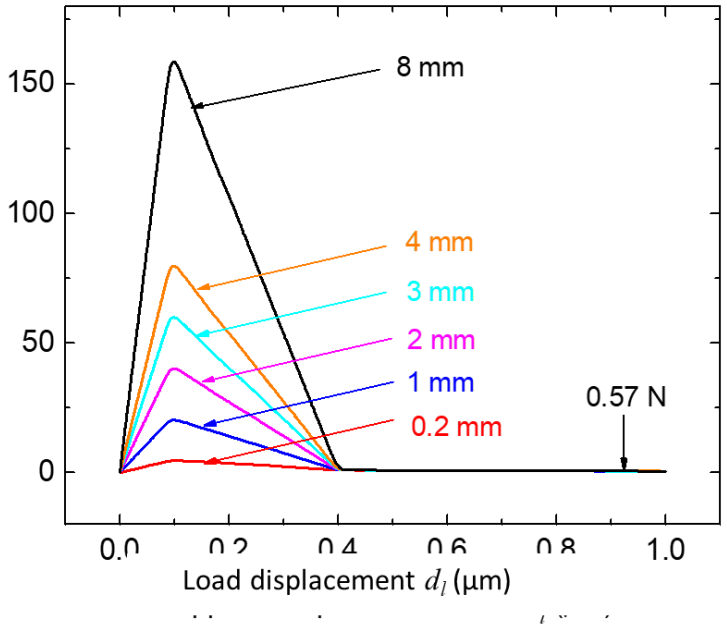
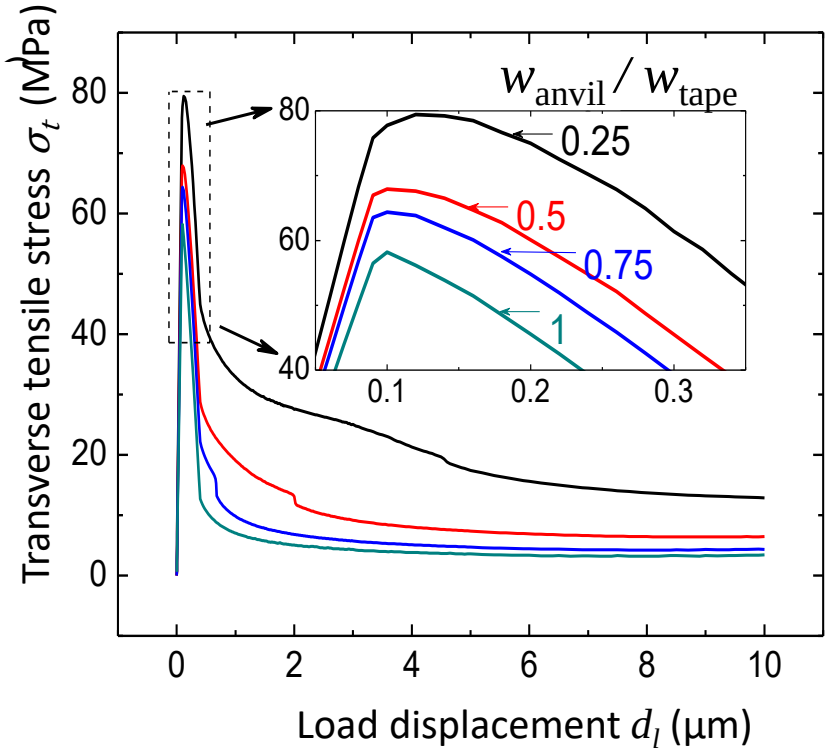
Effects of Anvil Size

- Larger anvil requires larger pulling force but results in smaller peak transverse tensile stress that is closer to the (CZM) interfacial cohesive normal strength $\sigma_n^0 = 50$ MPa
- Elasoplastic deformation effects seen clearly





Anvil length



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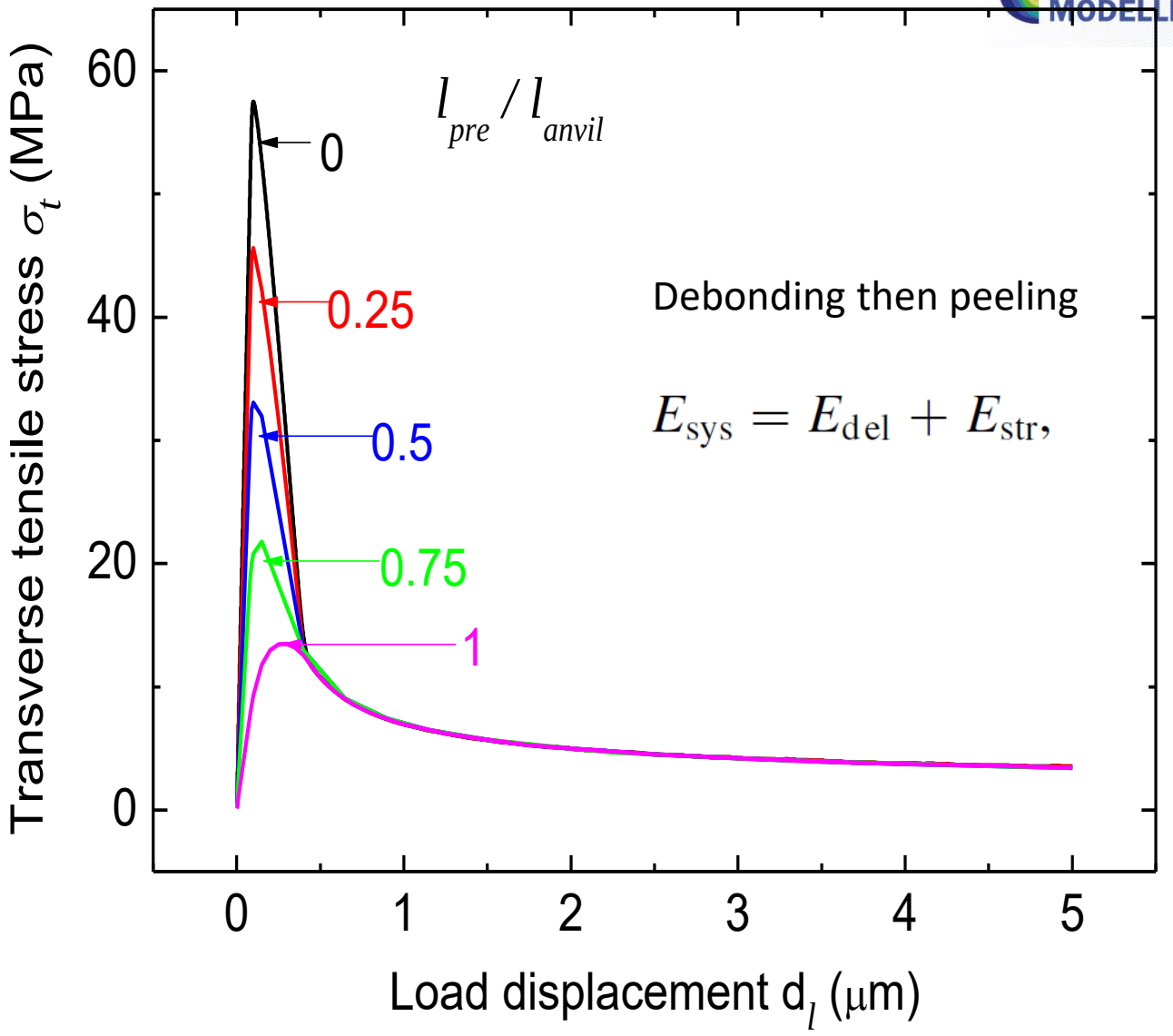
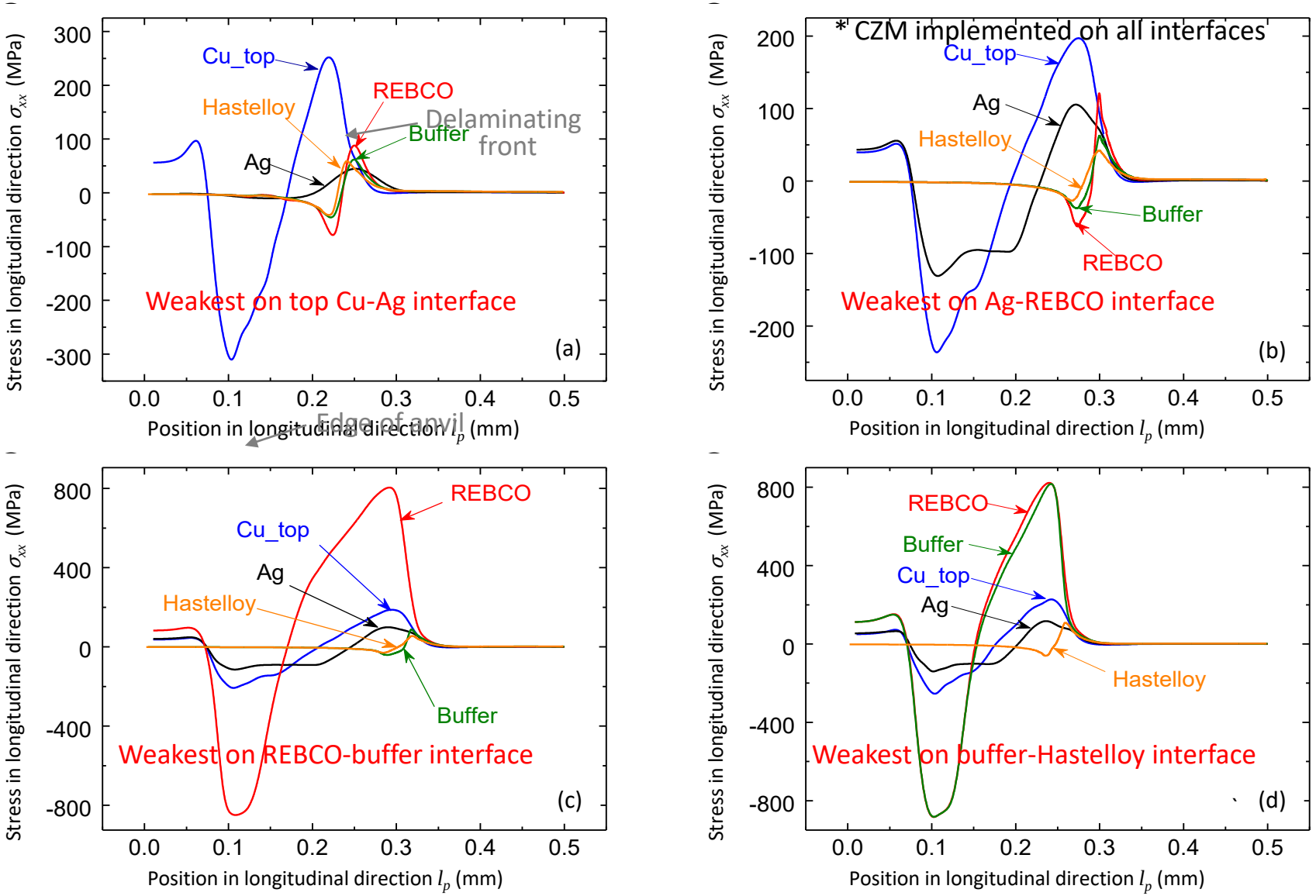
Effects of Pre-crack Length

- Pre-cracks located on REBCO-buffer interface
- Longer pre-crack results in smaller peak transverse tensile stress and smaller anvil pulling force
- Explains why experimentally observed c-axis failure/delamination stress varies wildly from 10 to 110 MPa; Unpredictable defect sizes give wide range of observed values



Delamination by Weakest CZM Interface

Weakest: $\sigma_n^0 = \sigma_s^0 = 50$ MPa
Remaining: $\sigma_n^0 = \sigma_s^0 = 500$ MPa



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Conclusions

- A general 3D/2D multiphysics modeling methodology is presented
  - Applicable to laminated composites composed of any number of stacked high-aspect-ratio (HAR) thin layers
  - Solved computational difficulties in modeling laminated HAR layers
  - Well-suited for REBCO coated conductors
- Cohesive zone model applied to interfaces sandwiched between 2D surfaces and/or 3D domains is used to model delamination in REBCO coated conductors
- Model is capable of generating stress/strain evolutional profiles on all constituent layers of a REBCO coated conductor during the processes of crack formation and delamination propagation
- More complicated, large scale multi-tape delamination models can be built by repeatedly applied the same 3D/2D modeling techniques for a single tape acting as a basic building block

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