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Progressive failure analysis of a Pi joint and Delaminated Panel with uncertainties in fracture properties

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Collaborative work with Prof. Wooseok Ji, UNIST and Dr. Ravi Raveendran, Comet Tech.

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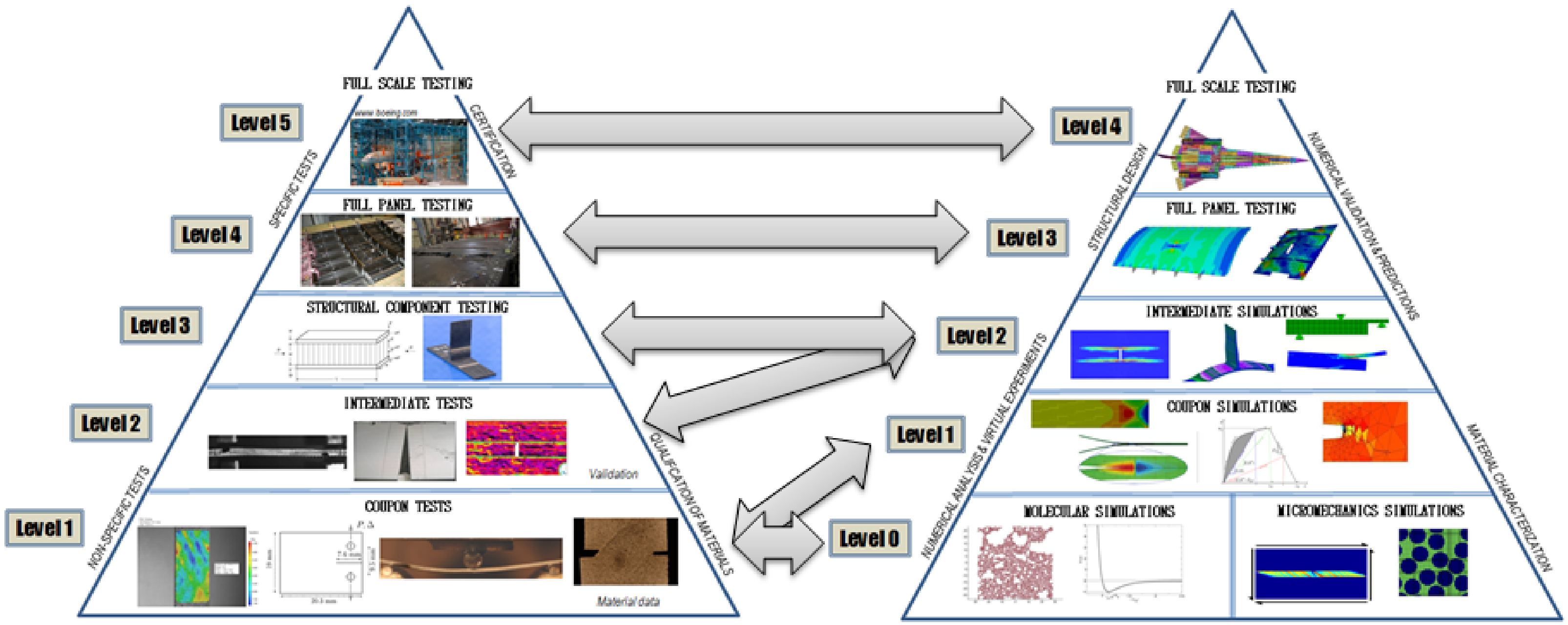
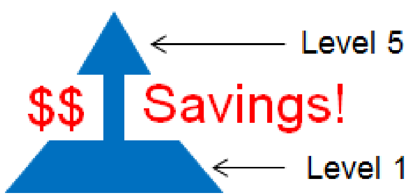
Motivation

Experimental Test Pyramid

Numerical Simulation Pyramid



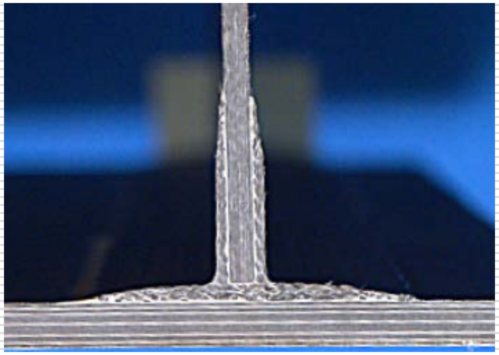


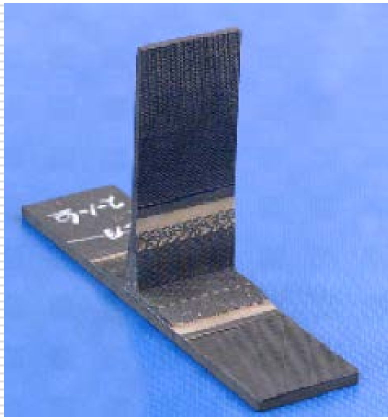
- Require a validated high-fidelity, physics-based simulation framework

Accurate Failure Models leads to Large Cost Savings

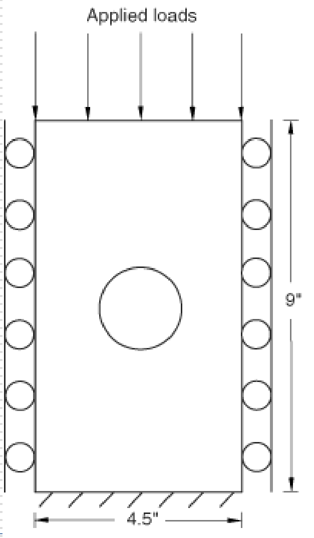
Two Examples

1. PI JOINT



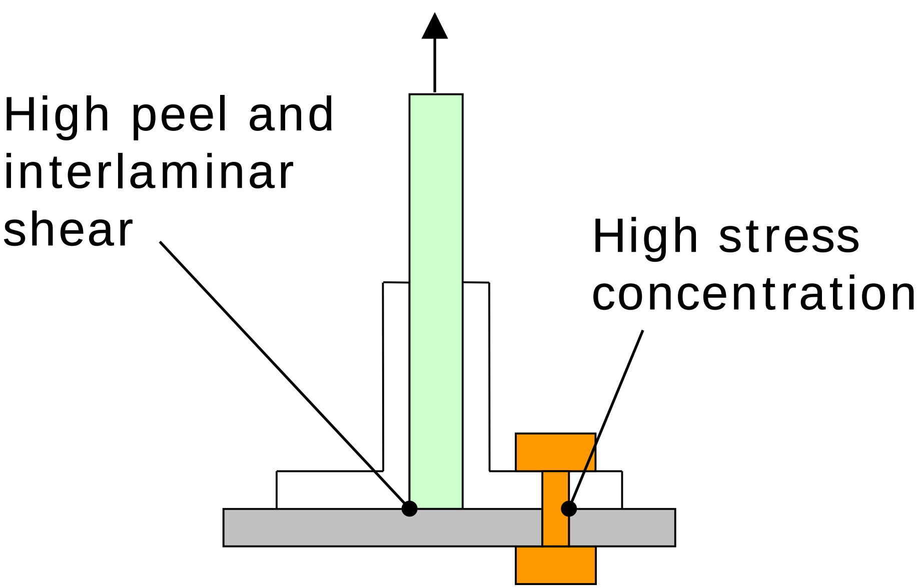


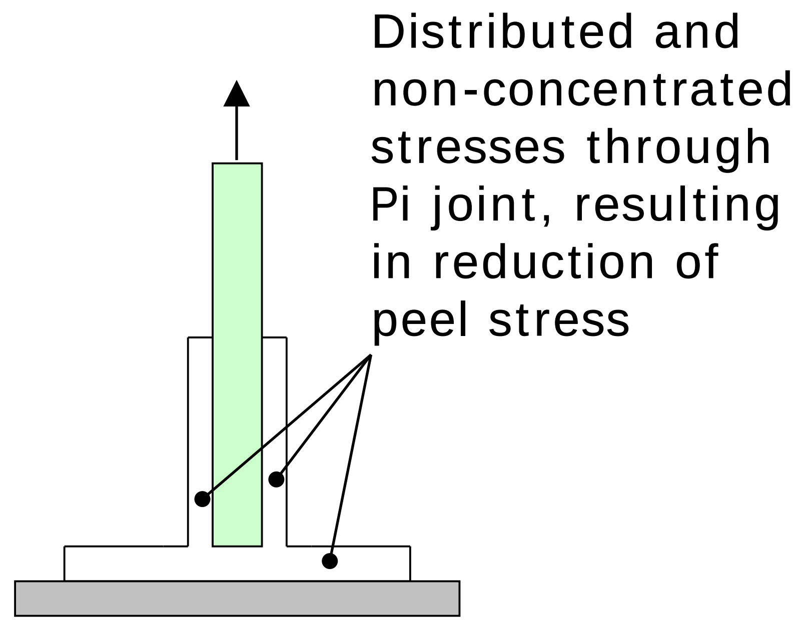
2. CAI STRENGTH



Pi Joint Composite Structure

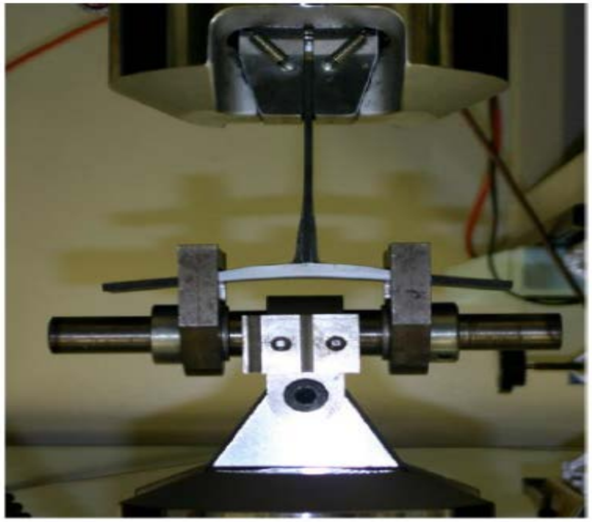
Conventional L-shape (Bolted) Composite Joints	Pi Joint Composite Structure

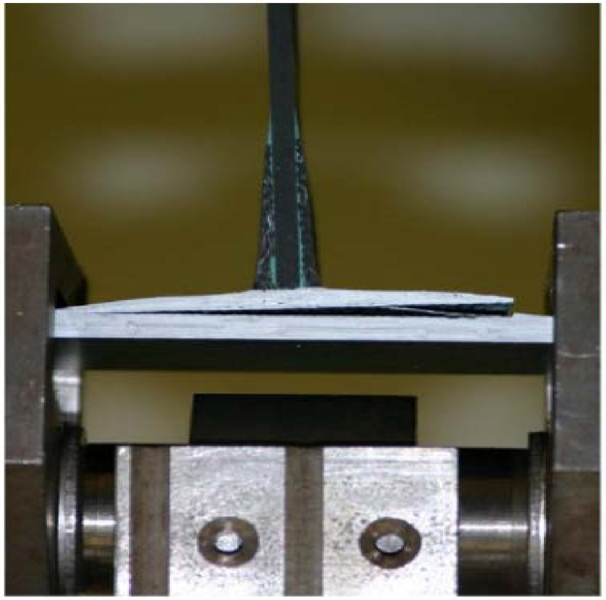


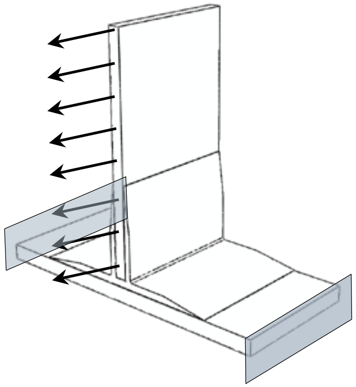


- Bonded interface is still the weakest link due to the large amount of load being transmitted over the region

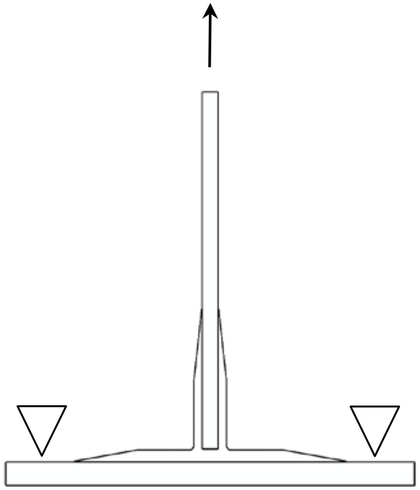
Characterization of Pi Joint Performance







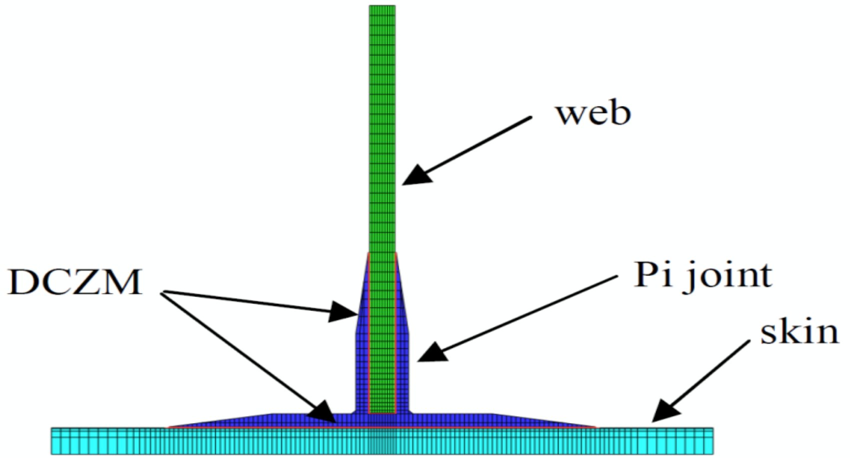
Shear test

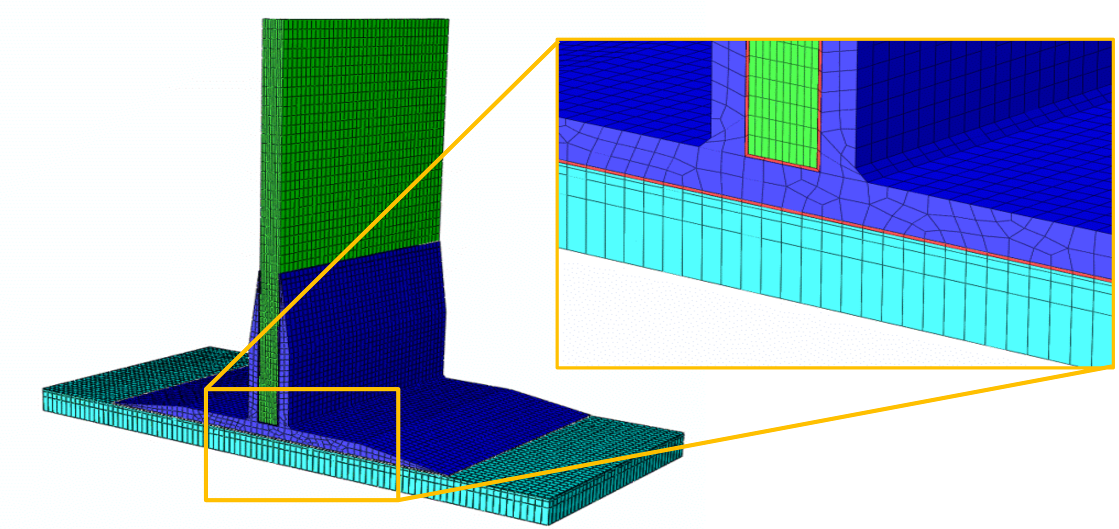


Pulloff test

- Collier, C., Yarrington, P., Pickenheim M., Bednarcyk B. and Jeans J. “Analysis methods used on the NASA composite crew module (CCM),” Proceedings of the 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 2008.

FE Model of Pi Joint Composite Structure





- Collier, C., Yarrington, P., Pickenheim M., Bednarcyk B. and Jeans J. "Analysis methods used on the NASA composite crew module (CCM)," Proceedings of the 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 2008.

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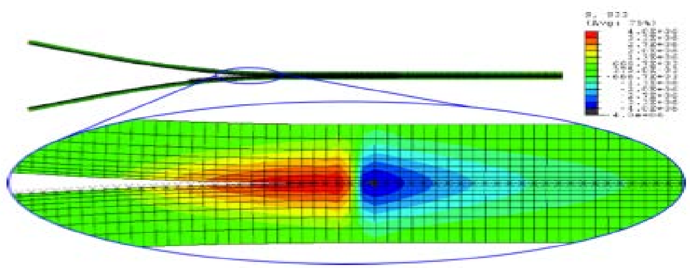
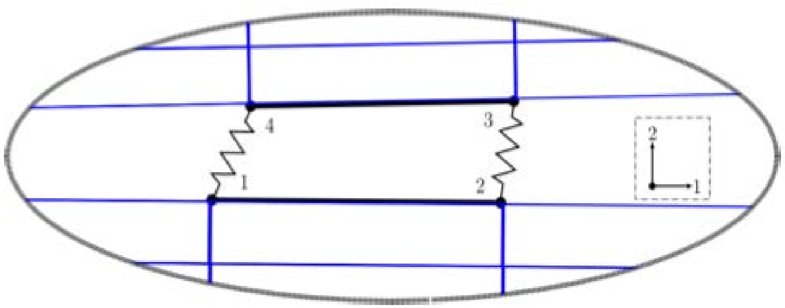
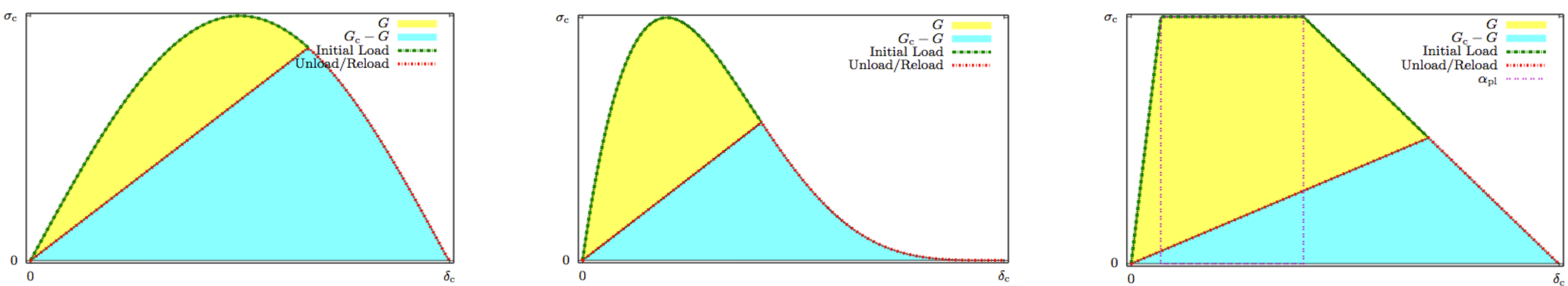
Discrete Cohesive Zone Model (DCZM)Element

- Decohesion process is discretized by successive failure of cohesive sub-elements governed by a traction separation law.
- Easily implemented into the conventional FE framework.
- Various failure modes (material failure, crack propagation, and local buckling) are tracked simultaneously, thus any potential interaction between the failure modes can be captured





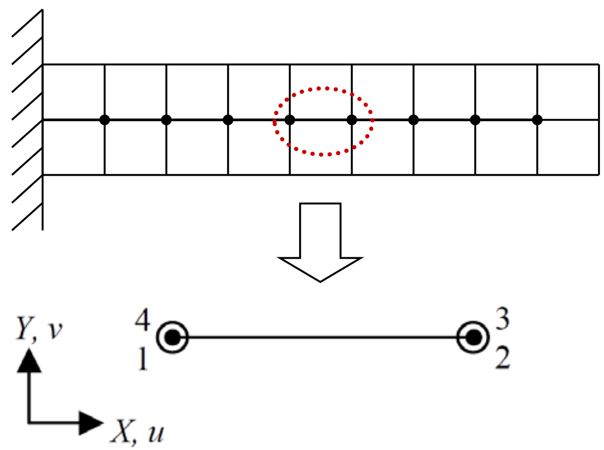


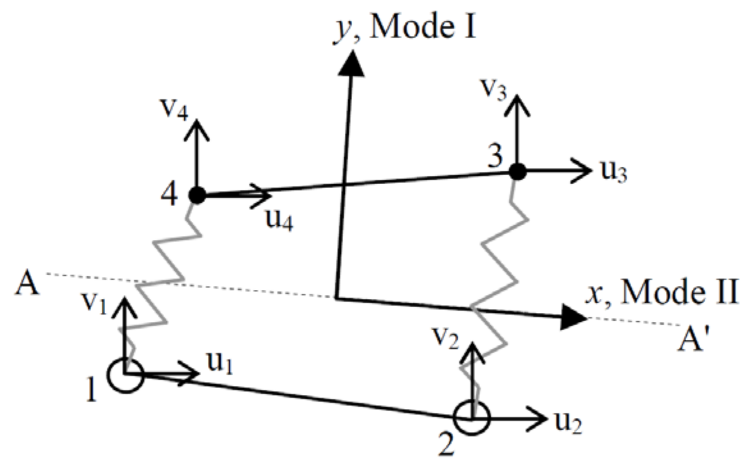
DCZM Element

Initial configuration before opening

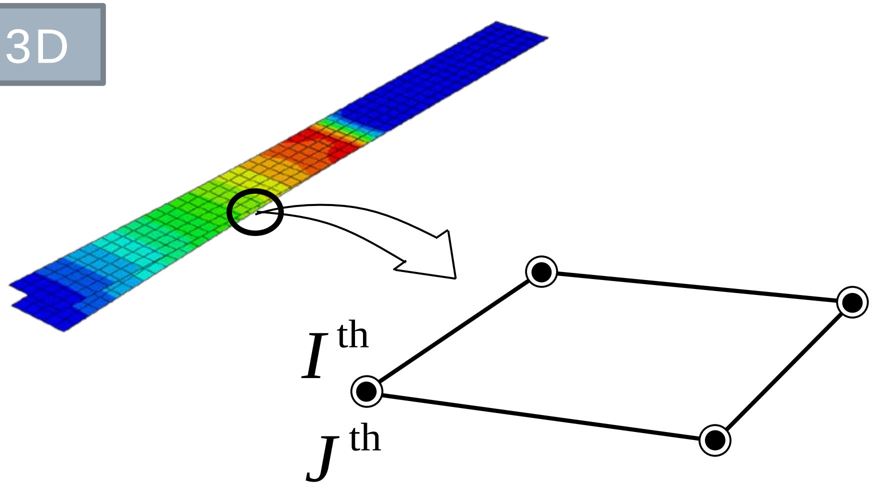
Deformed configuration

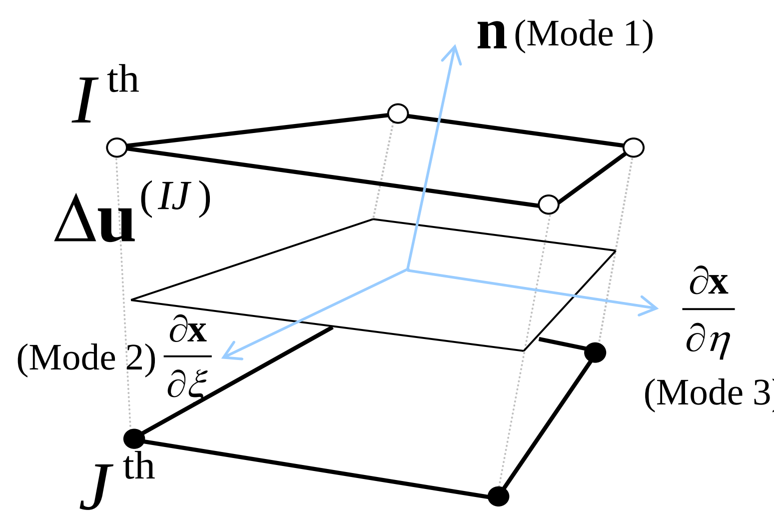
2D



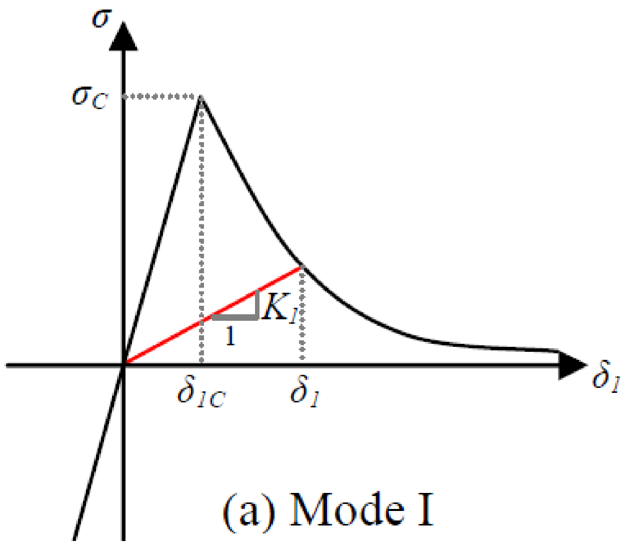


3D

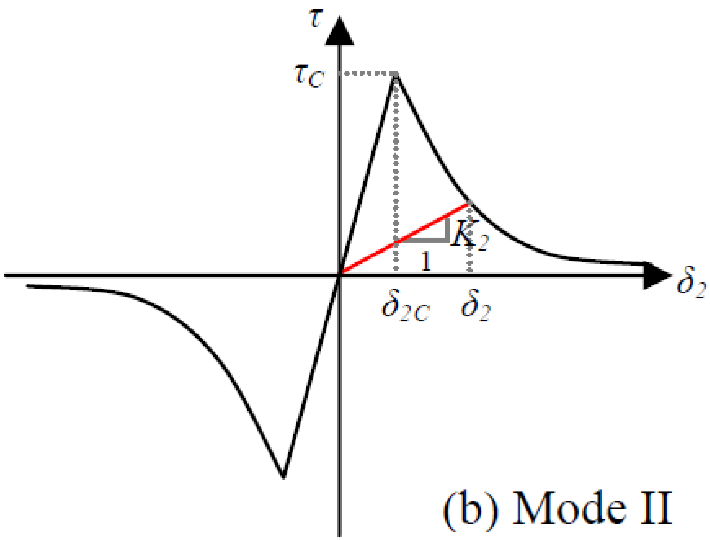




DCZM Element



(a) Mode I



(b) Mode II

$$F_1^{(mn)} = \begin{cases} \Delta a \tilde{K}_1^{(mn)} \delta_1^{(mn)} & \text{if} \quad \delta_1^{(mn)} \le \delta_{1C}^{(mn)} \\ \Delta a \tilde{K}_1^{(mn)} \delta_{1C}^{(mn)} \exp\left[\alpha_1 \left(1 - \frac{\delta_1^{(mn)}}{\delta_{1C}^{(mn)}}\right)\right] & \text{if} \quad \delta_1^{(mn)} > \delta_{1C}^{(mn)} \end{cases}$$

$$F_2^{(mn)} = \begin{cases} \Delta a \tilde{K}_2^{(mn)} \delta_2^{(mn)} & \text{if} \quad \left|\delta_2^{(mn)}\right| \le \delta_{2C}^{(mn)} \\ \Delta a \tilde{K}_2^{(mn)} \delta_{2C}^{(mn)} \exp\left[\alpha_2 \left(1 - \frac{\delta_2^{(mn)}}{\delta_{2C}^{(mn)}}\right)\right] & \text{if} \quad \left|\delta_2^{(mn)}\right| > \delta_{2C}^{(mn)} \end{cases}$$

Fracture toughness

$$G_{IC} = \int_0^\infty \frac{F_1^{(mn)}}{\Delta a} d\delta_1 \qquad G_{IIC} = \int_0^\infty \frac{F_2^{(mn)}}{\Delta a} d\delta_2$$

$\Rightarrow$

$$\alpha_1 = \frac{\sigma_C^2}{2G_{IC}\tilde{K}_1^{(mn)} - \sigma_C^2} \qquad \alpha_2 = \frac{\tau_C^2}{2G_{IIC}\tilde{K}_2^{(mn)} - \tau_C^2}$$

Cohesive strength

$$\sigma_C = \tilde{K}_1^{(mn)} \delta_{1C} \qquad \tau_C = \tilde{K}_2^{(mn)} \delta_{2C}$$

$\Rightarrow$

$$\delta_{1C} = \frac{\sigma_C}{\tilde{K}_1^{(mn)}} \qquad \delta_{2C} = \frac{\tau_C}{\tilde{K}_2^{(mn)}}$$

DCZM Element

- Direct-integration dynamic analysis
  - Hilber-Hughes-Taylor integration scheme

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F}$$

$$\mathbf{R}_{t+\Delta t} = -\mathbf{M}\ddot{\mathbf{u}}_{t+\Delta t} + (1+\alpha)(\mathbf{F}_{t+\Delta t} - \mathbf{K}_{t+\Delta t}\mathbf{u}_{t+\Delta t}) - \alpha(\mathbf{F}_t - \mathbf{K}_t\mathbf{u}_t)$$

$$\mathbf{u}_{t+\Delta t} = \mathbf{u}_t + \Delta t\dot{\mathbf{u}}_t + \Delta t^2[(0.5-\beta)\ddot{\mathbf{u}}_t + \beta\dot{\mathbf{u}}_{t+\Delta t}]$$

$$\mathbf{v}_{t+\Delta t} = \mathbf{v}_t + \Delta t[(0.5-\gamma)\ddot{\mathbf{u}}_t + \gamma\dot{\mathbf{u}}_{t+\Delta t}]$$

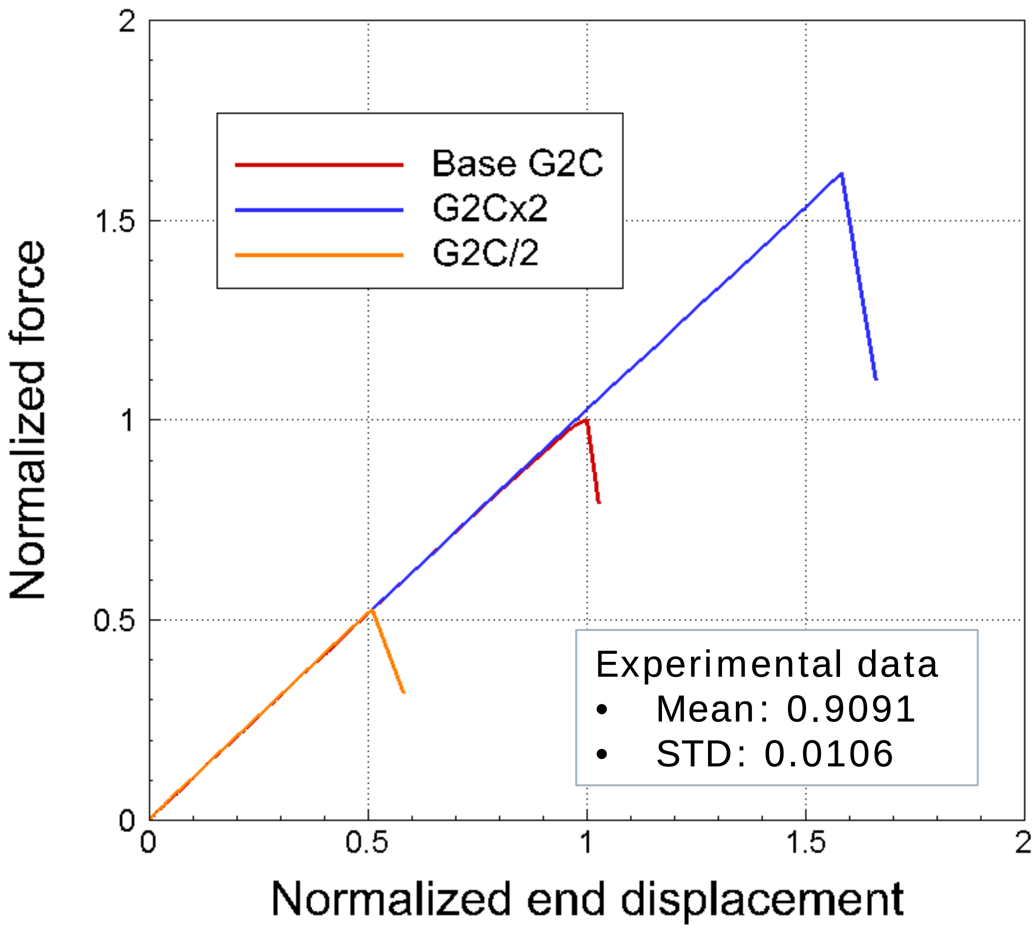
$$\mathbf{u}_0 = \mathbf{u}(0) \qquad \mathbf{v}_0 = \dot{\mathbf{u}}(0) \qquad \mathbf{a}_0 = \mathbf{M}^{-1}(\mathbf{F_0} - \mathbf{K_0}\mathbf{u_0})$$

  - ABAQUS implementation

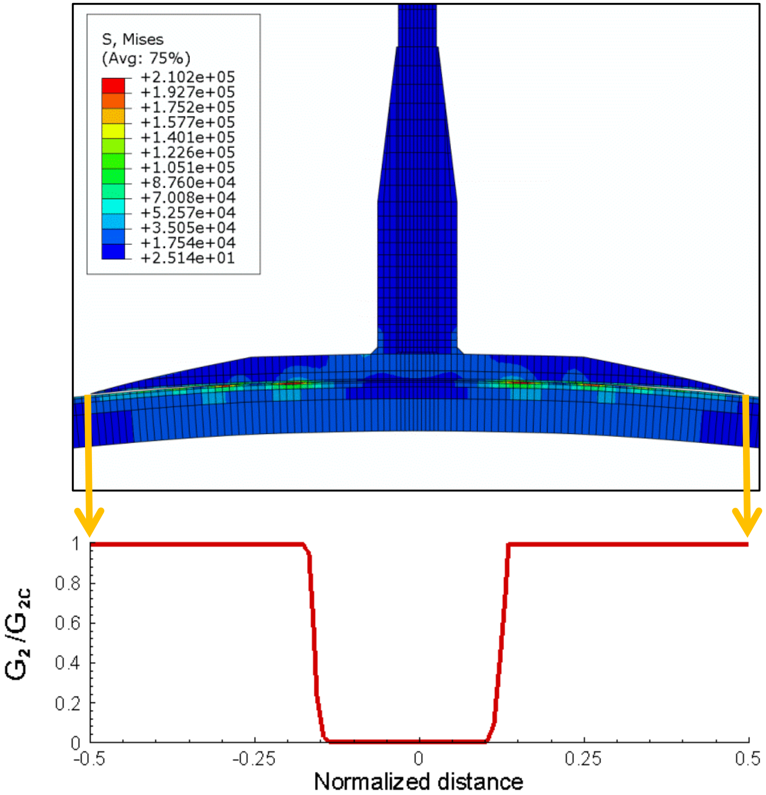
$$\mathrm{AMATRX} = \mathbf{M}^{\mathrm{el}}\frac{\mathrm{d}\ddot{\mathbf{u}}}{\mathrm{d}\mathbf{u}} + (1+\alpha)\frac{\partial\mathbf{K}^{\mathrm{el}}_{t+\Delta t}}{\partial\dot{\mathbf{u}}}\frac{\mathrm{d}\dot{\mathbf{u}}}{\mathrm{d}\mathbf{u}} + (1+\alpha)\mathbf{K}^{\mathrm{el}}_{t+\Delta t}$$

$$\mathrm{RHS} = \mathbf{R}^{\mathrm{el}}_{t+\Delta t}$$

Performance of 2D Pi Joint under pulloff loading

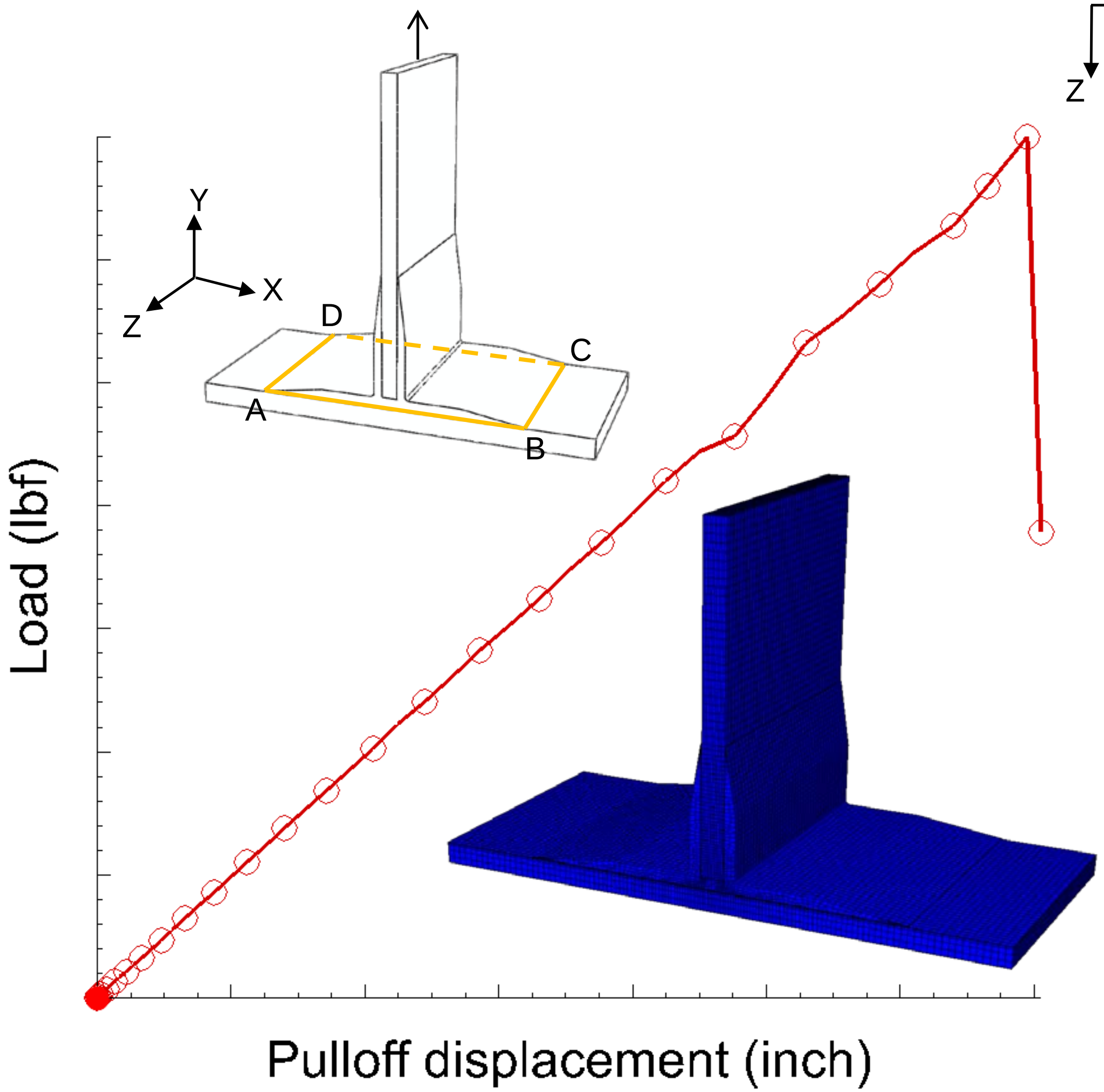


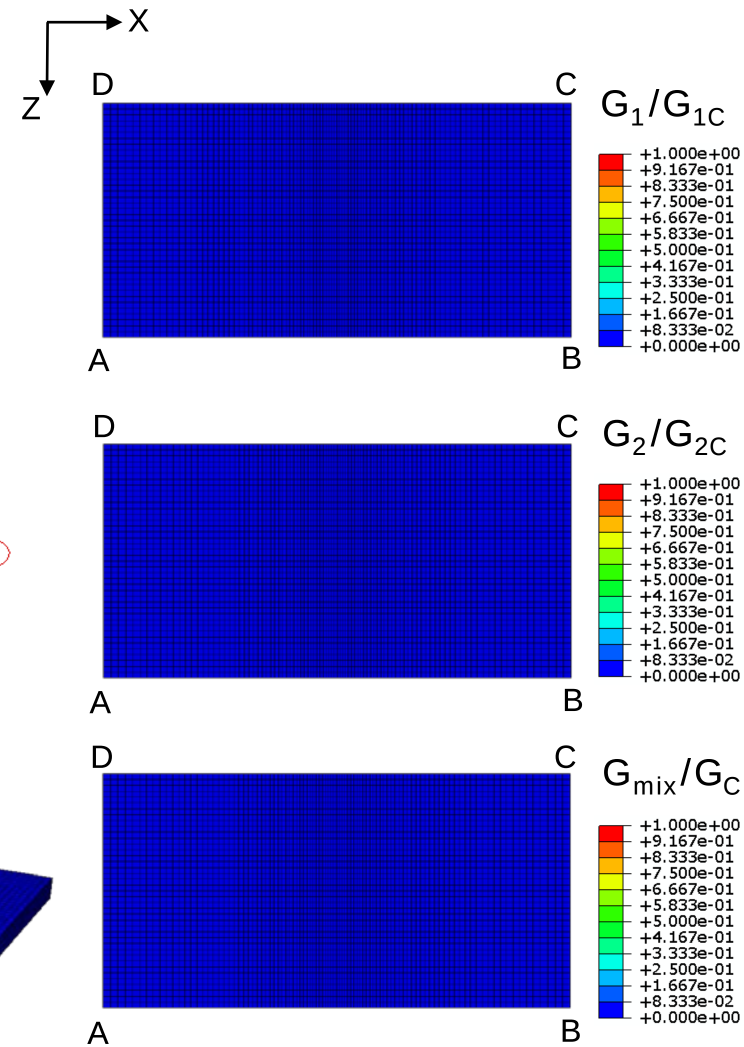
Failure mode of Pi joint with base G2C at the peak load



Note: Peak load and its corresponding displacement value of Base G_{2C} are used to normalize the axes

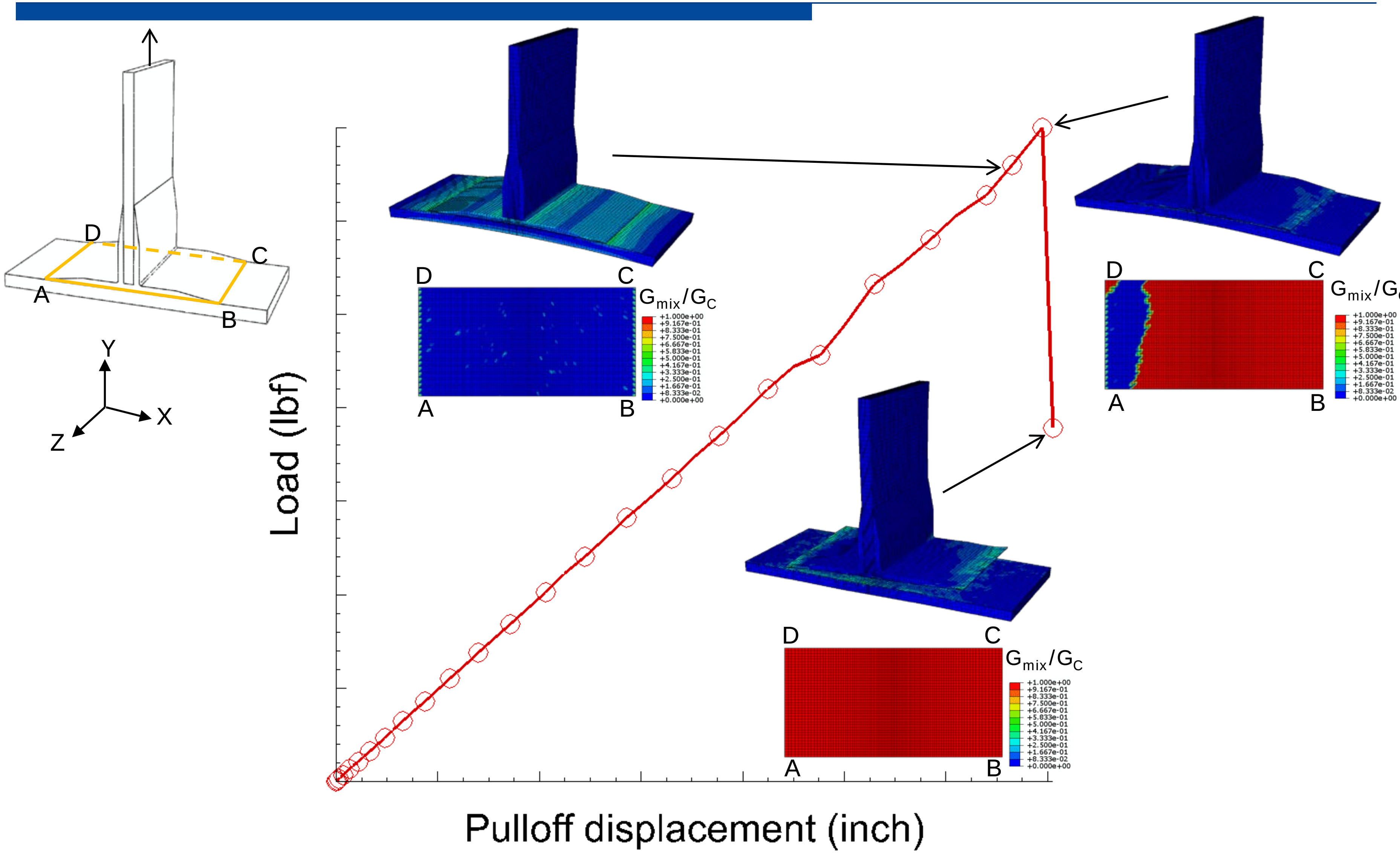
Performance of 3D Pi Joint under pulloff loading





$$G_{mix} = \frac{G_1}{G_{1C}} + \frac{G_2}{G_{2C}} + \frac{G_3}{G_{3C}}$$

Performance of 3D Pi Joint under pulloff loading



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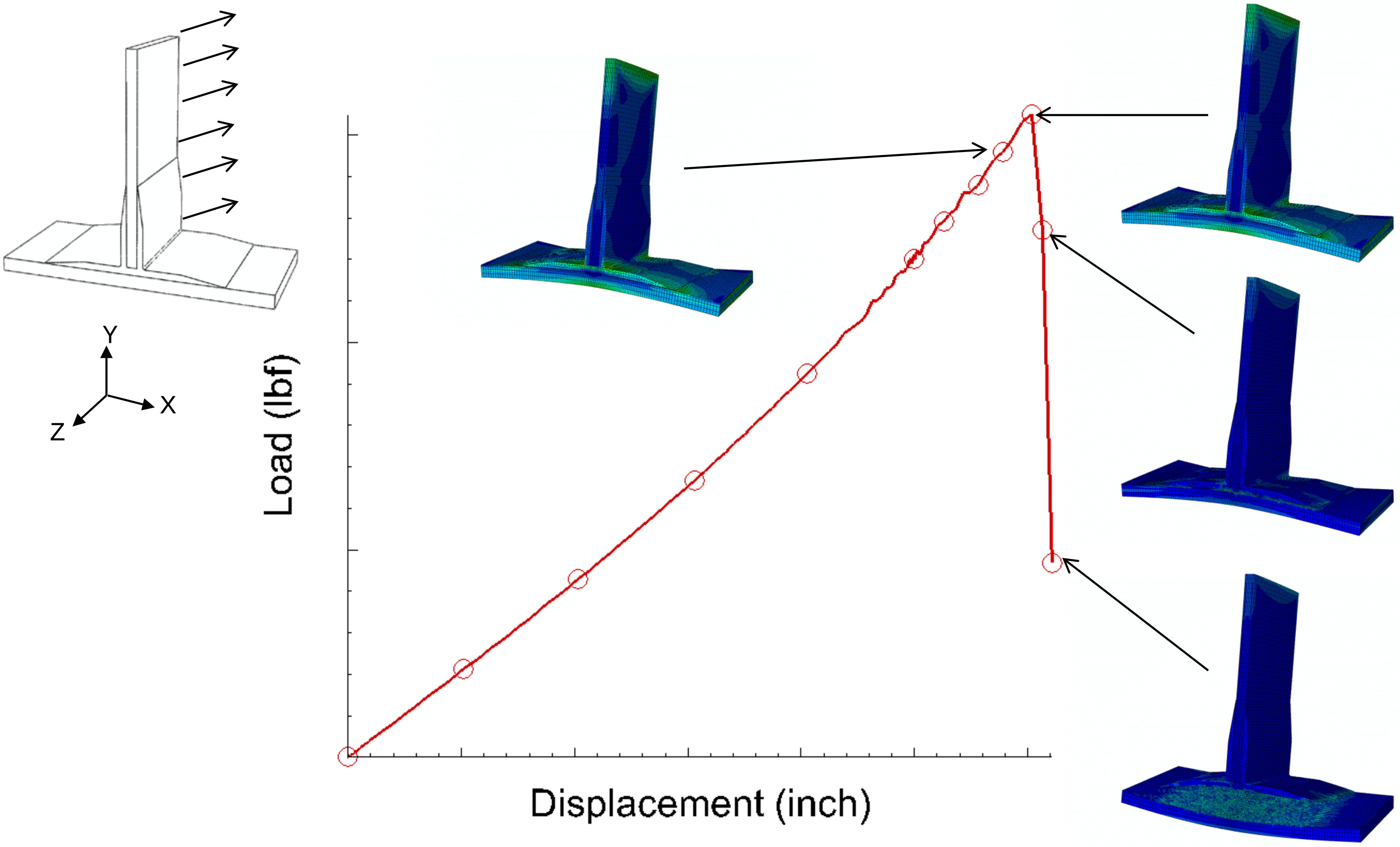
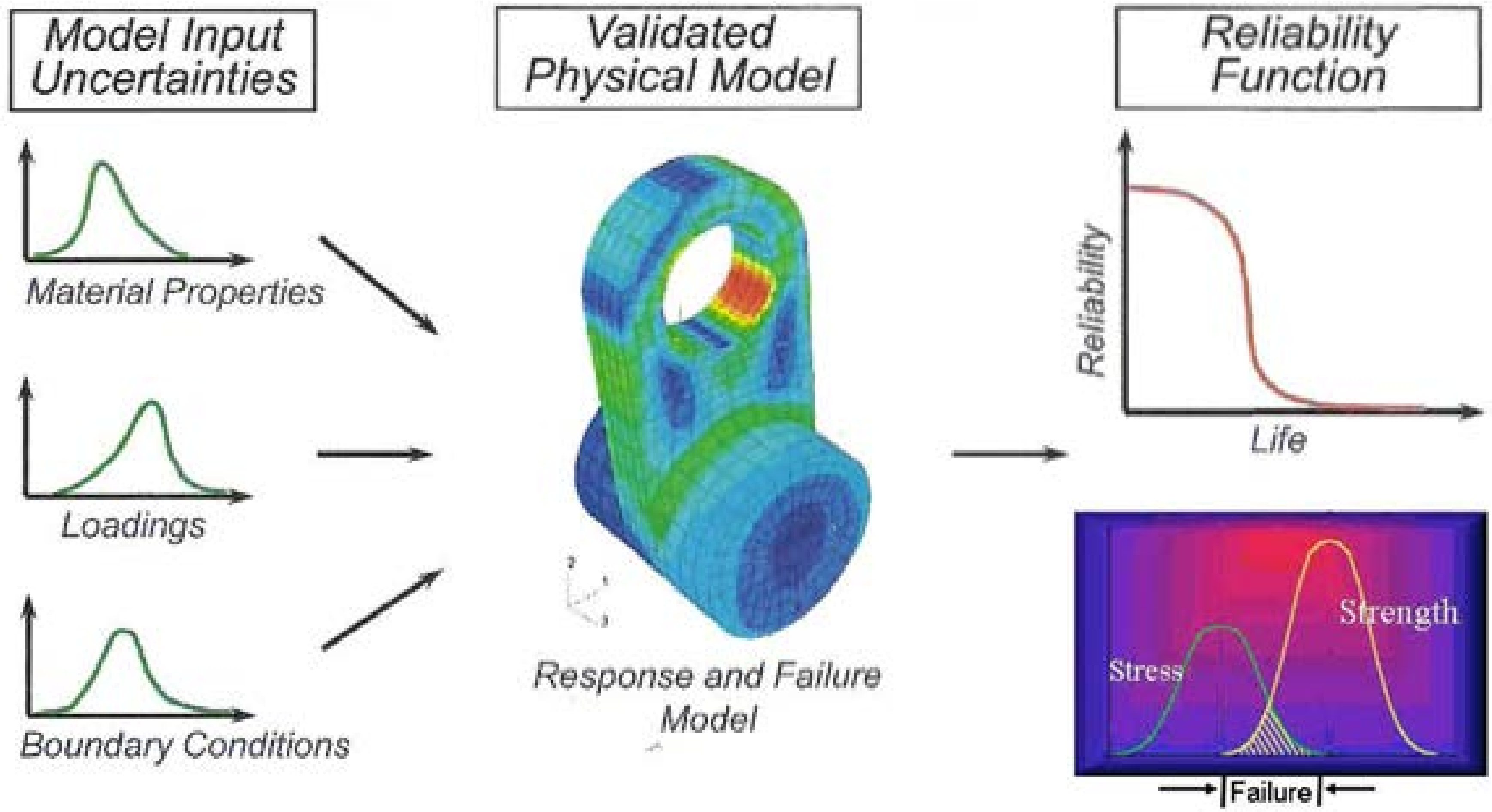
Performance of 3D Pi Joint under shear loading



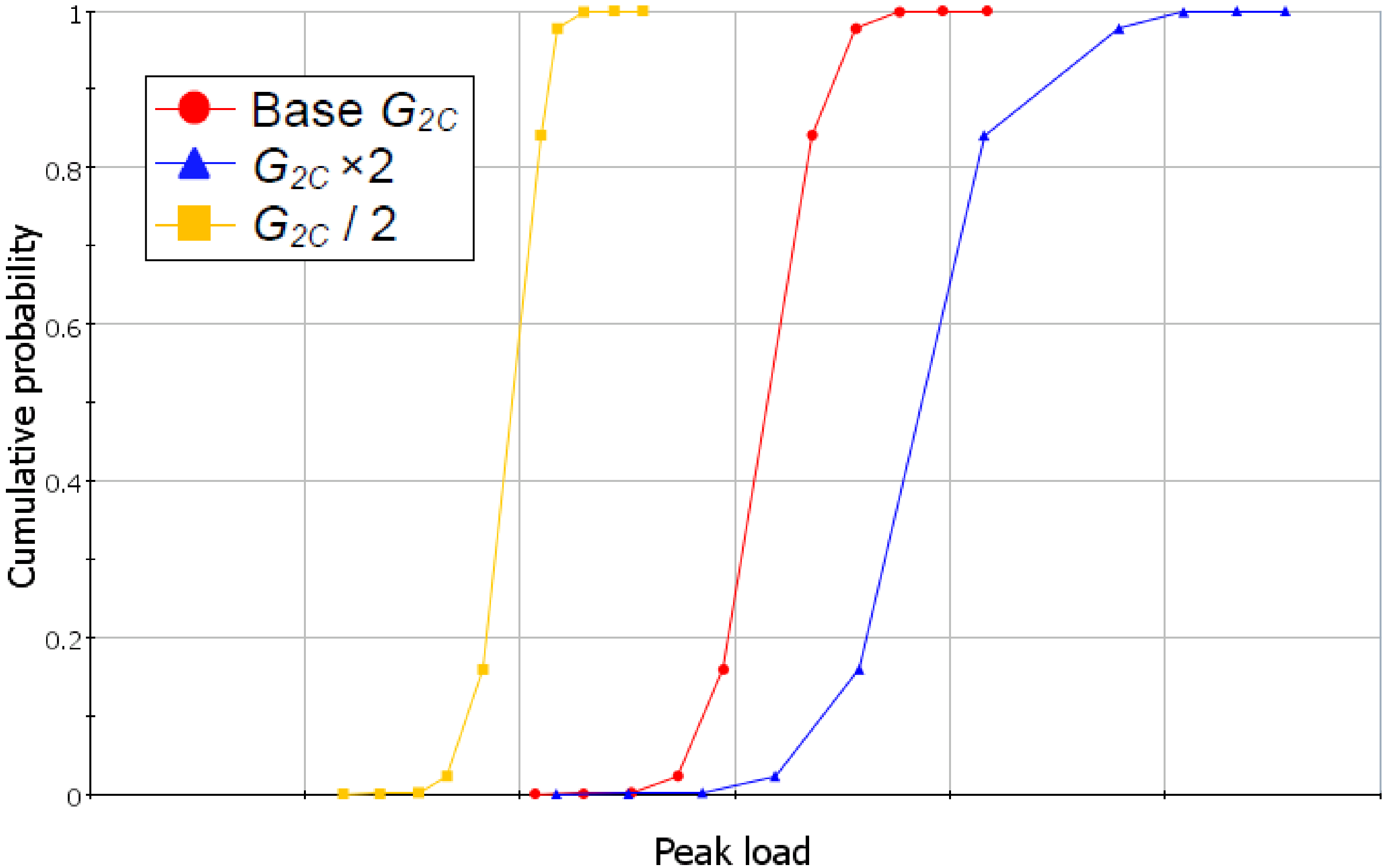
Probability Analysis with NESSUS – in the spirit of ICME



- Wu, Y. T., Millwater, H. R., and Cruse, T. A. (1990). “Advanced probabilistic structural-analysis method for implicit performance functions,” AIAA Journal, 28(9), p. 1663.
- Thacker, B.H., Riha, D.S., Fitch, S.K., Huyse, L.J., and Pleming, J.B. (2006). “Probabilistic engineering analysis using the NESSUS software,”. *Structural Safety*, 28(1-2), pp. 83-107.

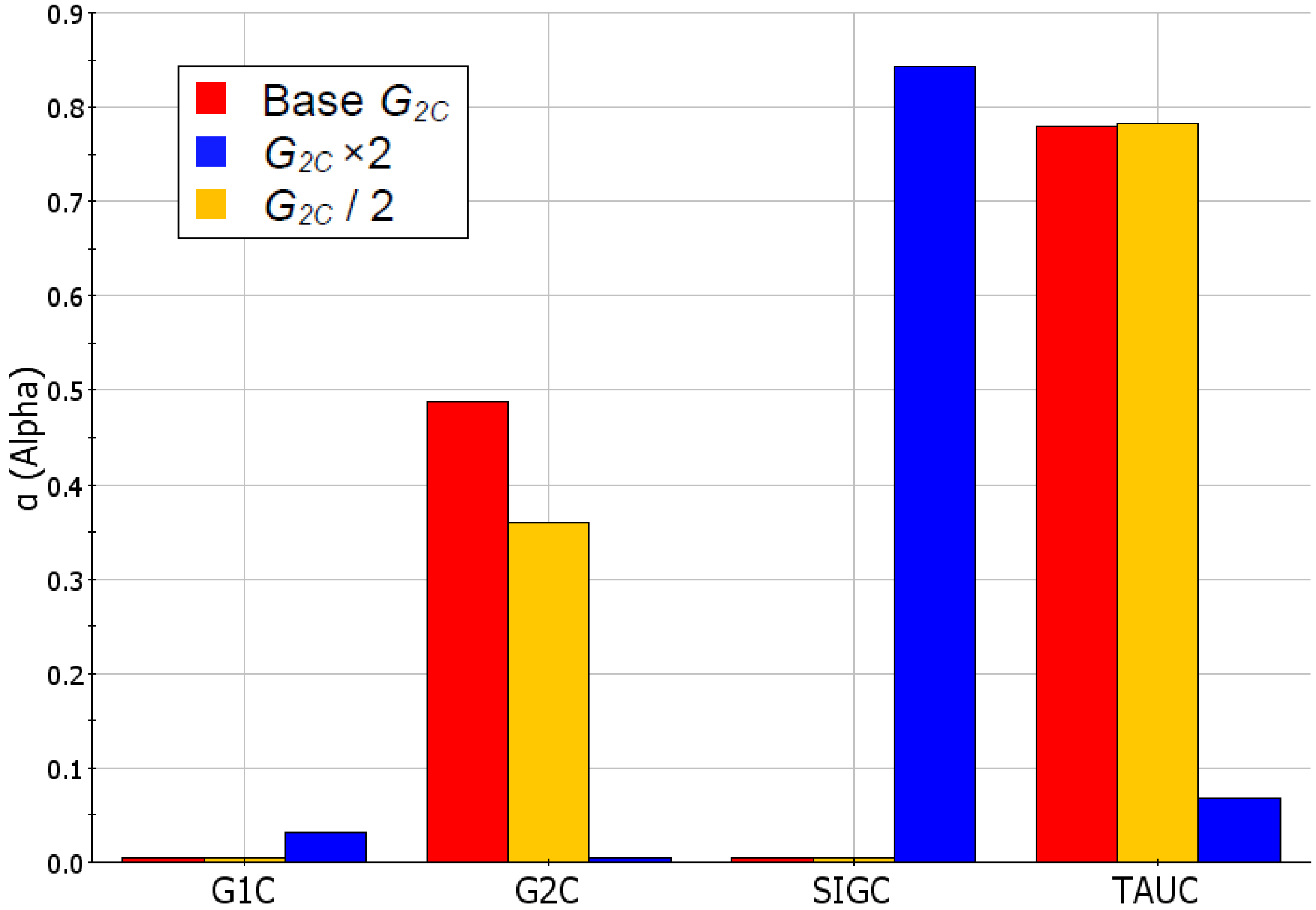
Probability Analysis with NESSUS

- Cumulative probability of peak load response of 2D Pi joint subject to pulloff loading

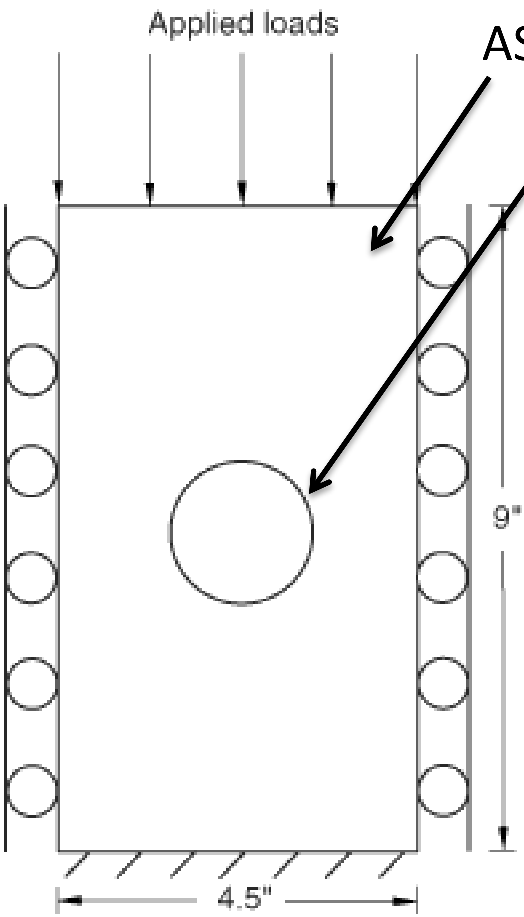


Probability Analysis with NESSUS

- Important factors affecting the peak load response



Composite Plate with an Initial Delamination

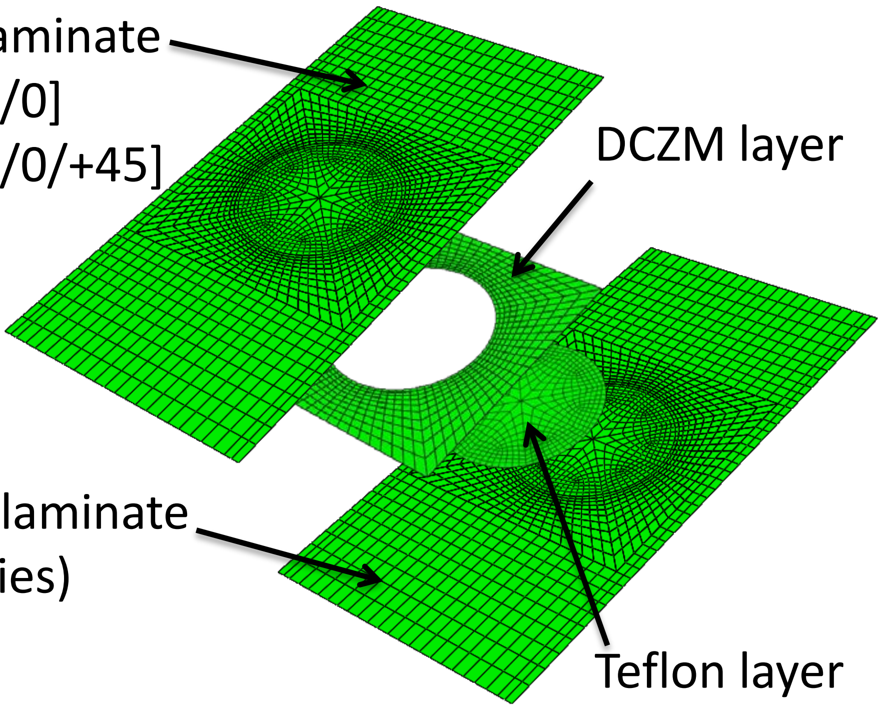


AS4/3501-6 [(±45/90/0)$_2$/±60/±15]s

R1.25 delamination region between 4th and 5th (Interface 1) or 5th and 6th (Interface 2) layers

Upper sublaminate
1. [±45/90/0]
2. [±45/90/0/+45]

DCZM layer



Lower sublaminate
(Rest of plies)

Teflon layer

Reeder, J., S. Kyongchan, P. B. Chunchu, and D. R. Ambur, "Postbuckling and Growth of Delaminations in Composite Plates Subjected to Axial Compression," 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Denver, Colorado, vol. 1746, p. 10, 2002.

Laminated composite degradation – Schapery theory (ST)

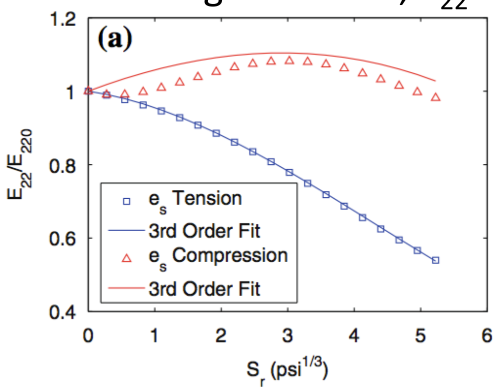
- Thermodynamics based, work potential theory for the progressive damage growth in a lamina, capable of capturing the effects of microdamage mechanisms, responsible for macroscopic, orthotropic material nonlinearity.
- Matrix microcracks induce degradation in properties of the laminae including changes in strengths, effective moduli, Poisson's ratios, and other material properties.
- The use of these modeling strategies computes lamina degradation evolution during the damage process using the physics of the failure mechanisms.
- ST can account for fiber direction damage -- an additional internal state variable associated with the fiber direction response is used.

*S. Basu, A. Waas and D. Ambur, "Progressive Failure of Notched Laminated Thick Composite Panels", International Conference on Computational and Experimental Engineering and Science (ICCES) 04, Madeira, Portugal, July 2004. Also, Basu S, Waas AM, Ambur DR, Prediction of Progressive Failure in Multidirectional Composite Laminated Panels, International J. of Solids and Structures, 44, pp2648-2676, 2007.

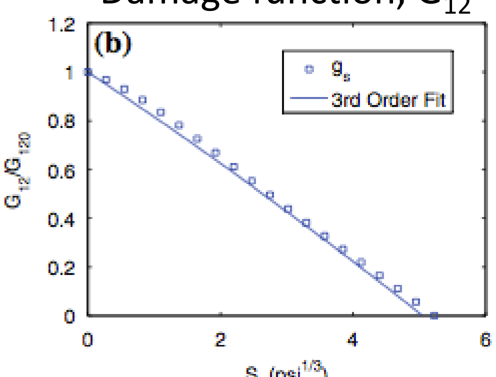
Laminated composite degradation – Schapery theory (ST)

Damage at lamina level

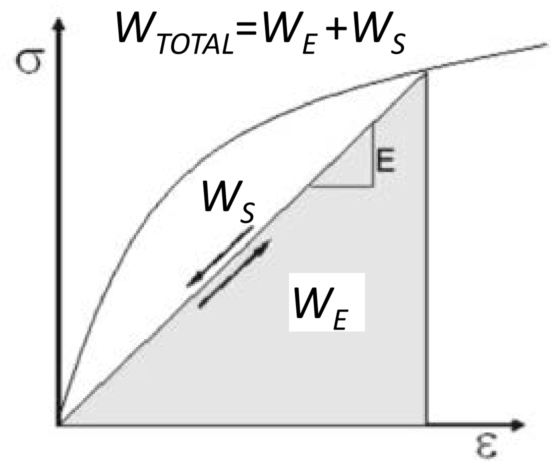
Damage function, E_{22}



Damage function, G_{12}



Thermodynamics-based work potential model

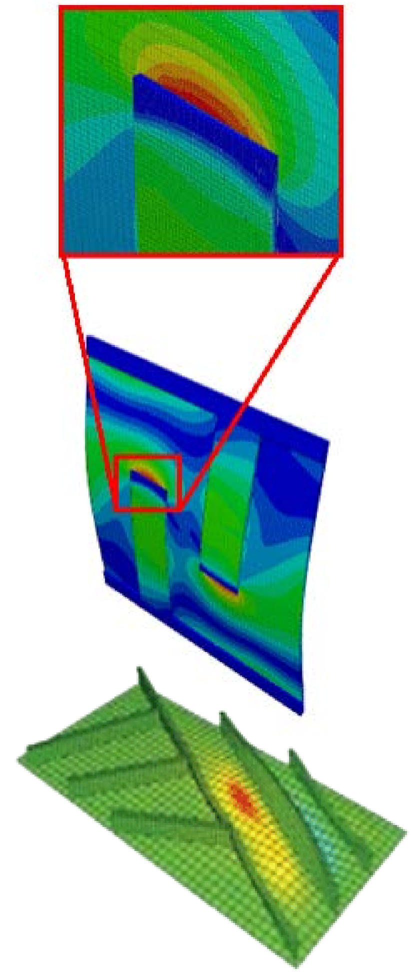


$$\frac{\partial W_T}{\partial S_i} = 0$$

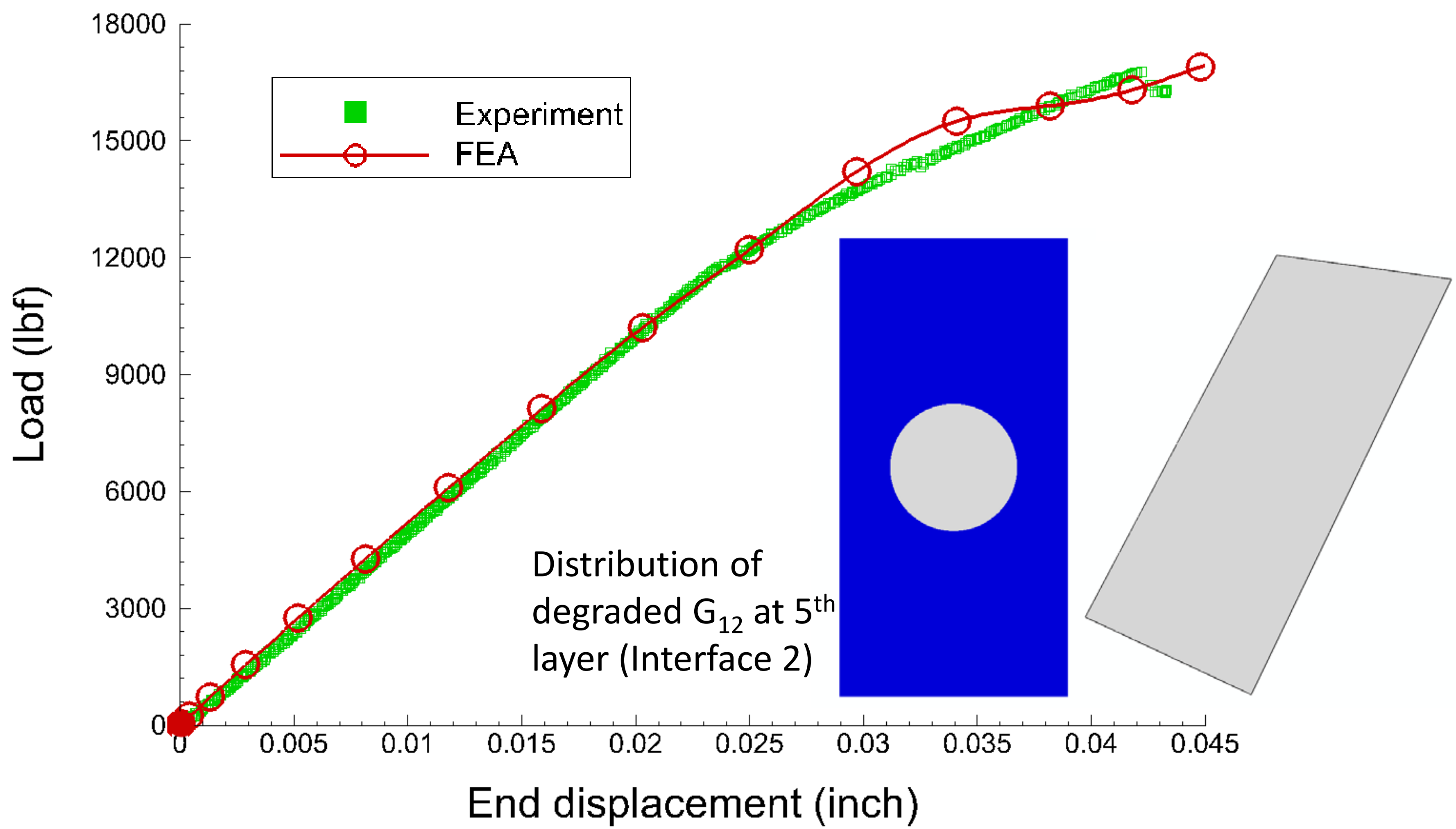
$$f_i = \frac{\partial W_S}{\partial S_i}$$

$$f_i \dot{S}_i \geq 0$$

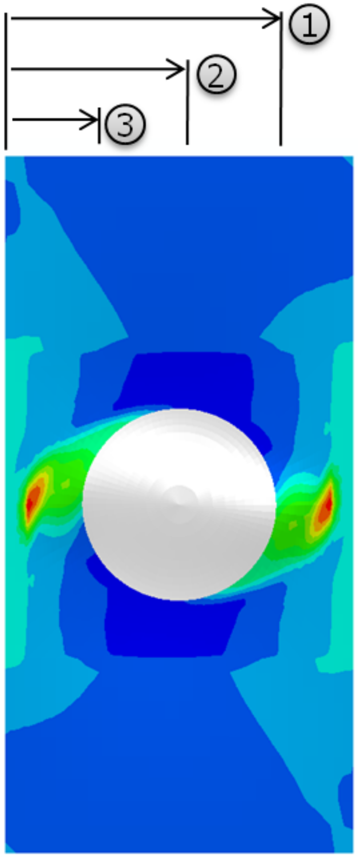
Progress damage prediction at macroscale



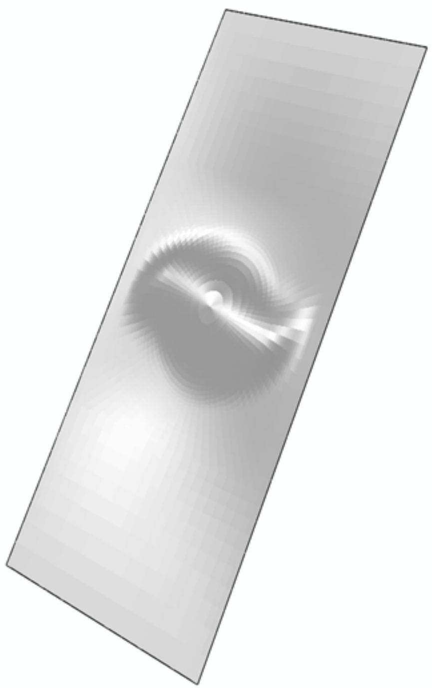
Composite Plate with an Initial Delamination



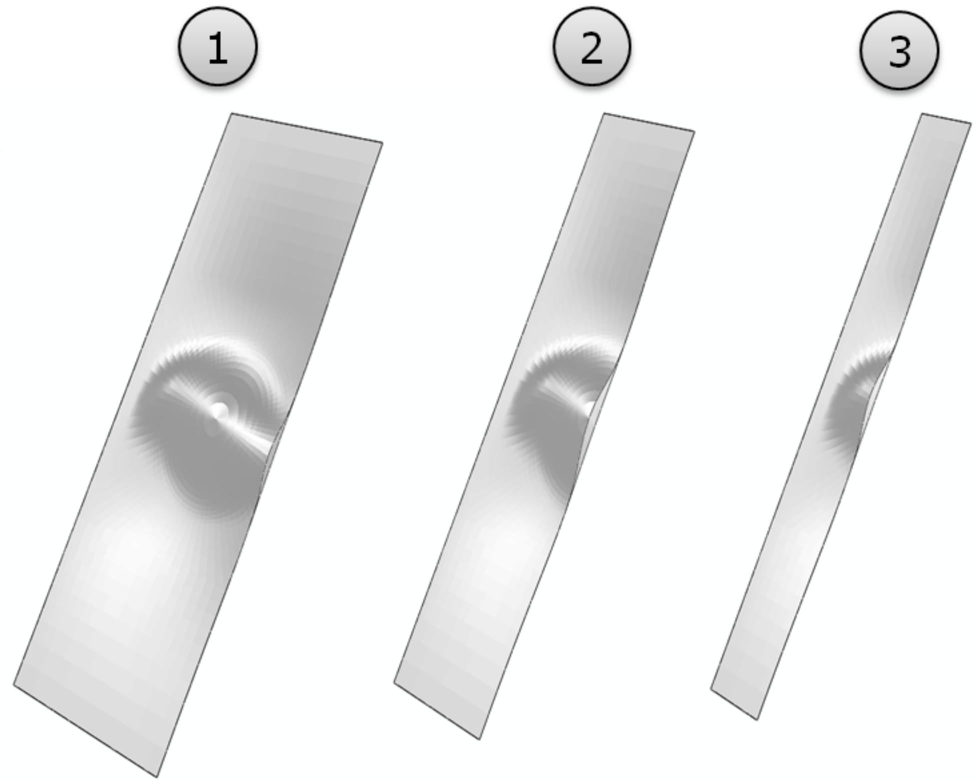
Composite Plate with an Initial Delamination



Distribution of degraded G_{12} at 5^{th} layer

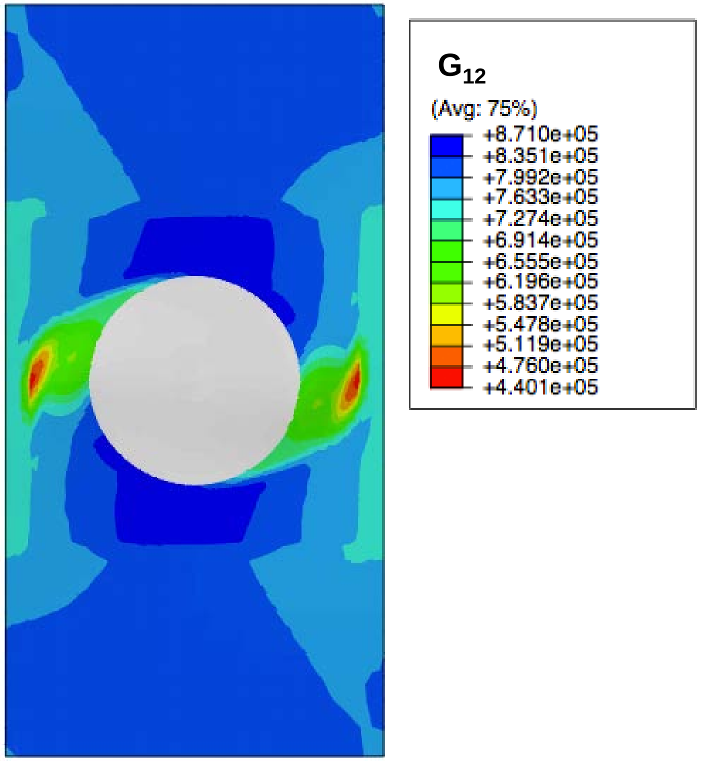


Full view

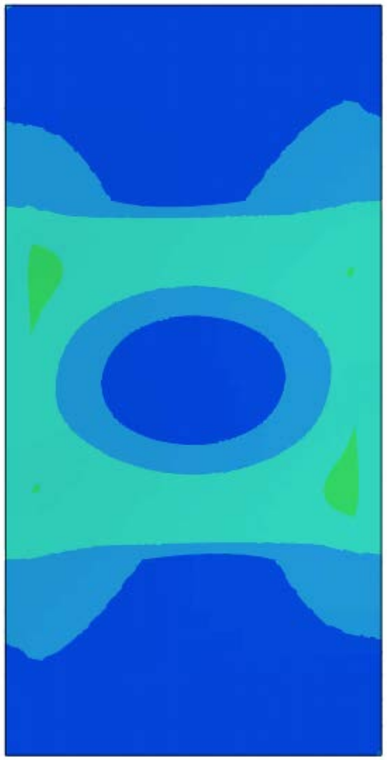


Section views for delamination pattern growth

Composite Plate with an Initial Delamination

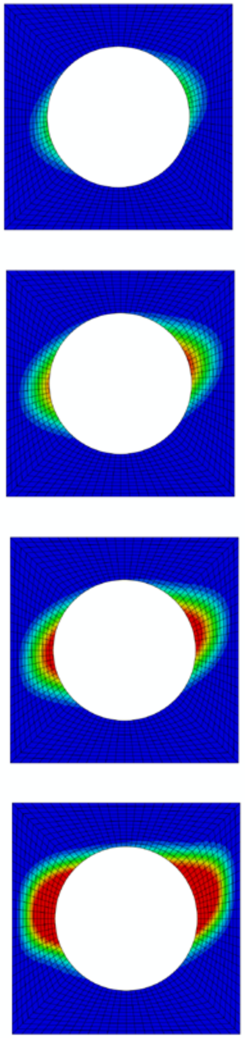


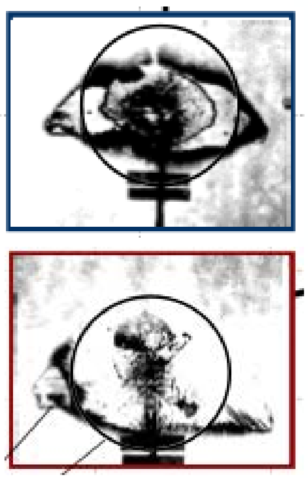
- Distribution of degraded G_{12} at 5th layer (Interface 2)



- Distribution of degraded G_{12} at 6th layer (Interface 2)

- Delamination pattern growth over the DCZM region with G_{mix} distribution





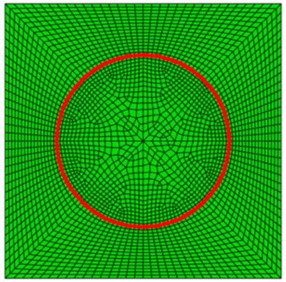
X-ray photographs of the final delamination pattern (Reeder et al. 2002)

Composite Plate with an Initial Delamination

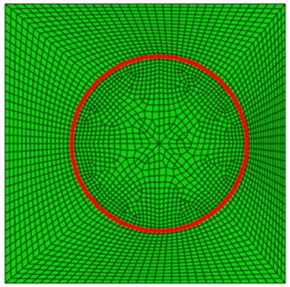
- PFA is coupled with the probabilistic analysis using NEESUS.
- Geometrical as well as material uncertainties are accounted for.
- A computationally efficient methodology is developed to consider the geometric variability on large nodal data.

Mean value, standard deviation (STD) value, and distribution type of the variable parameters

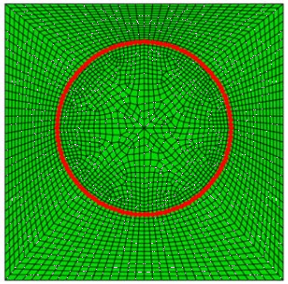
Parameter	Mean	STD	Type
E_{11} (msi)	18.25	1.83	Lognormal
E_{22} (msi)	1.35	0.3	Lognormal
G_{12} (msi)	0.74	0.3	Lognormal
radius (in)	1.25	0.1	Normal
x_{center} (in)	0.0	0.05	Normal
G_{1C} (lb/in)	0.50127	0.05	Normal
G_{2C} (lb/in)	3.31679	1.0	Normal
G_{3C} (lb/in)	3.31679	1.0	Normal
σ_{1C} (psi)	20	5	Normal
σ_{2C} (psi)	120	20	Normal
σ_{3C} (psi)	120	20	Normal



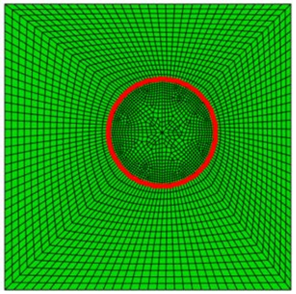
(a) Mean values



(b) x_{center} perturbed



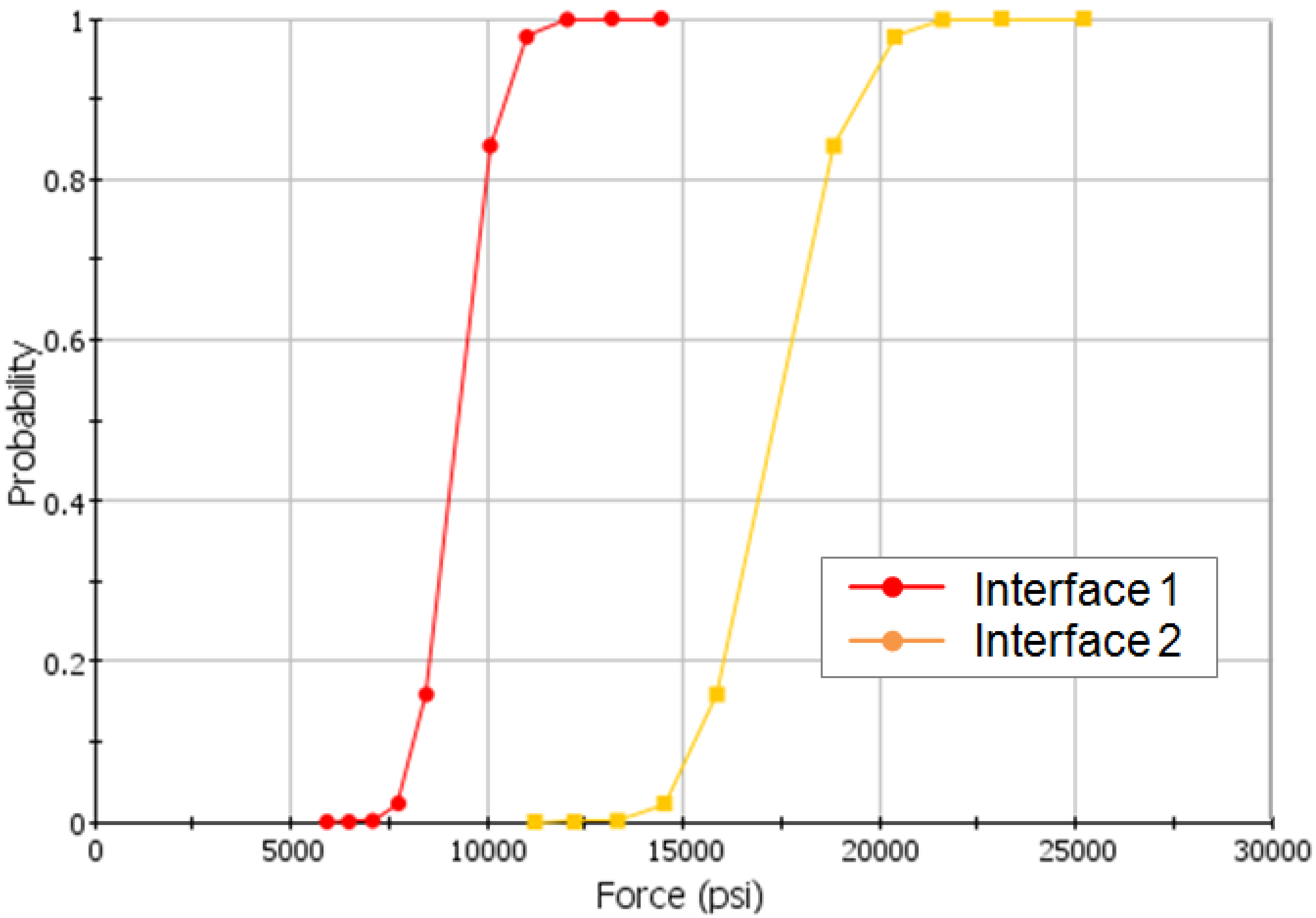
(c) y_{center} perturbed



(d) x_{center}, y_{center}, and r perturbed

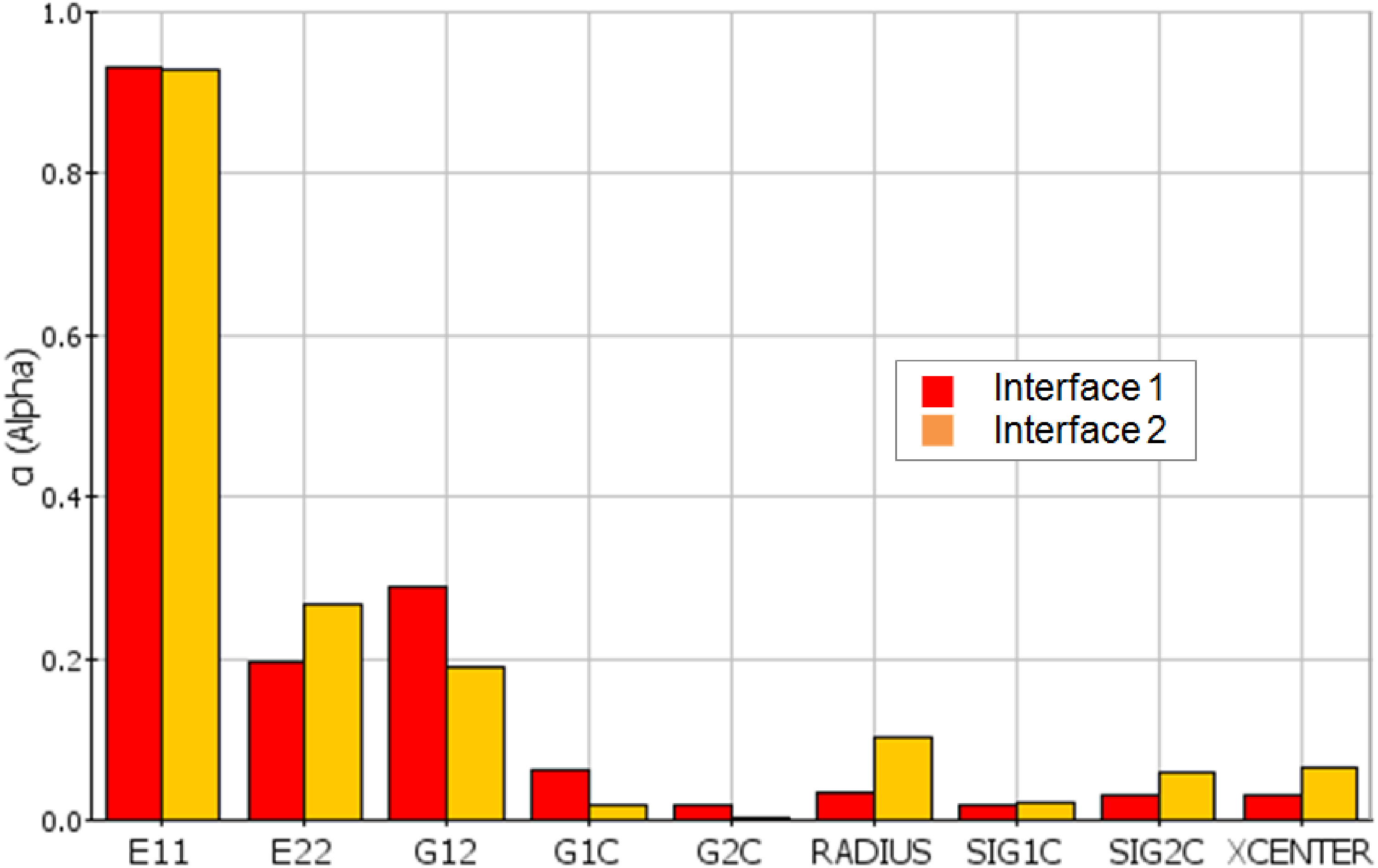
Composite Plate with an Initial Delamination

Cumulative probability distribution for peak load



Composite Plate with an Initial Delamination

Importance levels of modeling parameters on peak load



Concluding remarks

- Numerical framework for delaminations through the discrete cohesive zone model.
- Each fracture mode behavior and interactions of the modes can be captured.
- Probability analysis implemented to assess the reliability and quantify uncertainty in input properties and how these affect performance – using NEESUS
- Two example problems demonstrated in a unified numerical framework to predict interactive failure mechanisms.

Questions and Suggestions

Thank you!