# Damage Tolerance and Durability of Adhesively Bonded Composite Structures

04-C-AM-PU

Thomas Siegmund (PU-ME)
CT Sun (PU-AERO)

# Administrative Outline

- PIs:
  - Thomas Siegmund (PU-ME)
  - CT Sun (PU-AERO)
- Technical Monitor: Curt Davies

- Cost share: Purdue University
- Additional Funding: Caterpillar Inc.

# Research Outline: past years (also H. Kim)

- **Characterization of Adhesive Joints**
  - **Toughness**
  - **Strength**
  - **Environmental degradation**
  - **Bondline thickness**
  - **Size effects in joints**
- **Training**
  - **Computational Fracture Mechanics course (online offering in planning for Spring 09)**

# Research Outline 2009

- Project #1 (Siegmund):
  - **Numerical Simulation of Fatigue Crack Growth: Cohesive Zone Models vs. XFEM**
- Project #2 (Sun):
  - **Development of Improved Hybrid Joints**

# Numerical Simulation of Fatigue Crack Growth: Cohesive Zone Models vs. XFEM

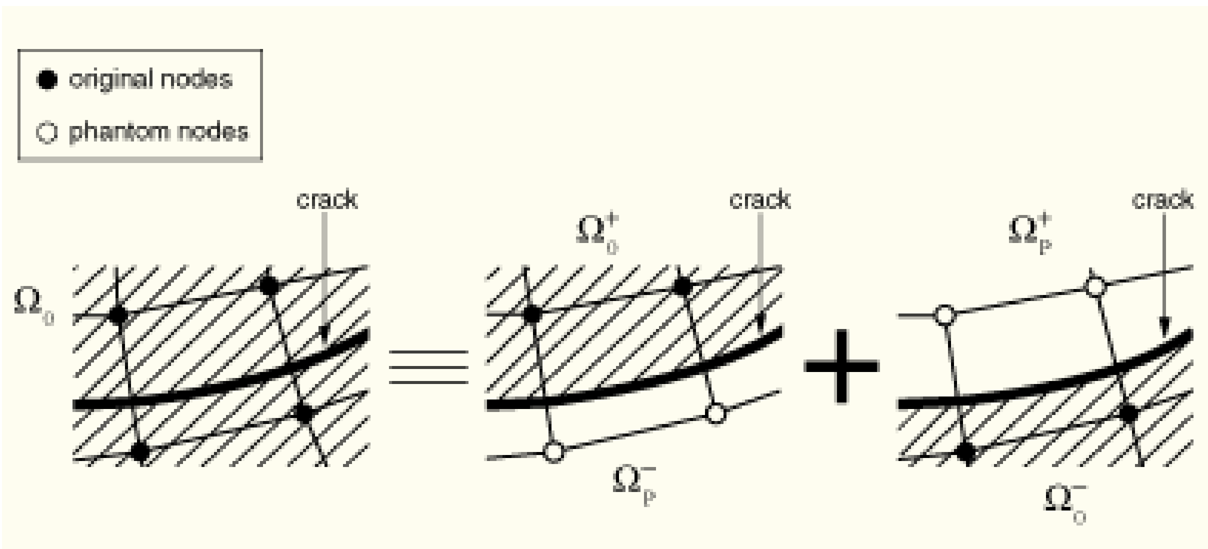
Thomas Siegmund
Purdue University

# Research Accomplishments

- Tools for “Certification by Simulation”
  - Crack initiation and growth at arbitrary site and path (**adhesive**)
    - Compare cohesive zone model approach to XFEM
    - Implement fatigue crack growth in XFEM
    - Scenario: Failure from
  - Study contact fatigue failure (**rivets**)

# XFEM-ABAQUS

- **eXtended Finite Element Method**
- Extension of conventional FEM based on the concept of partition of unity;



# XFEM-ABAQUS

$$\mathbf{u} = \sum_{I=1}^{N} N_I(x)\left[\mathbf{u}_I + H(x)\mathbf{a}_I\right]$$

$N_I$ shape function

$\mathbf{u}_I$ conventional nodal dispalcement

$\mathbf{a}_I$ enriched nodal displacements

# Traction-Sparation Law

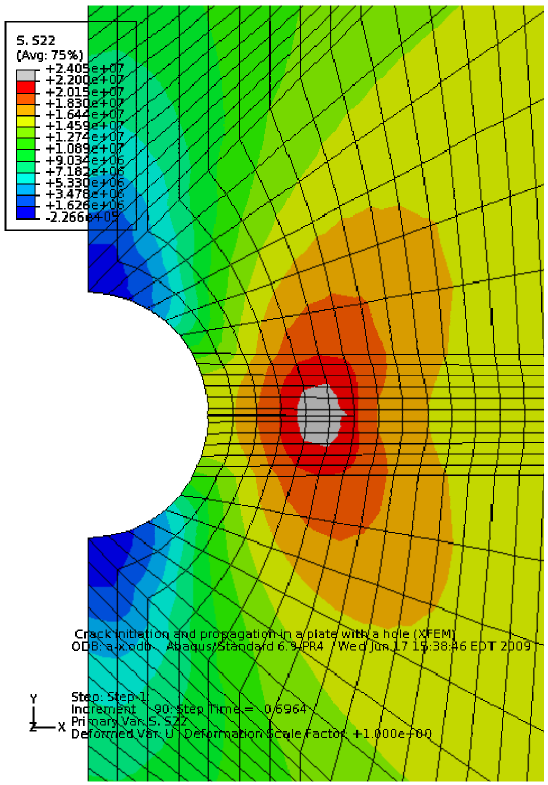
$$\begin{pmatrix} T_{n,0} \\ T_{t,0} \end{pmatrix} = \begin{bmatrix} K_0 & 0 \\ 0 & K_0 \end{bmatrix} \begin{pmatrix} \Delta_n \\ \Delta_t \end{pmatrix}$$

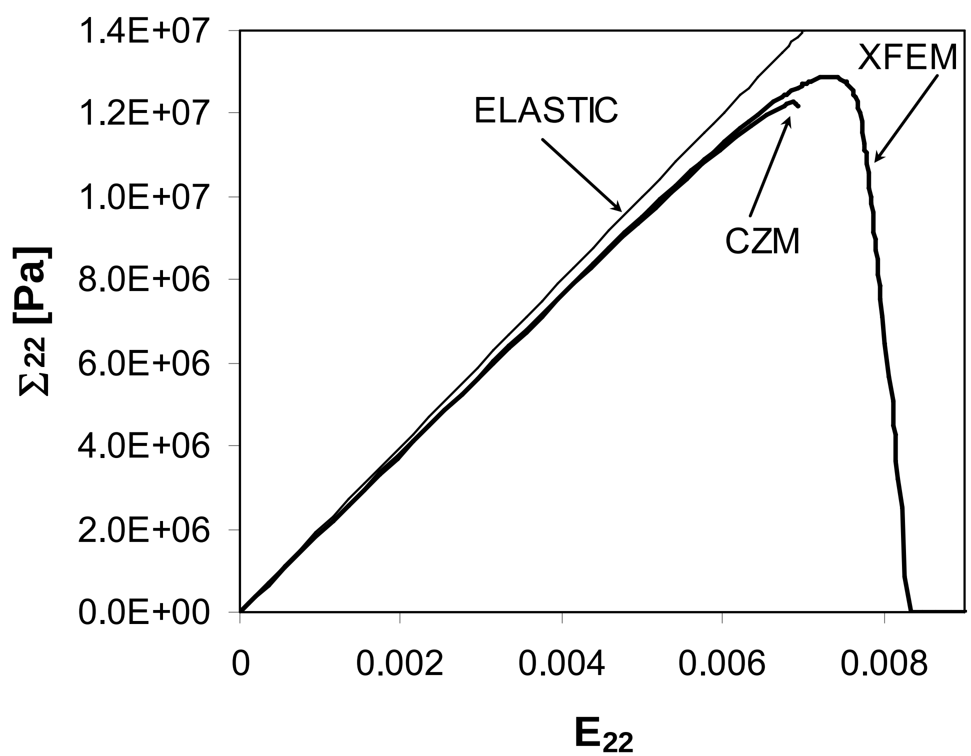
$$\max\left( \frac{\langle T_{n,0} \rangle}{\sigma_{\max,0}}, \frac{T_{t,0}}{\sigma_{\max,0}} \right) = 1$$

$$T_n = (1 - D) T_{n,0}, T_t = (1 - D) T_{t,0}$$

$$D_m = \int_{\Delta_m^0}^{\Delta_m} \frac{T_{eff} \, d\Delta_m}{\phi_0 - \phi_{el}}$$

# Monotonic Loading



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# Example: CZM vs. XFEM

- Plate with a central hole
- Remote displacements
- CZ elements along several radial lines
- XFEM enrichment throughout

# Fatigue Damage Model

Cyclic damage variable: $D_C = \frac{A_{damaged}}{A_0}$

Effective tractions: $\hat{T}_n = \frac{F}{A_0(1-D_C)} = \frac{T_n}{(1-D_C)}$

Since:
$$\hat{T}_n = \hat{T}_n\left(\sigma_{\max,0}, \delta_0\right)$$
$$T_n = T_n\left[\sigma_{\max,0}(1-D_C), \delta_0\right]$$

Current Cohesive Properties:
$$\sigma_{\max} = \sigma_{\max,0}(1-D_C),$$
$$\phi_n = \chi\sigma_{\max}\delta_0 = \chi\sigma_{\max,0}(1-D_C)\delta_0$$

$$\mathbf{Need\ to\ define:}\ \dot{\mathbf{D}}_\mathbf{C} = \dot{\mathbf{D}}_\mathbf{C}\left(\mathbf{D}_\mathbf{C}, \dot{\boldsymbol{\Delta}}_\mathbf{n}, \dot{\boldsymbol{\Delta}}_\mathbf{t}, \mathbf{T}_\mathbf{n}, \mathbf{T}_\mathbf{t} \ldots\right)$$

# Damage Accumulation Rule

- Damage accumulation starts if a deformation measure, accumulated or current, is greater than a critical magnitude.
- There exists an endurance limit which is a stress level below which cyclic loading can proceed infinitely without failure.
- The increment of damage is related to the increment of absolute value of deformation as weighted by the ratio of current load level relative to strength.

# Damage Accumulation Rules

$$CZM : dD_c = \frac{\left|\dot{\Delta}_m\right|}{\delta_\Sigma}\left[\frac{T_{eff}}{\sigma_{\max}} - C_f\right] \quad , \quad D_c = \int dD_c$$

$\sigma_f$.....cohesive endurance limit

$\delta_\Sigma$....cyclic cohesive length

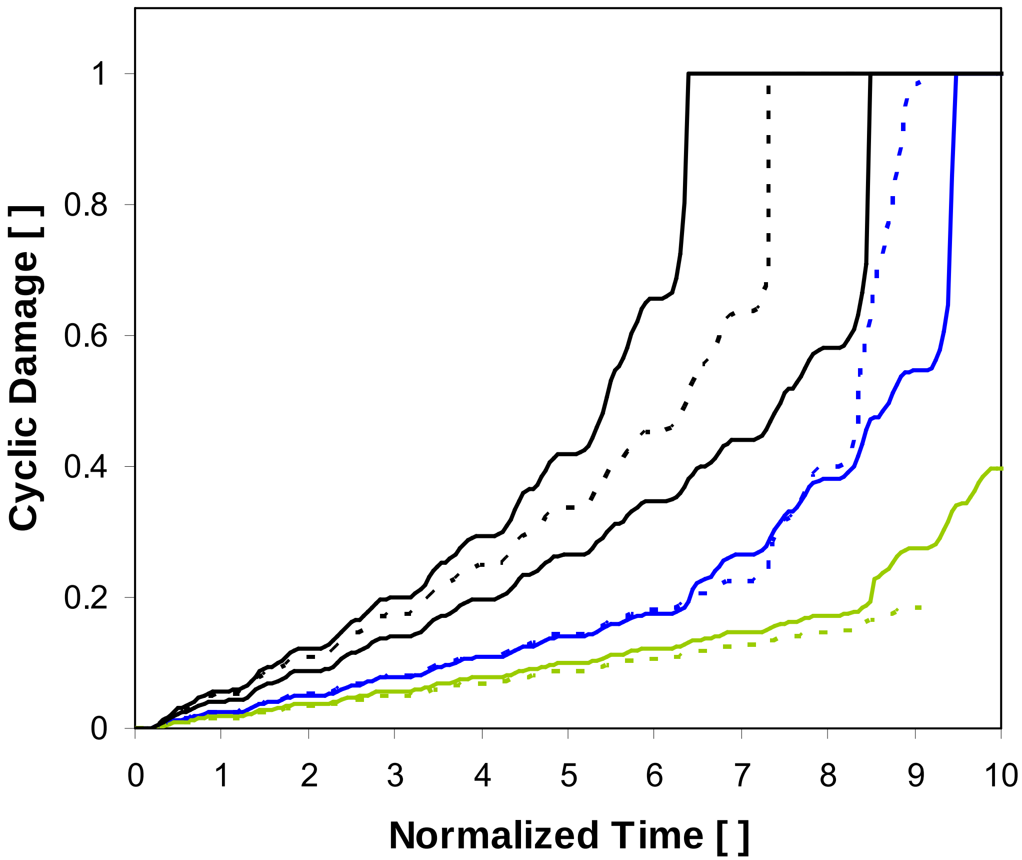
$$XFEM : dD_c = \frac{\left|\dot{\varepsilon}_{p1}\right|}{\varepsilon_\Sigma}\left[\frac{\sigma_{p1}}{\sigma_{\max}} - C_f\right] \quad , \quad D_c = \int dD_c$$

$\sigma_f$.....cohesive endurance limit

$\varepsilon_\Sigma$ cyclic reference strain

$$\frac{\delta_\Sigma}{\varepsilon_\Sigma} = \frac{K_0}{E_0}$$

# Cyclic Loading: Damage Evolution in Mode I




the first three elements of the row of elements emerging from the hole at . ---- 1st element CZM (both integration points shown), - - - 1st element XFEM, ---- 2nd element CZM (lagging integration point shown), - - - 2nd element XFEM, ---- 3rd element CZM (lagging integration point shown), - - - 3rd element XFEM.

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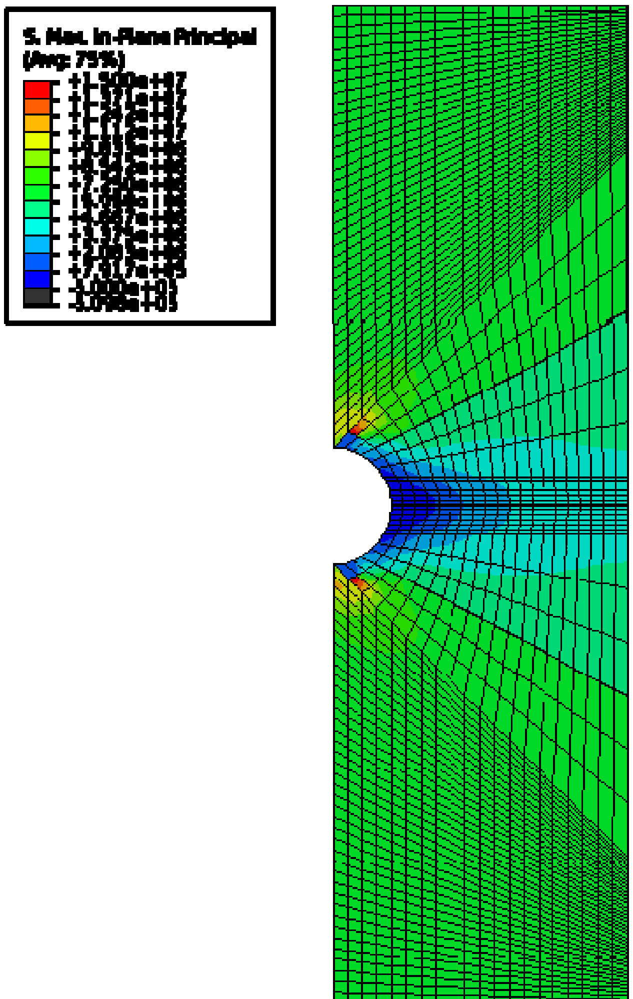
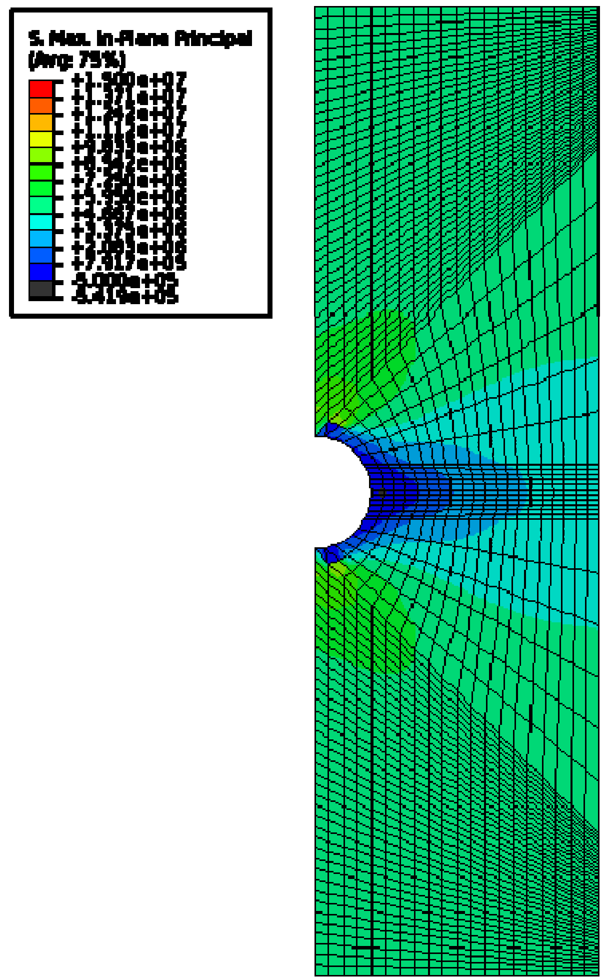
# Cyclic Loading: Mixed Mode

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# Contact Fatigue

- Multiaxial Fatigue Criteria:

Critical Plane Approach

E.g.: Findley Criterion:

$$\max\left\{\tau_a + \alpha_f \sigma_{n,\max}\right\} = \beta_f$$

$\tau_a$ shear stress amplitude on a plane

$\sigma_{n,\max}$ max. normal stress on that plane

# Contact Fatigue

- Multiaxial Fatigue Criteria:

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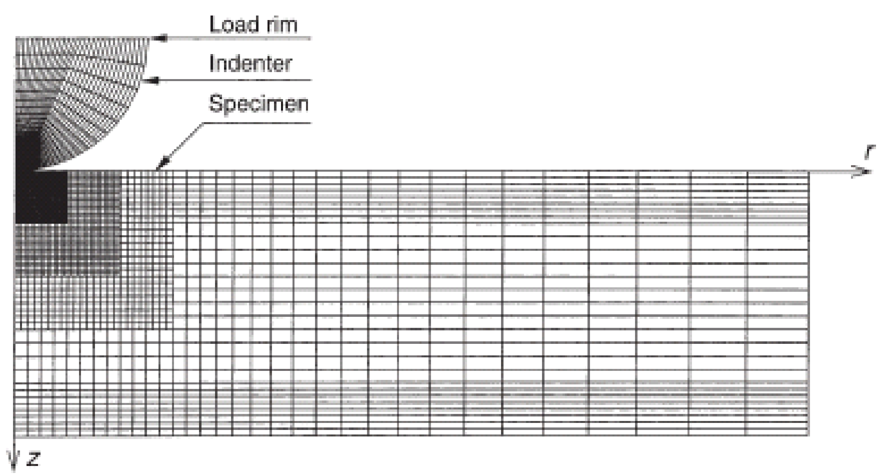
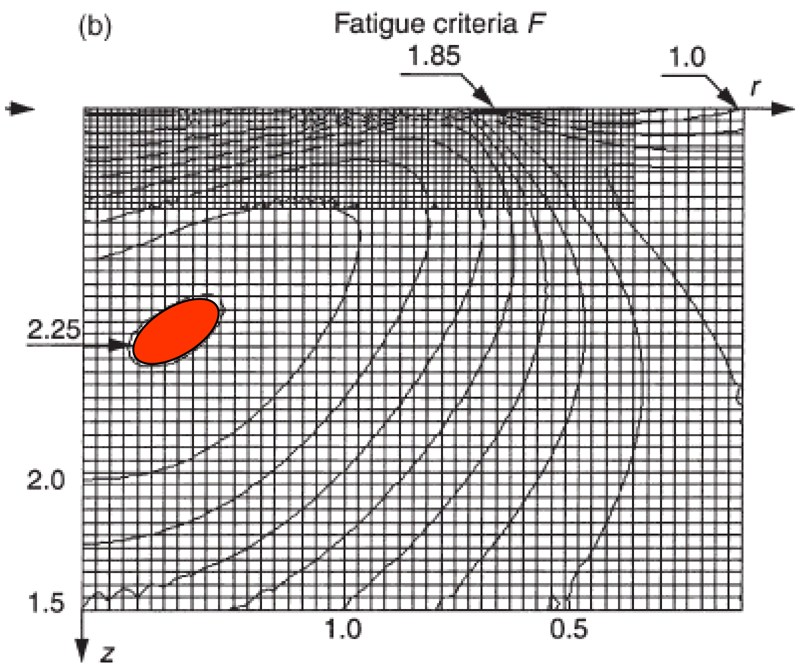
# Example Result

B. Alfredsson, M. Olsson / International Journal of Fatigue 23 (2001) 533–548

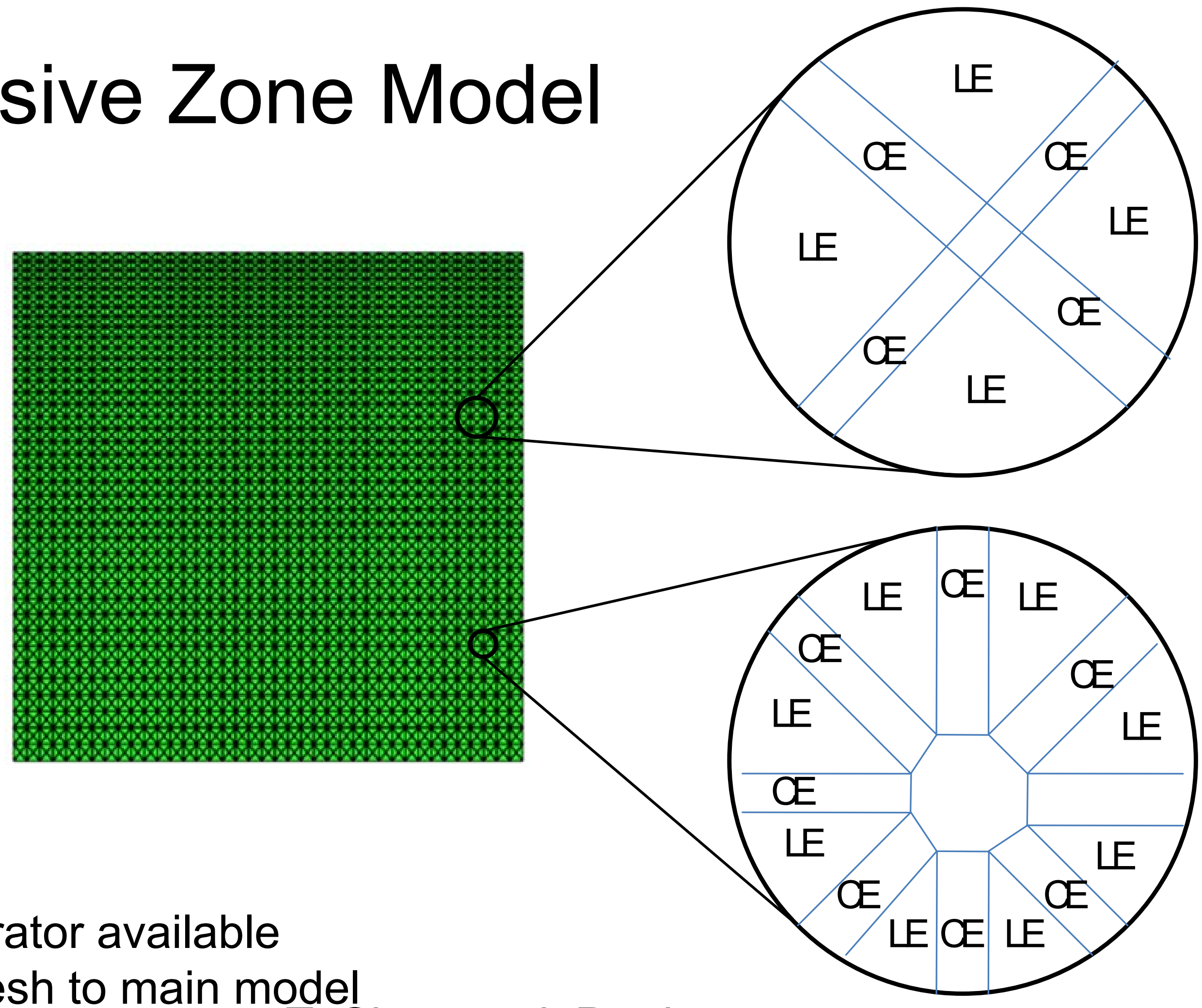



Provides location of crack initiation but not:
-- number of cycles to failure
-- not applicable to variable amplitude loading

# CZM Approach

- Cohesive Zone Model




Mesh generator available
"Tie" CZ mesh to main model

# Redefine: Effective Traction

Common Fatigue Crack Growth

$$\bar{T} = \sqrt{(T_n)^2 + (T_t)^2}$$

Contact Fatigue

$$\bar{T} = \sqrt{(\eta \times T_n)^2 + (\beta \times T_t)^2}$$

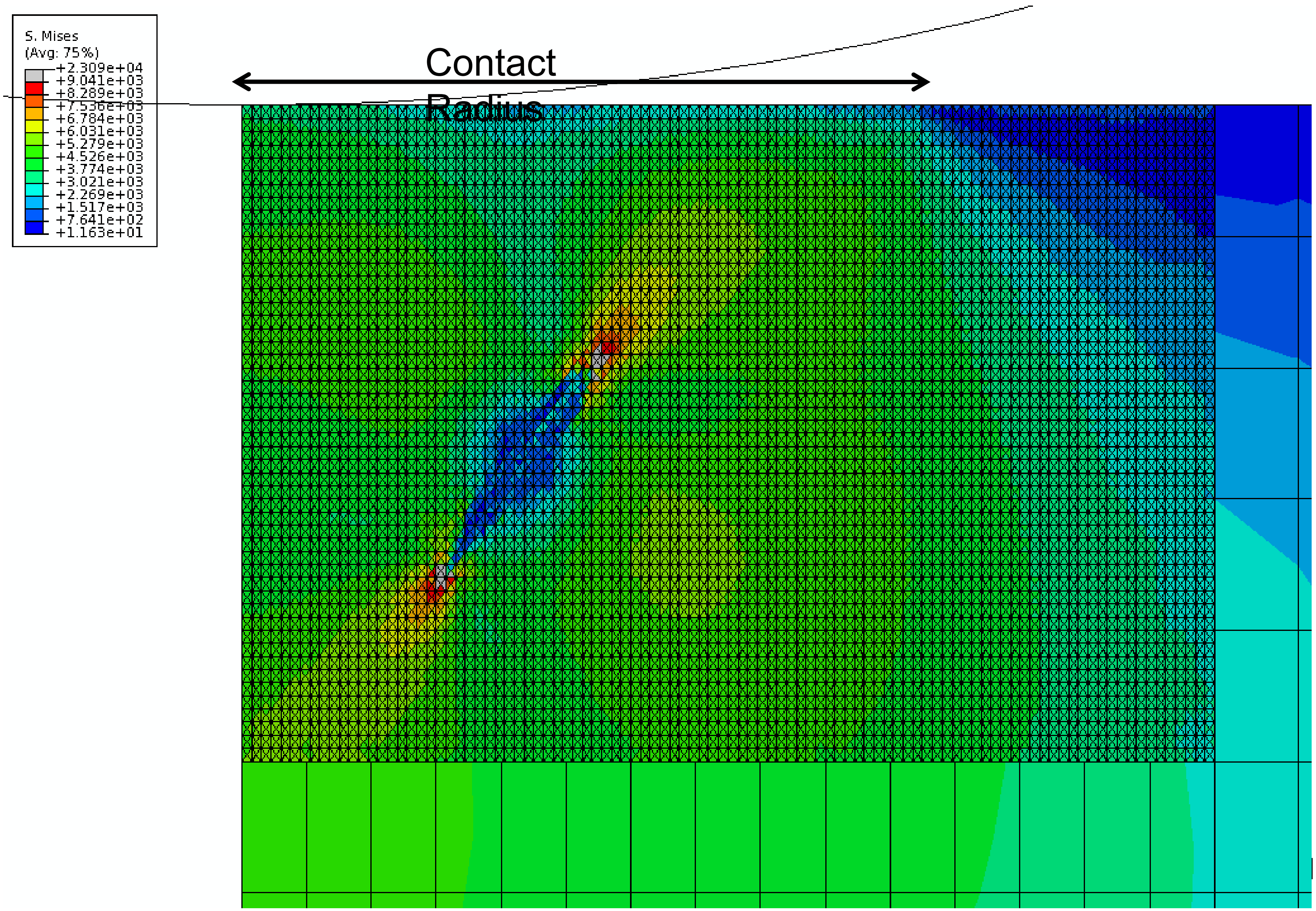
$$\bar{T} = \sqrt{\left(T_n \times \frac{0.64}{3}\right)^2 + (T_t)^2}$$

$$if \quad T_n > 0$$

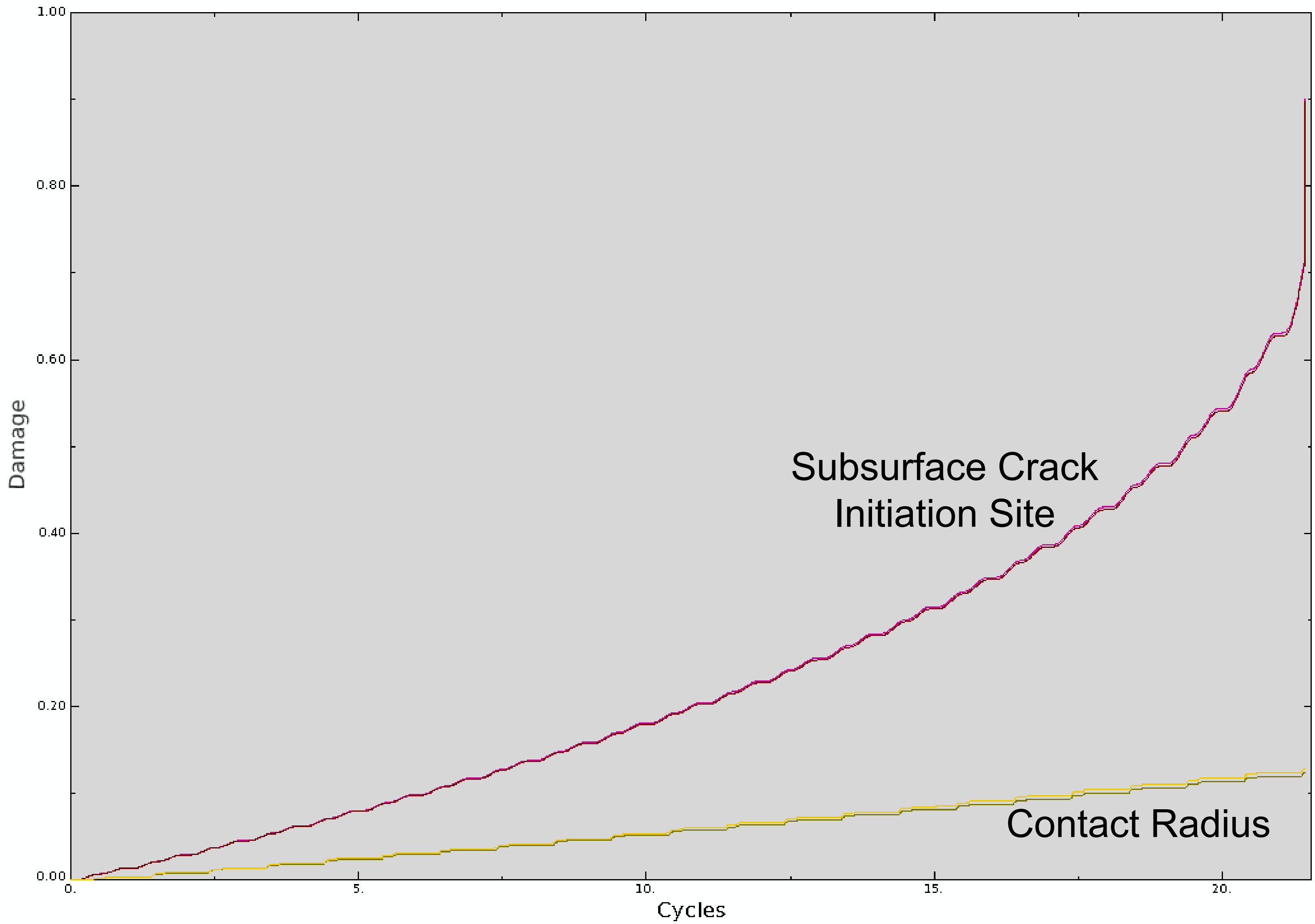
$$\bar{T} = \frac{0.64}{3} \times T_n + T_t$$

$$if \quad T_n < 0$$

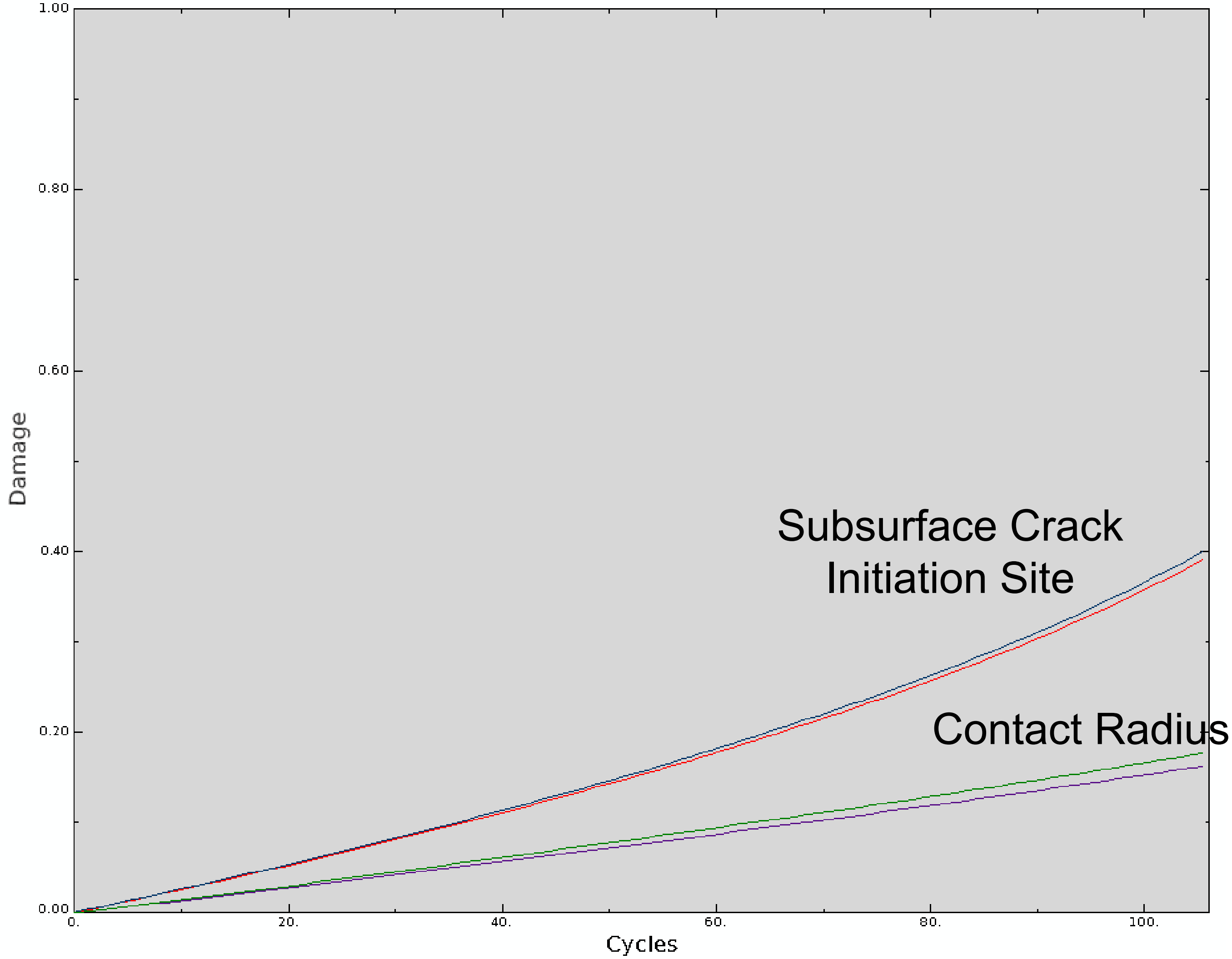
# $P_{max}$ = 16800 N at Failure



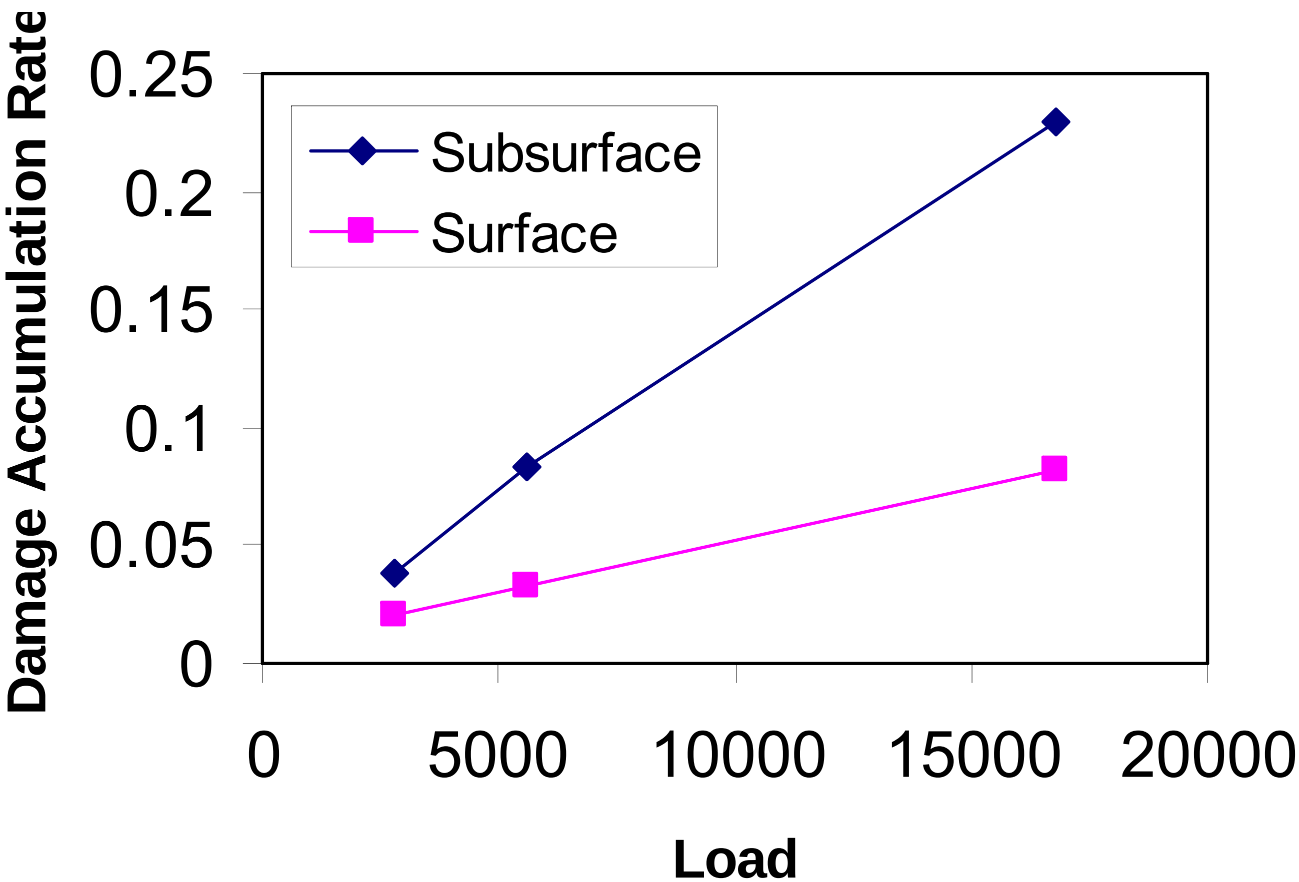
# Damage Evolution



# Damage Evolution
# $P_{max}$ = 2800 N



# Comparison

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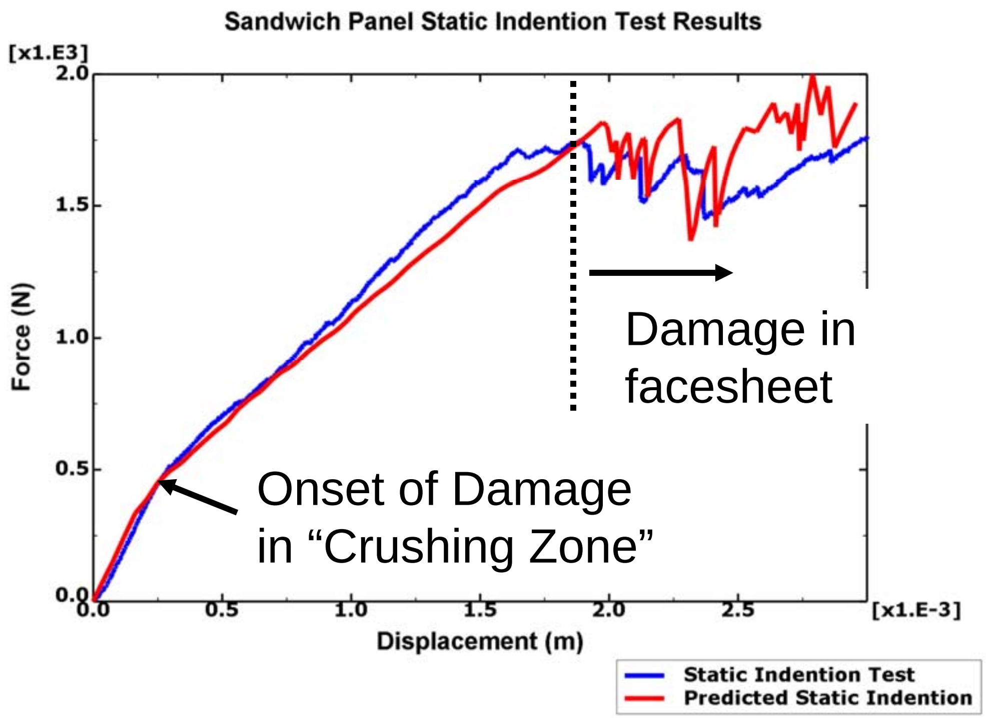
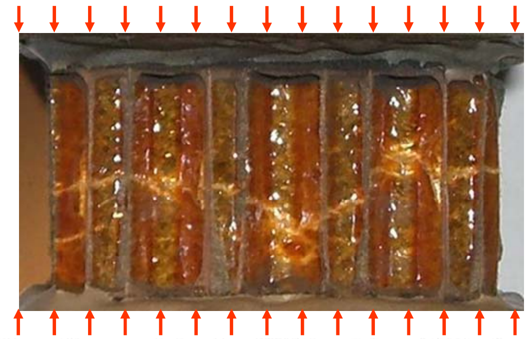
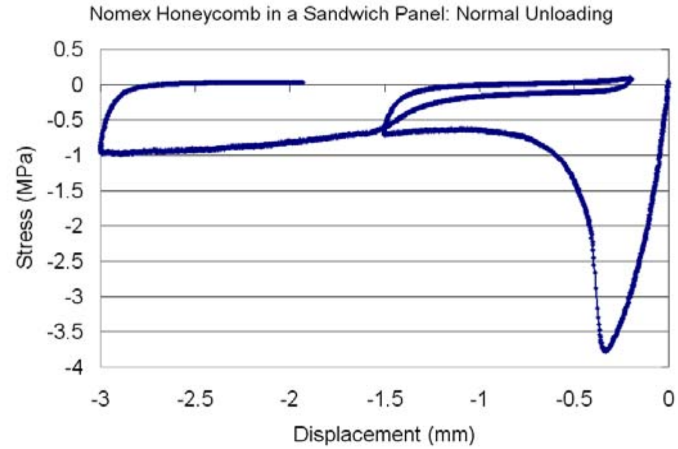
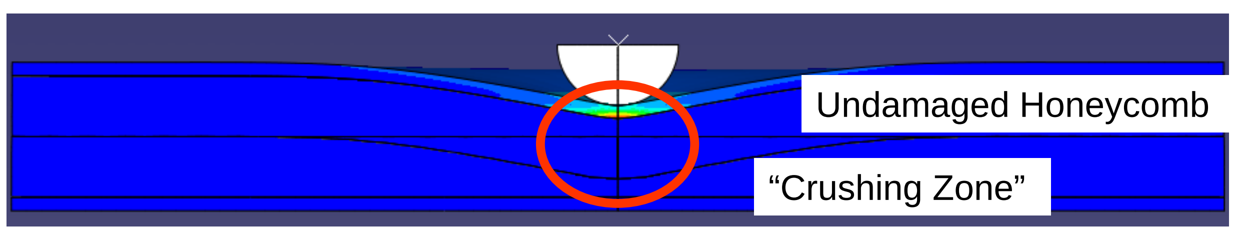
# Related Work (CACI) : Sandwich Panel Integrity





# Summary

- CZM vs. XFEM:
  - Provide close results if correctly calibrated
  - CZM is mesh dependent, XFEM less
- Contact Fatigue:
  - Multifacet CZM
  - Effective traction
  - Variable amplitude loading or tilted geometry