

Damage Tolerance and Durability of Adhesively Bonded Composite Structures

04-C-AM-PU

Thomas Siegmund (PU-ME)

CT Sun (PU-AERO)

Administrative Outline

- Pls:

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 (Siegmond):
 - **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

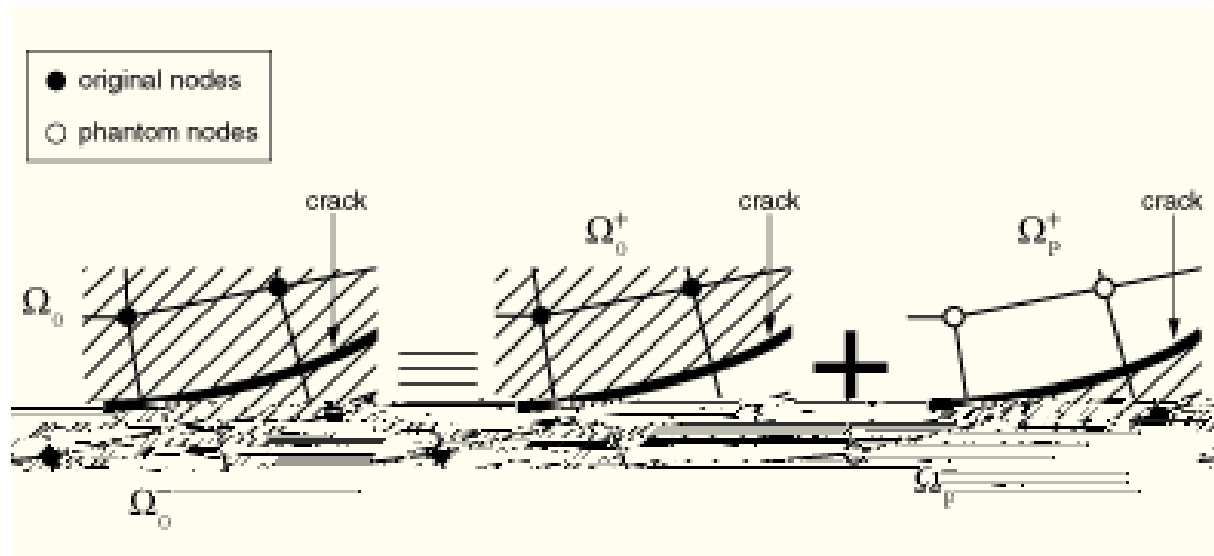
Thomas Siegmund
Purdue University

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

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

N_I shape function

\mathbf{u}_I conventional nodal displacement

\mathbf{a}_I enriched nodal displacements

Traction-Separation Law

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

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

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

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

T. Siegmund, Purdue

Monotonic Loading



T. Siegmund, Purdue

Example: CZM vs. XFEM

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

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.

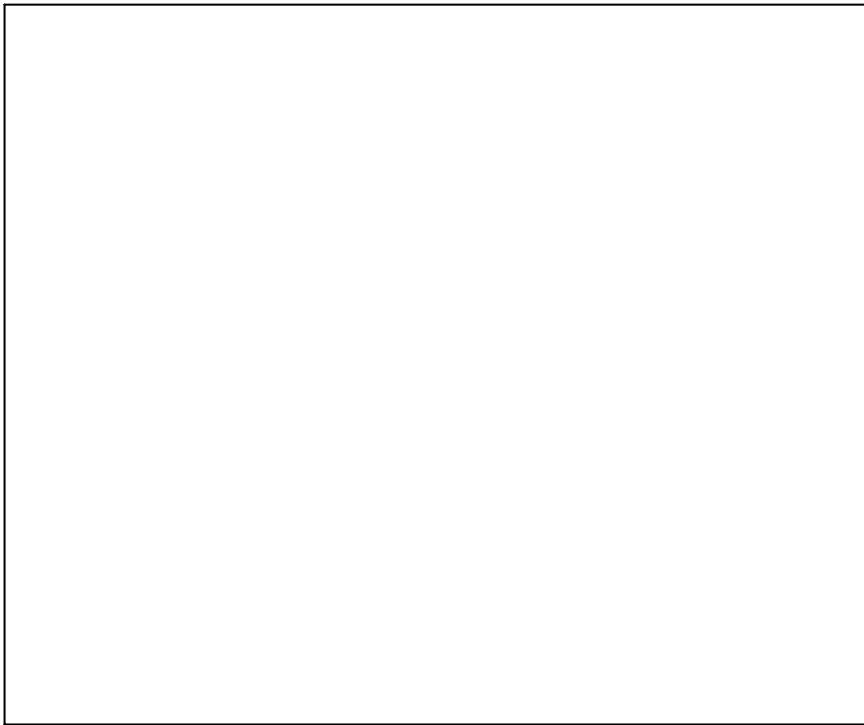
The increment of damage is related to

Damage Accumulation Rules

$$= \frac{|\Delta|}{\delta_{\Sigma}} \frac{1}{\sigma} - = \int$$

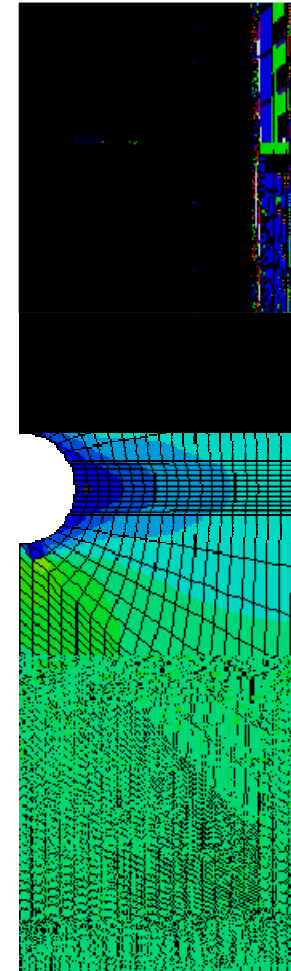
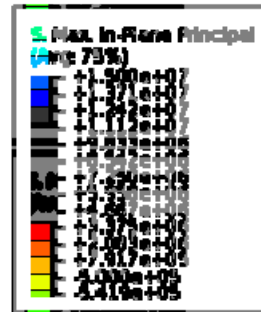
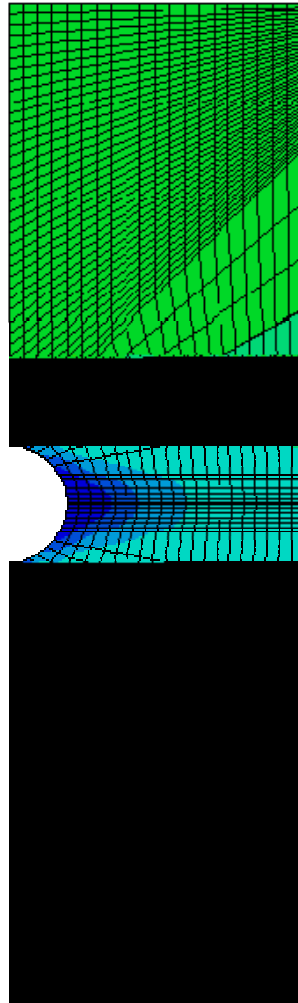
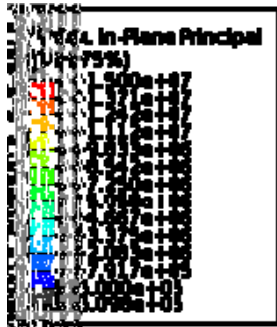
σ_fcohesive endurance limit
 δ_{Σ}cyclic cohesive length

Cyclic Loading: Damage Evolution in Mode I



T. Siegmund, Purdue

Cyclic Loading: Mixed Mode



T. Siegmund, Purdue

Contact Fatigue

- Multiaxial Fatigue Criteria:

Critical Plane Approach

E.g.: Findley Criterion:

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

τ_a shear stress amplitude on a plane

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

Contact Fatigue

- Multiaxial Fatigue Criteria:

Critical Plane Approach

E.g.: Findley Criterion:

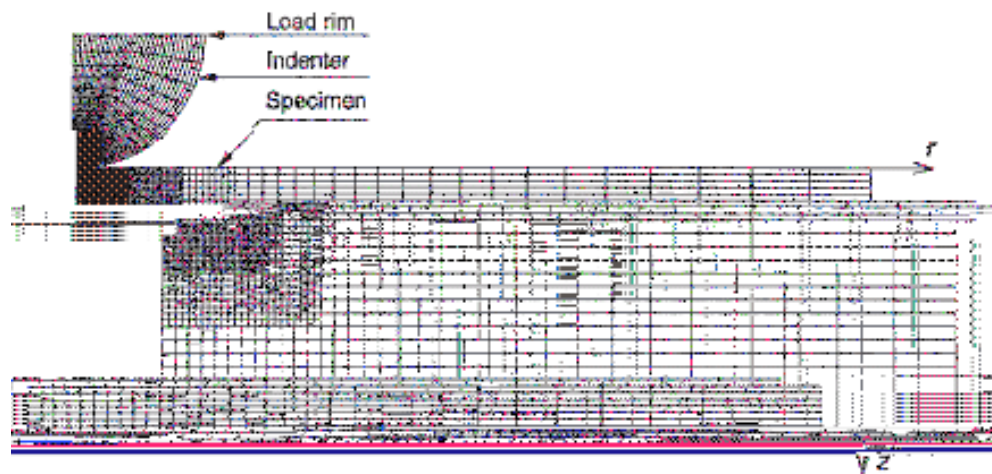
$$\max \left\{ \tau_a + \alpha_f \sigma_{n,\max} \right\} = \beta_f$$

τ_a shear stress amplitude on a plane

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

Example Result

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

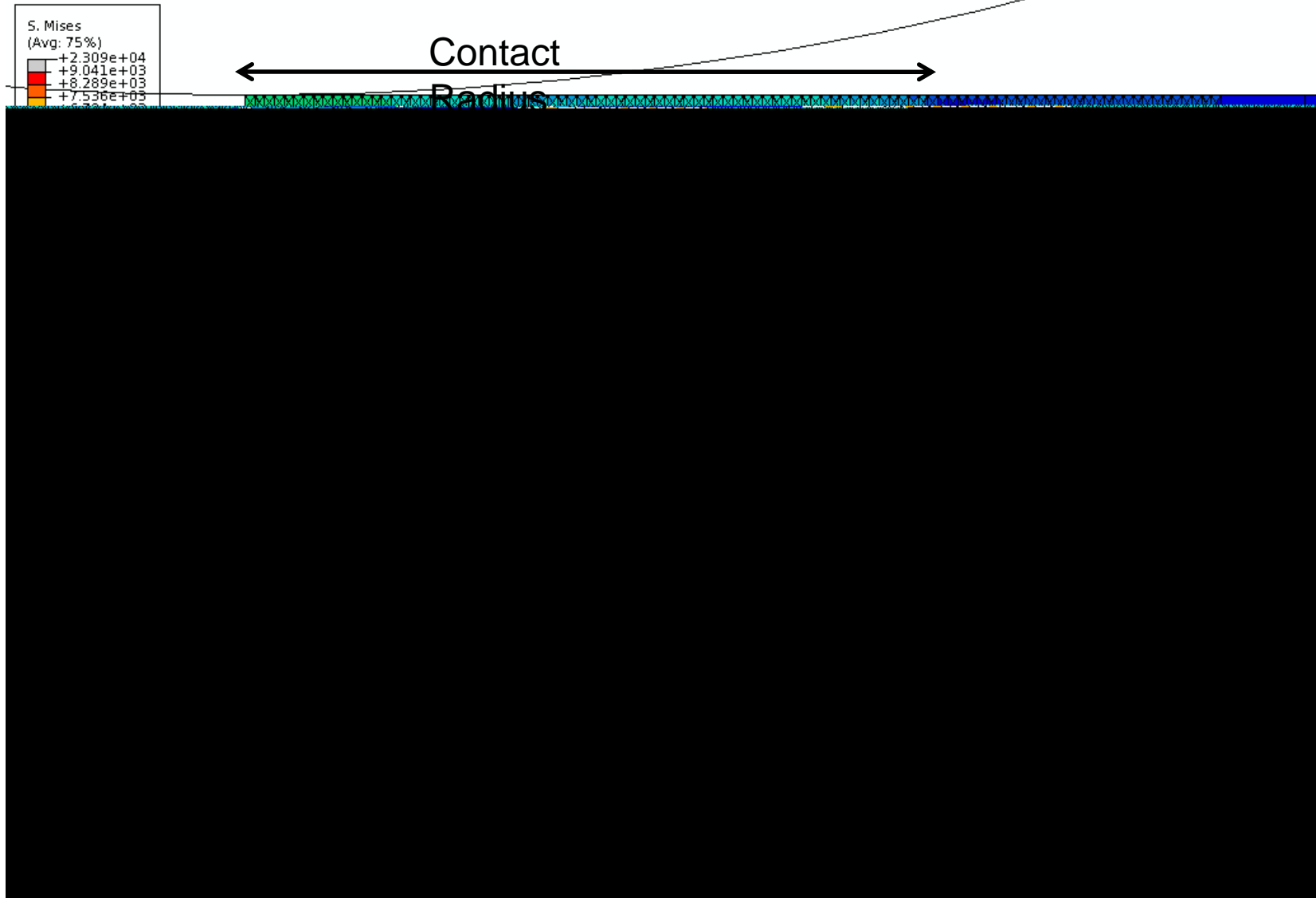


- Provides location of crack initiation but not:
- number of cycles to failure
 - not applicable to variable amplitude loading

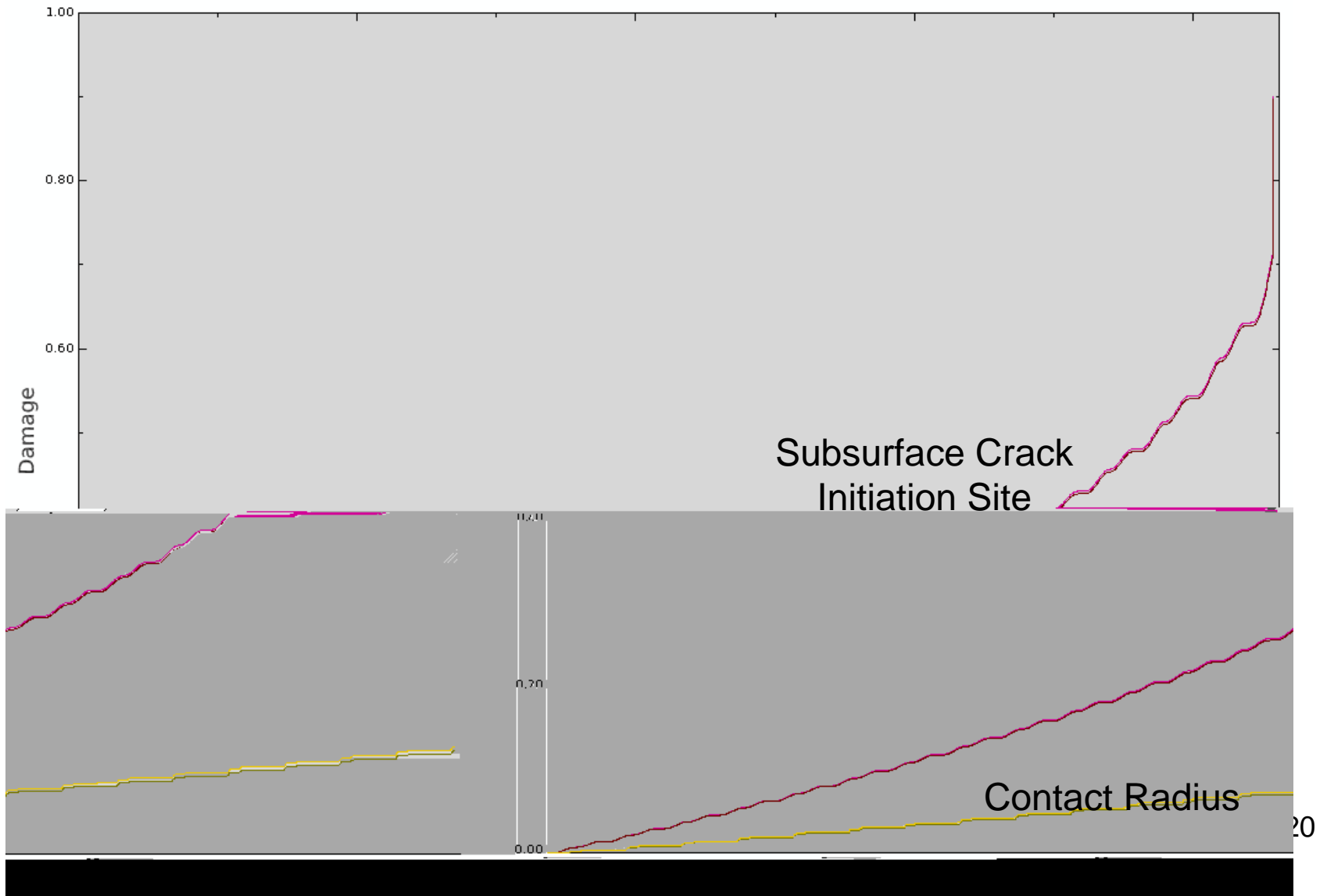
Redefine: Effective Traction

$$- \sqrt{\frac{\sigma^2}{E^2} \left(\frac{\sigma}{E} \right)^2}$$
$$- \frac{\sigma}{E}$$

$P_{\max} = 16800 \text{ N at Failure}$

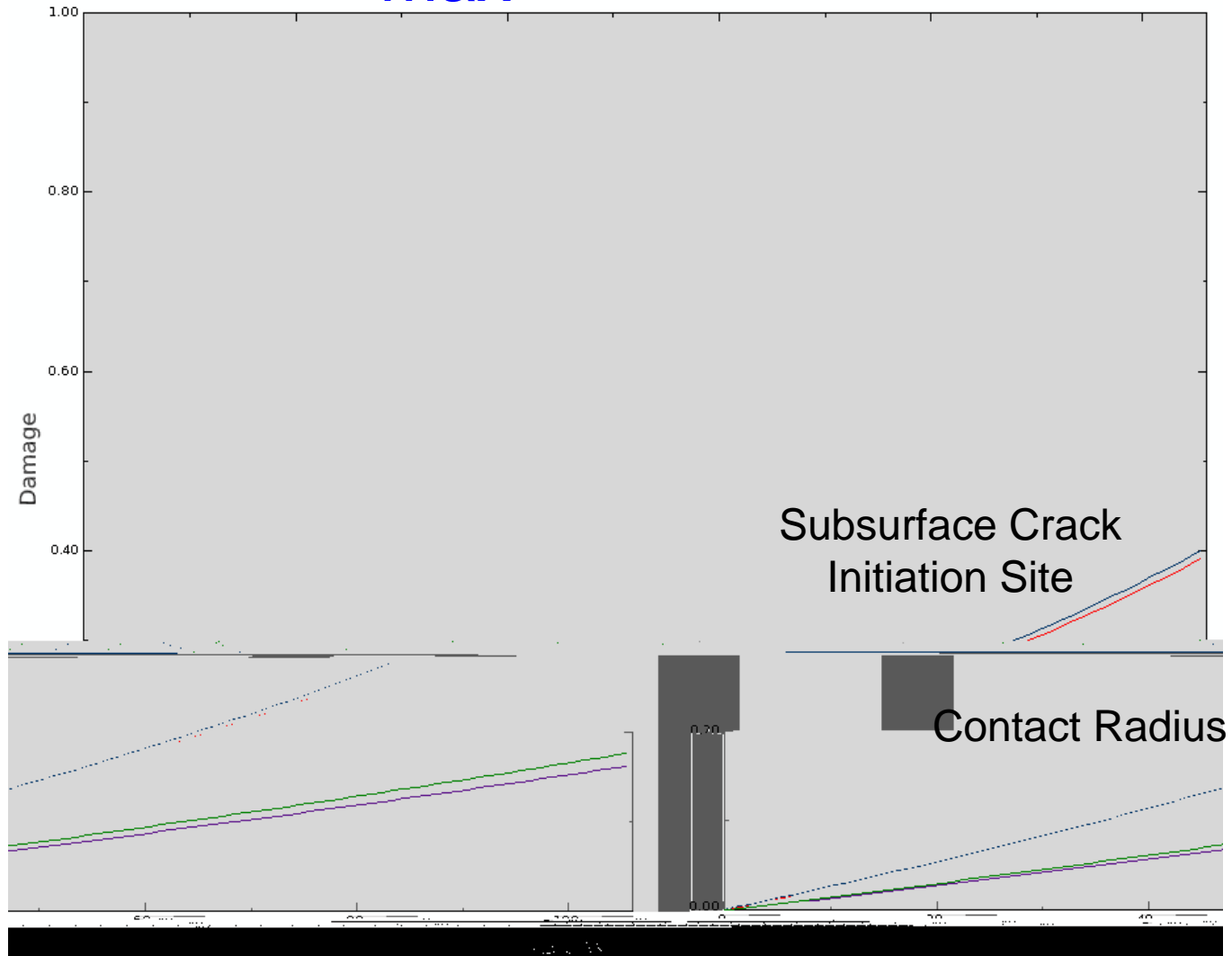


Damage Evolution

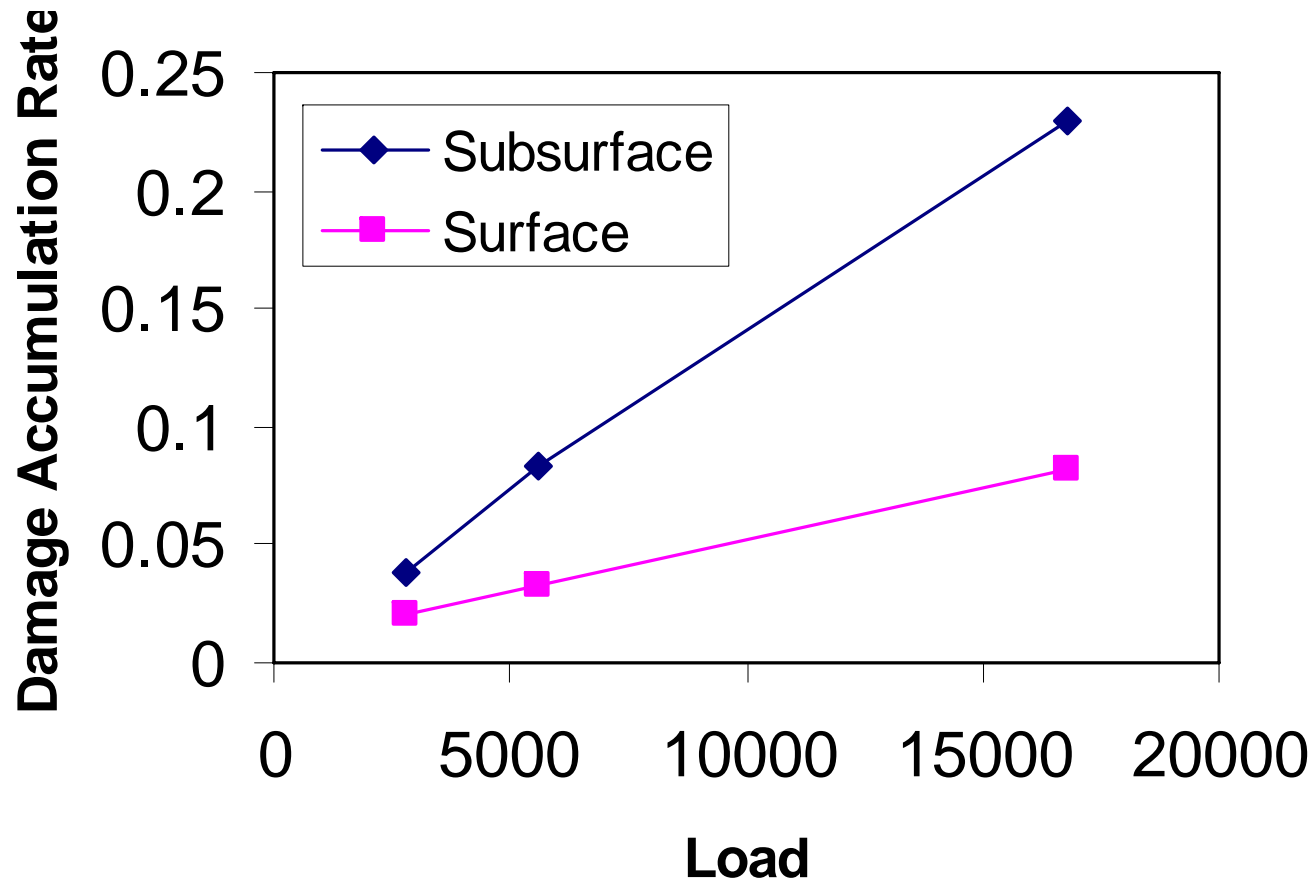


Damage Evolution

$$P_{\max} = 2800 \text{ N}$$



Comparison



T. Siegmund, Purdue

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