Simulation of Discrete-source Damage Growth in Aircraft Structures:
A 3D Finite Element Modeling Approach

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Presentation Overview

- Motivation and Objective
- Proposed Methodology and Toolset
- Past Research (Aging Aircraft Program)
  - Thin-shell fracture simulation
- Current Research (Discrete-source Damage)
  - An integrally stiffened wing panel
  - 3D simulation of damage propagation
- Preliminary Results
- Summary
- Ongoing Work

Motivation

- Need for *real-time residual strength predictions* of damaged structures
- Example application: aircraft structures subject to discrete-source damage

Airbus A300 shortly after takeoff from Baghdad, November, 2003*

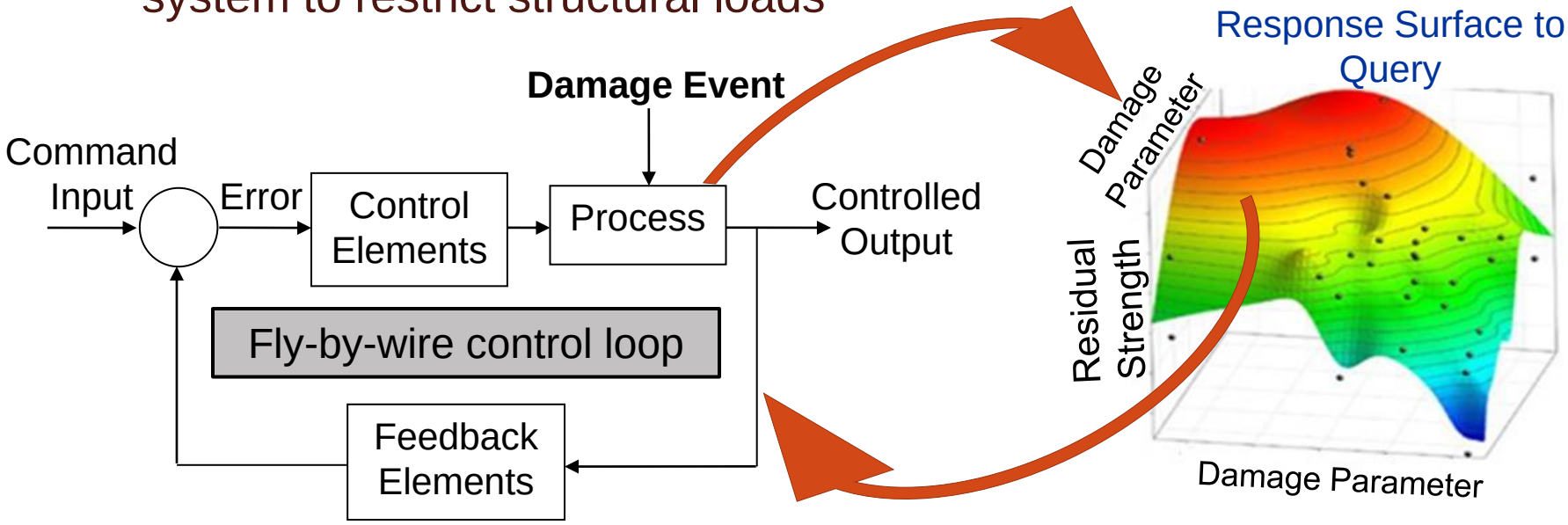
Boeing 747-438 en route from London to Melbourne, July, 2008*

* Image from public domain

Objective:

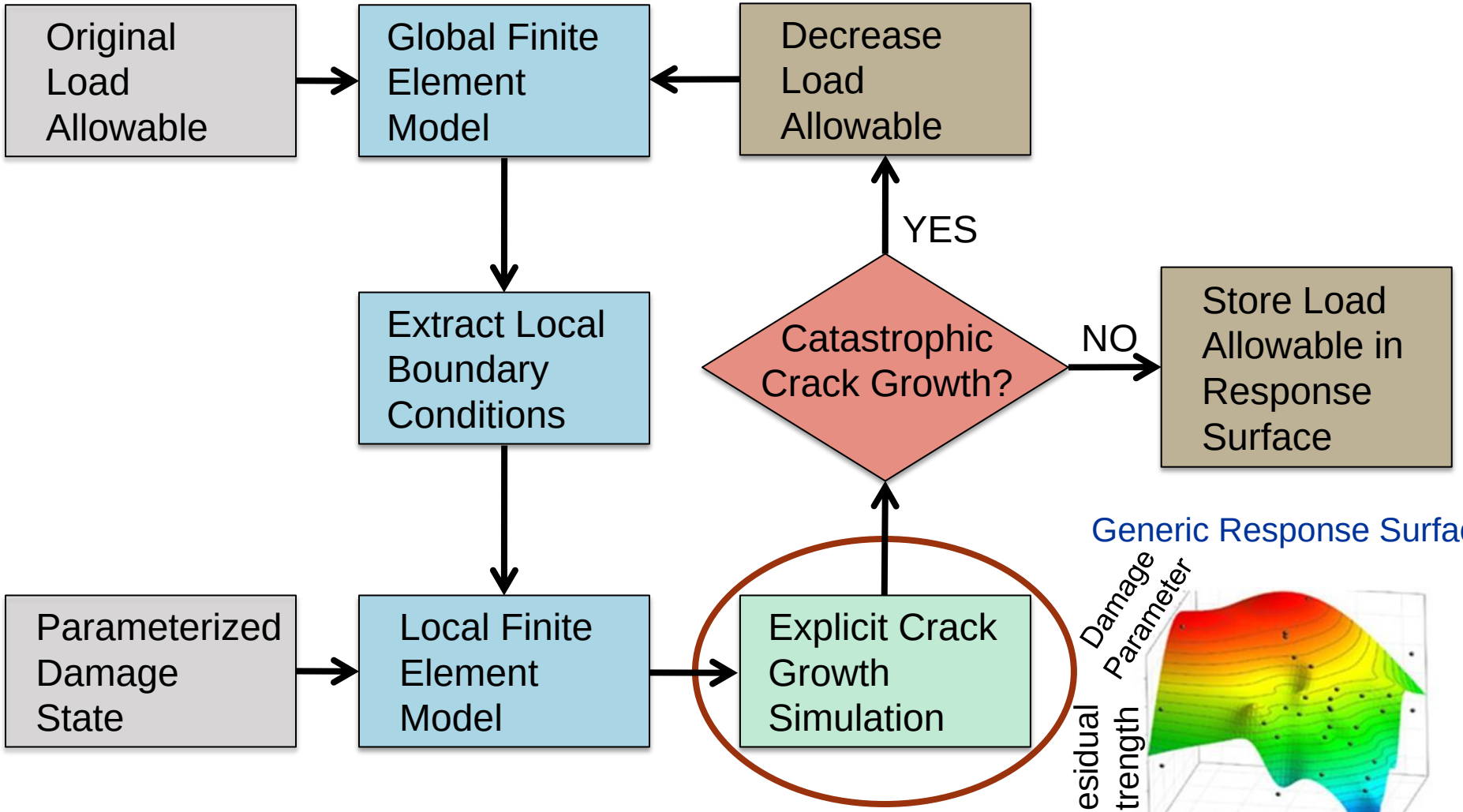
Integrated Resilient Aircraft Control (IRAC)

- IRAC objective: enable safe flight and landing after adverse event
  - Will require interfacing *real-time damage assessment tools* with control system to restrict structural loads

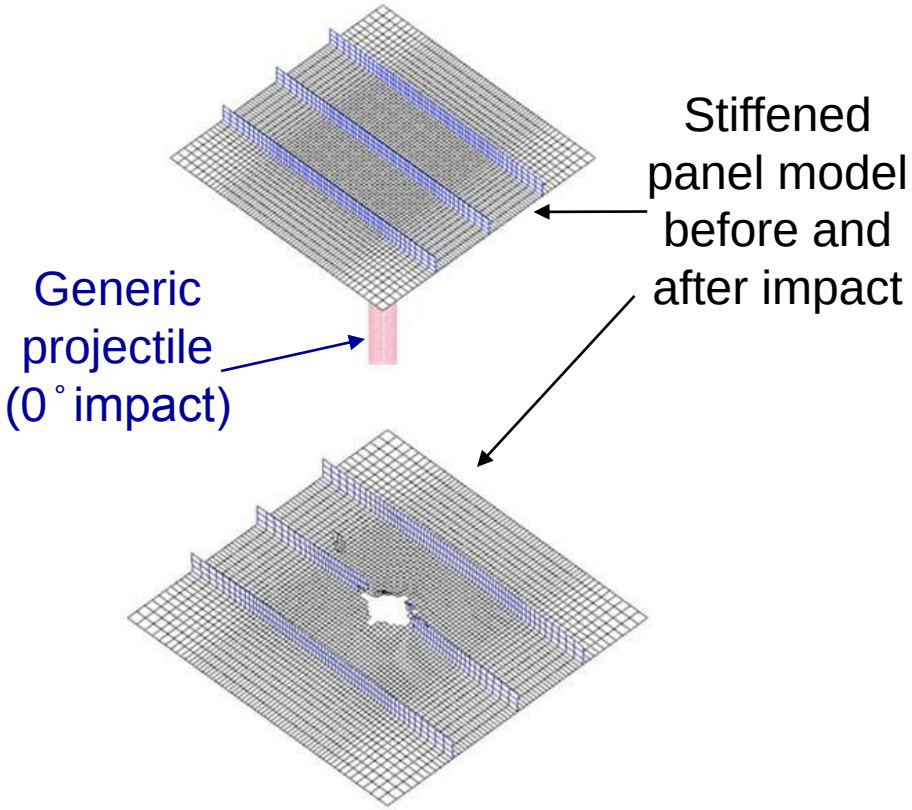


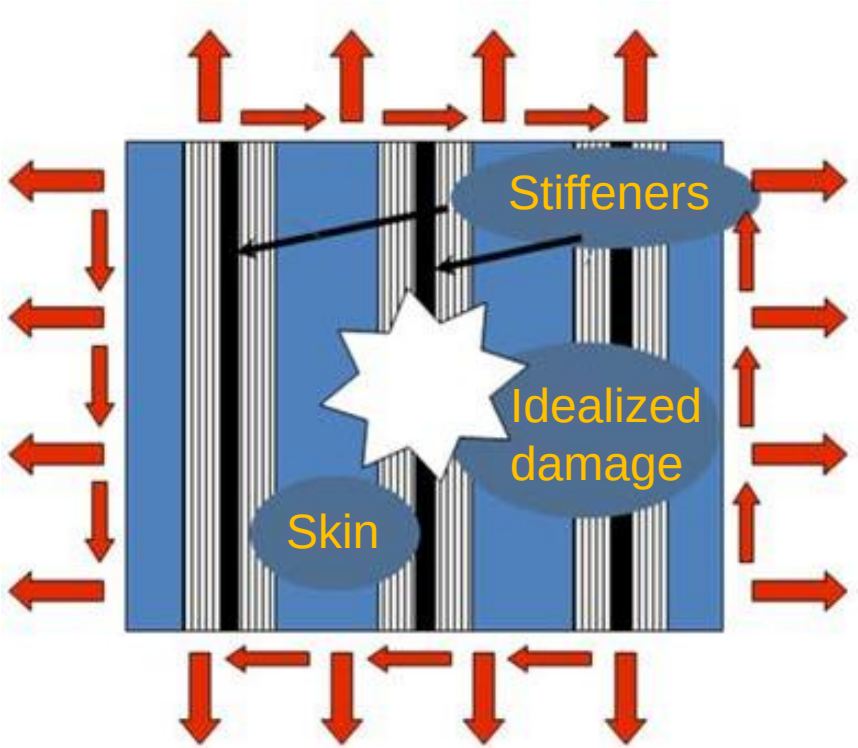
- Current objective: develop 3D finite element (FE)-based fracture mechanics methodology to predict residual strength of damaged airframe structures

A Proposed Methodology



Parameterized Damage State





*Characterizing Damage**

Damage models characterize damage resulting from projectile impact to stiffened panels

Parameterizing Damage

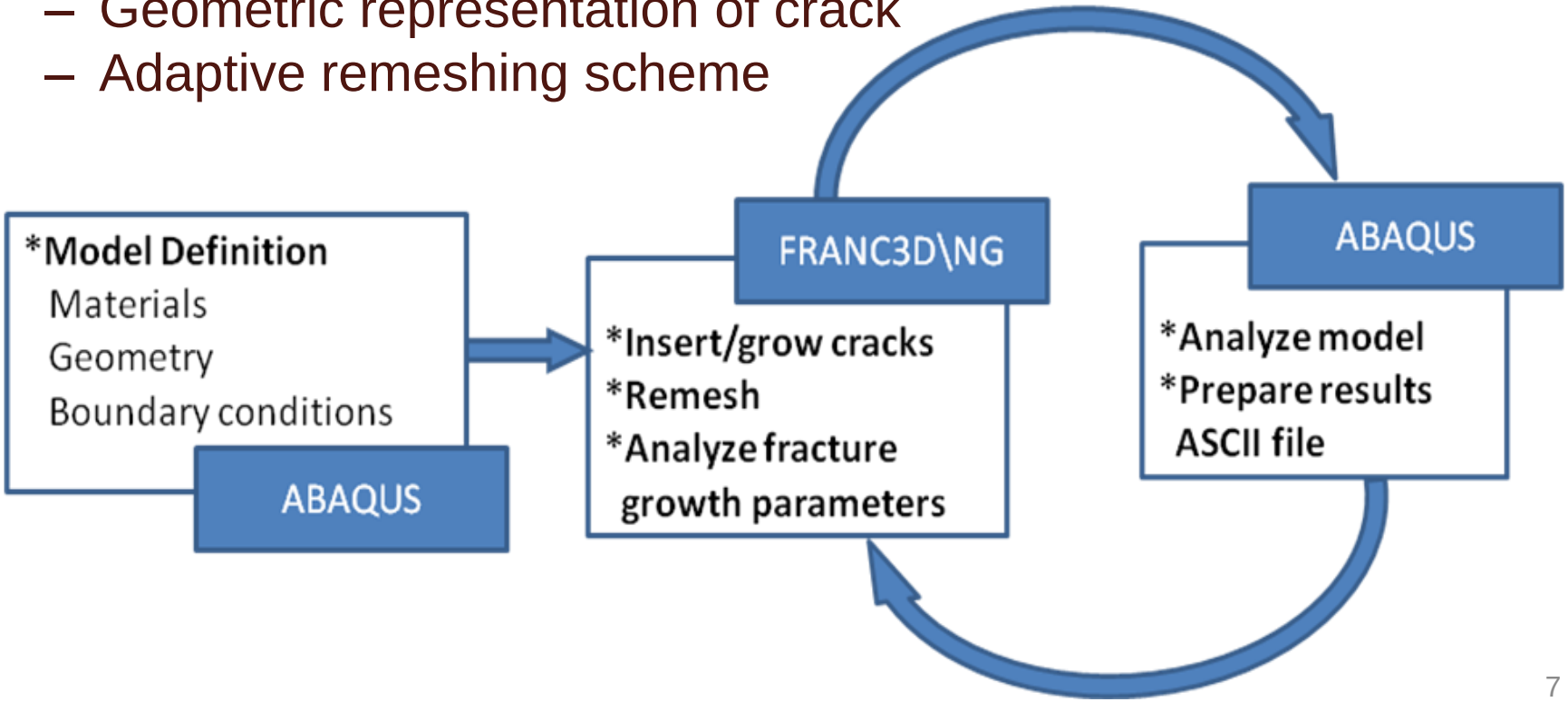
Use damage models to parameterize initial damage in terms of size, shape, location

* Hinrichsen *et al.*, *AIAA J.*, 2008

Toolset and Technology:

Geometrically Explicit Crack Growth Simulations

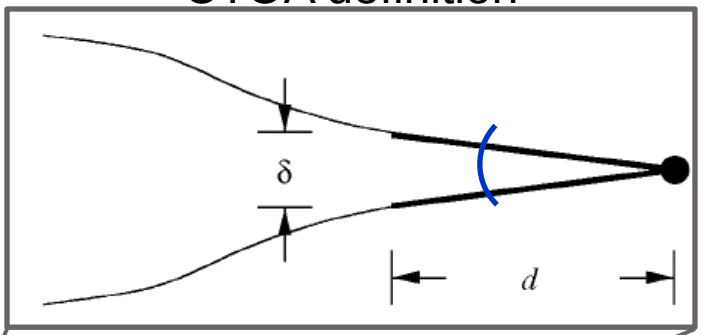
- ABAQUS
  - Commercial FE modeling code
- FRANC3D\NG
  - 3D fracture analysis code
  - Geometric representation of crack
  - Adaptive remeshing scheme



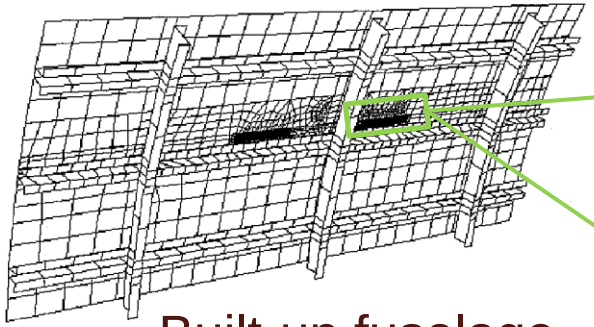
Past Research (Aging Aircraft):
Stable Tearing, Residual Strength Predictions

- Geometric and material nonlinearities
- Shell model with plane strain core[1]
- EPFM
- Predicted effects of multi-site damage and plastic zone evolution
  - $CTOA_c$ for crack growth criterion
  - Prescribed, self-similar path

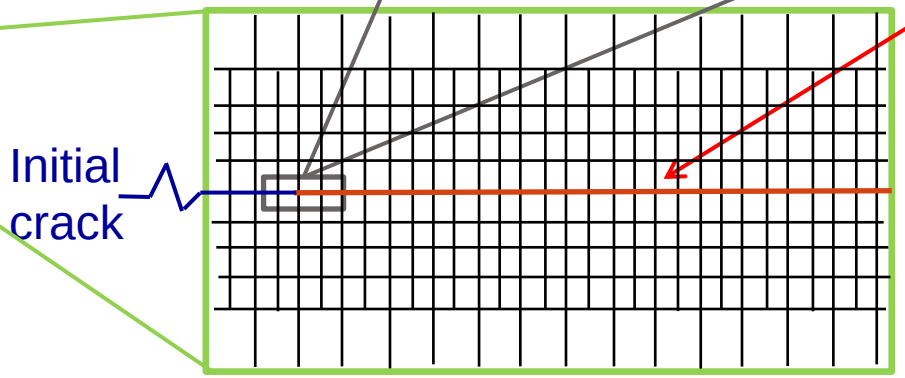
Illustration of Mode I CTOA definition



$$CTOA = 2\tan^{-1}\frac{\delta}{2d}$$



Built-up fuselage panel model



From Chen *et al*., *AIAA J.,* 2002

[1] Core height determined to correlate with results from Dawicke and Newman, *ASTM STP 1332,* 1998

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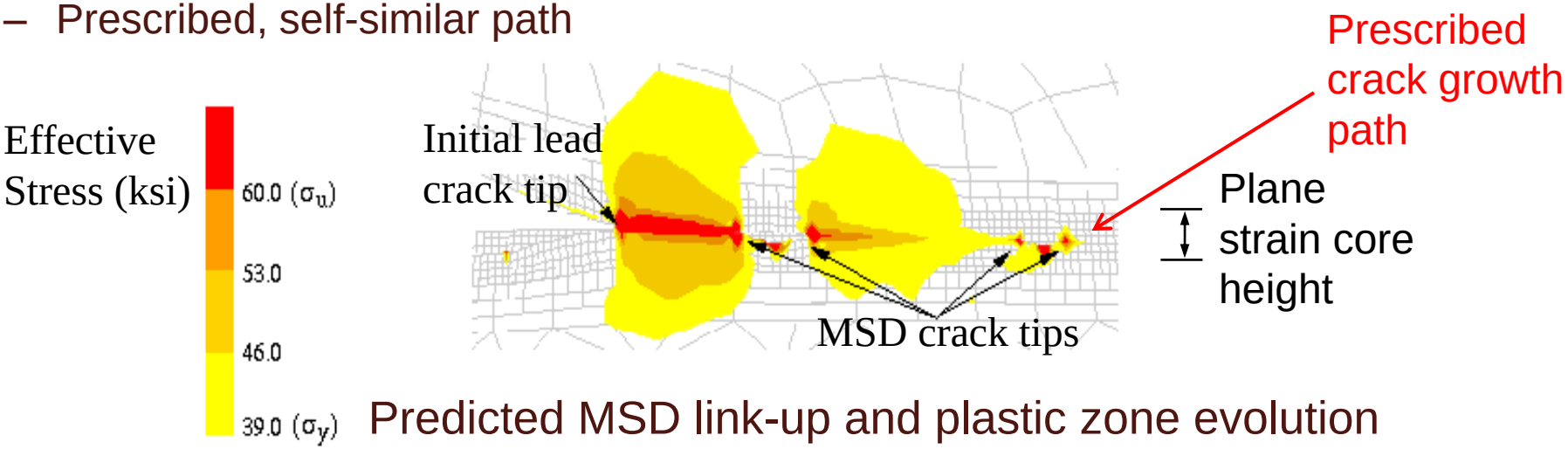


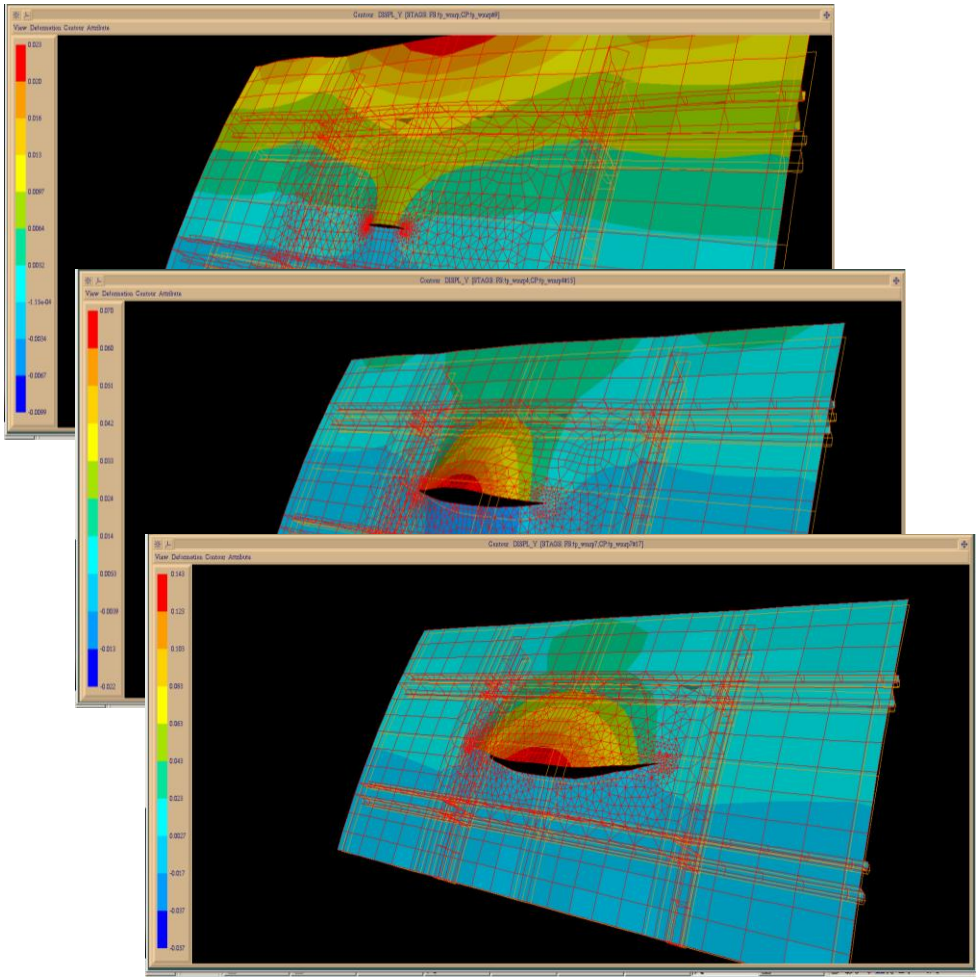
Predicted MSD link-up and plastic zone evolution using shell model with plane strain core

From Chen *et al.*, *AIAA J.*, 2002

[1] Core height determined to correlate with results from Dawicke and Newman, *ASTM STP 1332*, 1998

Past Research (Aging Aircraft):
Curvilinear Crack Growth Predictions

- Predicted effects of T-stress and fracture toughness orthotropy
- Geometric nonlinearity
- Small-scale yielding assumptions (LEFM)
  - Modified crack closure integral to compute shell SIF's (K_I, K_{II}, k_1, k_2)[1]
  - Directional criteria based on max. tangential stress theory[2] accounting for toughness anisotropy[3,4]



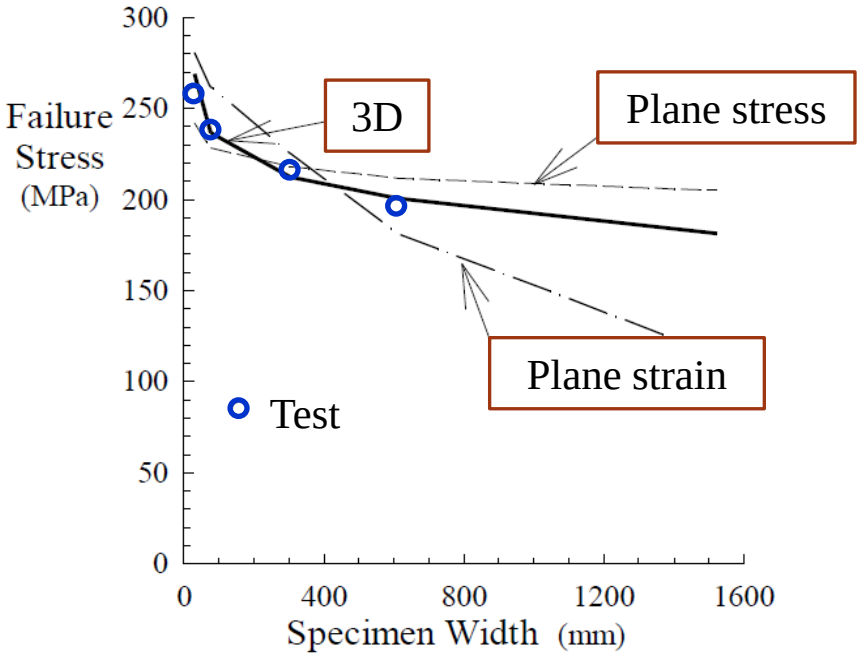
Curvilinear crack growth due to bulging in pressurized fuselage panel (contour shows out-of-plane displacements)

From Chen *et al*., *AIAA J.,* 2002
[1] Viz *et al*., *Int.J. Fract.,* 1995
[2] Erdogan and Sih, *J. Basic Eng.,* 1963
[3] Williams and Ewing, *Int. J. Fract.,* 1972
[4] Finnie and Saith, *Int.J. Fract.,* 1973

Past Research:
Findings and Conclusions

- Findings:
  - Predicted fracture behavior (and subsequent residual strength predictions) depends upon plane strain core height[1]
  - 3D modeling better predicts failure stress

Experimental and predicted failure loads for different size M(T) configurations[2]



- Contributing Conclusion:
  - Use 3D modeling techniques to capture crack front behavior and obviate need for constraint assumptions

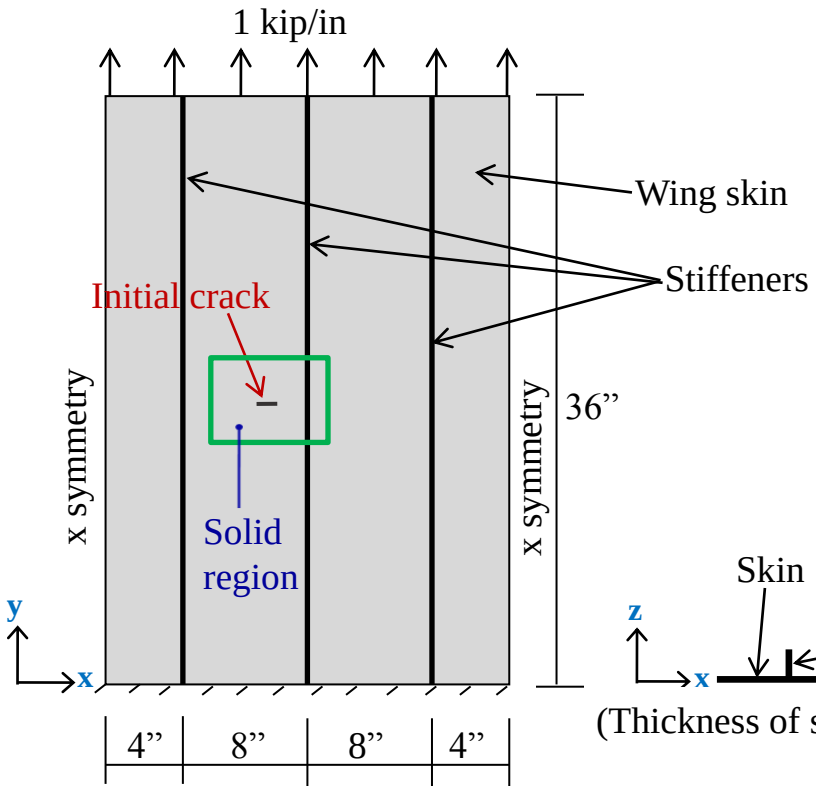
[1] Chen *et al.*, *AIAA J.*, 2002

[2] Results from Dawicke and Newman, *ASTM STP 1332*, 1998

Current Work:
Stiffened Wing Panel (Discrete-source Damage)

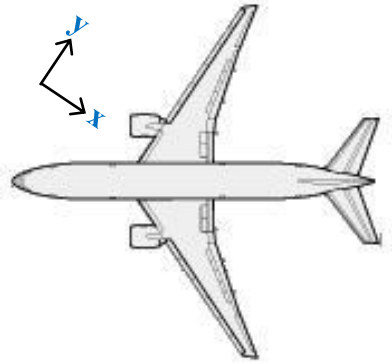
Model Assumptions

- Material
  - Elastic, isotropic
  - E = 10,600 ksi
  - v = 0.33
- Boundary conditions
  - Fixed along wing root end
  - x-symmetry on sides
- 1.5” initial through-crack
- Shell edge loading
- Shell/solid modeling approach
- LEFM

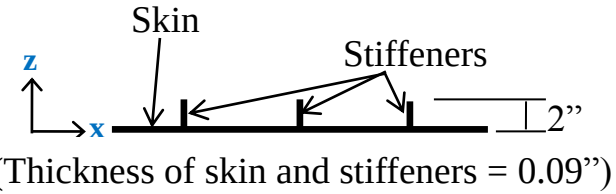


Plan View

(Green line indicates shell/solid boundary)

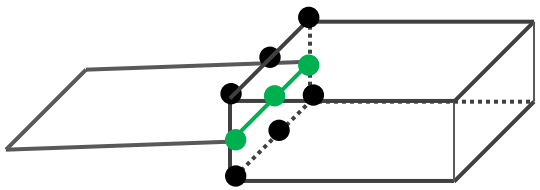


Coordinate System



(Thickness of skin and stiffeners = 0.09”)

Section View

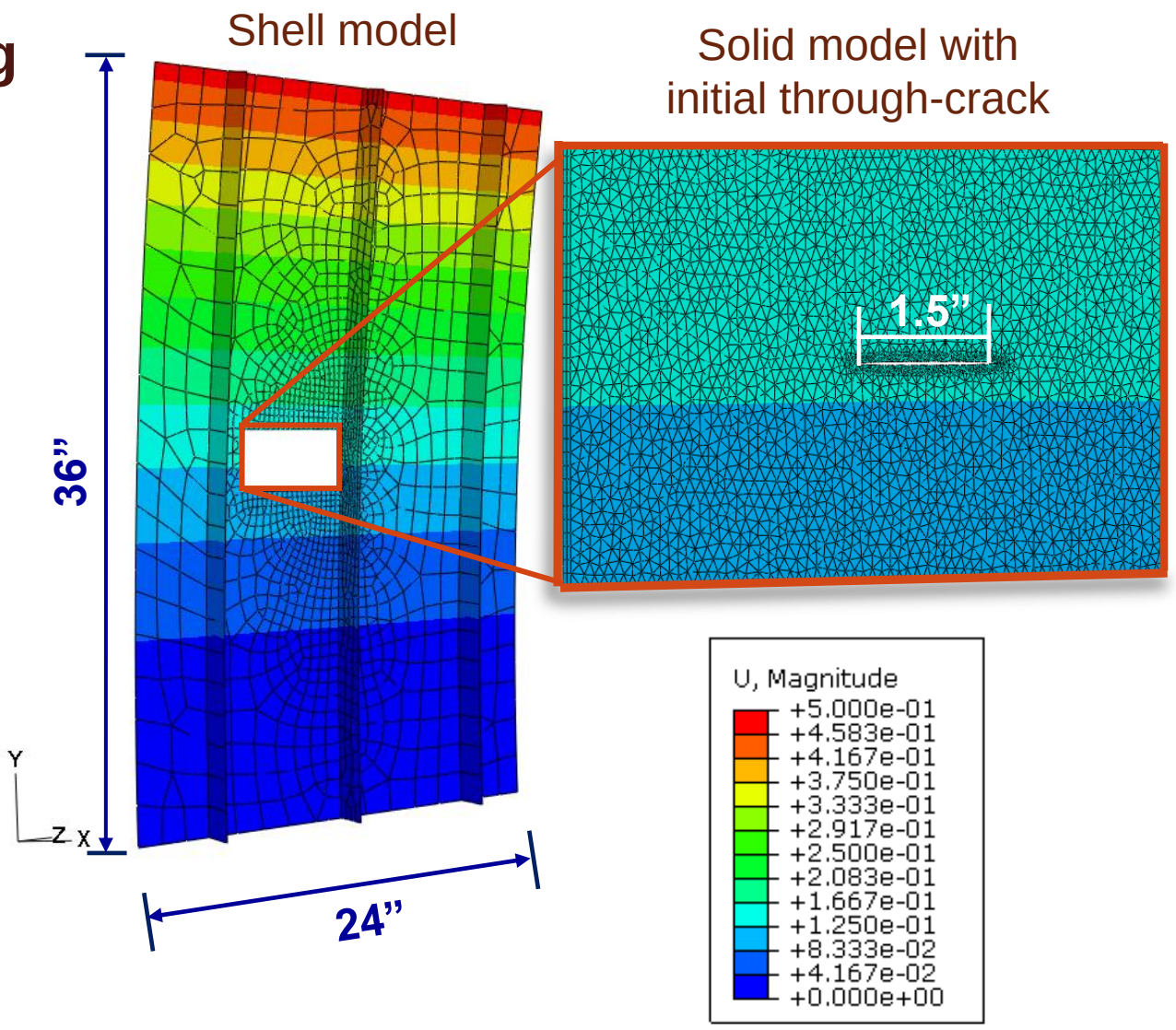


Shell-solid Modeling Concept

Current Work:
Stiffened Wing Panel (Discrete-source Damage)

Shell-solid Modeling Approach

- Global shell model
- Contained solid model
  - Model to be cracked
  - Coupled to shell model using MPC's
- Analysis
  - Full model analyzed at each increment of crack growth



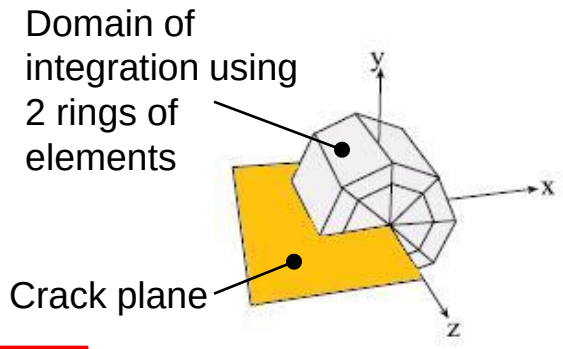
Contour shows displacement (inches)

Current Work:
Stiffened Wing Panel (Discrete-source Damage)

Fracture Simulations in F3DNG (LEFM)

- SIF computation:

$$M^{(1,2)} = \frac{1}{A_x}\int_V [\sigma_{ij}{}^{(1)}\frac{\partial u_i{}^{(2)}}{\partial x_1} + \sigma_{ij}{}^{(2)}\frac{\partial u_i{}^{(1)}}{\partial x_1} - W^{(1,2)}\delta_{1j}]\frac{\partial q_1}{\partial x_j}\,dV \quad *$$



- Crack extension specification:

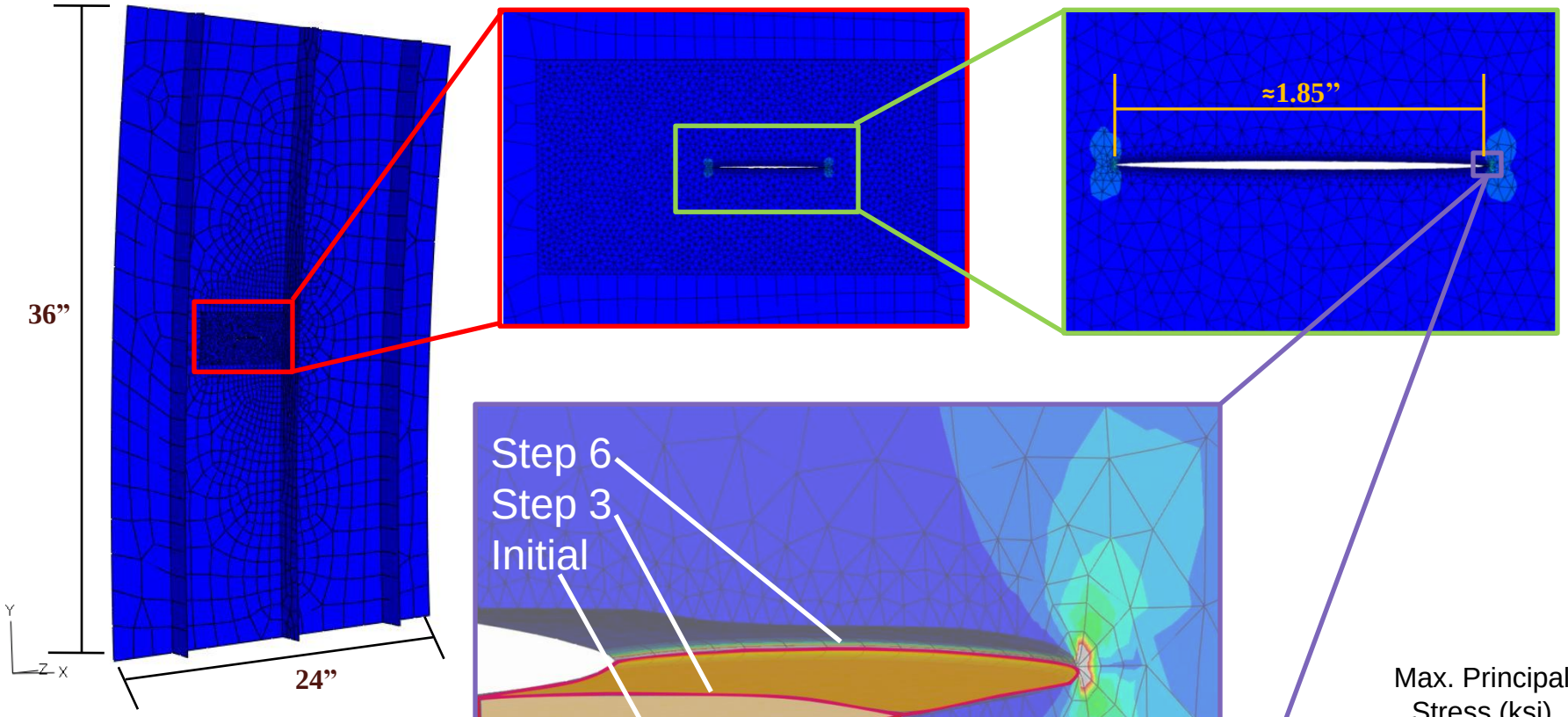
$$\Delta a_i = \Delta a_{mean}\left(\frac{\Delta K_i}{\Delta K_{mean}}\right)^n, \quad i = 1...\#crack\ \ front\ nodes$$

- Propagation direction criterion:

$$\theta_{kink} = \theta \quad such\ that \quad MAX\{\sigma_{\theta\theta}(\theta)\}$$

* For complete derivation see L. Banks-Sills *et al*., *Eng. Fract. Mech.* (2006)

Current Work:
Example Results



3D FE modeling captures constraint effects

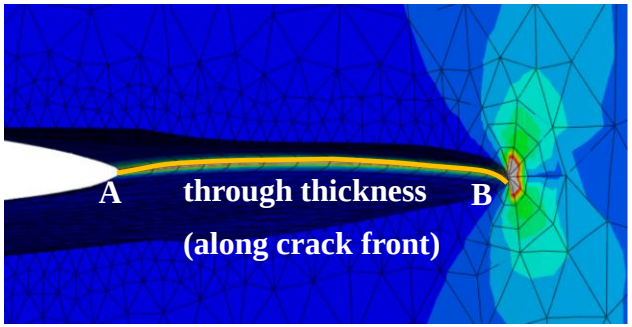
(*e.g.* crack tunneling shown here by step 6)

≈1 million D.O.F.’s

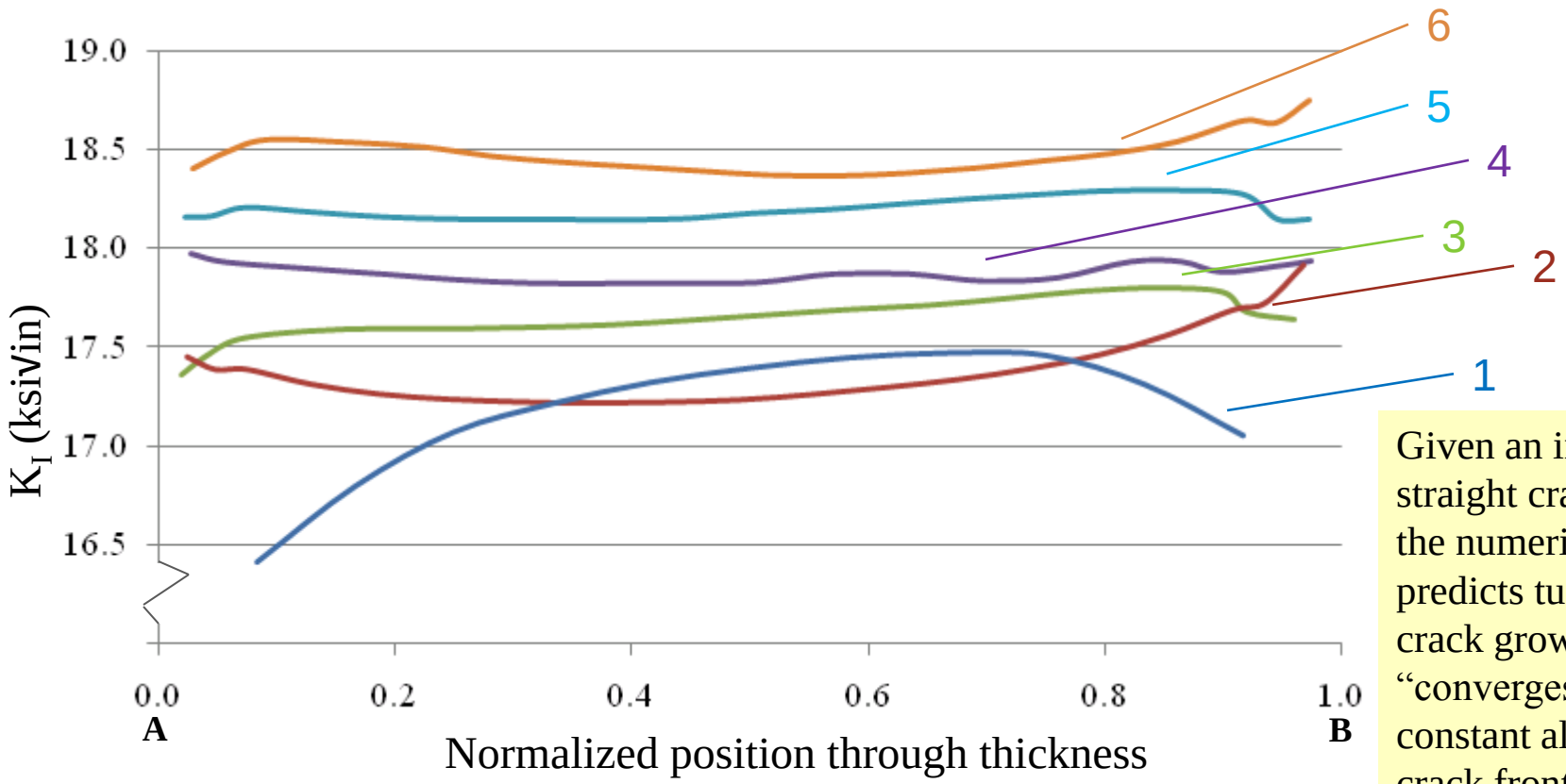
≈ 15 min. wall clock time

2 dual-core processors (typical desktop)

Current Work:
Example Results



Mode I SIF *variation* along crack front



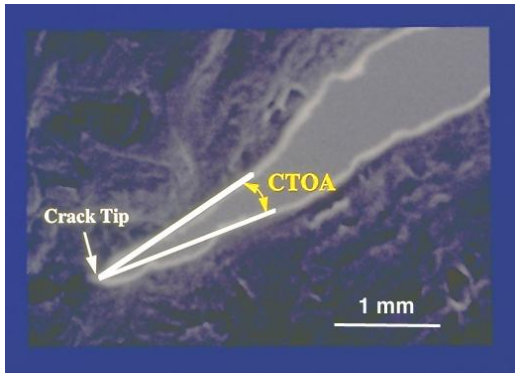
Given an initially straight crack front, the numerical model predicts tunneling as crack grows while K_I "converges" to be constant along the crack front

Summary

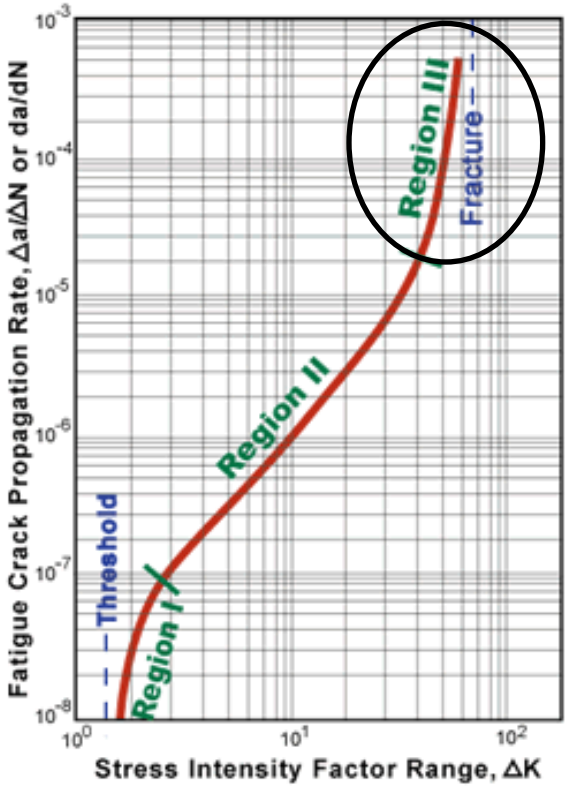
- Overall IRAC objective: enable safe flight and landing in adverse conditions
- Methodology is being developed for assessing residual strength of airframe structures with discrete-source damage
- Past work (aging aircraft) using plane strain core concept indicates need for higher fidelity crack propagation modeling
  - Use 3D modeling approach instead
- Methodology presented for performing explicit crack growth simulations from discrete-source damage
  - Simulations employ ABAQUS/F3DNG framework
- Example using a shell-solid FE modeling technique is presented along with preliminary fracture results

Ongoing Work

- Inelastic crack growth (*e.g.* $CTOA_c$)
  - Validate with simple geometry and loading
- Low-cycle fatigue crack growth
  - Remaining time to land aircraft
- More complex damage and geometry
  - Damage from generic projectile
  - Full wing model
- Response surface approach
  - Consider neural network or surrogate model
- Validate methodology and toolset



D.S. Dawicke and M.A. Sutton, *Exp. Mech.*, 1993



Acknowledgements

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