May 9, 2012

ASTM Sub-Committee E08.04 on Structural Applications
Workshop on Verification and Validation of Life Prediction Softwrae

Verification and Validation of XFEM Toolkit for Fracture and Fatigue Assessment of Metallic Structures

Dr. Jim Lua, Dr. Phillip Liu, and Dr. Michael Stuebner
Global Engineering and Materials, Inc.
1 Airport Place, Suite 1
Princeton, NJ 08540

Phone: (609) 356-5155 X 214 Fax: (609) 924-3999

Dr. Ted Belytschko and Dr. David Chopp
School of Engineering and Applied Science
Northwestern University
2145 Sheridan Road
Evanston, IL 60208

Outline

- Introduction
  - GEM (www.GEM-INNOVATION.com)
  - Fracture and Fatigue Prediction Toolkits for Metallic Structures (XFA3D & XSHELL)
- Background and Problem Challenges
- Summary of Toolkits Methodology and Their Modeling Capabilities
- Toolkits Demonstration and V&V Study
- Summary and Future Plan

GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

Collaborators and Sponsors for Metallic Fracture Toolkit Development

- ***XFA3D*** – 3D X-FEM Toolkit for Abaqus Implicit Solver
  - Residual strength and life prediction under static and cyclic loading
  - Mesh independent crack insertion and simulation of crack growth without remeshing
- ***XSHELL*** - Mesh Independent Crack Growth Prediction for Abaqus Explicit Solver
  - Crack path and load deflection prediction for large scale thin-walled structure
  - Element stepwise crack propagation and cohesive zone for nonlinear fracture

Collaborators for XFA3D

Ted Belytschko, David Chopp, **Northwestern University**
N. Sukumar, **University of California, Davis**
Bruce Englemann, **Dassault Systèms Simulia Corporation**
Steve Engelstad , **Lockheed Martin Aero**
Mikhail Chaplya, **Caterpillar**

Collaborators for XSHELL

Ted Belytschko, David Chopp, **Northwestern University**
Jack Chessa, **The University of Texas at El Paso**
Robert Dodds, **University of Illinois at Urbana-Champaign**
Xiaosheng Gao, **University of Akron**
David Williams, **Alcoa Technical Center**
Frank Springett, **National Oilwell Varco**

Support Programs

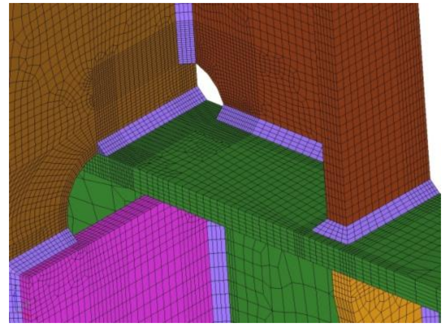
US Navy with Dr. Paul Hess as the Program Monitor
US Air Force with Dr. David Mollenhauer as the Program Monitor
US NAVAIR with Dr. Anisur Rahman as the Program Monitor

DoD and Industrial Relevance

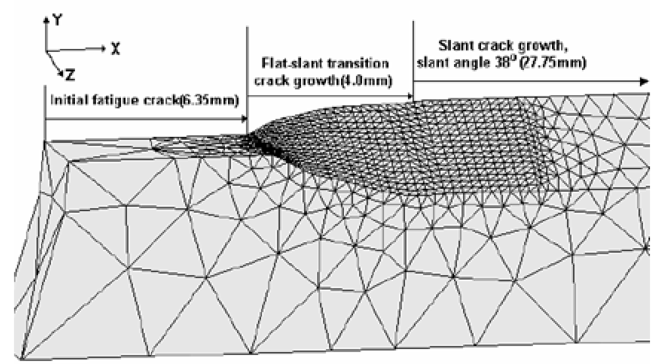
- **Immediate Needs**
  - a verified computational tool to efficiently perform
    - Structural integrity and residual strength assessment;
    - Durability assessment for a given cyclic loading; and
    - Reliability based performance evaluation with in-service structural healthy monitoring
  - a high-fidelity virtual testing tool to address
    - What is the critical damage size at onset and growth phase?
    - When should the structure be repaired?
    - Is the damage critical to the structure?
    - What are the residual strength and design allowables under monotonic and cyclic loading

Summary of Problem Challenges (Metallic)

- Large scale airframe structural components with material nonlinearity and mode mixity
- Curvilinear crack growth in a multi-bay stiffened panel under cyclic loading
- Process zone dependent fracture failure
- Unknown initial defect and crack growth pattern
- Prohibitively large computational effort based on a mesh dependent FEM model for probabilistic analysis

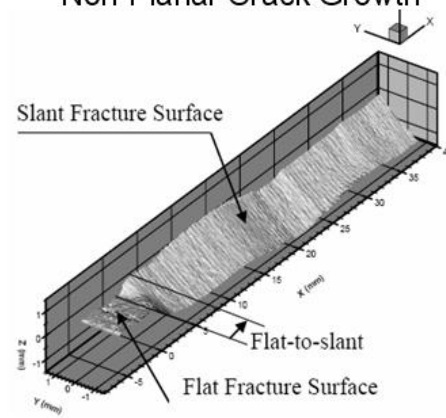


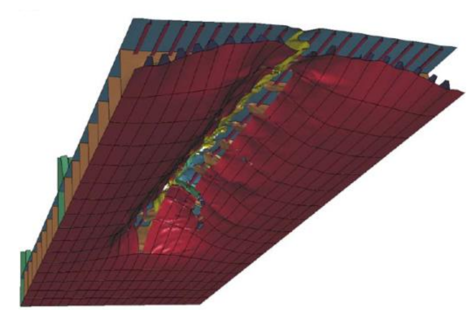
Laborious Remeshing in Conventional Finite Element Method



Computational intensive to characterize arbitrary multiple initial defects and their growth

Non-Planar Crack Growth





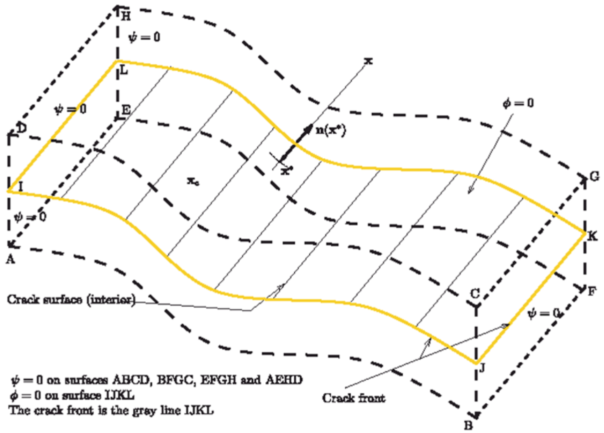
XFA3D

ϕ – Crack Surface Function

Ψ - Crack Front Function

$$\Psi(\mathbf{x},t) = \sum_I N_I(\mathbf{x})\Psi_I(t)$$

$$\Phi(\mathbf{x},t) = \sum_I N_I(\mathbf{x})\Phi_I(t)$$



$$u(\xi,\eta,\zeta) = \sum_i N_i(\xi,\eta,\zeta)U_i + \sum_i N_i(\xi,\eta,\zeta)H(\xi,\eta,\zeta)b_i + \sum_i N_i(\xi,\eta,\zeta)\left(\sum_j \Psi_j(r,\theta)\,c_{ji}\right)$$

$$H(\xi,\eta,\zeta) = \begin{cases} +1: \varphi(\xi,\eta,\zeta) > 0 \\ -1: \varphi(\xi,\eta,\zeta) < 0 \\ \pm 1: \varphi(\xi,\eta,\zeta) = 0 \end{cases}$$

$$\Psi_j = \left\{\sqrt{r}\sin\left(\frac{\theta}{2}\right), \sqrt{r}\cos\left(\frac{\theta}{2}\right), \sqrt{r}\sin\left(\frac{\theta}{2}\right)\sin(\theta), \sqrt{r}\cos\left(\frac{\theta}{2}\right)\sin(\theta)\right\}$$

The crack surface is given by

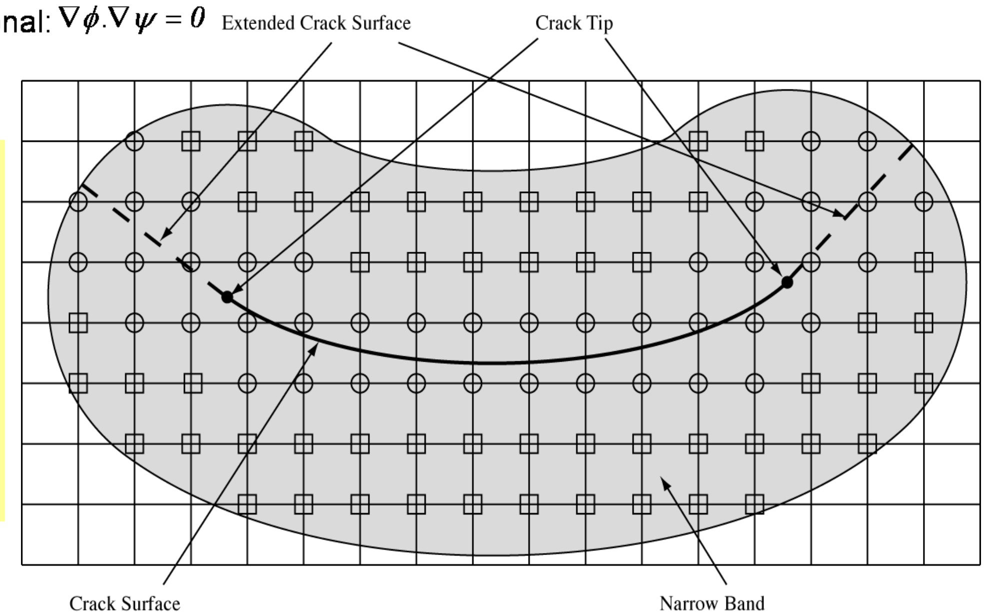
$\phi(\mathbf{x},t) = 0 \quad \psi(\mathbf{x},t) < 0$ on Γ_{cr}

$\phi(\mathbf{x},t) = 0 \quad \psi(\mathbf{x},t) = 0$ is crack front

$\psi(\mathbf{x},t) > 0$ does not intersect the crack

Representation of a general crack

For convenience, $\phi(\mathbf{x},t)$ and $\psi(\mathbf{x},t)$ are constructed to be orthogonal: $\nabla\phi . \nabla\psi = 0$



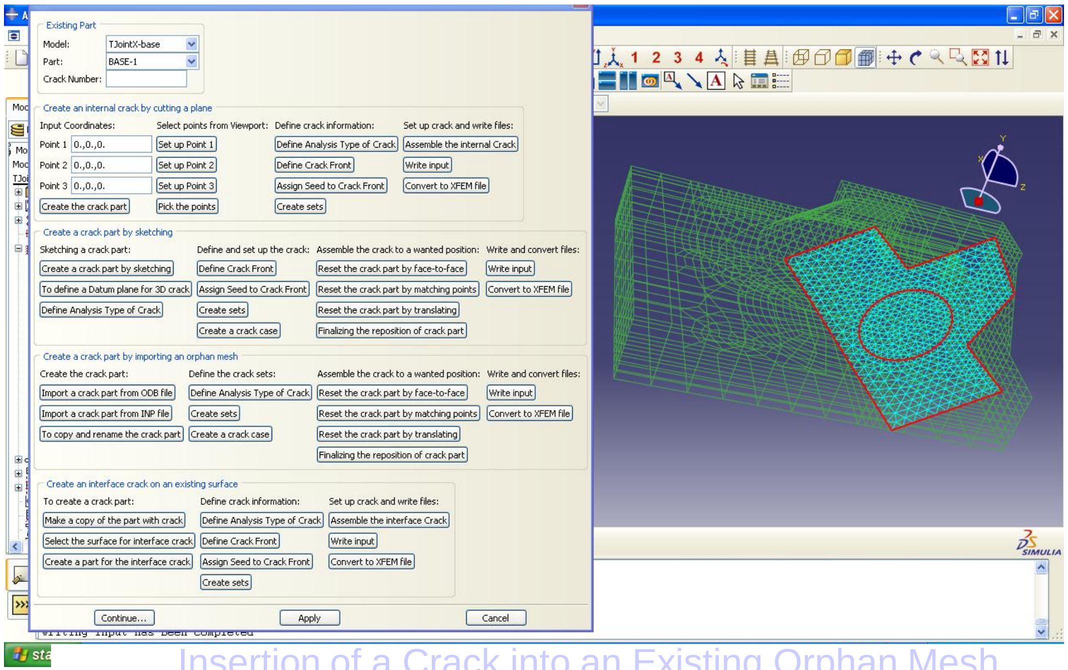
Narrow-band, in gray, of points around the crack surface, in cross-section, where the FMM mesh maintains signed values.

Circles: computed directly from signed distance function
Squares: computed using the FMM.

GLOBAL ENGINEERING & MATERIALS, INC.

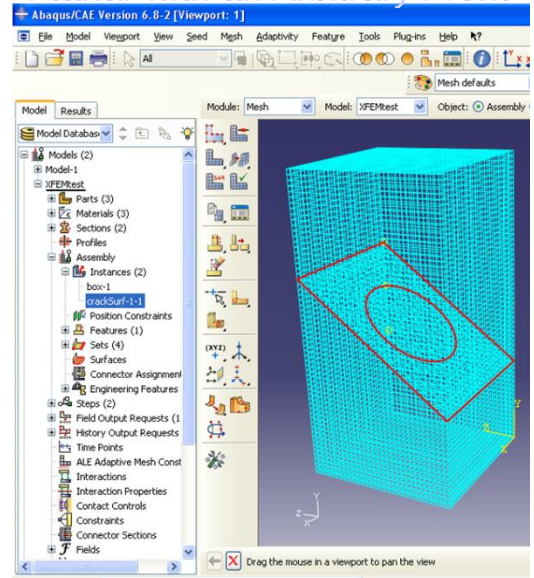
Engineering and Innovative Solutions

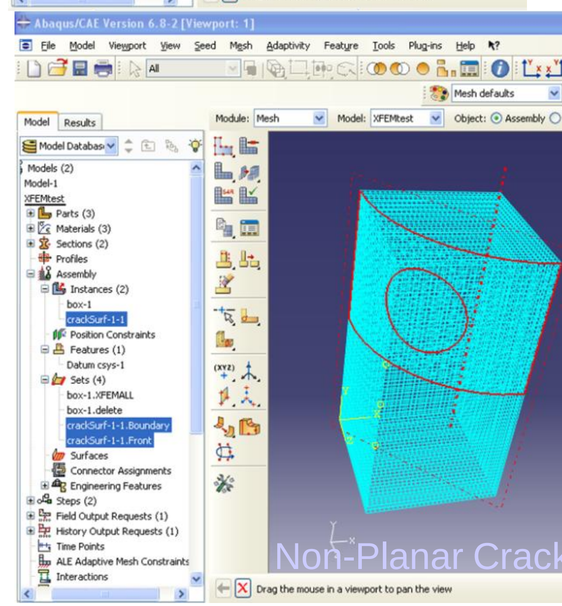
Customized ABAQUS' CAE for Crack Insertion



Insertion of a Crack into an Existing Orphan Mesh

Planar with an Arbitrary Front





Non-Planar Crack

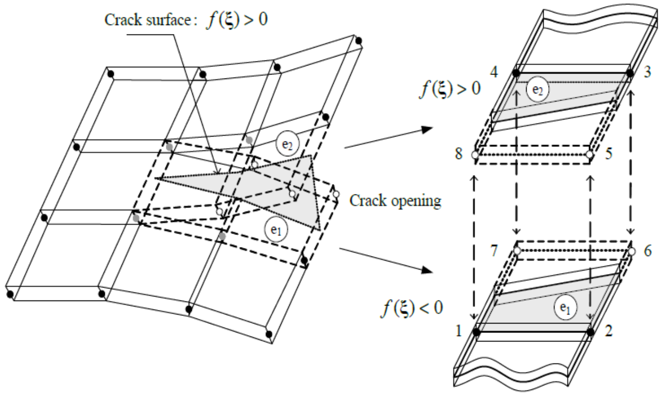
- Importation of base mesh without crack
- Definition of user-defined crack plane and front
- Model assembly and Levelset initialization
- Generation of X-FEM input files

GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

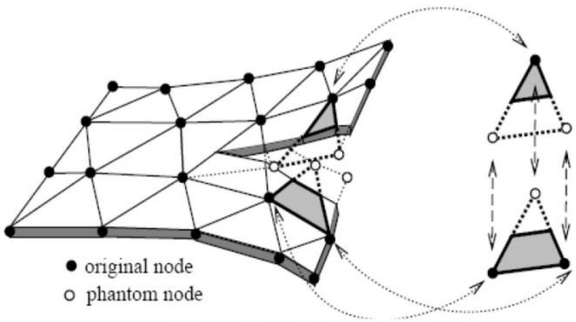
XSHLL Toolkit for Explicit Dynamic Fracture Prediction

Crack Representation via a Pair of Phantom Element

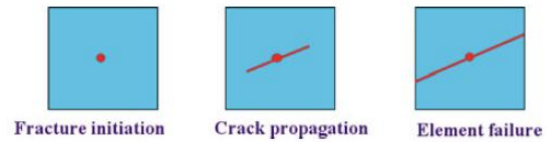
Quadrilateral XSHELL



Triangular XSHELL

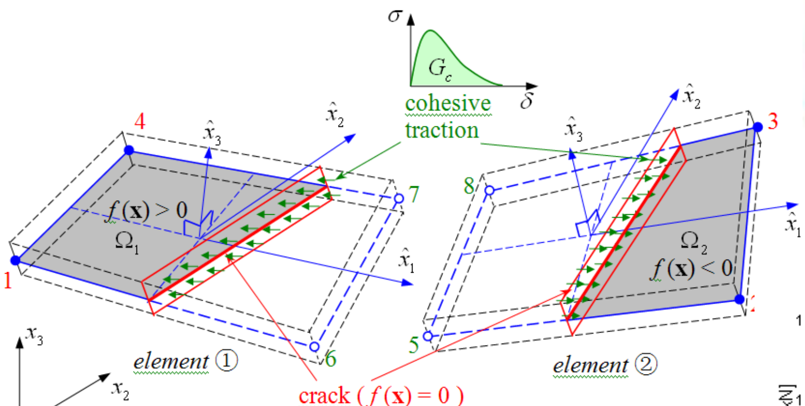


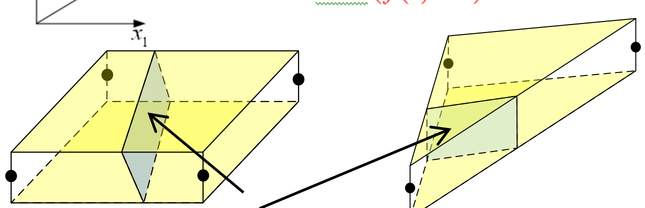
Crack Initiation, Growth Direction, Cohesive Insertion, and Energy Dissipation



$$D=\int_0^{\bar{\varepsilon}_f}\frac{d\bar{\varepsilon}_p}{f(\eta,\bar{\theta})}$$ (Crack Initiation)

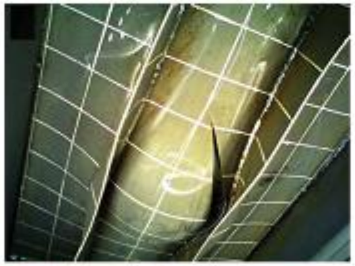
Crack Growth Direction Law: $\varepsilon^I_{\max}/\sigma^I_{\max}$

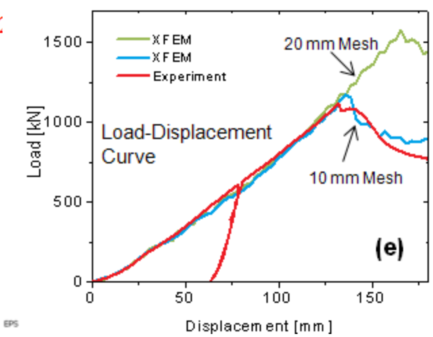




Cohesive Interaction on a Crack Plane

Response and Failure Prediction

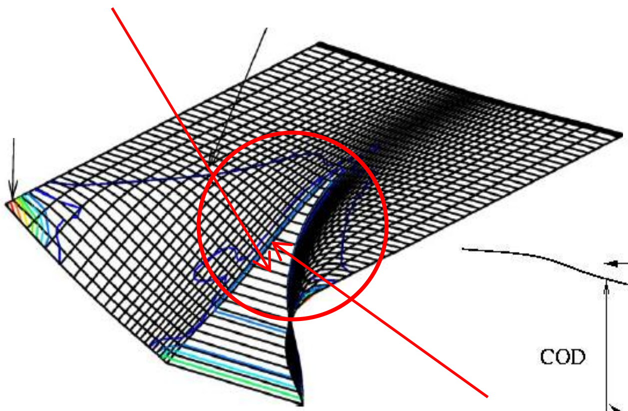




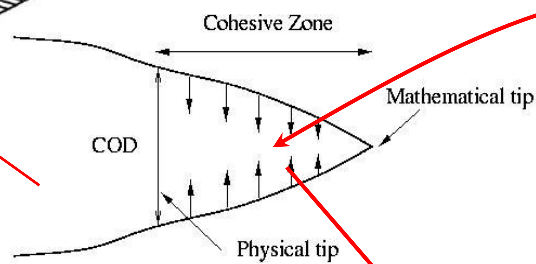
GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

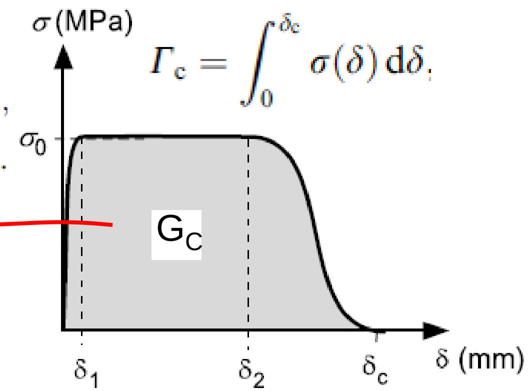
Embedded Cohesive Interaction for Crack Propagation

Energy Dissipation
During Crack Propagation



$$\sigma = \sigma_c f(\delta) = \sigma_c \begin{cases} 2\left(\frac{\delta}{\delta_1}\right) - \left(\frac{\delta}{\delta_1}\right)^2 & \text{for } \delta \leqslant \delta_1, \\ 1 & \text{for } \delta_1 \leqslant \delta \leqslant \delta_2, \\ 2\left(\frac{\delta-\delta_2}{\delta_c-\delta_2}\right)^3 - 3\left(\frac{\delta-\delta_2}{\delta_c-\delta_2}\right)^2 + 1 & \text{for } \delta_2 \leqslant \delta \leqslant \delta_c. \end{cases}$$





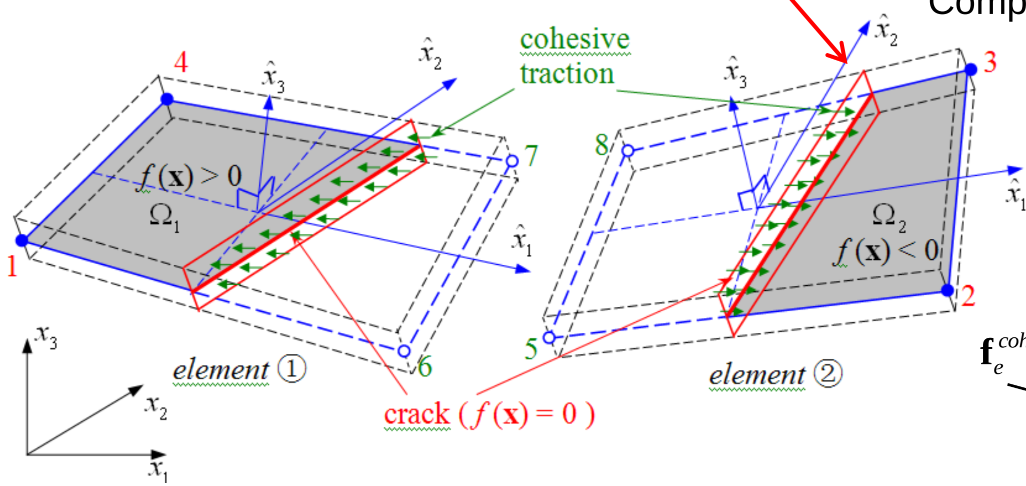
$$\Gamma_c = \int_0^{\delta_c} \sigma(\delta)\, d\delta$$

Mode I Correction Due to Mixed Mode Interaction $\sigma_I = \sigma_{Ic} f(\delta_I)\sqrt{g(\delta_{II})g(\delta_{III})}$

$$g(\delta_i) = 2(\delta_i/\delta_{ic})^3 - 3(\delta_i/\delta_{ic})^2 + 1, \quad i = II,\ III$$

Insertion of Cohesive Interaction in XSHELL

Computation of d_n via a Pair of Phantom Elements



Crack Opening Displacement (d_n)

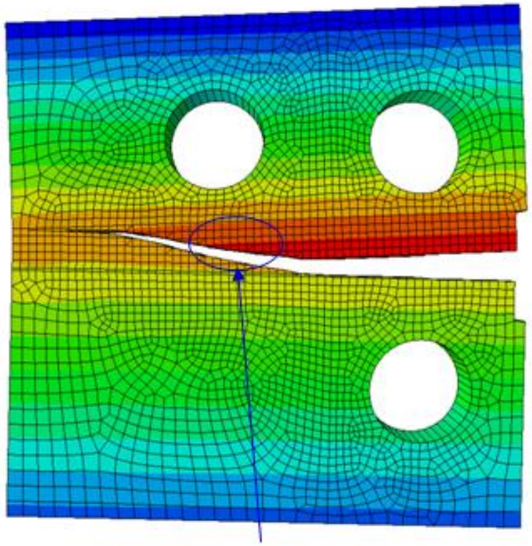
$$\delta_n = \hat{\mathbf{n}} \cdot \left(\hat{\mathbf{u}}^{e2}(\xi,t) - \hat{\mathbf{u}}^{e1}(\xi,t)\right)_{\xi\in\Gamma_c}$$

Cohesive Force Vector at Nodal Points

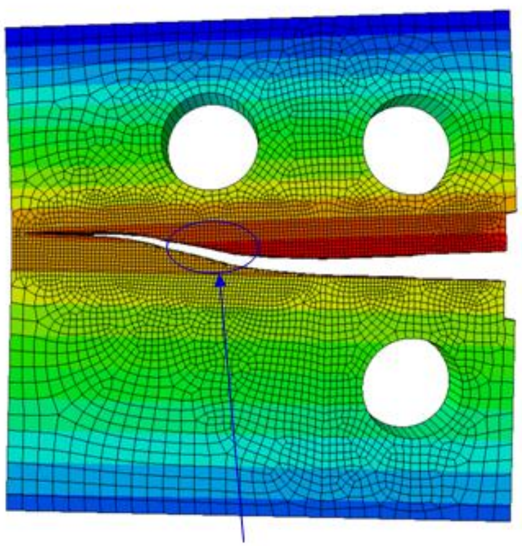
$$\mathbf{f}_e^{coh} = \mathbf{R}_{e1}^T \int_{\Gamma_c} -N^T \tau_c(\delta_n)\hat{\mathbf{n}}\, d\Gamma + \mathbf{R}_{e2}^T \int_{\Gamma_c} N^T \tau_c(\delta_n)\hat{\mathbf{n}}\, d\Gamma$$

Discretized FEM Equations $\mathbf{f}^{\text{kin}} = \mathbf{f}^{\text{ext}} - \mathbf{f}^{\text{int}} + \mathbf{f}^{\text{coh}}$

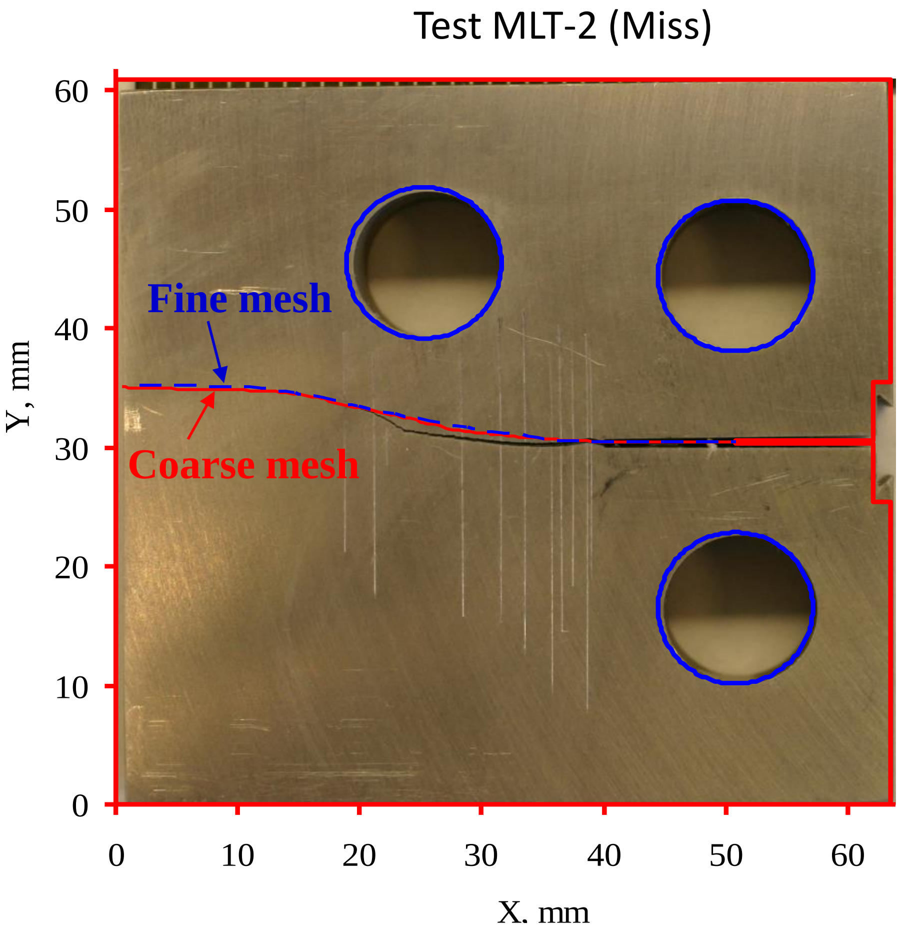
Comparison of Crack Path Predictions (Miss Hole Case)



Mesh size 1mm*1mm

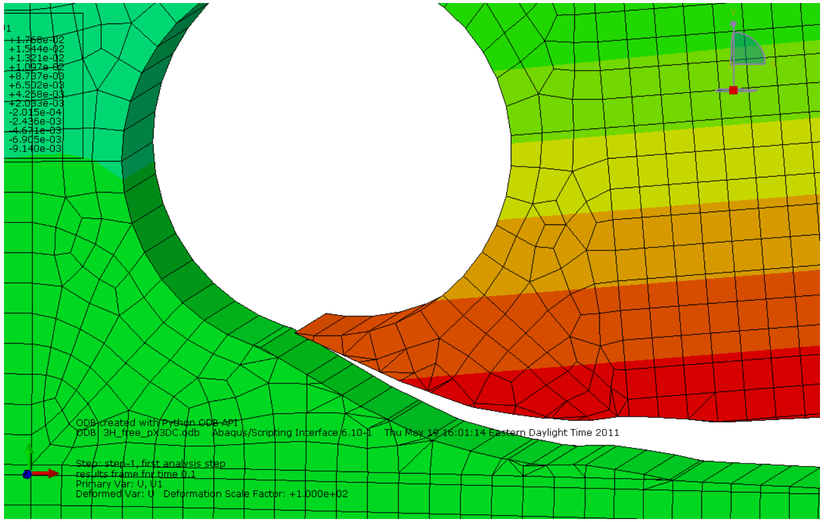


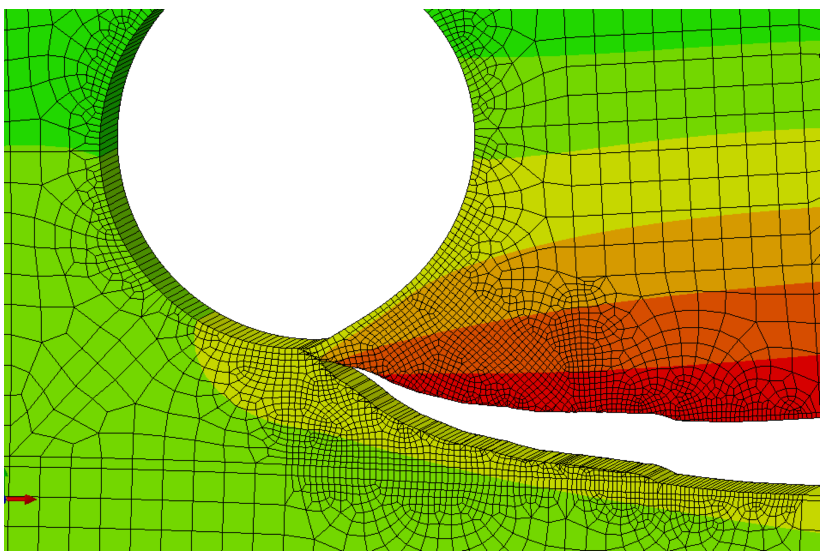
Mesh size 0.5 mm*0.5 mm

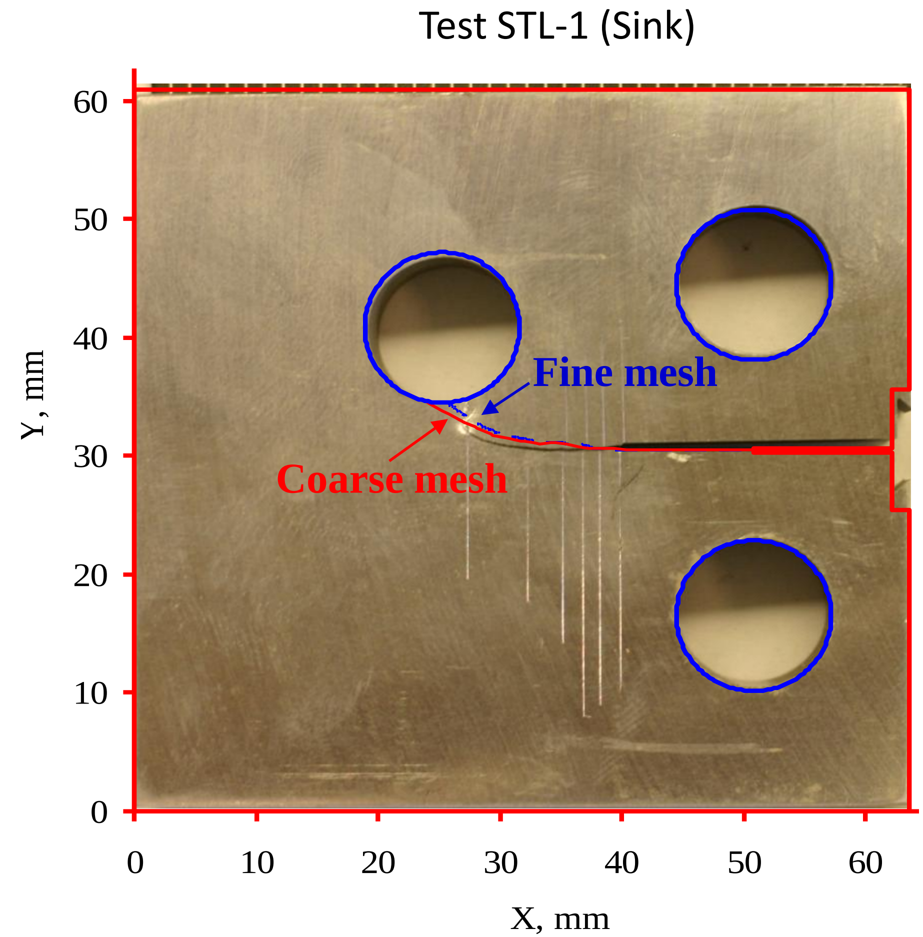


GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

Comparison of Crack Path Predictions (Sink Hole Case)





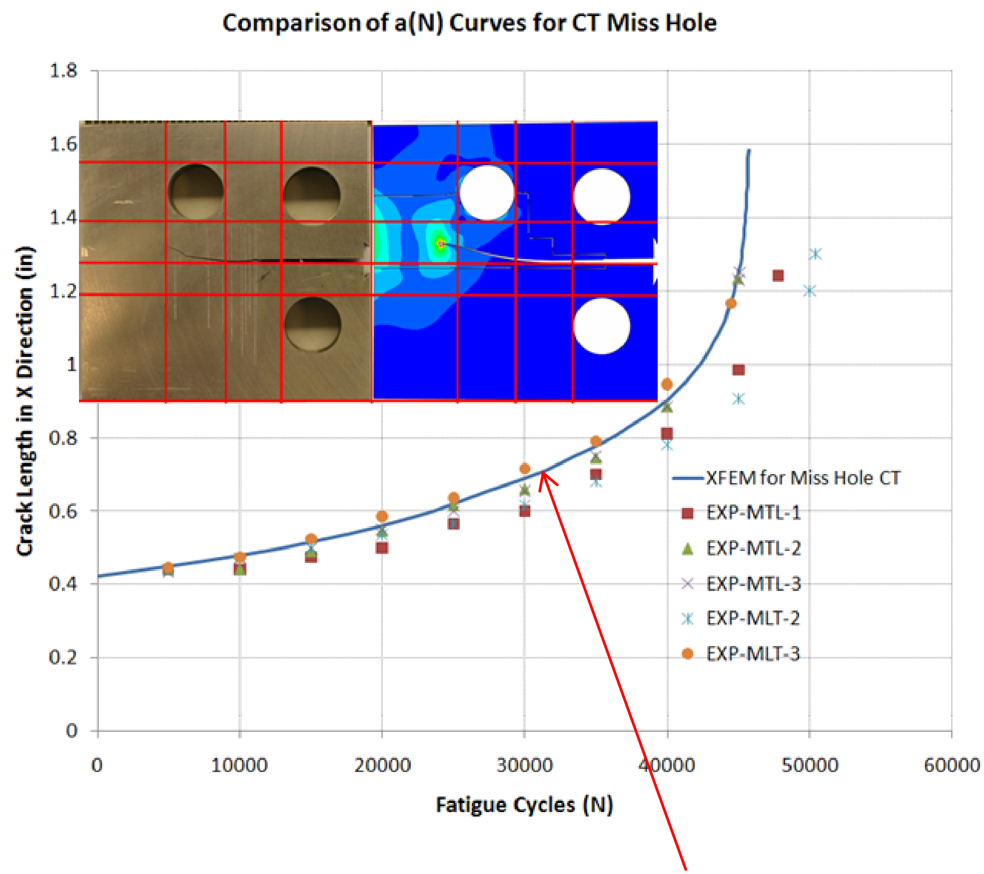


Life Prediction Results on Miss Specimen

Cycles	Crack Length* (in) Side A	Crack Length* (in) Side B	Average Crack Length from Load Line (in)
5,000	0.20	0.18	0.4405
10,000	0.23	0.21	0.4705
15,000	0.24	0.26	0.5005
20,000	0.27	0.3	0.5355
25,000	0.31	0.32	0.5655
30,000	0.36	0.37	0.6155
35,000	0.43	0.43	0.6805
40,000	0.51	0.55	0.7805
45,000	0.64	0.67	0.9055
50,000	0.93	0.97	1.2005
50,389	1.02	1.08	1.3005
*Length from diameter of 3rd hole			

Material: AL-5085-H116
E=1.02E+04 *ksi*
n=0.33
Yield Strength = 31 *ksi*

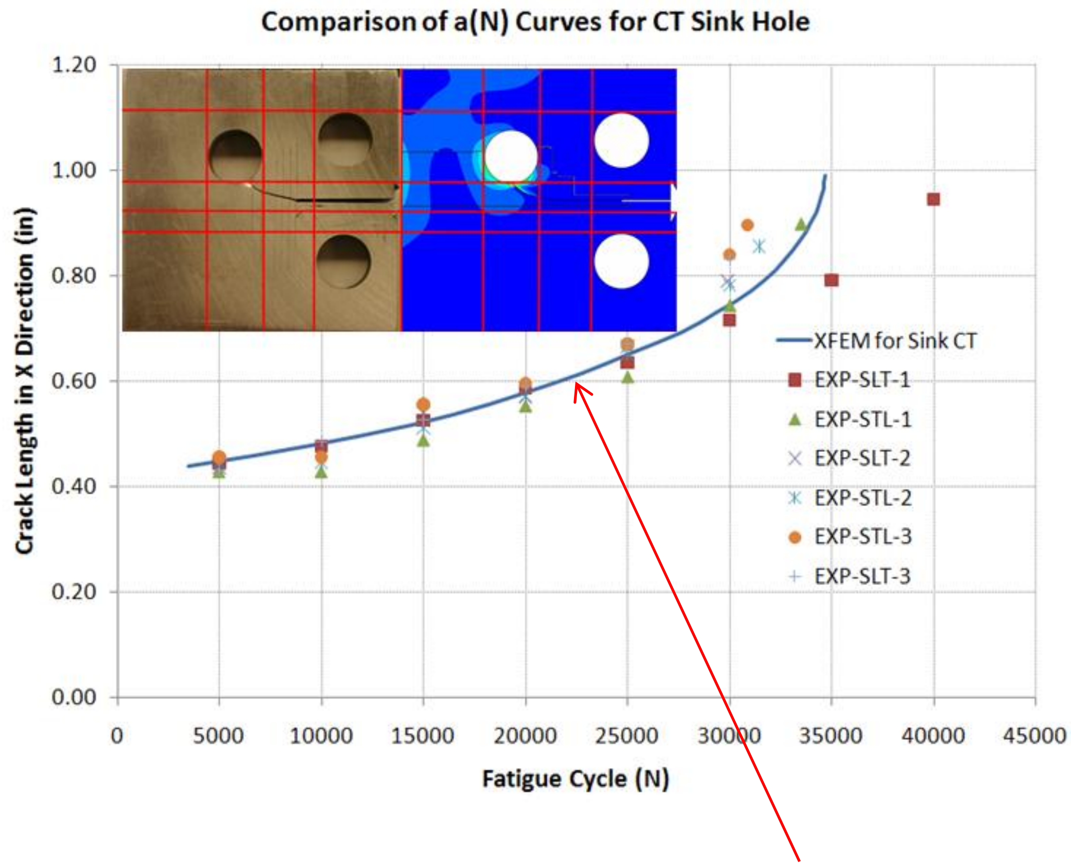
Crack Path and Life Prediction a(N) Using Both TL and LT Test Data for Miss Hole CT Specimen



Using Both TL and LT Test Data for Sink Hole CT Specimen

Life Prediction Results on Sink Specimen

Cycles	Crack Length* (in) Side A	Crack Length* (in) Side B	Average Crack Length from load line (in)
5,000	0.19	0.2	0.446
10,000	0.19	0.2	0.446
15,000	0.25	0.27	0.511
20,000	0.32	0.32	0.571
25,000	0.38	0.42	0.651
30,000	0.51	0.55	0.781
31,440	0.61	0.6	0.856
*Length from diameter of 3rd hole			

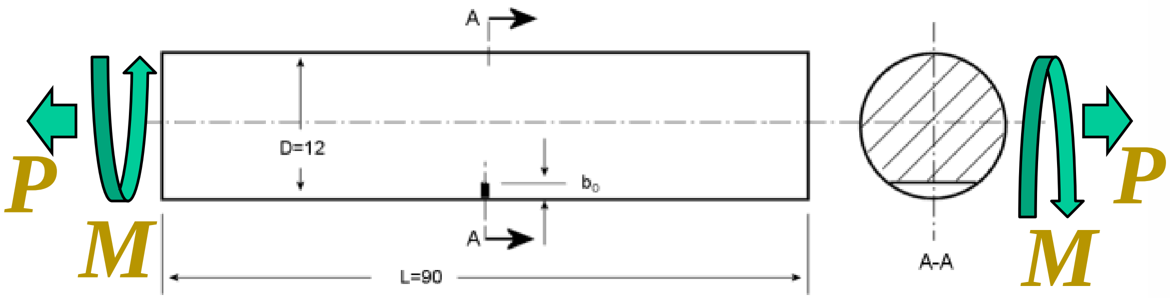


Material: AL-5085-H116
E=1.02E+04 *ksi*
n=0.33
Yield Strength = 31 *ksi*

Using Both TL and LT Test Data for Sink Hole CT Specimen

Crack Path and Life Prediction of a Notched Round Bar under Mixed Loading

Life Prediction for an Initial Straight-Fronted Edge Crack in Elastic Round Bar Under Cyclic Axial (P=25kN) & Constant Torque (M=40Nm) Loading



MATERIAL PROPERTIES (S45 Steel)

tensile yield strength σ_o=635 MPa

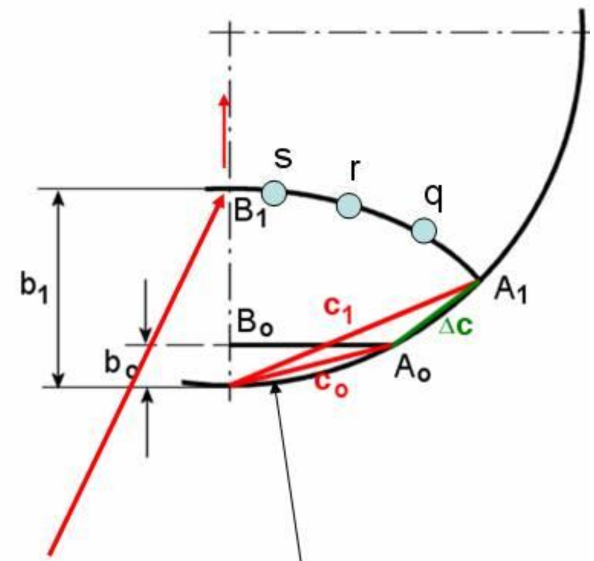
nominal ultimate tensile strength σ_m=776 MPa

true ultimate tensile strength σ_t=2102 MPa

reduction of area ϕ=62.87%

Young's modulus E=205 GPa

true fracture logarithmic strain ε_f=0.99



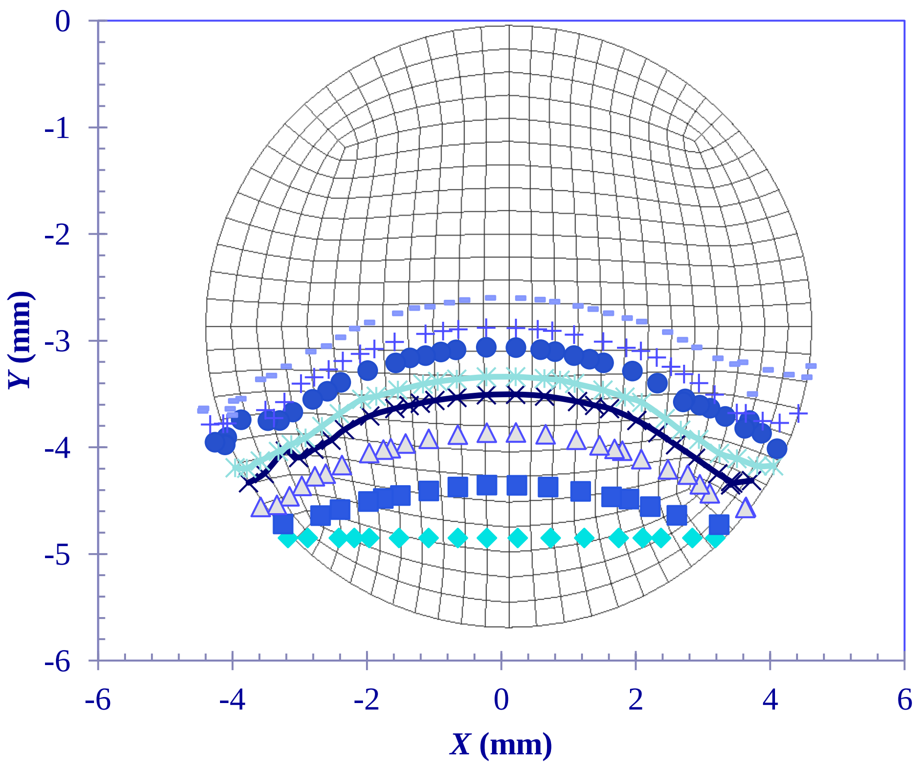
$$\frac{db}{dN} = 1.9037E^{-9}(\Delta K)^{3.256}$$

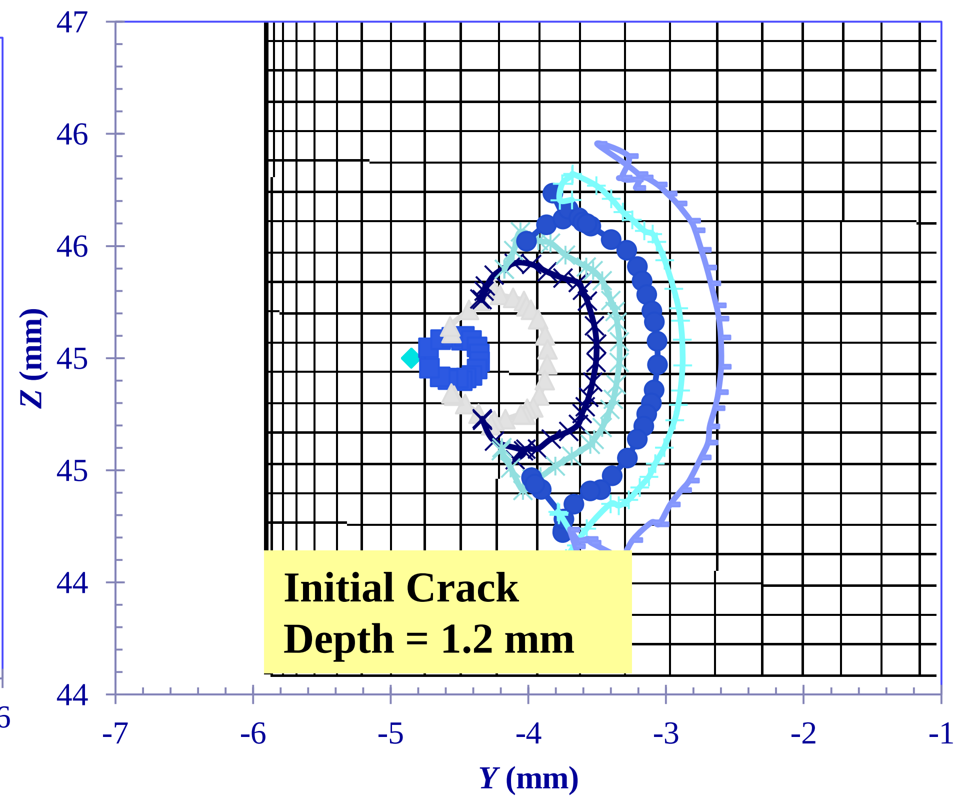
FATIGUE PROPERTIES

$$\frac{dc}{dN} = 1.2082E^{-9}(\Delta K)^{3.293}$$

- Yang FP, Kuang ZB, Shlyannikov VN. Fatigue crack growth for straight-fronted edge crack in a round bar. Int J Fat. 28:431-437, 2006.
- Yang FP, Kuang ZB. Stress intensity factors for surface fatigue crack in a round bar under cyclic axial loading. Fat Fract Eng Mat Struct. 30: 621-628, 2007.

Projection of Crack Front for the Non Planar Crack Growth





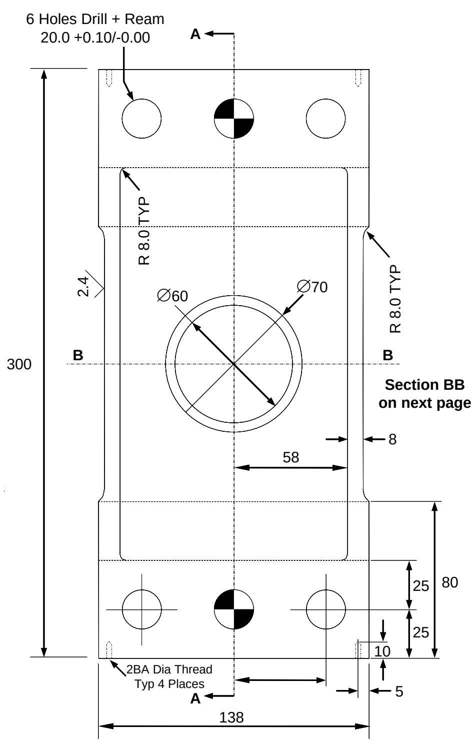
Predictions of Life of Rod Specimen and Its Comparison with Test Data

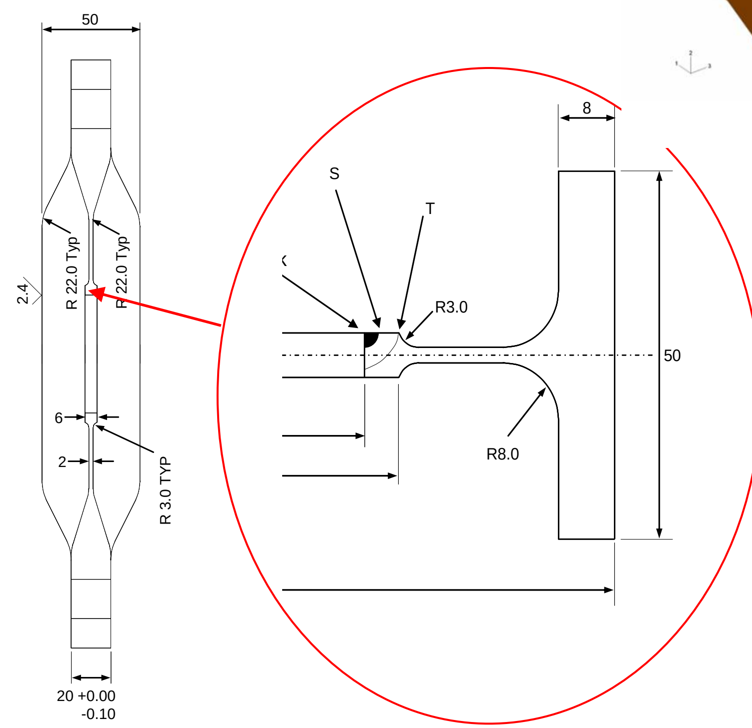
Case number	Diameter D, [mm]	Initial depth b0, [mm]	Max force F, [kN]	Stress ratio $\sigma_{min}/\sigma_{max}$	Fracture cycles N_f, predicted by XFA3D	Actual fracture cycles N_f, from experiments	Actual diameter D, [mm]	Actual initial depth b0, [mm]
1	12.00	1.00	22	0.1	542,400	778,542	11.94	1.004
2	-	-	25	-	348,933	323,627	11.92	0.918
3	-	-	25	-	348,933	378,216	12.00	0.906
4	-	-	28	-	234,446	186,689	11.94	0.958
5	-	2.00	17	-	386,529	380,934	11.94	1.900
6	-	-	20	-	220,528	184,103	11.96	1.890
7	-	-	25	-	102,990	72,521	11.98	1.916
8	-	-	28	-	70,007	59,025	11.98	1.914
9	-	3.00	12	-	472,727	1,064,689	11.88	2.900
10	-	-	13	-	357,730	344,836	11.88	2.860
11	-	-	15	-	217,366	141,303	11.96	2.962
12	-	-	17	-	141,660	112,488	11.88	2.900
1	**-**	**1.20**	**25 (Toq=40Nm)**	**-**	**113,299**	**92,362**	**11.98**	**1.189**

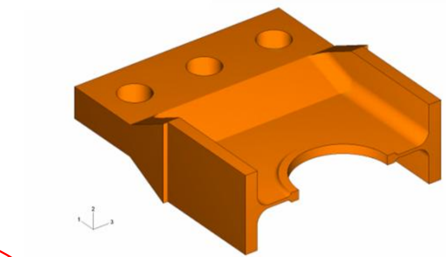
GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

Life Prediction of Fatigue Crack Growth under Variable Loading

Example: Round-Robin Fatigue Life Prediction under Spectrum Loading, J. C. NEWMAN Jr., P. E. IRVING, J. LIN and D. D. LE, *Crack growth predictions in a complex helicopter component under spectrum loading, Fatigue Fract Engng Mater Struct 29, 949–958.*

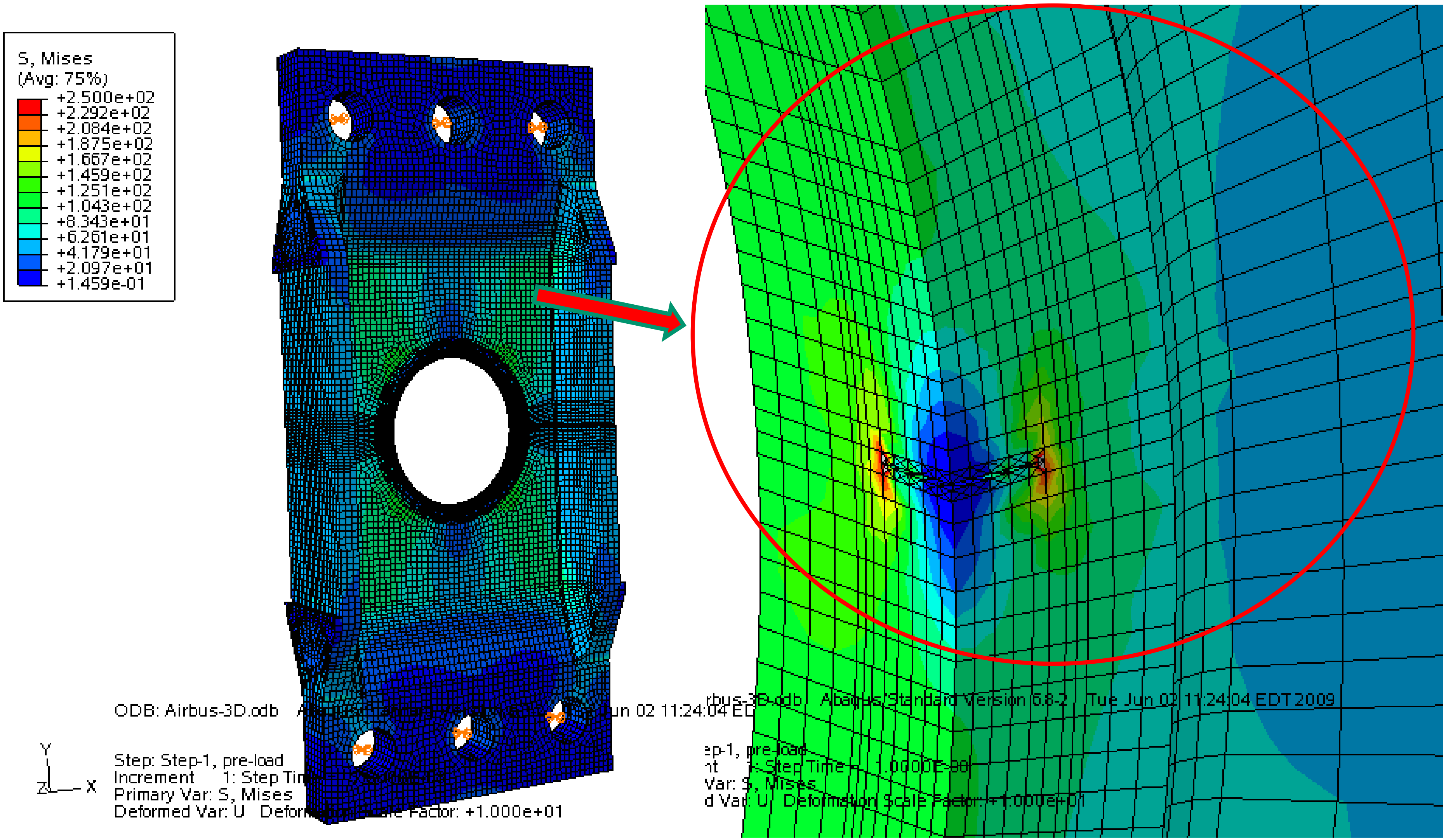






GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

Initial Crack under Nominal Load (Maximum Far-Field Stress 130MPa at Raised Hole Flange)



Movie Showing Crack Growth

Movie files: Airbus-3D-50mm-LSET1.wmv
Airbus-3D-50mm.wmv

Evolution of Crack Front

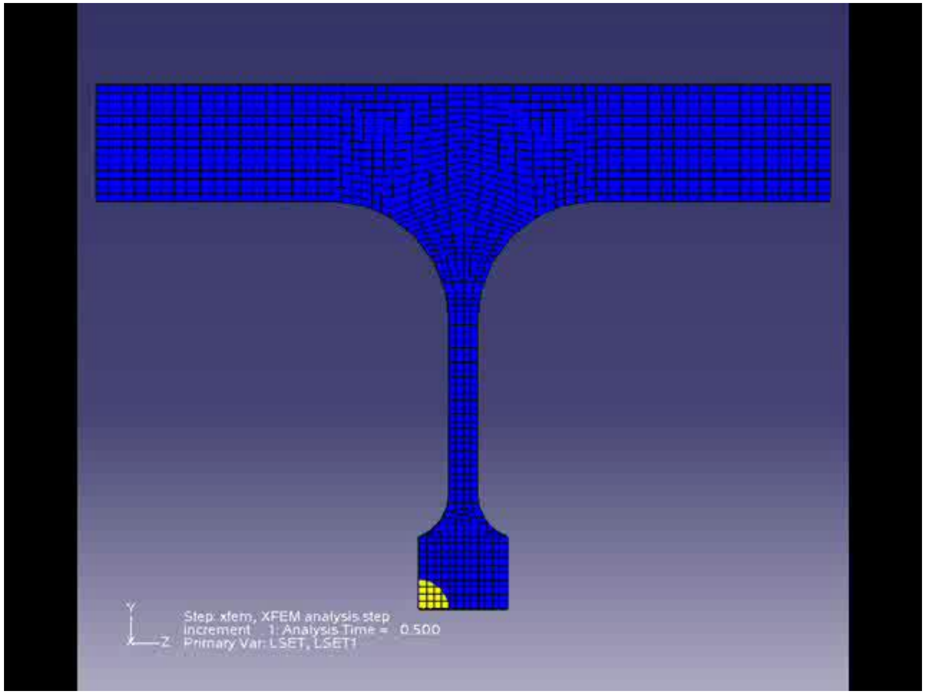
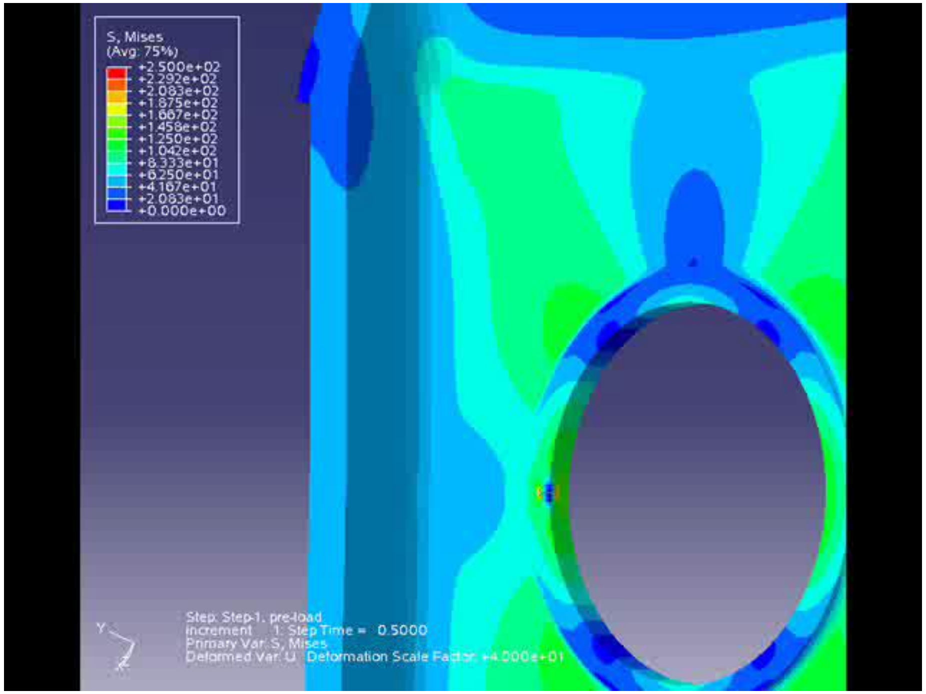
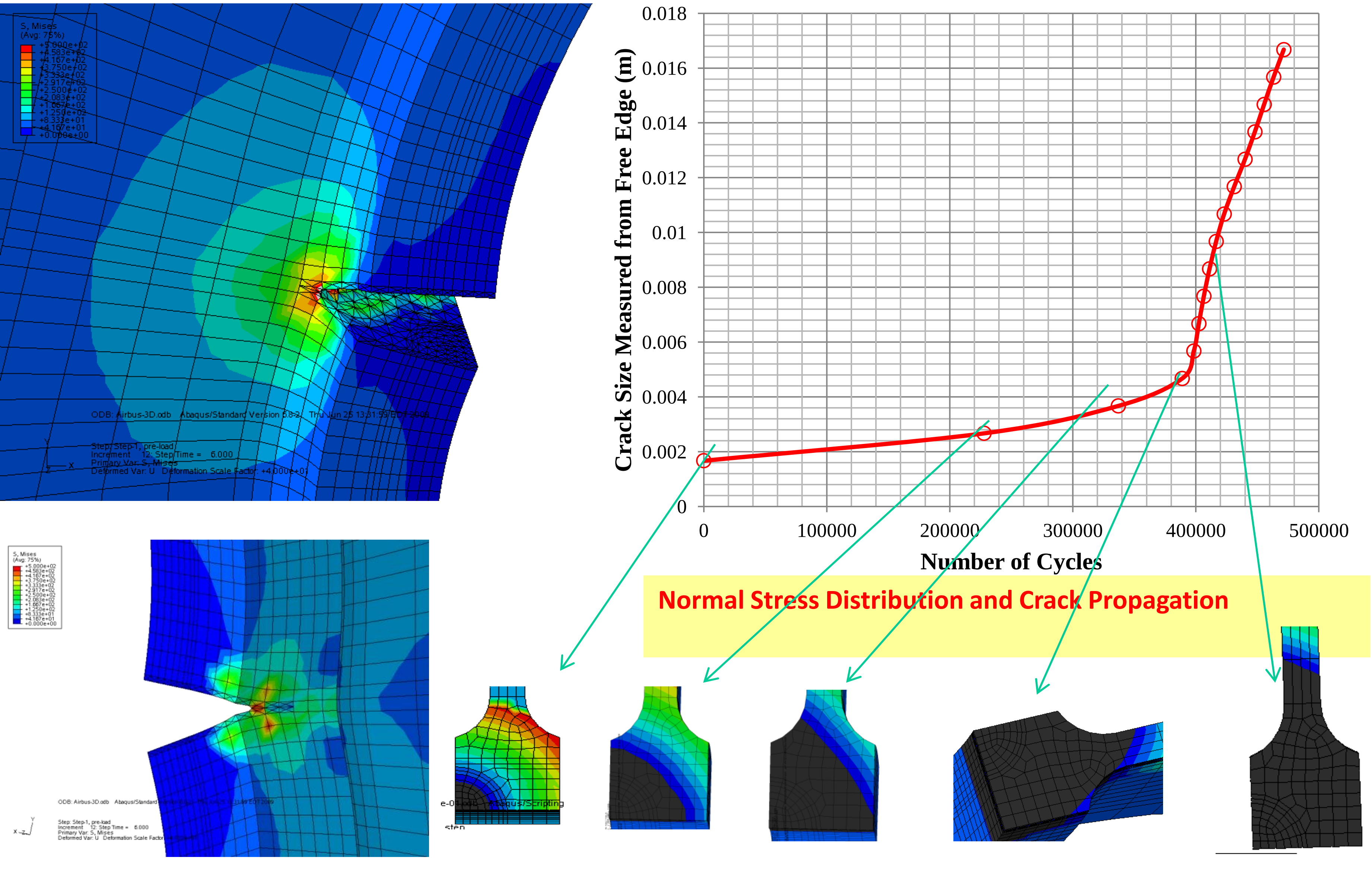


Illustration of Crack Propagation

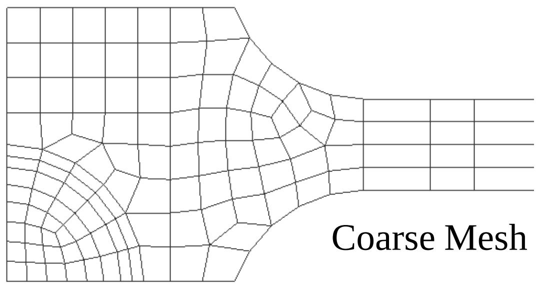


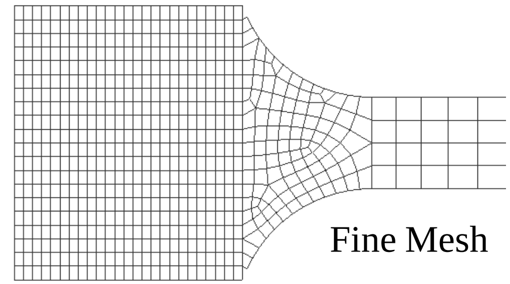
Crack Length and Life Prediction of a(N)

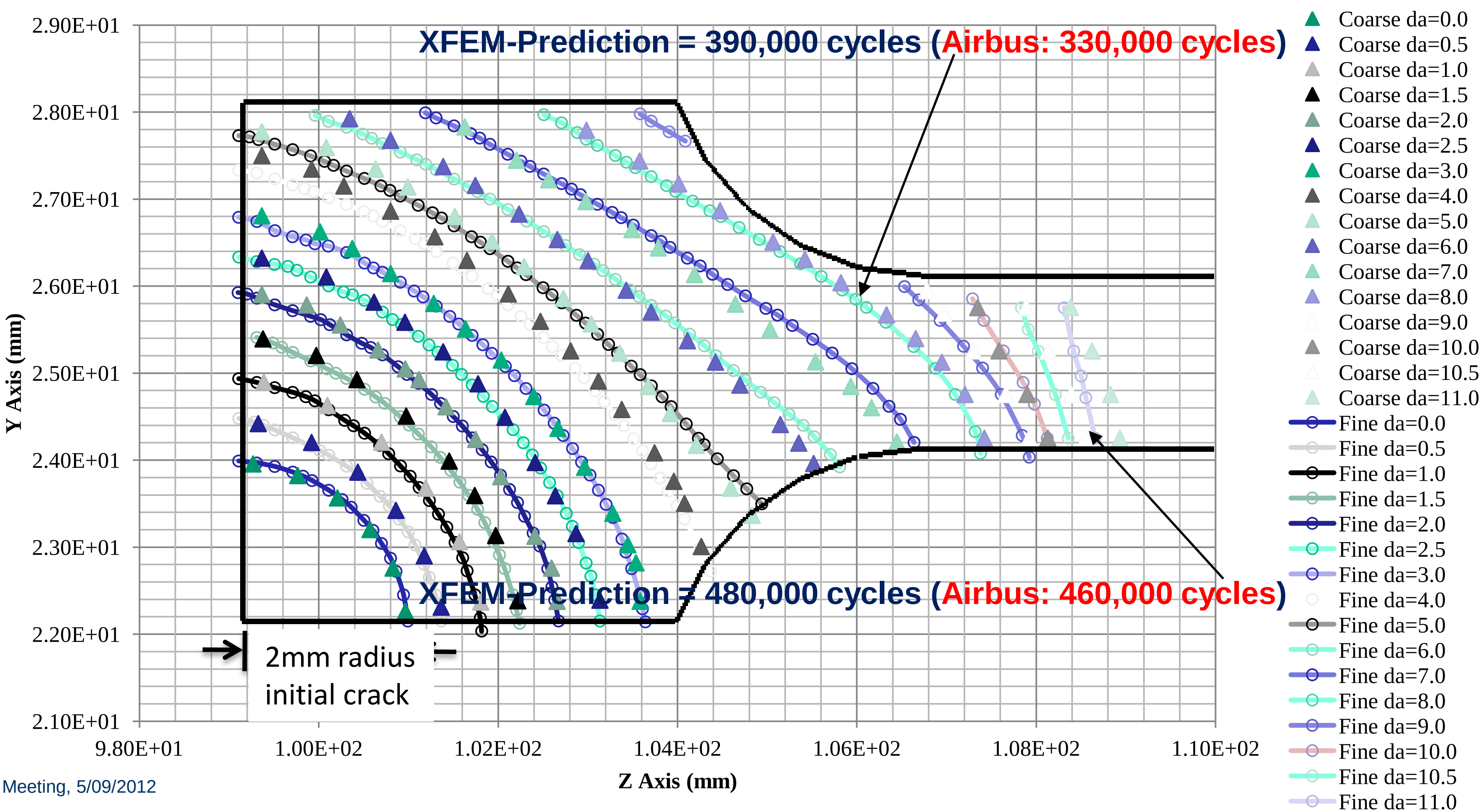


GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

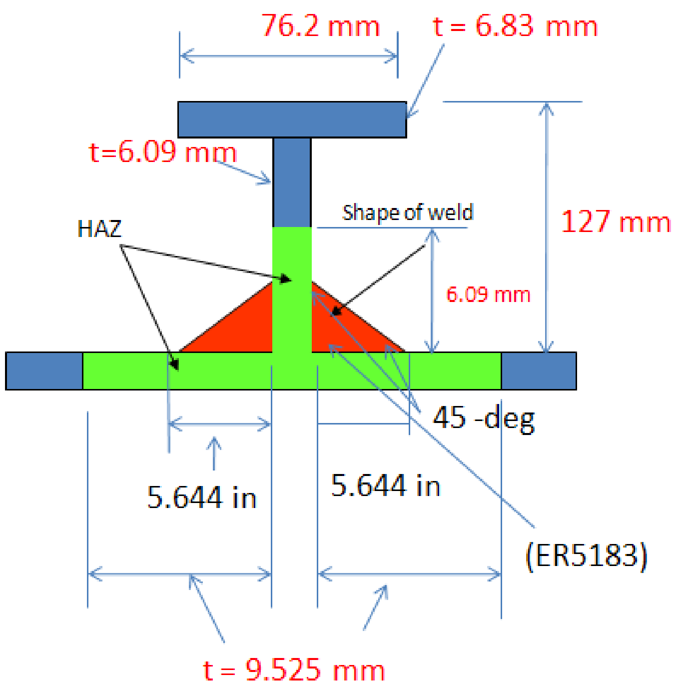
Comparison of Crack Growth Profile Using Different Mesh Designs







XFA Application for a Single Stiffened Panel with an Edge Crack



Material: AL5083-H116

E=70.3 MPa = 10.2 msi
Yield Strength = 27.5 ksi

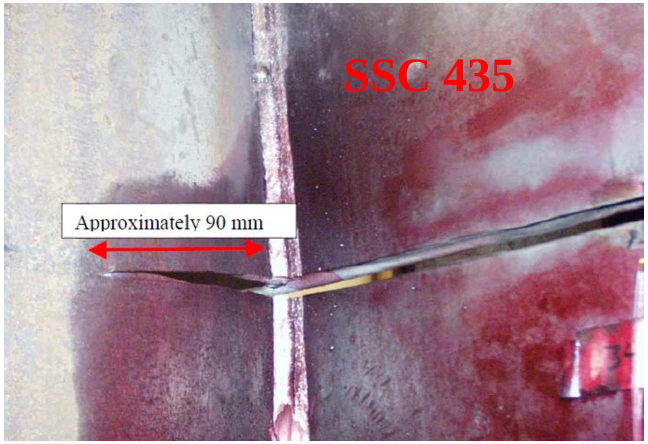
Weld Material: ER5183

E=70.3 MPa=10.2 msi
Yield Strength = 19 ksi

HAZ Material = Weld Material

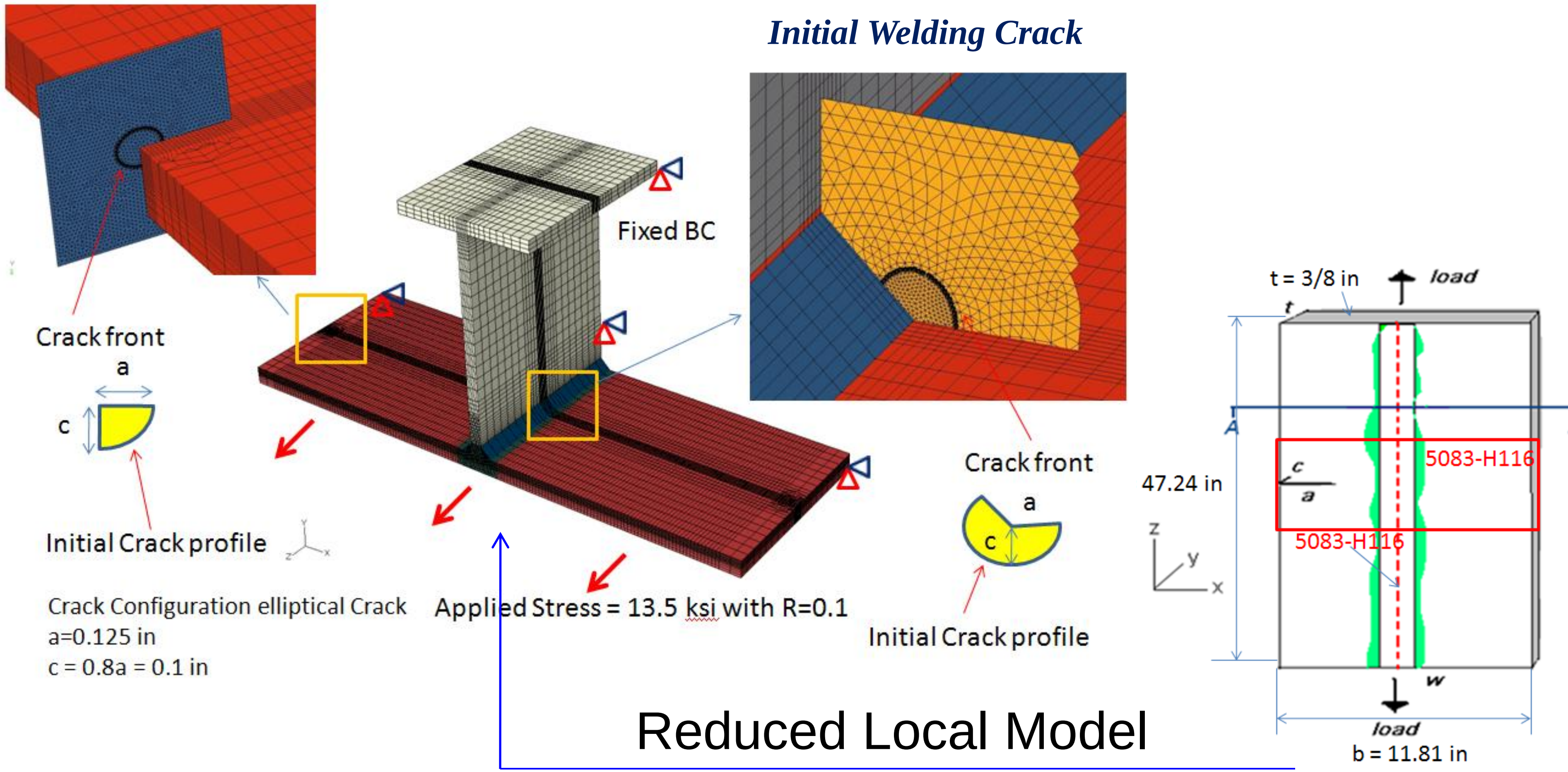
Fatigue Properties
5083-H116: *C=3.2976e-09, n=3.4073*
Weld/HAZ: *C=3.8958e-08, n=2.6057*

ΔK: ksi in$^{1/2}$; da/dN: in/cycle



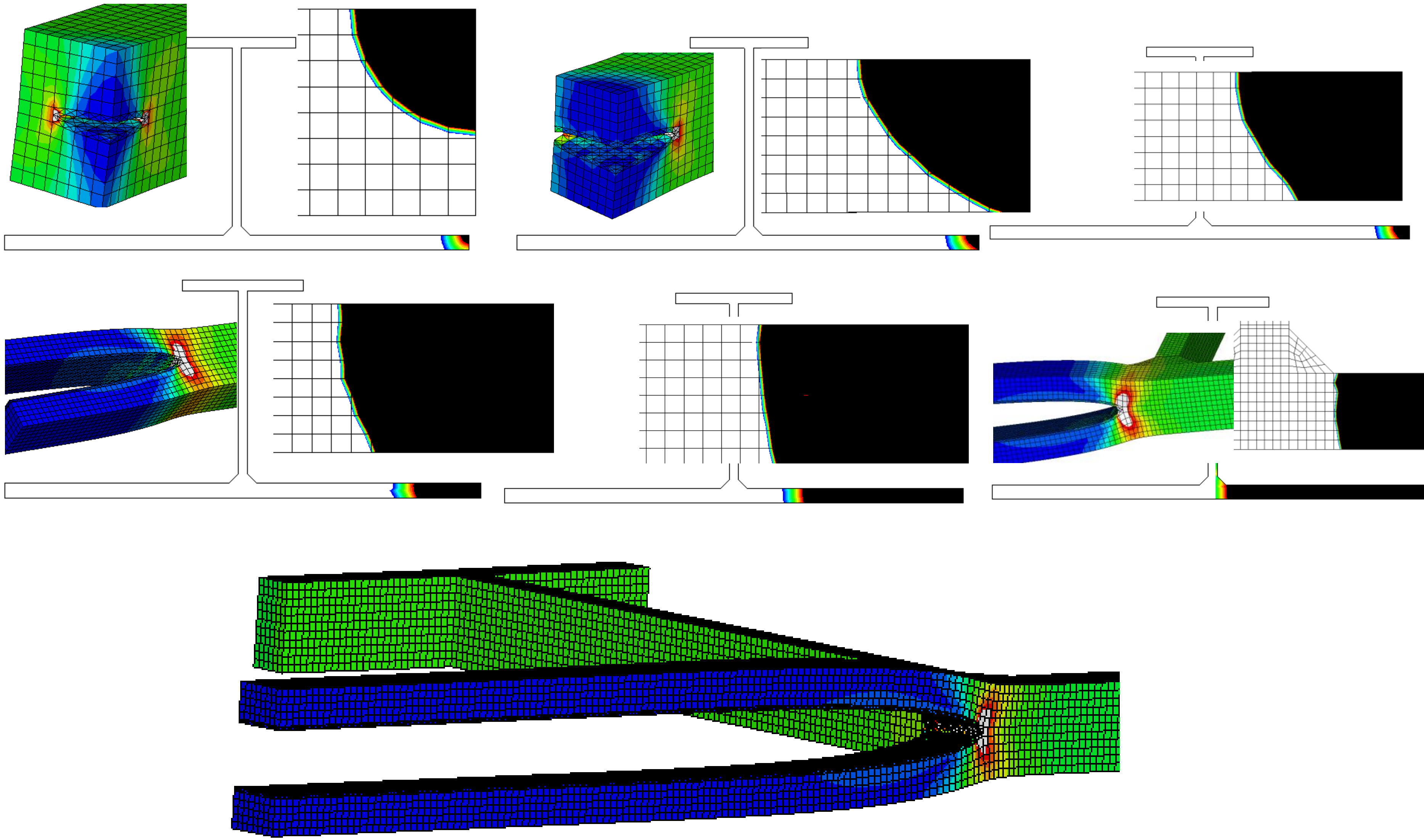
Two Initial Crack Configurations

Initial Edge Crack



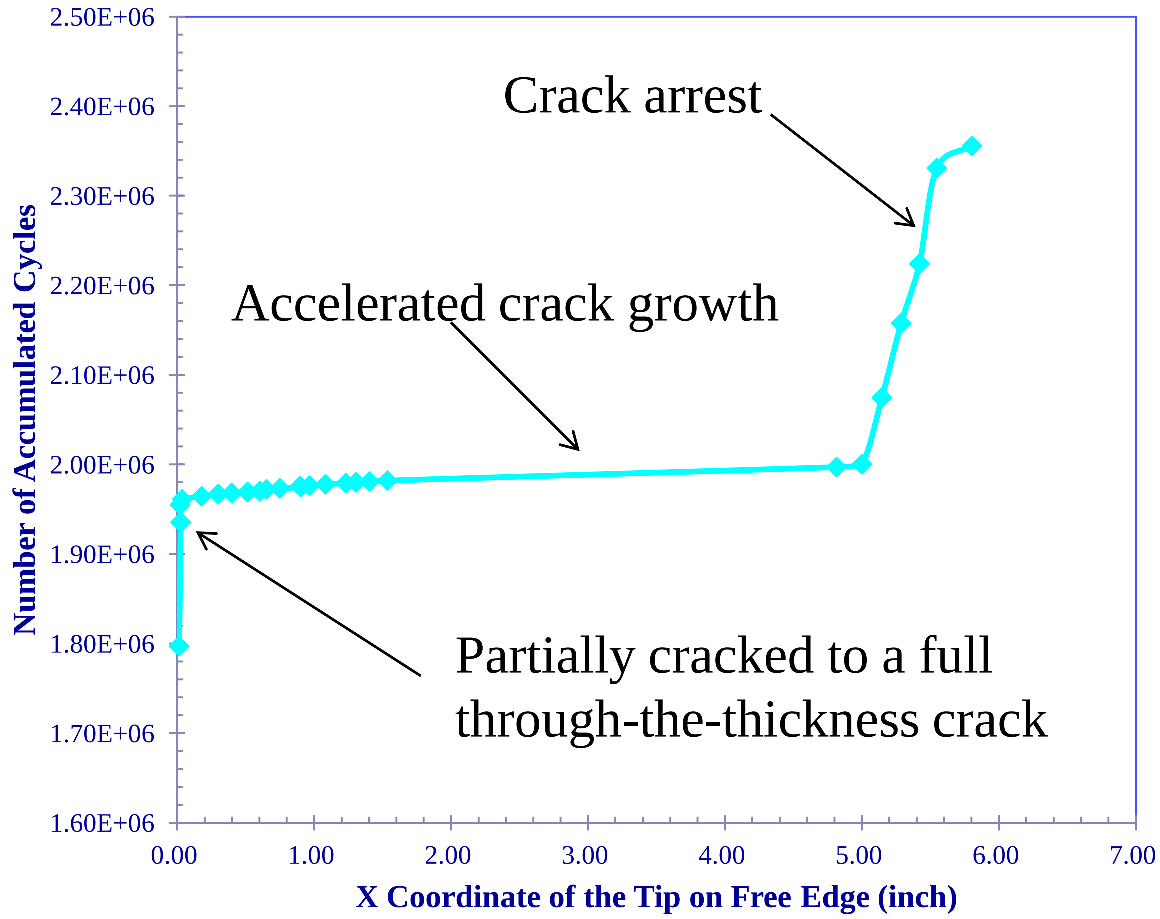
GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

Snapshots of Crack Growth and Its Moving Front(Edge Crack)



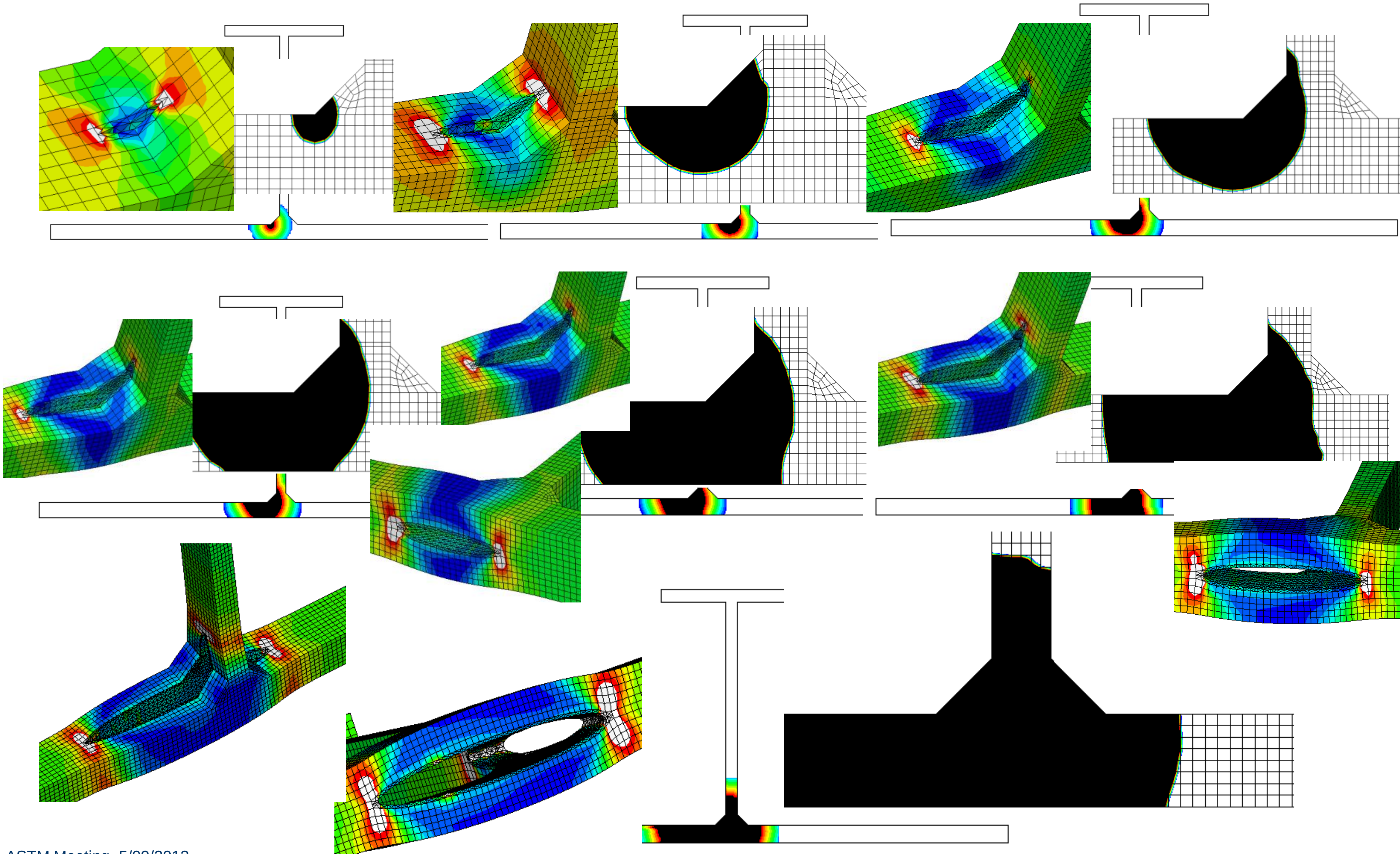
GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

Display of a(N) Curve for an Edge Cracked Single Stiffener Plate

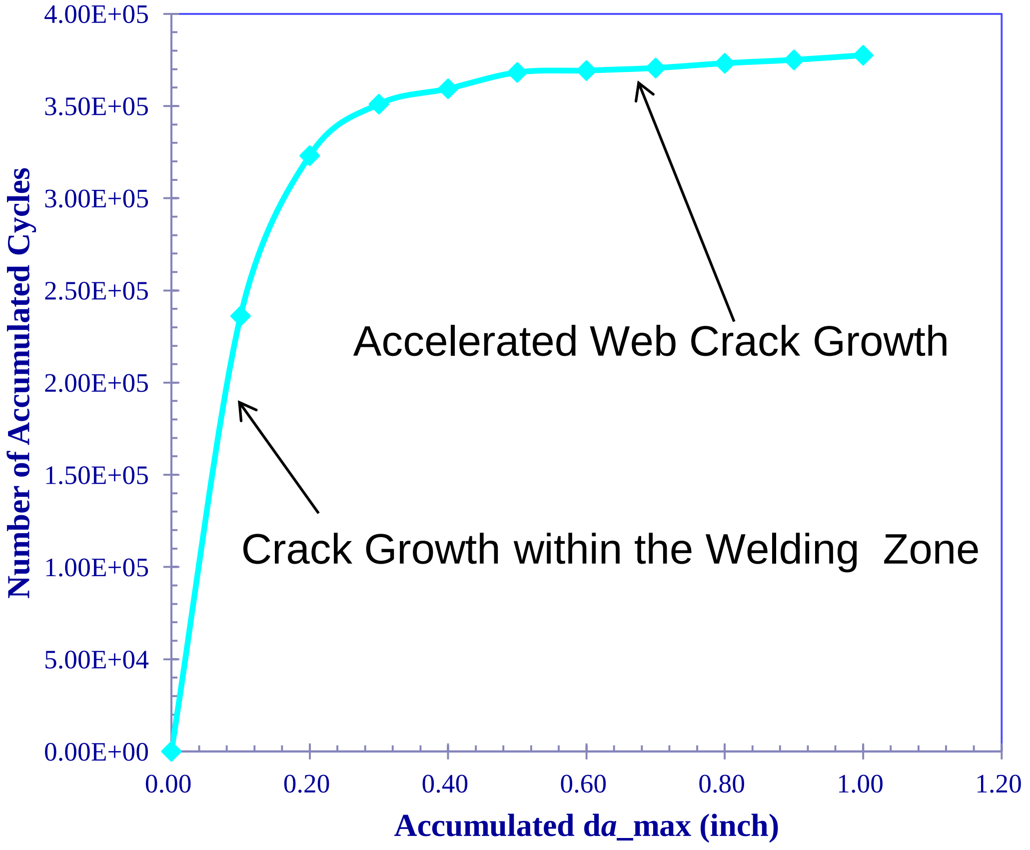


GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

Snapshots on Crack Growth and Its Moving Front

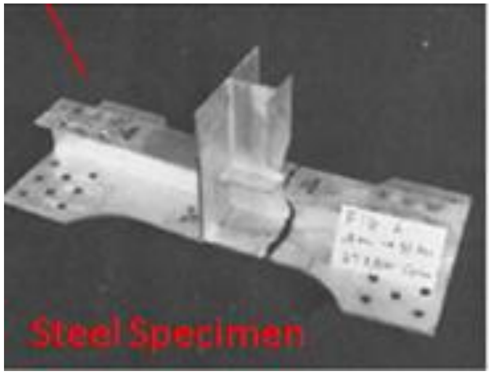


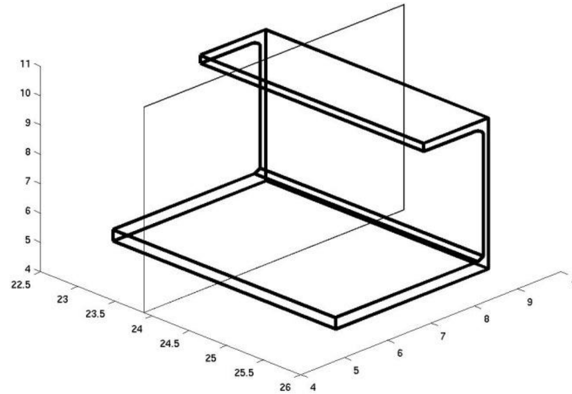
Display of a(N) Curve for a Single Stiffener Plate with a Welding Toe Crack

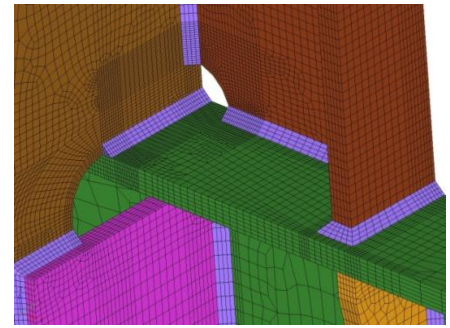


GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

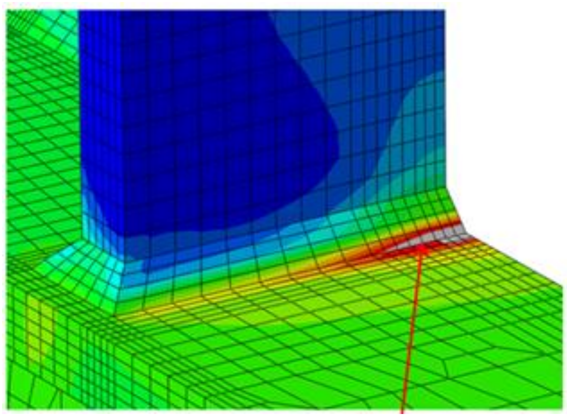
NSWCCD Testing Specimen

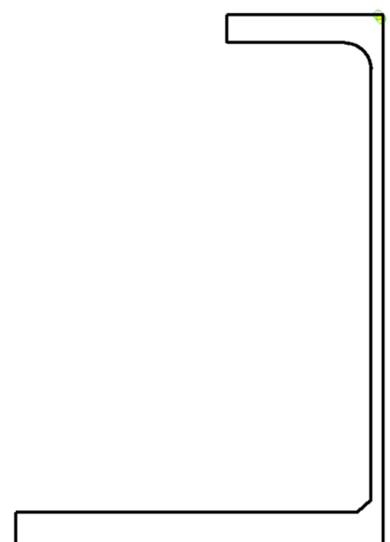






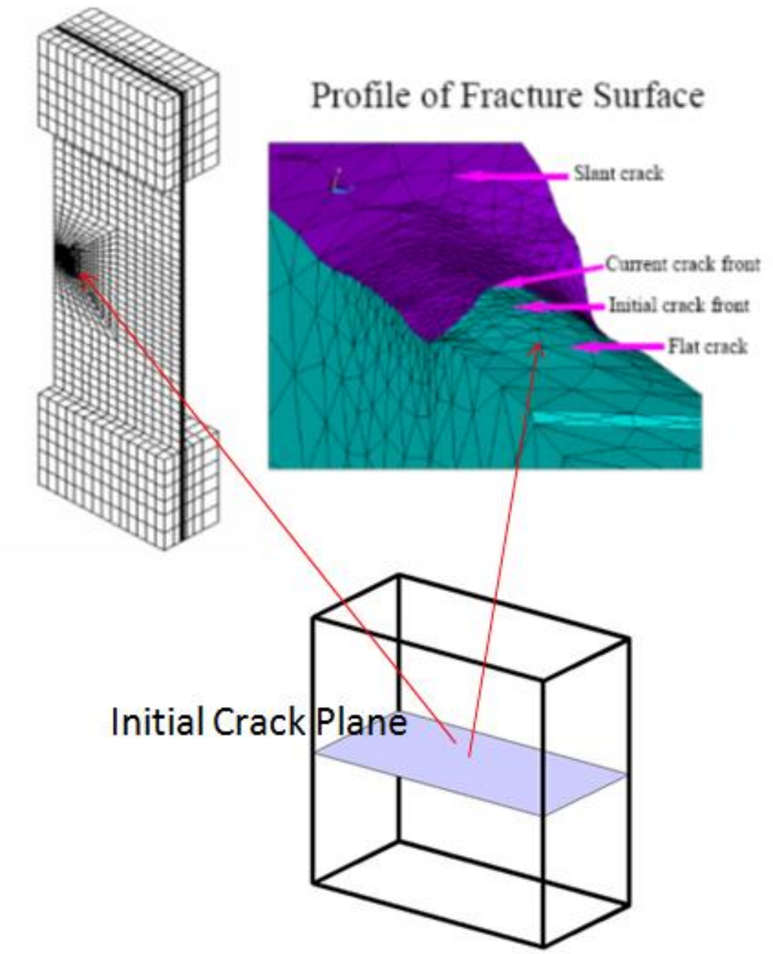
Crack Propagation Movie



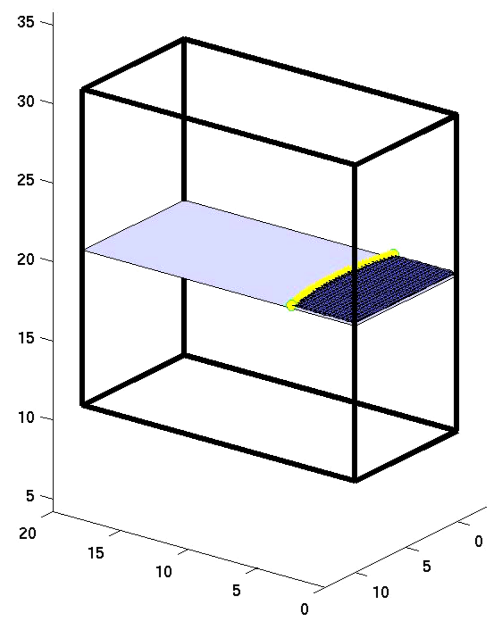


GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

Nonplanar Crack Validation

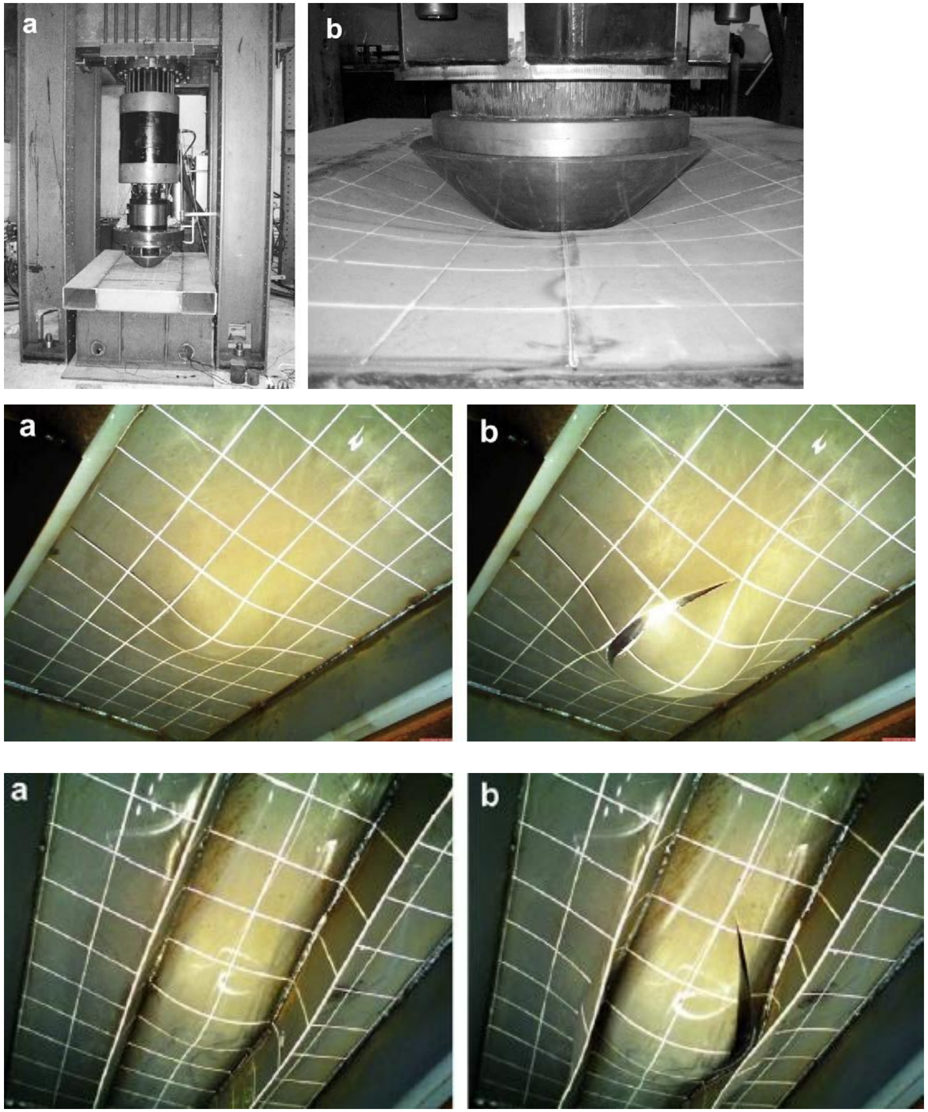


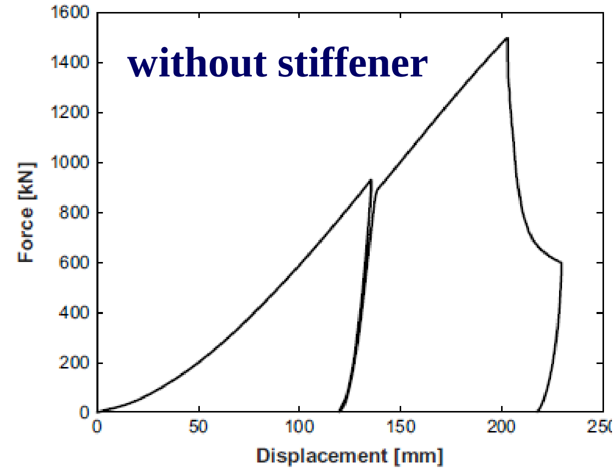
(Non-Planar Crack Growth Movie)

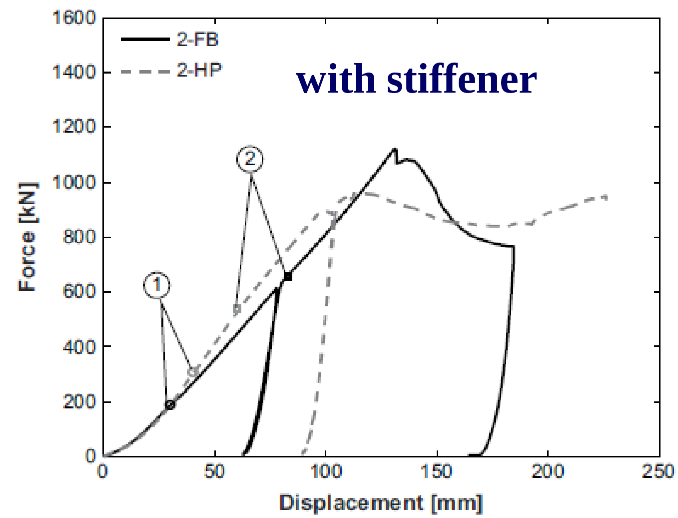


GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

Validation of XSHELL's Package Using Indentation Test Data







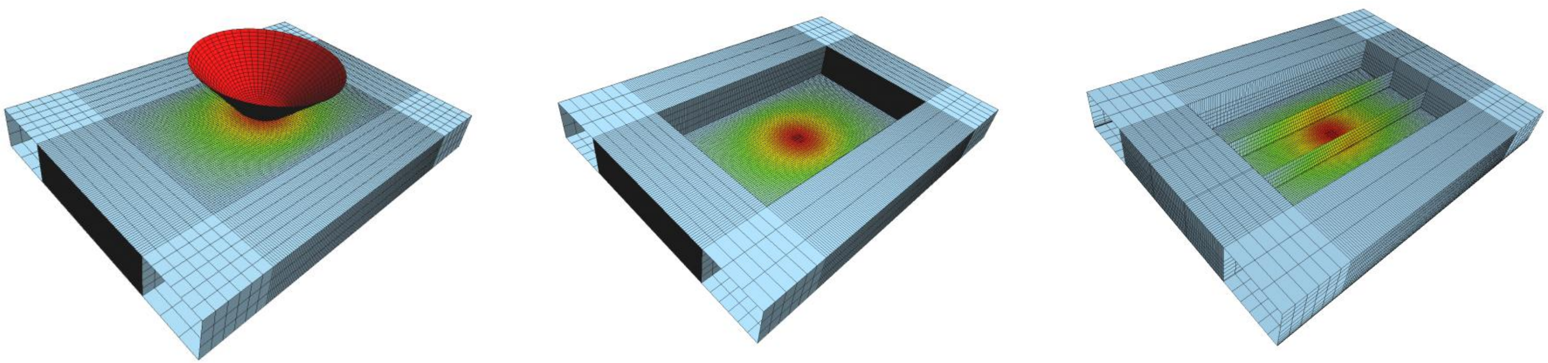
Hagbart S. Alsos, and Jogen Amdahl (2009a). On the resistance to penetration of stiffened plates, Part I – Experiments, *International Journal of Impact Engineering*, 36: 799-807.
Hagbart S. Alsos, and Jogen Amdahl (2009b). On the resistance to penetration of stiffened plates, Part II – Numerical analysis, *International Journal of Impact Engineering*, 36: 875-887.

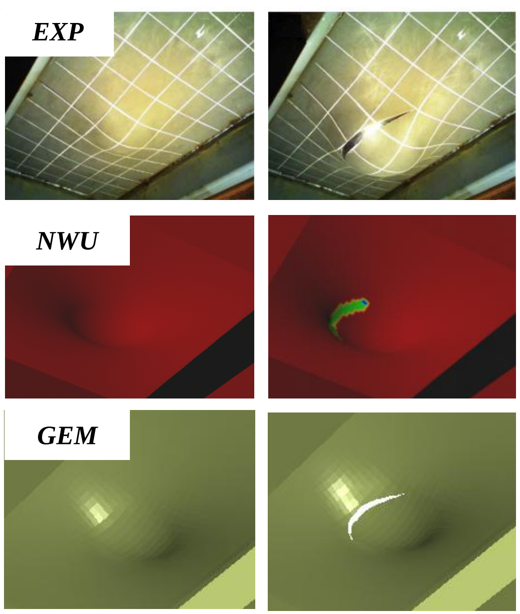
GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

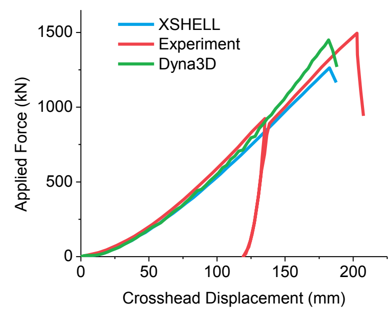
Summary of XSHELL Predictions for Unstiffened and Stiffened and Panels

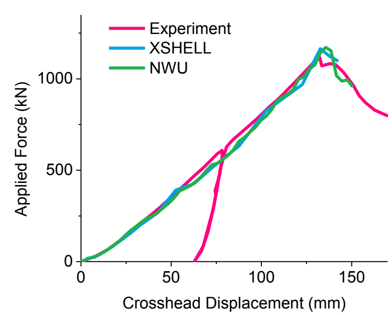
Grounding without Stiffener

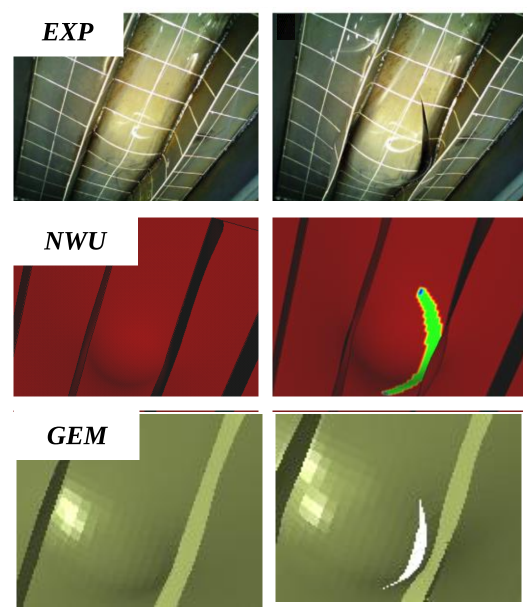
Grounding with Stiffener







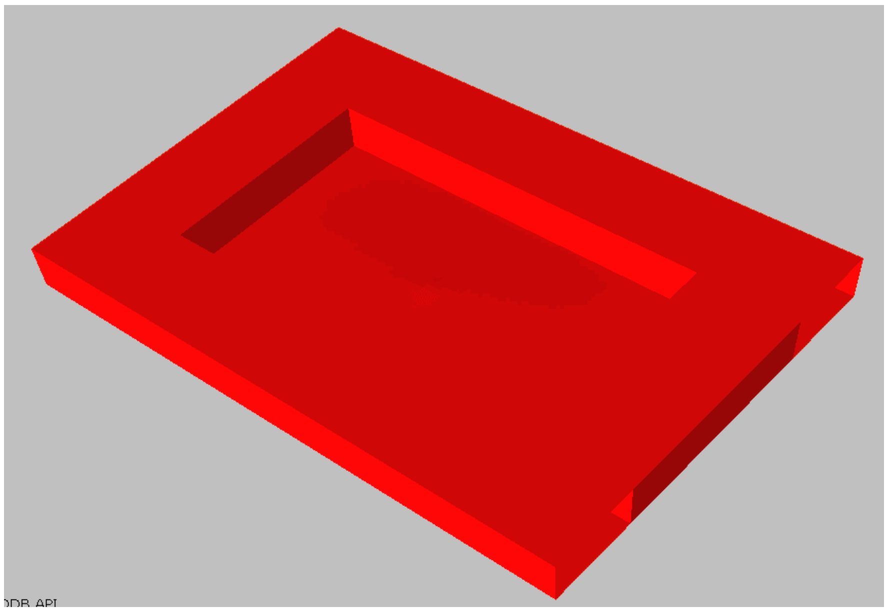




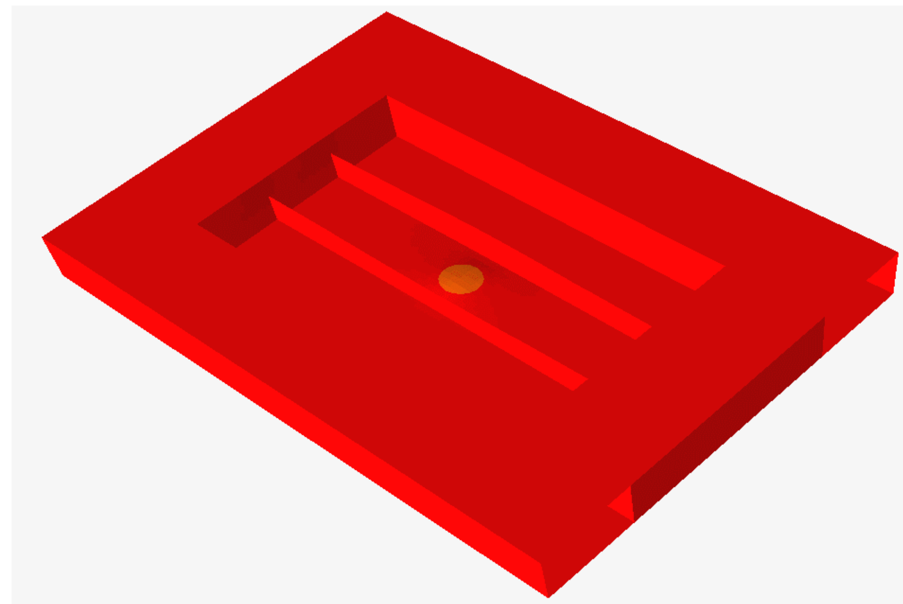
GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

Crack Propagation Movies

Unstiffened Panel



Stiffened Panel

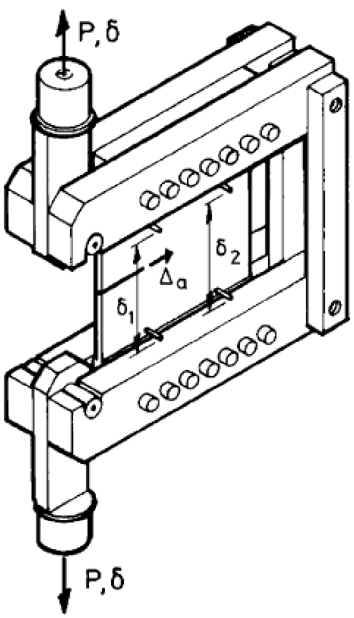


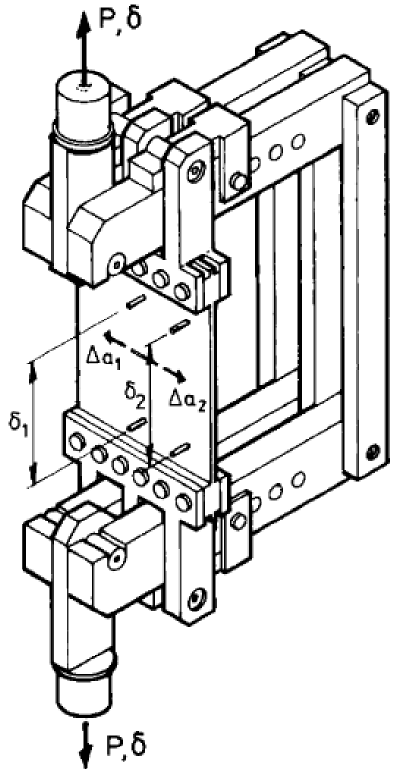
GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

Ductile Crack Growth in Large-Scale Shell under Mode I Loading (XSHELL Verification)

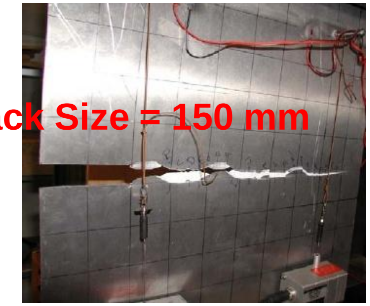
- Edge and Centre Cracked Specimens

Test Setup





580 x 820
Al 5083-H116



Initial Crack Size = 150 mm

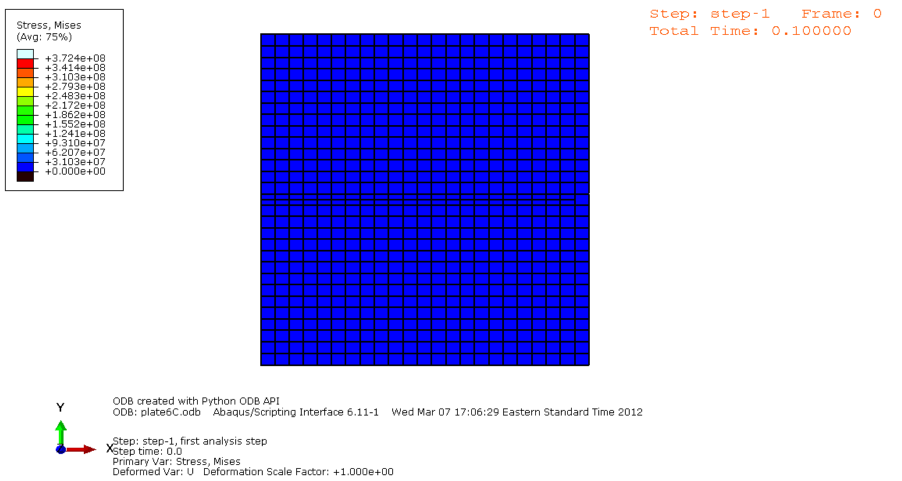
806 x 500
Normal Steel (NS)

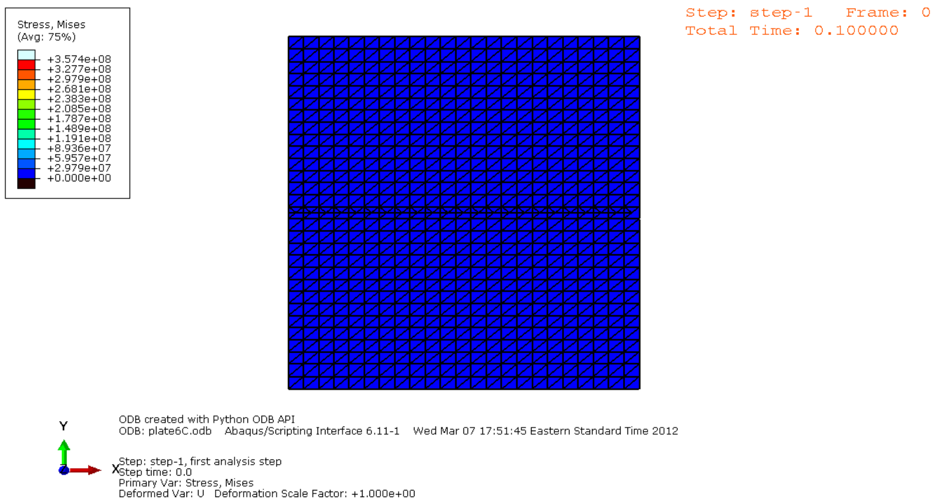
Initial Crack Size = 100 mm

GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

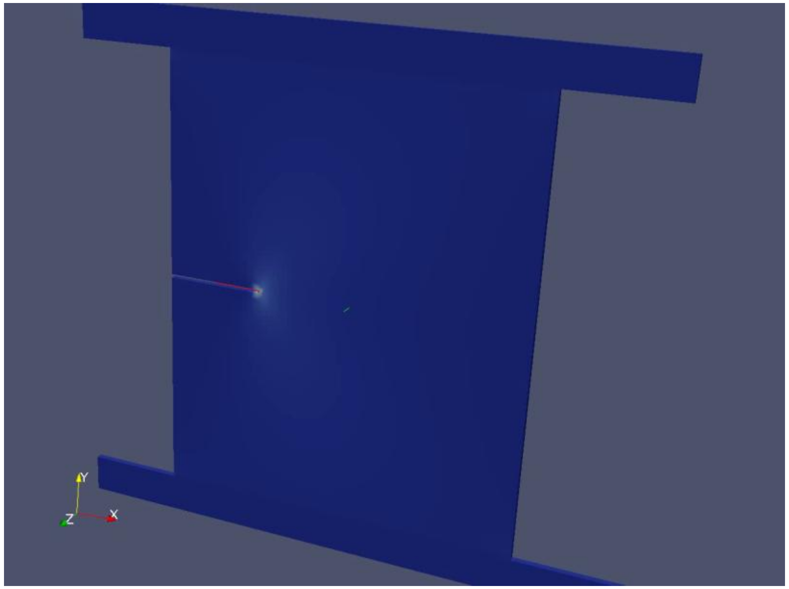
Crack Growth Movies (XSHELL vs. WARP3D)

XSHELL



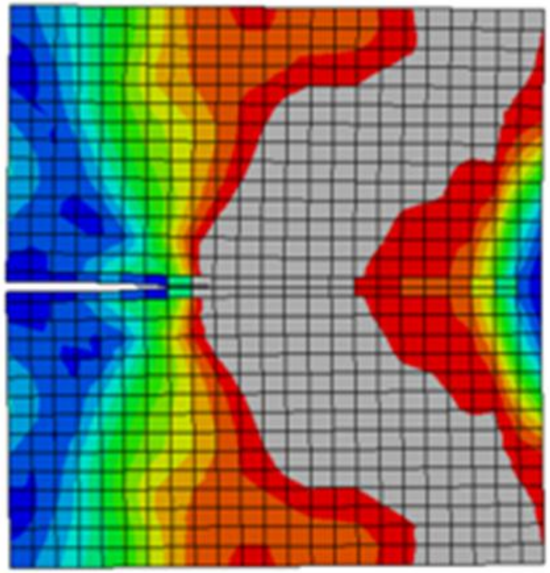


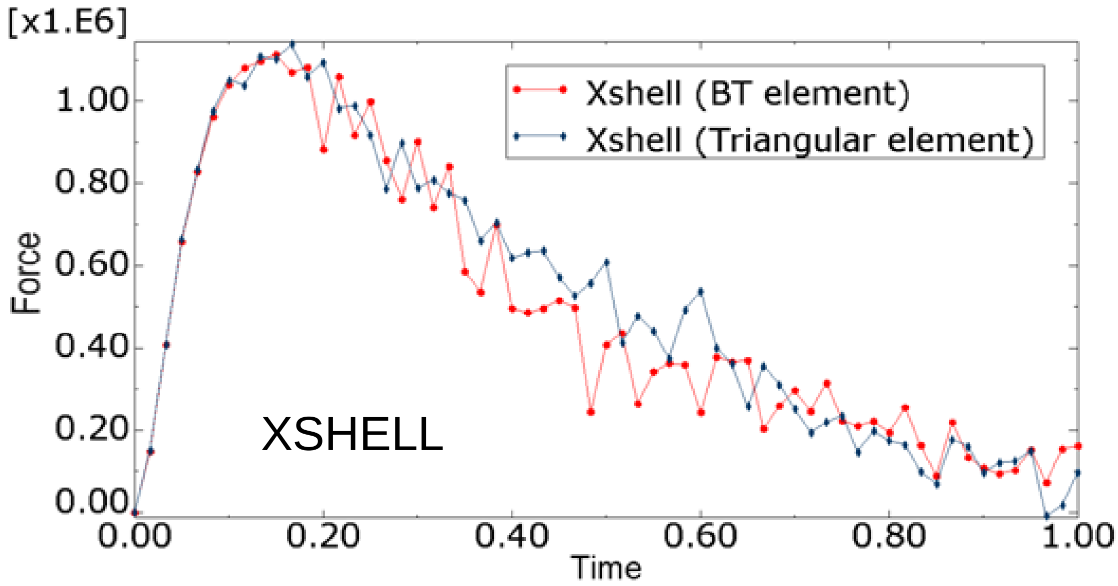
WARP3D

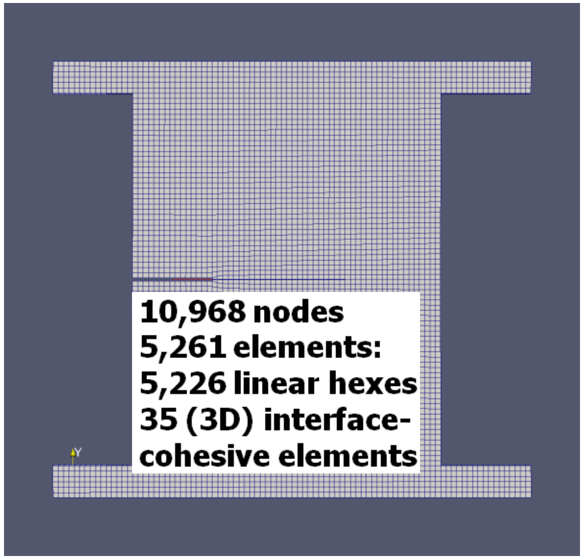


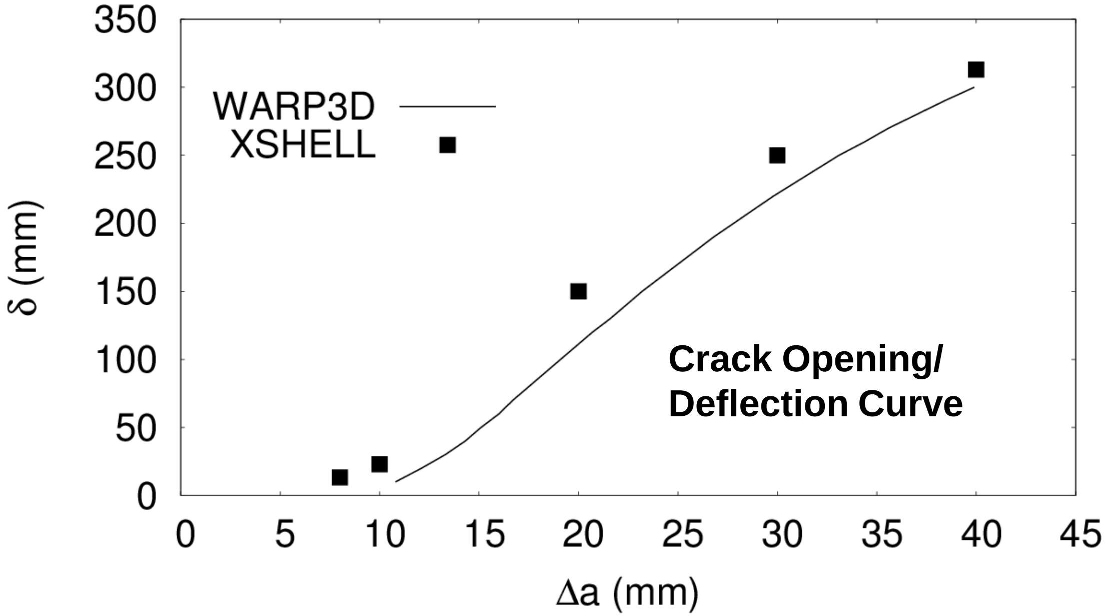
Comparison of Force/Deflection Curves

of Elements = 667



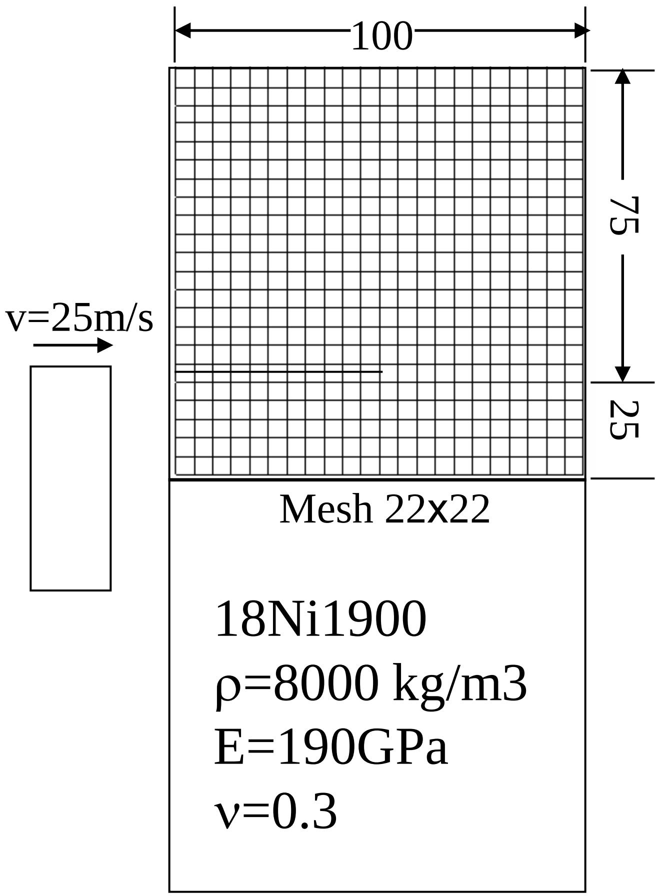


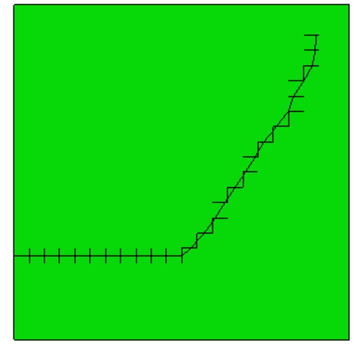


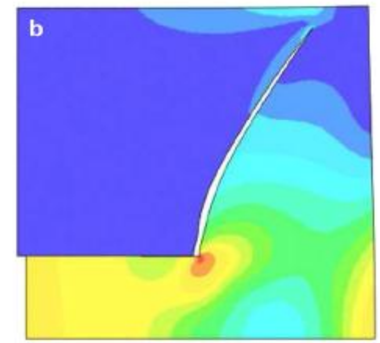


GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

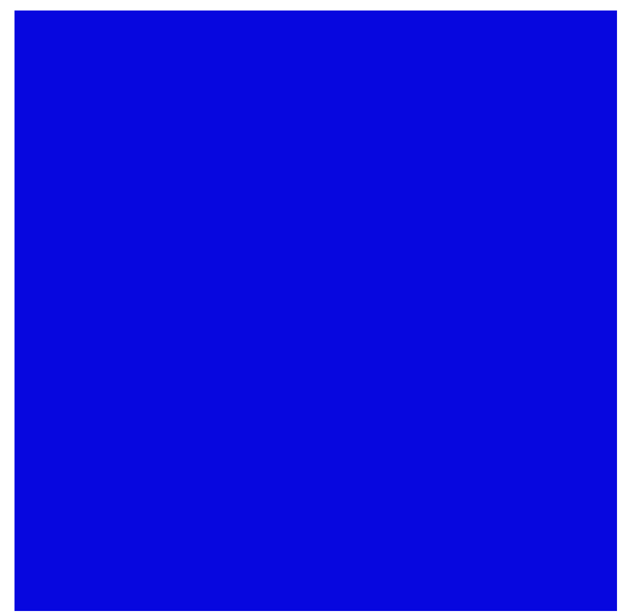
Kalthoff Impact Test







S. Wang*, H. Liu, I J Impact Eng, 37 (2010) 783–791



GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

Summary and Future Plan

- High fidelity, add-on software toolkit to work with commercial, off-the-shelf Abaqus and Abaqus CAE for
  - Static and fatigue failure prediction using 3D solid element via Abaqus' implicit solver (XFA3D)
  - Dynamic crack path and load-deflection prediction using shell element via Abaqus explicit solver (XSHELL)
- Use of two mesh independent formulations for kinematic representation of a cracked body
  - Nodal enrichment (tip and wake) for XFA3D
  - Additional phantom nodes for XSHELL
- Use of LEFM with K extraction along an arbitrary moving crack front in XFA3D
- Use of nonlinear fracture mechanics with cohesive injection to dissipate the energy during the crack growth in XSHELL

GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

Capability Extension in Metallic Fatigue/Fracture Analysis Toolkit

- Shell-solid coupling for large scale welded aluminum structures
- Advanced nonlinear crack initiation and propagation models to capture i) rate dependence; ii) lode angle and triaxiality dependent plasticity; and iii) anisotropic plastic flow
- Material characterization of environment induced aging (sensitization)
- Verification and validation at structure level using available test data