ASTM

Sixth Symposium on Application of Automation Technology in Fatigue and Fracture Testing and Analysis

Applications of Automation Methods for Nonlinear Fracture Test Analysis

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Introduction

- Fracture mechanics test standards take a complicated physical process, the fracture of materials, and distill the test output through fracture mechanics principles to a single material value – the fracture toughness.

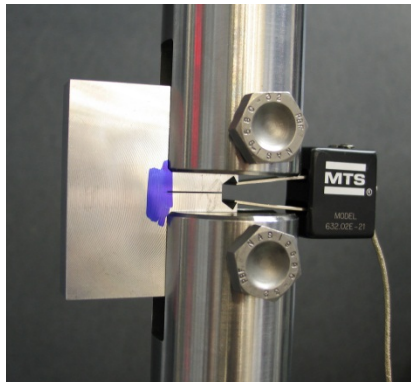
- Current ASTM fracture testing standards use equations expressed directly in the text of the standard to asses the experimental result.

- The equation-based methods of fracture test evaluation have not changed appreciably over the last few decades….In contrast, test measurement and data recording techniques have evolved drastically.

- The use of human useable equations is self limiting in the complexity that can be reasonably captured – usually can only address 1 form of nonlinearity.

- Ideally, test standards should capture and explain the best current understanding of the physics of the problem without being overly complex or burdensome for the user.

- Use of automated analysis techniques in computer programs allows non-expert users to obtain highly reliable assessments of tests involving complex, non-linear fracture behavior.



Introduction

Equations for *J*-integral calculation for SE(B) specimens from E1820:

Equations address material nonlinearity

E1820 – 11$^{\varepsilon 1}$

ANNEXES

(Mandatory Information)

A1. SPECIAL REQUIREMENTS FOR TESTING SINGLE EDGE BEND SPECIMENS

NOTE A1.1—Annex A1-Annex A3 cover specimen information.

A1.1 Specimen

A1.1.1 The standard bend specimen is a single edge-notched and fatigue-cracked beam loaded in three-point bending with a support span, S, equal to four times the width, W. The general proportions of the specimen configuration are shown in Fig. A1.1.

A1.1.2 Alternative specimens may have $1 \le W/B \le 4$. These specimens shall also have a nominal support span equal to $4W$.

A1.2 Apparatus

A1.2.1 For generally applicable specifications concerning the bend-test fixture and displacement gage see 6.5.1 and 6.2.

A1.3 *Specimen Preparation:*

A1.3.1 For generally applicable specifications concerning specimen configuration and preparation see Section 7.

A1.3.2 All specimens shall be precracked in three-point bending fatigue based upon the force P_m, as follows:

$$P_m = \frac{0.5Bb_o^2\sigma_Y}{S} \qquad (A1.1)$$

See 7.4.5 for fatigue precracking requirements.

A1.4 Calculation

A1.4.1 *Calculation of K*—For the bend specimen at a force $P_{(i)}$, calculate K as follows:

$$K_{(i)} = \left[\frac{P_i S}{(BB_N)^{1/2} W^{3/2}}\right] f(a_i/W) \qquad (A1.2)$$

where:

$$f\left(\frac{a_i}{W}\right) = \frac{3\left(\frac{a_i}{W}\right)^{1/2}\left[1.99 - \left(\frac{a_i}{W}\right)\left(1 - \frac{a_i}{W}\right)\left(2.15 - 3.93\left(\frac{a_i}{W}\right) + 2.7\left(\frac{a_i}{W}\right)^2\right)\right]}{2\left(1 + 2\frac{a_i}{W}\right)\left(1 - \frac{a_i}{W}\right)^{3/2}} \qquad (A1.3)$$

A1.4.2 *Calculation of J:*

For the single edge bend specimen, calculate J as follows:

$$J = J_{el} + J_{pl} \qquad (A1.4)$$

where:

J_{el} = elastic component of J, and
J_{pl} = plastic component of J.

A1.4.2.1 *J Calculations for the Basic Test Method*—At a point corresponding to v and P on the specimen force versus displacement record, calculate the J integral as follows:

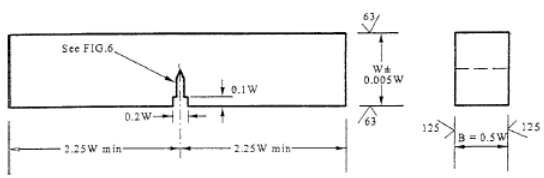
$$J = \frac{K^2(1 - \nu^2)}{E} + J_{pl} \qquad (A1.5)$$

where K is from A1.4.1 with $a = a_o$, and

$$J_{pl} = \frac{\eta_{pl} A_{pl}}{B_N b_o} \qquad (A1.6)$$

where:

A_{pl} = area under force versus displacement record as shown in Fig. A1.2,
η_{pl} = 1.9 if the load-line displacement is used for A_{pl},
= $3.667 - 2.199(a_o/W) + 0.437(a_o/W)^2$ if the crack mouth opening displacement record is used for A_{pl},
B_N = net specimen thickness ($B_N = B$ if no side grooves are present), and
b_o = $W - a_o$.



NOTE 1—The two side planes and the two edge planes shall be parallel and perpendicular as applicable to within 0.5°.
NOTE 2—The machined notch shall be perpendicular to specimen length and thickness to within ±2°.

FIG. A1.1 Recommended Single Edge Bend [SE(B)] Specimen

E1820 – 11$^{\varepsilon 1}$

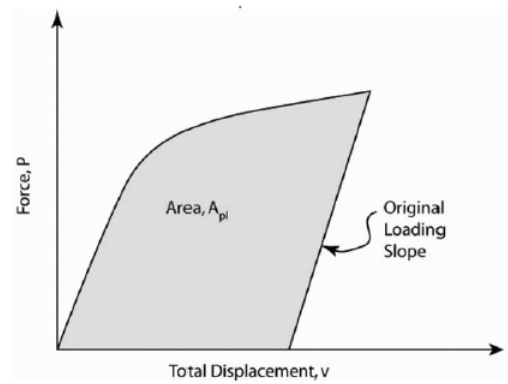


FIG. A1.2 Definition of Area for J Calculation Using the Basic Method

All basic test method J integral values shall be corrected for crack growth using the procedure of Annex A16.

A1.4.2.2 *J Calculations for the Resistance Curve Test Method*—At a point corresponding to $a_{(i)}$, $v_{(i)}$, and $P_{(i)}$ on the specimen force versus displacement record, calculate the J integral as follows:

$$J_{(i)} = \frac{(K_{(i)})^2(1 - \nu^2)}{E} + J_{pl(i)} \qquad (A1.7)$$

where $K_{(i)}$ is from A1.4.1, and

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{\eta_{pl(i-1)}}{b_{(i-1)}}\right)\left(\frac{A_{pl(i)} - A_{pl(i-1)}}{B_N}\right)\right] \times \left[1 - \gamma_{pl(i-1)}\left(\frac{a_{(i)} - a_{(i-1)}}{b_{(i-1)}}\right)\right] \qquad (A1.8)$$

where:

$\eta_{pl(i-1)}$ = 1.9, and
$\gamma_{pl(i-1)}$ = 0.9

if the load-line displacement is used to measure A_{pl} and,

$$\eta_{pl} = 3.667 - 2.199\left(\frac{a_{(i-1)}}{W}\right) + 0.437\left(\frac{a_{(i-1)}}{W}\right)^2$$

and

$$\gamma_{pl} = 0.131 + 2.131\left(\frac{a_{(i-1)}}{W}\right) - 1.465\left(\frac{a_{(i-1)}}{W}\right)^2$$

if the crack mouth opening displacement is used to measure A_{pl}.

In Eq A1.8, the quantity $A_{pl(i)} - A_{pl(i-1)}$ is the increment of plastic area under the chosen force versus plastic displacement record between lines of constant plastic displacement at points i–1 and i shown in Fig. A1.3. The quantity $J_{pl(i)}$ represents the total crack growth corrected plastic J at point i and is obtained in two steps by first incrementing the existing $J_{pl(i-1)}$ and then by modifying the total accumulated result to account for the crack growth increment. Accurate evaluation of $J_{pl(i)}$ from the Eq A1.8 relationship requires small and uniform crack growth increments consistent with the suggested elastic compliance spacing of Annex A8 and Annex A10. The quantity $A_{pl(i)}$ can be calculated from the following equation:

$$A_{pl(i)} = A_{pl(i-1)} + [P_{(i)} + P_{(i-1)}][v_{pl(i)} - v_{pl(i-1)}]/2 \qquad (A1.9)$$

where:

$v_{pl(i)}$ = plastic part of the load-line or crack mouth opening displacement = $v_{(i)} - (P_{(i)} C_{(i)})$, and
$C_{(i)}$ = experimental compliance, $(\Delta v/\Delta P)_{(i)}$, corresponding to the current crack size, a_i.

For test methods that do not evaluate an experimental load-line elastic compliance, the load-line compliance $C_{(i)}$ can be determined from the following equation:

$$C_{(i)} = \frac{1}{EB_e}\left(\frac{S}{W - a_i}\right)^2 \times \left[1.193 - 1.98\left(\frac{a_i}{W}\right) + 4.478\left(\frac{a_i}{W}\right)^2 - 4.443\left(\frac{a_i}{W}\right)^3 + 1.739\left(\frac{a_i}{W}\right)^4\right] \qquad (A1.10)$$

where:

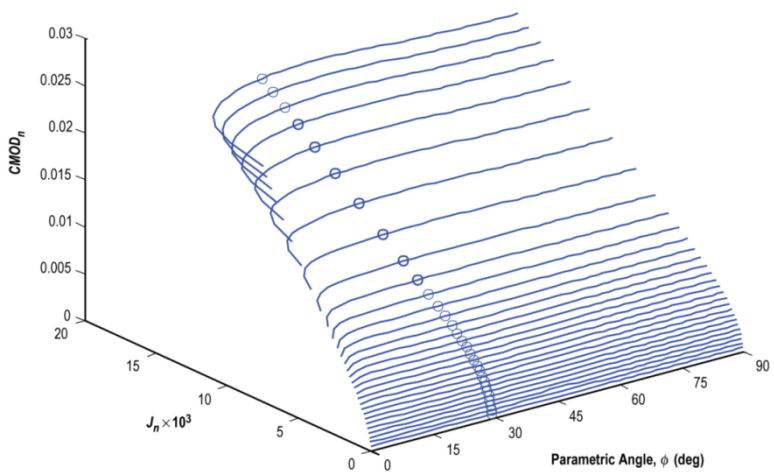
B_e = $B - (B - B_N)^2/B$

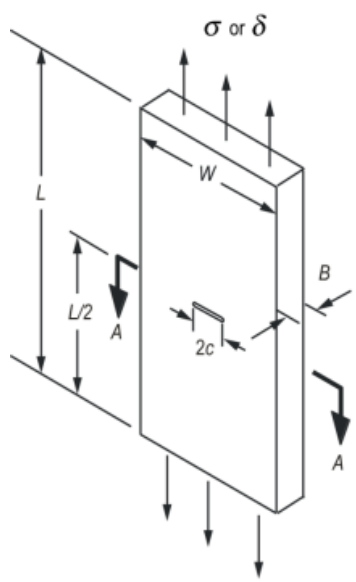
while for the crack mouth opening displacement case:

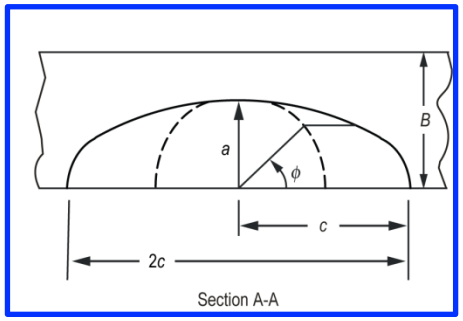
Introduction

Consider the difficulties in assessing laboratory fracture toughness tests with surface cracks……

- Fracture toughness often reached beyond LEFM limit
- Crack driving force varies nonlinearly around crack perimeter and is a nonlinear function of deformation
- *J – CMOD* trajectory is unique for each crack perimeter location
- Force - *CMOD* trajectory becomes nonlinear at higher deformation levels





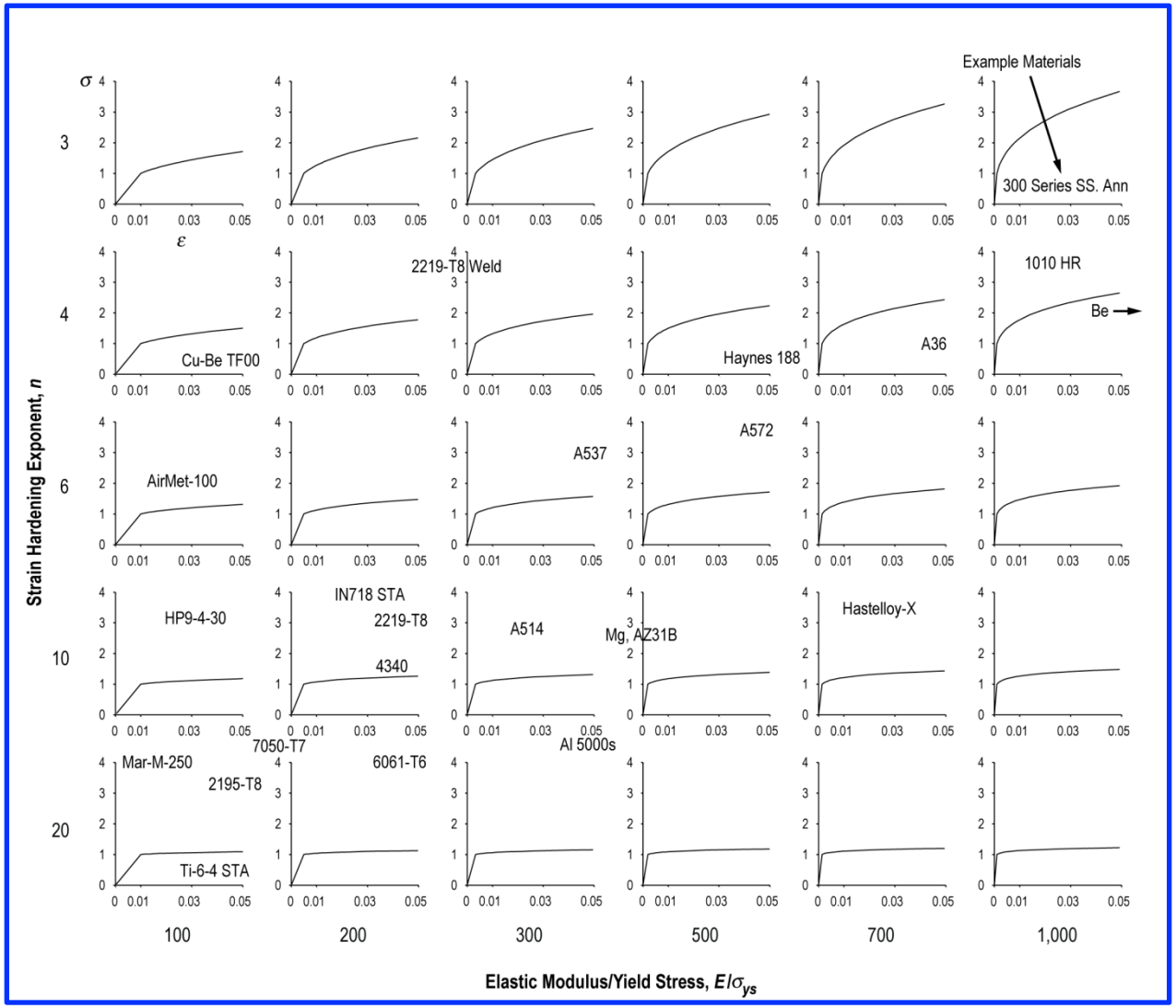


Introduction

What about pre-solving the solution space?

- A fracture mechanics test, even a complicated one such as the elastic-plastic surface crack test, is a bounded problem based on the practical limitations of specimen geometries, engineering material properties, and defined loading conditions.
- What if we pre-solve the nonlinear solution space and use interpolation to find the solution?
- This methodology directly utilizes 3-D FEA solutions, avoiding the need to fit numerous nonlinear equations to the solutions space with the usual loss of fidelity.
- We will use the surface crack in tension as a test case for the pre-solved solution methodology.

Material Space



- 30 material combinations
- Stress-strain response represented by linear then power law (LPPL)

$$\frac{\varepsilon}{\varepsilon_{ys}} = \frac{\sigma}{\sigma_{ys}} \quad \varepsilon \le \varepsilon_{ys}$$

$$\frac{\varepsilon}{\varepsilon_{ys}} = \left(\frac{\sigma}{\sigma_{ys}}\right)^n \quad \varepsilon > \varepsilon_{ys}$$

- $3 \le n \le 20$
- $100 \le E/\sigma_{ys} \le 1{,}000$
- $\sigma_{ys} = 1$, $\nu = 0.30$

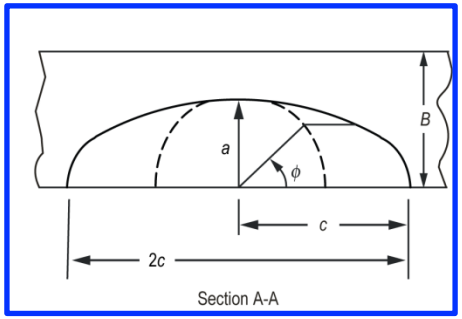
Geometric Space

Crack Depth-to-Thickness Ratio, *a/B*

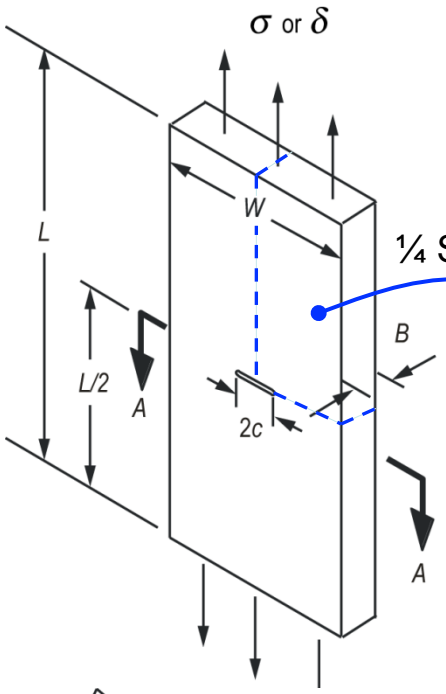
	0.2	0.4	0.6	0.8	1
0.2	2c: 2 W: 10 L: 20 No. Nodes: 41,146 No. Elements: 8,876 No. CF Nodes: 91	2c: 1 W: 5 L: 10 No. Nodes: 21,332 No. Elements: 4,520 No. CF Nodes: 49	2c: 0.67 W: 5 L: 10 No. Nodes: 21,332 No. Elements: 4,520 No. CF Nodes: 49	2c: 0.5 W: 5 L: 10 No. Nodes: 21,332 No. Elements: 4,520 No. CF Nodes: 49	2c: 0.4 W: 5 L: 10 No. Nodes: 21,332 No. Elements: 4,520 No. CF Nodes: 49
0.4	2c: 4 W: 20 L: 40 No. Nodes: 80,872 No. Elements: 17,632 No. CF Nodes: 133	2c: 2 W: 10 L: 20 No. Nodes: 4,330 No. Elements: 9,324 No. CF Nodes: 91	2c: 1.33 W: 6.67 L: 13.34 No. Nodes: 24,868 No. Elements: 5,280 No. CF Nodes: 49	2c: 1 W: 5 L: 10 No. Nodes: 21,332 No. Elements: 4,520 No. CF Nodes: 49	2c: 0.8 W: 5 L: 10 No. Nodes: 21,332 No. Elements: 4,520 No. CF Nodes: 49
0.6	2c: 6 W: 30 L: 60 No. Nodes: 82,894 No. Elements: 18,164 No. CF Nodes: 175	2c: 3 W: 15 L: 30 No. Nodes: 55,626 No. Elements: 11,940 No. CF Nodes: 91	2c: 2 W: 10 L: 20 No. Nodes: 43,330 No. Elements: 9,324 No. CF Nodes: 91	2c: 1.5 W: 8 L: 15 No. Nodes: 29,428 No. Elements: 6,236 No. CF Nodes: 49	2c: 1.2 W: 6 L: 12 No. Nodes: 23,100 No. Elements: 4,900 No. CF Nodes: 49
0.8	2c: 8 W: 40 L: 80 No. Nodes: 122,396 No. Elements: 26,928 No. CF Nodes: 217	2c: 4 W: 20 L: 40 No. Nodes: 80,872 No. Elements: 17,632 No. CF Nodes: 133	2c: 2.67 W: 13.33 L: 26.66 No. Nodes: 49,174 No. Elements: 10,568 No. CF Nodes: 91	2c: 2 W: 10 L: 20 No. Nodes: 43,330 No. Elements: 9,324 No. CF Nodes: 91	2c: 1.6 W: 8 L: 16 No. Nodes: 29,428 No. Elements: 6,236 No. CF Nodes: 49

Crack Depth-to-Half-Length Ratio, *a/c*

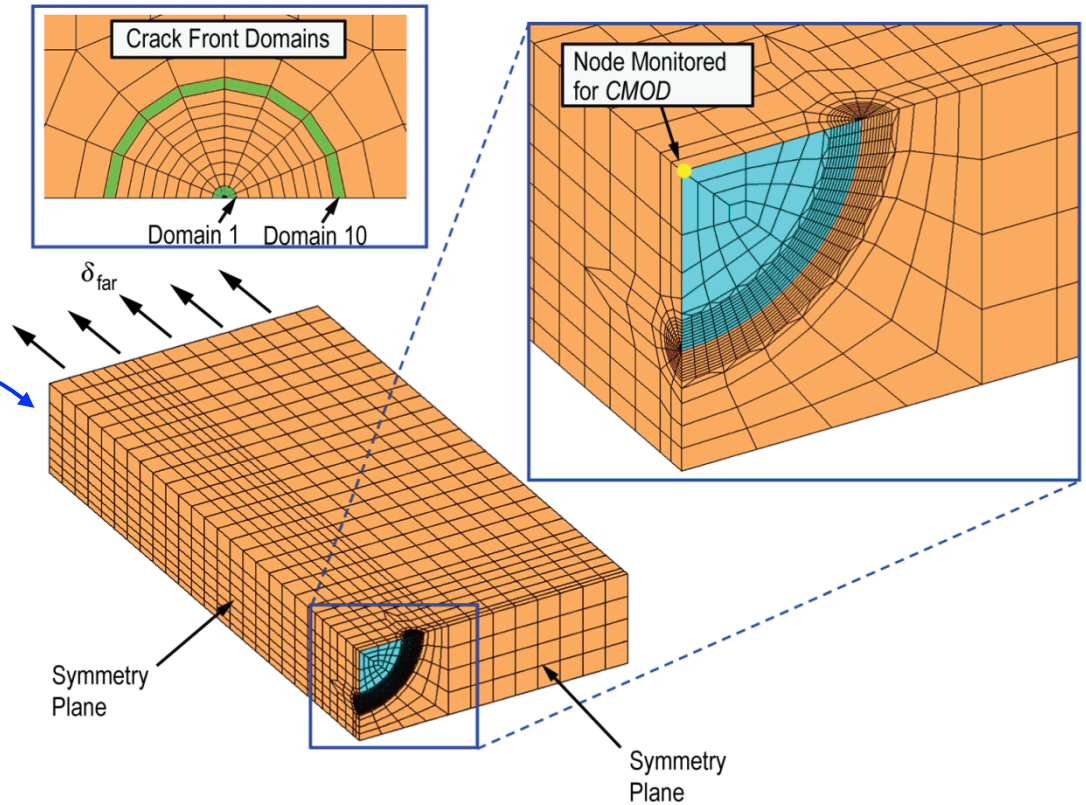
- 20 geometric combinations
- $0.2 \le a/B \le 0.8$
- $0.2 \le a/c \le 1.0$
- $B = 1$
- $W = \max(5*2c, 5*B)$
- $L = 2*W$

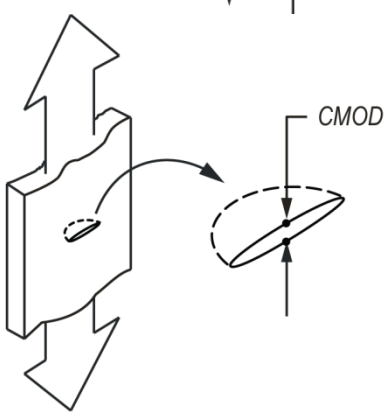


Surface Crack FEMs



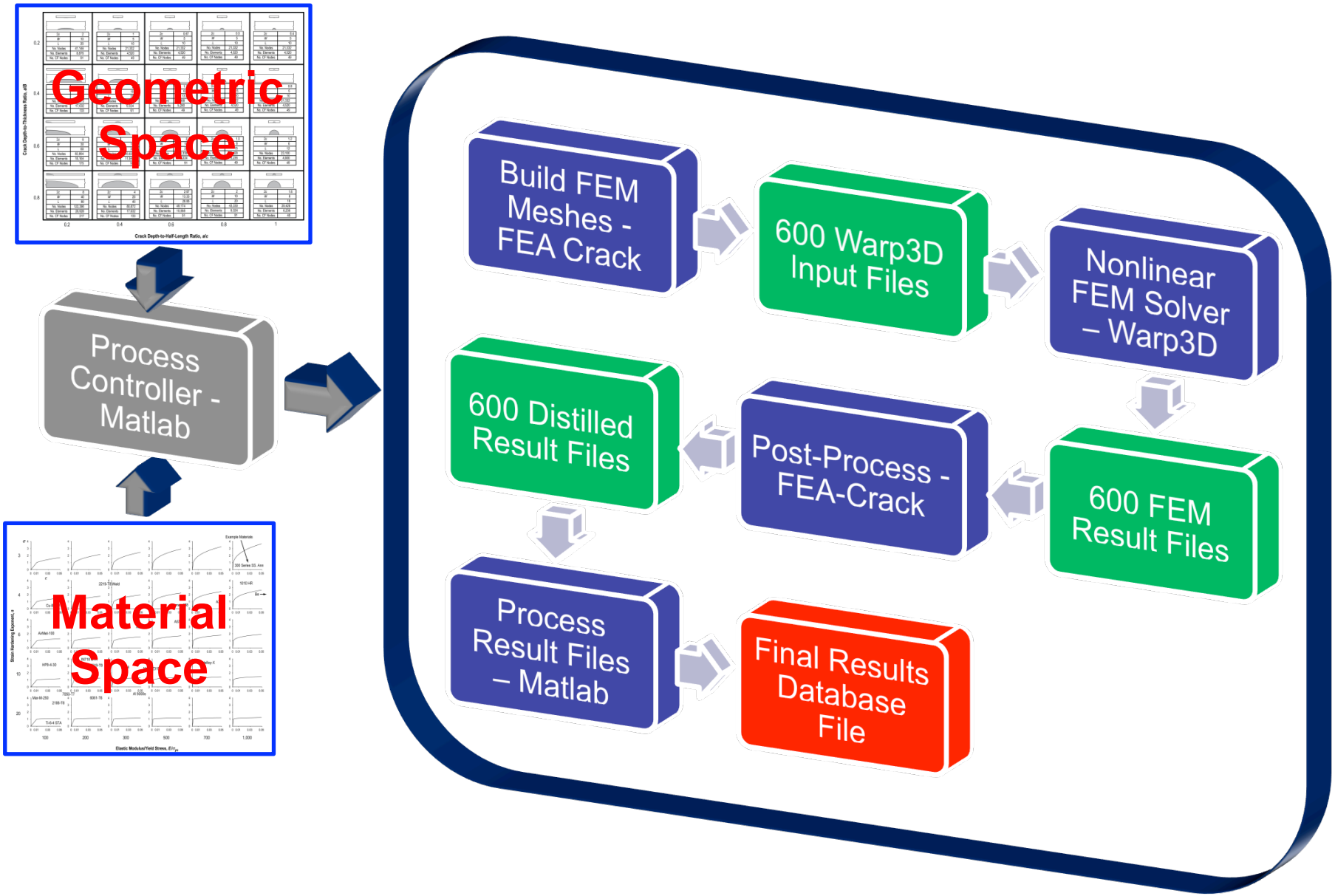
¼ Symmetry FEM



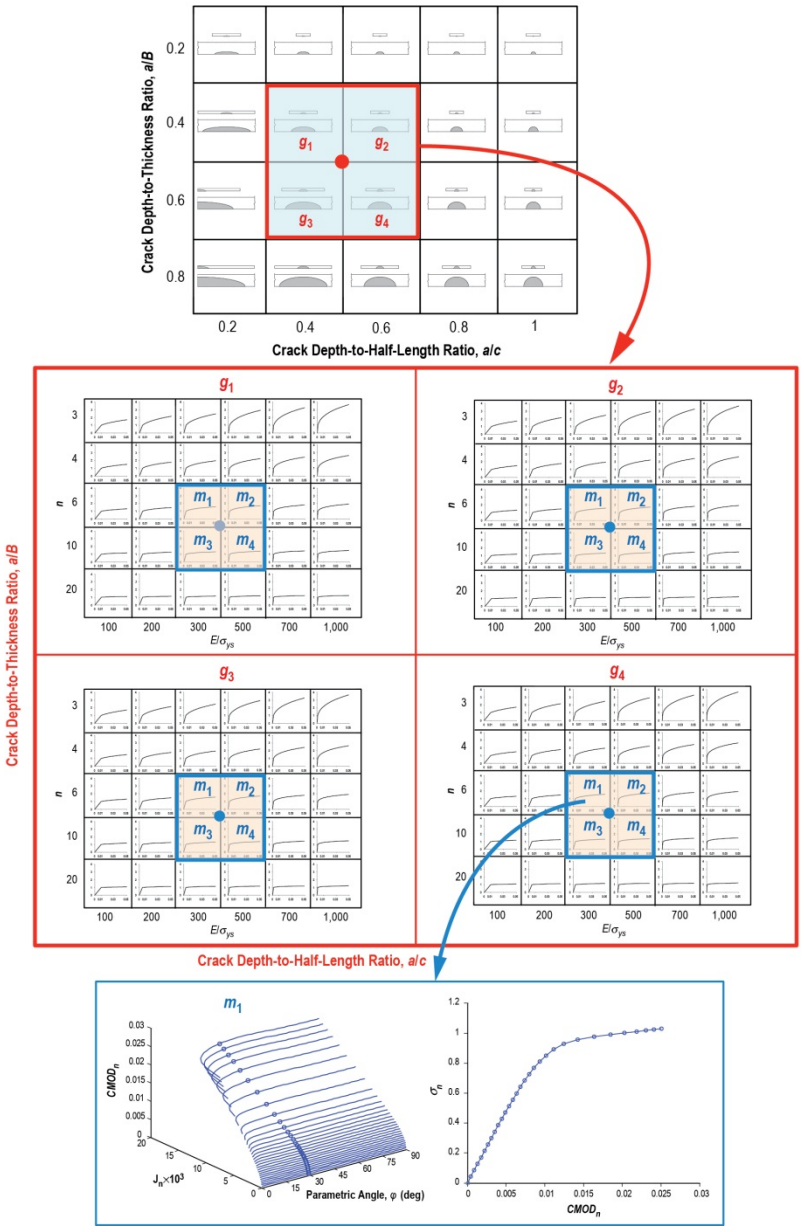


- Total of 600, ¼ Symmetry FEMs
- 20 Node, reduce integration elements
- FEMs built and post-processed with FEA-Crack
- Analysis performed with Warp3D 16.3.1
- *J*-integral results from domain 10

Solution Database Automation



Solution Interpolation

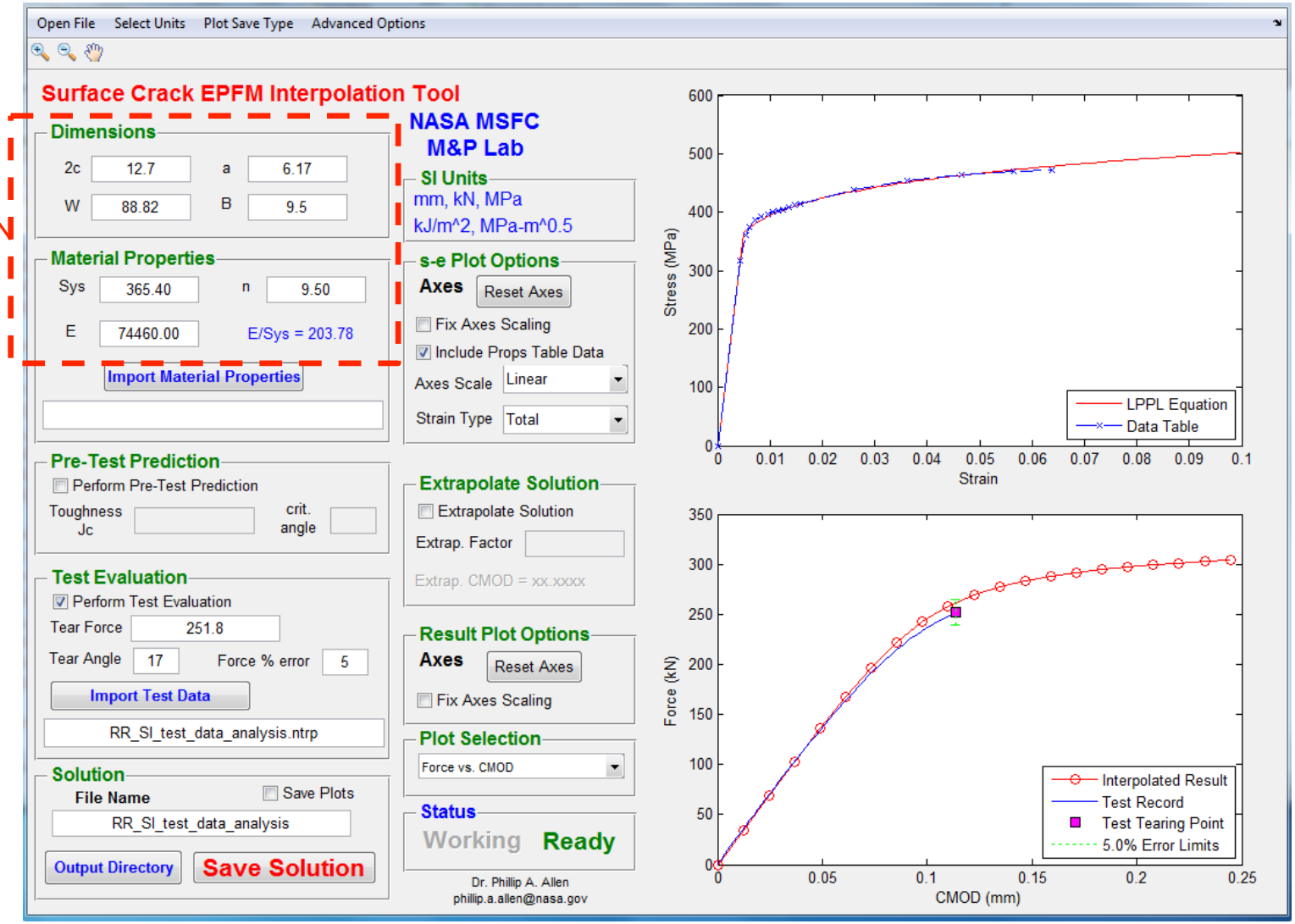


- Interpolation within the solution space provides an estimated solution, $\bar{R}\left(a/B, a/c, n, E/\sigma_{ys}\right)$
- The solution space can be visualized as a four-dimensional array with two geometric dimensions and two material dimensions.
- The graphic at the left illustrates the selection of the 16 "nearest neighbor" solutions for an interpolated solution for $\bar{R}\left(0.5, 0.5, 8, 400\right)$
- Extensive automated verification of solutions:
  - LEFM J-integral solutions vs. Newman-Raju soln.
  - Domain convergence
  - Interpolated solutions to 25 benchmark FEMS
- Details of the solution space, verification procedures, and interpolation procedures are available in NASA/TP-2013-217480, *Elastic-Plastic J-Integral Solutions for Surface Cracks in Tension Using an Interpolation Methodology*.

Graphical User Interface

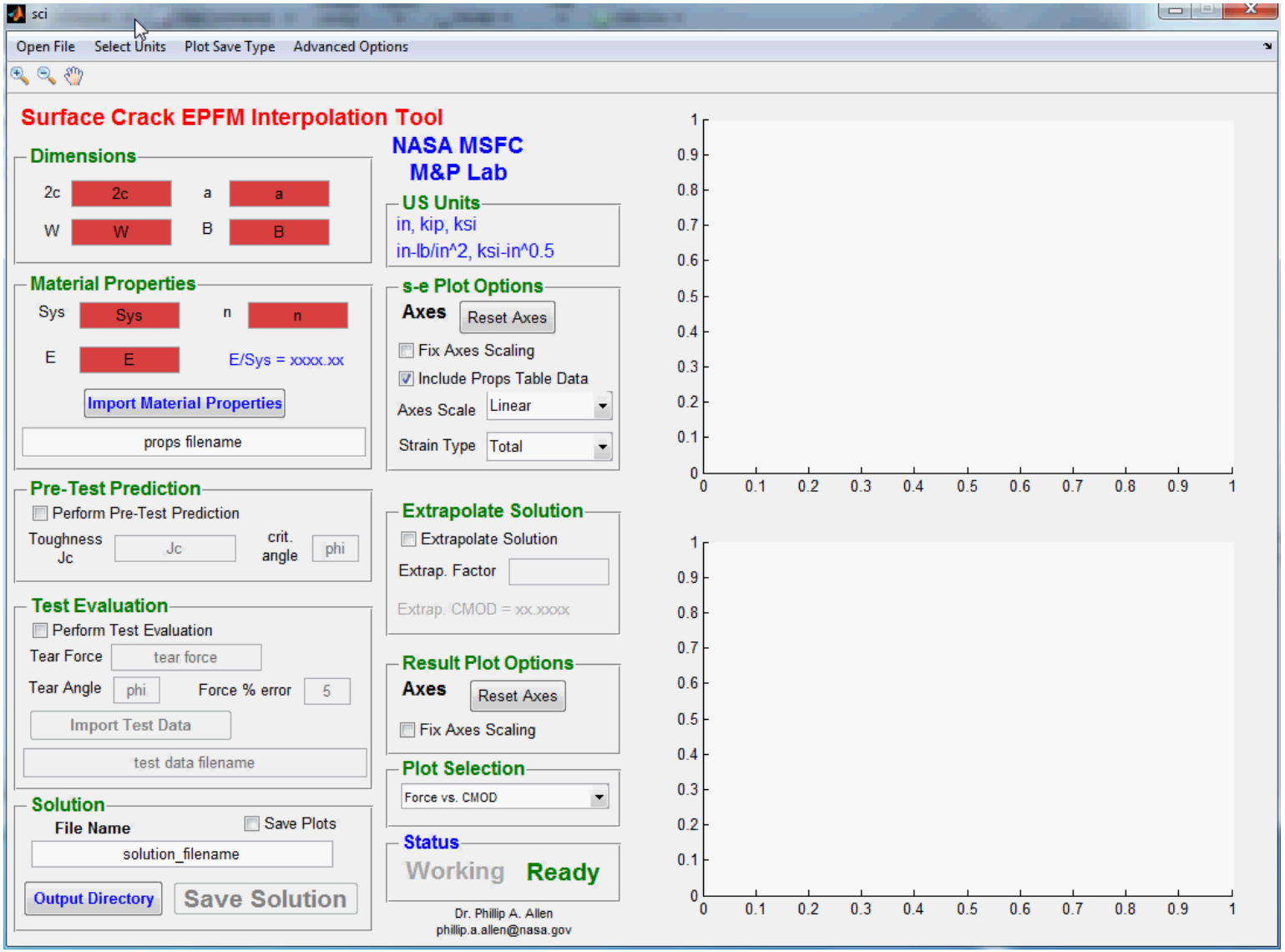
Graphical User Interface (GUI) tool developed to allow easy access to solutions

Only inputs required for full 3-D nonlinear solution



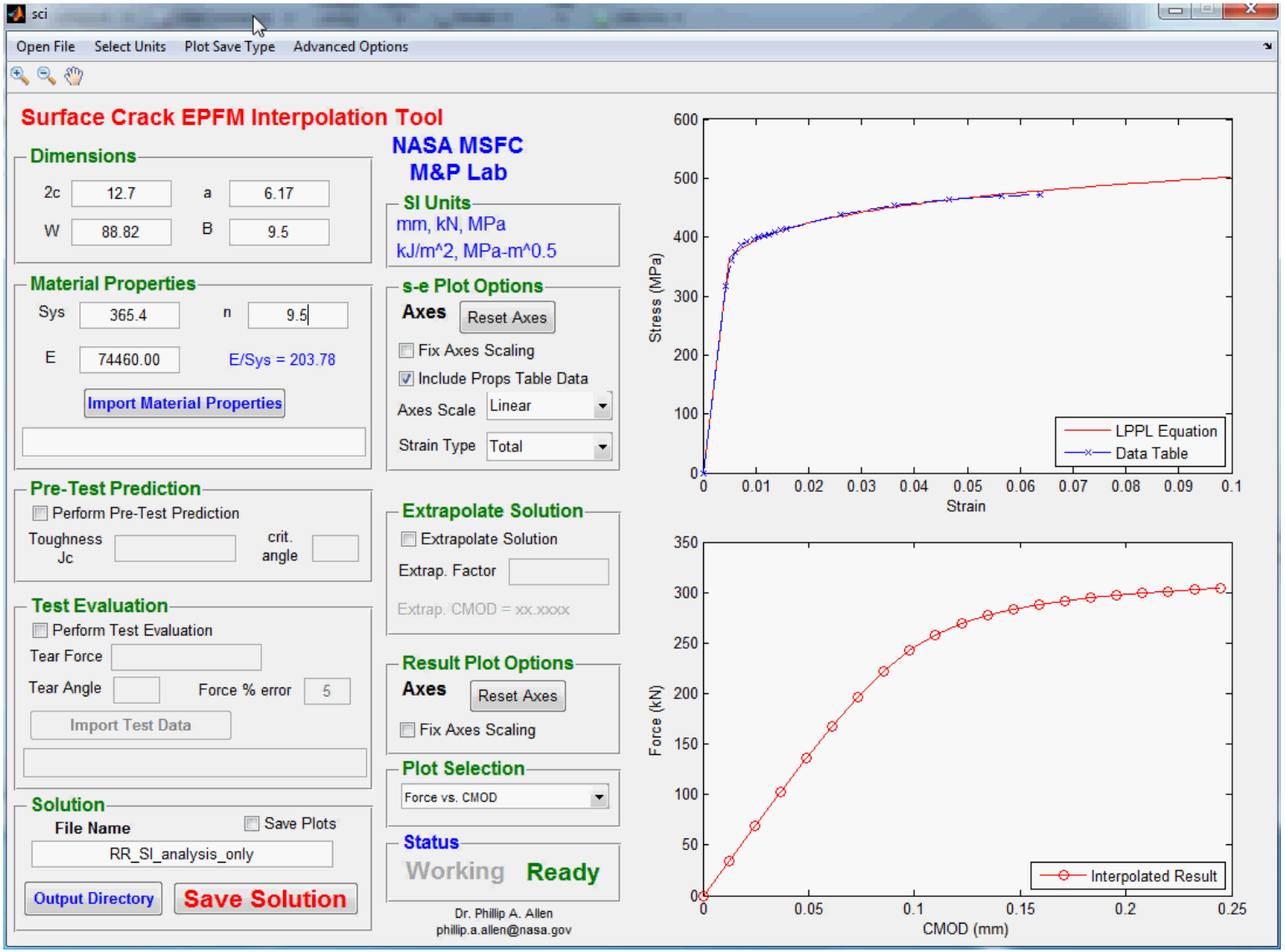
Graphical User Interface

Automated interpolated analysis



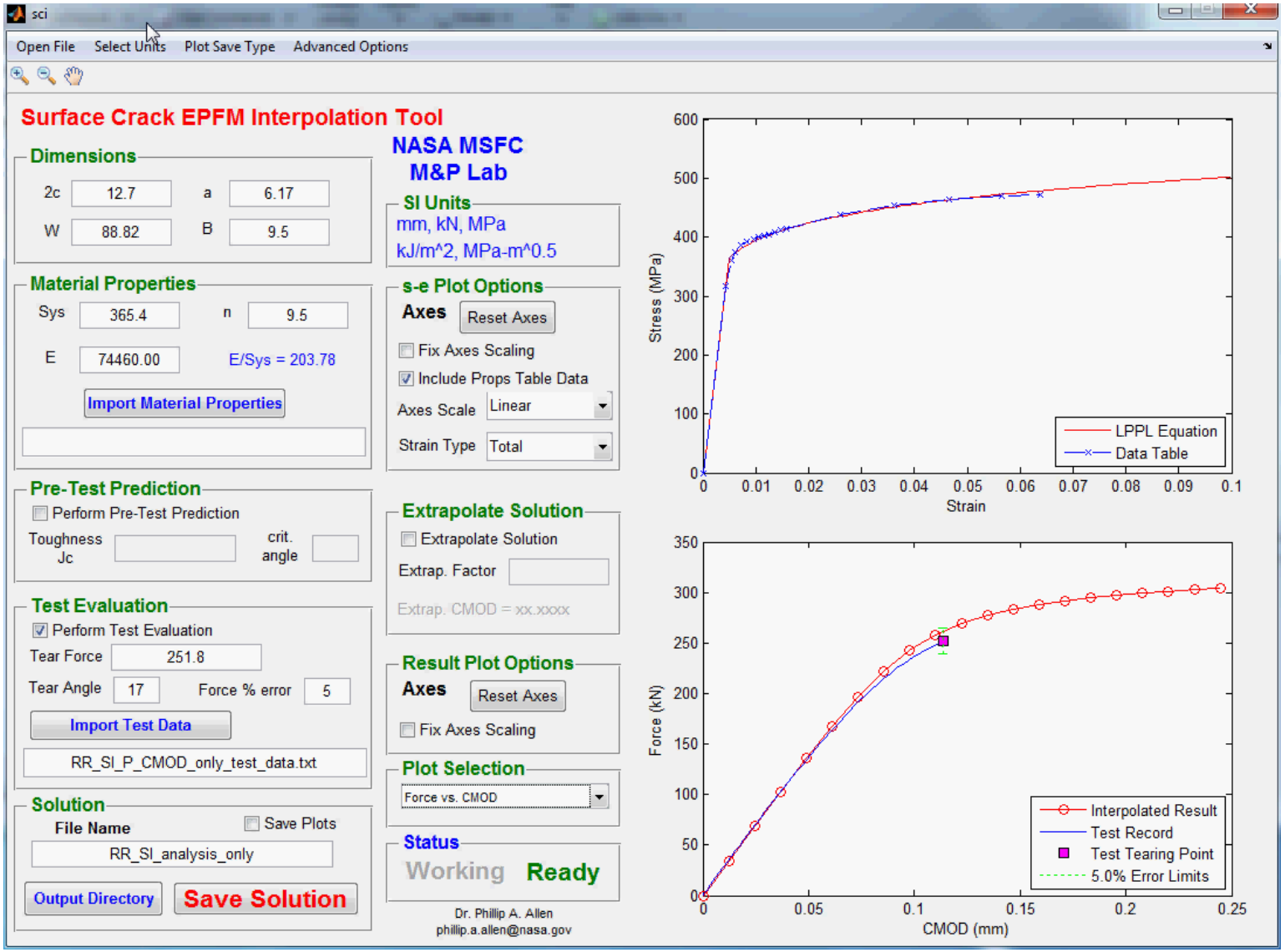
Graphical User Interface

Automated interpolated analysis - Pre-Test Prediction

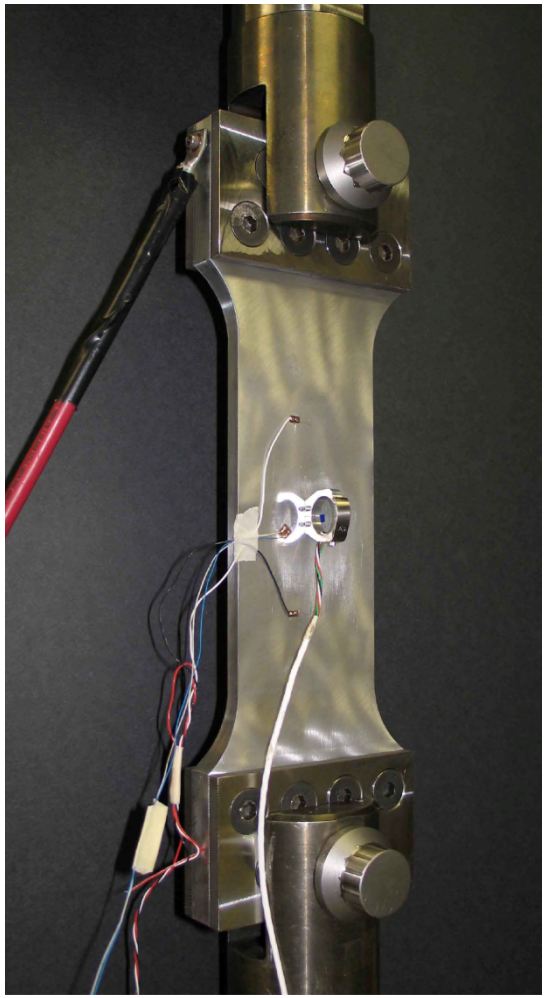


Graphical User Interface

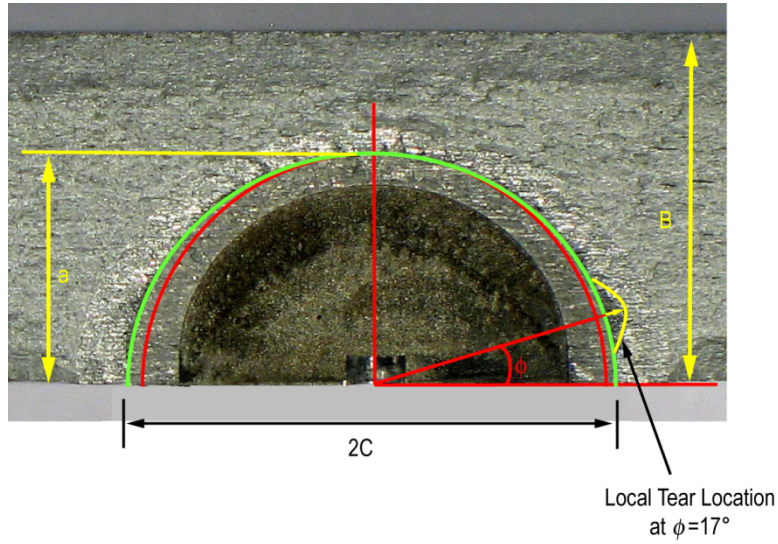
Automated interpolated analysis - Result Interrogation



Round Robin Surf. Crack Test



In 2011, 15 Laboratories participated in an analytical round robin based on a 2219-T87 surface crack tension test, and the results of the RR are documented in NASA/TM-2012-217456

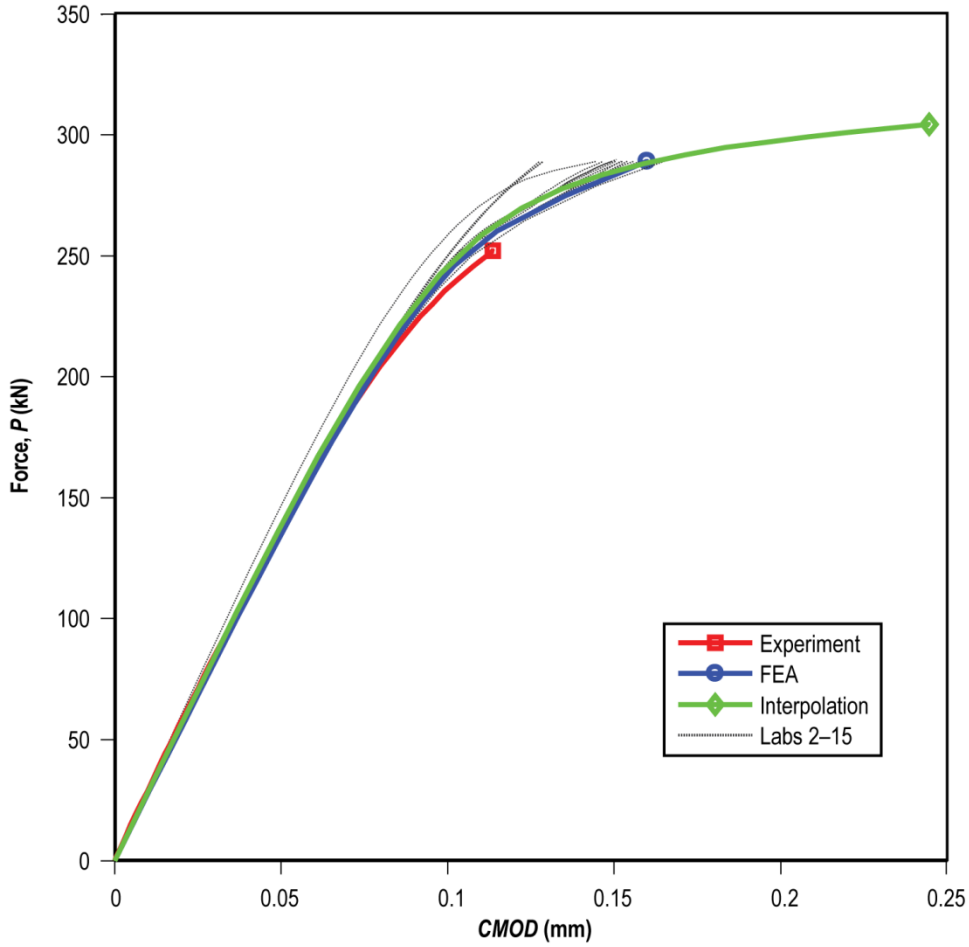


Sample description:
2219-T87 aluminum

- W = 88.82 mm
- B = 9.50 mm
- 2c = 12.70 mm
- a = 6.17 mm
- a/c = 0.97
- a/B = 0.65

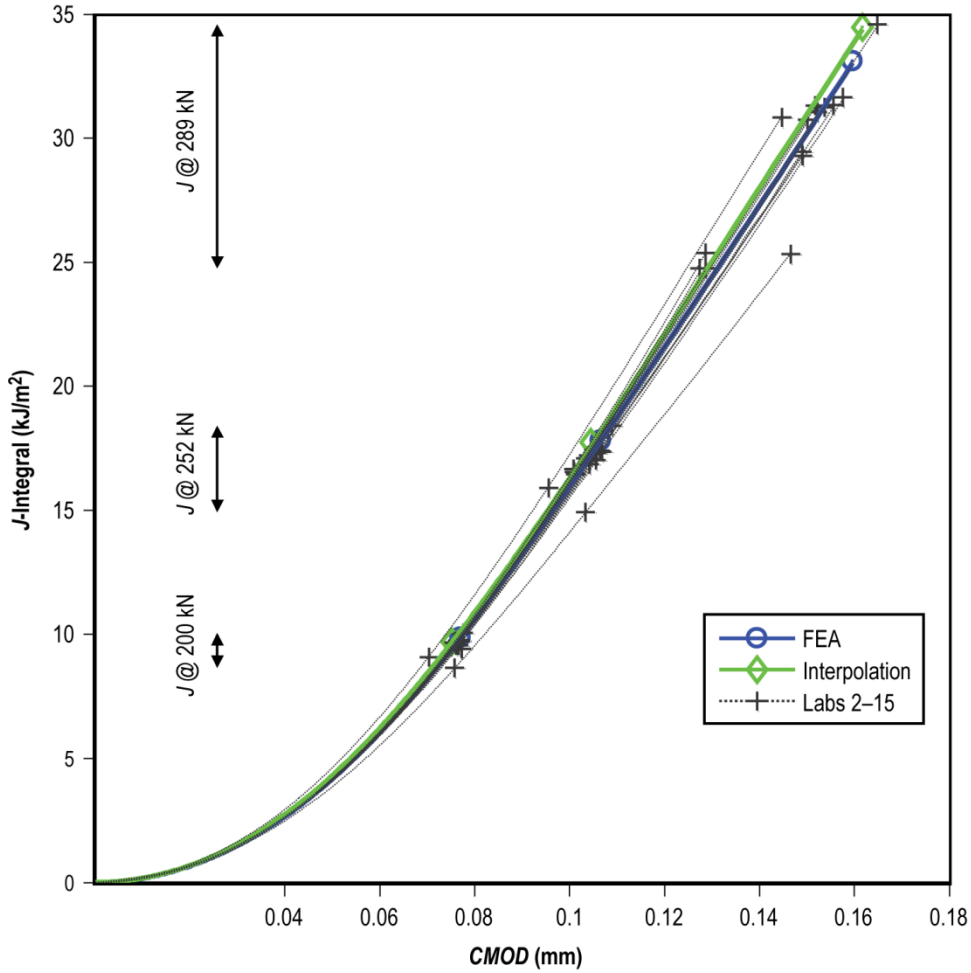
Tear Force = 251.8 kN
Tear CMOD = 0.114 mm
Maximum tearing at ϕ = 17°

Round Robin Interpolated Solution



- GUI tool used to create an interpolated solution to RR test
- σ_{ys} = 365.4, n = 9.5 in interpolated solution
- "FEA" is the author's RR FEA solution
- Interpolated solution passes through family of RR results

Round Robin Interpolated Solution



- Interpolated solution passes through family of RR results
- Interpolated solution is equivalent quality as may be expected from custom finite element analysis

Conclusions

- Using automated and standardized computer tools to calculate the pertinent test result values has several advantages such as:

  1. allowing high-fidelity solutions to complex nonlinear phenomena that would be impractical to express in written equation form,
  2. eliminating errors associated with the interpretation and programing of analysis procedures from the text of test standards,
  3. lessening the need for expertise in the areas of solid mechanics, fracture mechanics, numerical methods, and/or finite element modeling, to achieve sound results,
  4. and providing one computer tool and/or one set of solutions for all users for a more “standardized” answer.

- In summary, this approach allows a non-expert with rudimentary training to get the best practical solution based on the latest understanding with minimum difficulty.

Conclusions

- Other existing ASTM standards that cover complicated phenomena use standard computer programs:

  1. ASTM C1340/C1340M-10 - *Standard Practice for Estimation of Heat Gain or Loss Through Ceilings Under Attics Containing Radiant Barriers by Use of a Computer Program*
  2. ASTM F 2815 - *Standard Practice for Chemical Permeation through Protective Clothing Materials: Testing Data Analysis by Use of a Computer Program*
  3. ASTM E2807 - *Standard Specification for 3D Imaging Data Exchange, Version 1.0*

- The verification, validation, and round-robin processes required of a computer tool closely parallel the methods that are used to ensure the solution validity for equations included in test standard.

- The use of automated analysis tools allows the creation and practical implementation of advanced fracture mechanics test standards that capture the physics of a nonlinear fracture mechanics problem without adding undue burden or expense to the user.

- The presented approach forms a bridge between the equation-based fracture testing standards of today and the next generation of standards solving complex problems through analysis automation

Questions?