Applications of Automation Methods for Nonlinear Fracture Test Analysis

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• 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 assess 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
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)
  \[
  \frac{\varepsilon}{\varepsilon_{ys}} = \frac{\sigma}{\sigma_{ys}}, \quad \varepsilon \leq \varepsilon_{ys}
  \]
  \[
  \frac{\varepsilon}{\varepsilon_{ys}} = \left(\frac{\sigma}{\sigma_{ys}}\right)^n, \quad \varepsilon > \varepsilon_{ys}
  \]
- \(3 \leq n \leq 20\)
- \(100 \leq E/\sigma_{ys} \leq 1,000\)
- \(\sigma_{ys} = 1, \nu = 0.30\)
Geometric Space

- 20 geometric combinations
- \(0.2 \leq \frac{a}{B} \leq 0.8\)
- \(0.2 \leq \frac{a}{c} \leq 1.0\)
- \(B = 1\)
- \(W = \max(5 \times 2c, 5 \times B)\)
- \(L = 2 \times W\)
Surface Crack FEMs

- 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

Geometric Space

Process Controller - Matlab

Material Space

Build FEM Meshes - FEA Crack → 600 Warp3D Input Files → Nonlinear FEM Solver – Warp3D

600 Distilled Result Files → Post-Process - FEA-Crack → 600 FEM Result Files

Process Result Files – Matlab → Final Results Database File
• Interpolation within the solution space provides an estimated solution, $\bar{R}(a/B, a/c, n, E/\sigma_{YS})$

• 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 $\bar{R}(0.5, 0.5, 8, 400)$

• Extensive automated verification of solutions:
  - 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 (GUI) tool developed to allow easy access to solutions

Only inputs required for full 3-D nonlinear solution
Graphical User Interface

Automated interpolated analysis

[Image: Graphical User Interface showing a software interface for surface crack EPFM interpolation tool with options for dimensions, material properties, pre-test prediction, test evaluation, solution, and status.]
Graphical User Interface

Automated interpolated analysis - Pre-Test Prediction

Surface Crack EPFM Interpolation Tool

Dimensions

\[
\begin{align*}
2c &= 12.7 \\
W &= 88.82 \\
a &= 5.17 \\
B &= 9.6
\end{align*}
\]

Material Properties

\[
\begin{align*}
E &= 74460.00 \\
\frac{E}{\text{Sys}} &= 203.76
\end{align*}
\]

Import Material Properties

Pre-Test Prediction

Perform Pre-Test Prediction

Toughness

Jc

Test Evaluation

Perform Test Evaluation

Tear Force

Tear Angle

Force % error

5

Import Test Data

Extrapolate Solution

Extrapolate Solution

Extrap. Factor

Result Plot Options

Axes

Reset Axes

Fix Axes Scaling

Plot Selection

Force vs. CMOD

Status

Working

Ready

File Name

Save Plots

RR_SI_analysis_only

Save Solution

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SI Units

mm, kN, MPa

kJ/m², MPa·m⁰.⁵

s-e Plot Options

Axes

Reset Axes

Fix Axes Scaling

Include Props. Table Data

Axes Scale

Linear

Strain Type

Total

Import Test Data

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Graphical User Interface

Automated interpolated analysis - Pre-Test Prediction
### Graphical User Interface

#### Automated interpolated analysis - Result Interrogation

![Graphical User Interface](image)

**Surface Crack EPFM Interpolation Tool**

**Dimensions**

- \( c = 12.7 \)
- \( a = 5.17 \)
- \( W = 88.82 \)
- \( B = 9.6 \)

**Material Properties**

- \( E = 74460.00 \)
- \( v = 0.3 \)
- \( f_y = 203.76 \)

**Pre-Test Prediction**

- Perform Pre-Test Prediction
- Toughness
- Jc

**Test Evaluation**

- Perform Test Evaluation
- Tear Force
- Tear Angle
- Force % error

**Result Plot Options**

- Axes
- Axes Scale
- Strain Type

**Extrapolate Solution**

- Extrapolate Solution
- Extrap. Factor

**Plot Selection**

- Force vs. CMOD

**Status**

- Working
- Ready

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- SI Units
- \( \text{mm, kN, MPa} \)
- \( kJ/m^2, \text{MPa}-m^{0.5} \)

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**Graphs**

- Stress vs. Strain
- Force vs. CMOD

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**File Name**

- RR_SI_analysis_only

**Output Directory**

- Save Solution

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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 \( \phi = 17^\circ \)
Round Robin Interpolated Solution

- GUI tool used to create an interpolated solution to RR test

- $\sigma_{ys} = 365.4$, $n = 9.5$ 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

• 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?