A 3D Discrete Damage Modeling Methodology for Abaqus for Fatigue Damage Evaluation in Bolted Composite Joints

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Introduction to the R&D Team at GEM (www.gem-innovation.com)

• Overview and Capabilities
  – Founded in 2001 as an engineering service and software development company
  – Specialized in
    • R&D consulting for DoD, Marine & Aerospace;
    • Technology transfer from research labs to industries
    • Developing analysis/design tools for advanced materials/structures;

Strategic Alliance and Business Partnership
  – Business partnership and collaboration with SIMULIA (Abaqus), Marine and Aerospace industries
  – Jointly exploring business opportunities within government agencies and commercial industries
Outline

- Background on tool development
- Introduction of key solution modules
- Implementation in Abaqus
- Application examples
- Summary and conclusions
Challenges in Progressive Damage Analysis

(Hallet & Wisnom, 2007)

• Analyses demonstrate that fracture is dominated by interactions between transverse matrix cracks and delaminations

How to define such critical crack patterns \textit{a priori}?

Develop methods to model arbitrary cracking!
Discrete Crack Network (DCN) Module for Abaqus for Residual Strength and Life Prediction of Bolted Composite Joint

Regularized X-FEM

X-FEM/Phantom

Application

- Operational profile
- Structural configuration
- Material/fracture/fatigue data
- Global FEM analysis

Tool Validation

Discrete Damage at Laminate Level
Matrix Cracking & Delamination

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Discrete Damage Modeling

Goal:
Discrete Modeling of Matrix Cracking and Delamination Networks

- General approach based on X-FEM ideas
- Must accommodate cracking & delamination interaction

Kinematic Description of a Discrete Crack

![Diagram showing X-FEM and Rx-FEM with displacement jump and crack location.]
Crack description: X-FEM and RX-FEM

\[ f_\alpha(x) = \text{sign}(\mathbf{n}(\bar{x})(x - \bar{x})) \min_{x \in \Gamma_\alpha} \| x - \bar{x} \| \]

Standard FE

\[ u(x) = \sum_{i \in I} X_i(x) u_i \]

Jump function introduction

\[ u(x) = \sum_{i \in I \cup J} X_i(x) u_i + H(f_\alpha(x)) \sum_{j \in J} X_j(x) u_j^{(1)} + \left[1 - H(f_\alpha(x))\right] \sum_{j \in J} X_j(x) u_j^{(2)} \]

\[ H(x) = \begin{cases} +1 & x \geq 0 \\ 0 & x < 0 \end{cases} \]

Standard X-FEM

Regularized X-FEM

\[ \tilde{H}(x) = \sum_{i \in \Omega} X_i(x) h_i \quad h_i = \frac{1}{2} \left[ 1 + \frac{\int_V X_i(x) f_\alpha(x) dV}{\int_V X_i(x) |f_\alpha(x)| dV} \right] \]

Endel Iarve. Mesh independent modelling of cracks by using higher order shape functions. IJNME, 56(6), 2003: 869:882
VCCT Based G Extraction: Matrix Cracking

VCCT based G extraction

Crack propagation

\[ \theta = \cos^{-1} \left( \frac{3K_{II}^2 + \sqrt{K_I^4 + 8K_I^2K_{II}^2}}{K_I^2 + 9K_{II}^2} \right) \]
Crack Front Tracking and Extraction of SERR via Spring Model: Delamination

- Entire interface is described by UINTER/UEL
- Bonded zone is filled with BONDED SPRINGS
- Debonded zone is filled with DEBONDED SPRINGS

**Abaqus Implementation of the Spring Model**

- **UINTER**
  - Input: RDISP, STATEV
  - Output: STRESS: Surface stress
  - Cohesive Law
  - Spring Model
  - STATEV: updated variables

- **UEL**
  - Input: U, PROPS
  - Output: NDSN: Nodal forces
  - Cohesive Law
  - Spring Model
  - AMATEX: Stiffness matrix
  - SVARS: updated variables

**Spring Model**

\[
\sigma = \frac{E(1-v)}{(1+v)(1-2v)} \Delta_1
\]

\[
\tau_i = \frac{E}{2(1+v)} \Delta_i \quad (i = 2, 3)
\]

**Debonded:**

\[
\sigma = \begin{cases} 
0, & \Delta_i \leq 0 \\
\frac{E(1-v)}{(1+v)(1-2v)} \Delta_i, & \Delta_i > 0 
\end{cases}
\]

\[
\tau_i = 0 \quad (i = 2, 3)
\]

**Geometric Tracking of Arbitrary Delamination Front**

- Virtual Front
- FE Front
  - Node on FE front
  - Point for computing G with relevant node
  - Point on original virtual front
  - Point on new virtual front
Merging of Delamination Fronts

Merging Fronts

- Front 1
- Front 2
- Delaminated Area 1
- Delaminated Area 2
- Merged Front

Merging Front with Boundary

- Front
- Geometric Boundary
- Physical Delaminated Area
- Virtual Delaminated Area
Turon’s Cohesive Damage Accumulation Model For
Delamination Fatigue Prediction

The strategy can be summarized as follows:

(1) Determination of cohesive stress via a quasi-static analysis;

(2) Degradation of both cohesive strength and toughness under cyclic load based on an S-N curve; and

(3) Crack initiation via monitoring cohesive elements with traction-free displacement jump
Phantom-Paired X-FEM for Residual Strength Prediction

Initial stress → External loading

Failure reached? Y

Matrix crack injection

Update cohesion status

back to the beginning with evolved structure

\[ G_t = \int_0^{\delta_e} \sigma(\delta) d\delta \]

Cohesive law

\[ K = (1 - d)K_0 \]

\[ K_t = K + G_{d} \]

\[ G_{d} = \int_{\delta_{0}}^{\delta_{c}} \sigma(\delta^{'}) d\delta^{'} \]

Symmetric Model of an T300/3506 Laminates with a Ply Stacking Sequence of [+45/-45/0]
Co-Simulation of Matrix Cracking and Delamination Growth

**Constant Amplitude**

- Maximum load $F_{\text{max}}$
- Minimum load $F_{\text{min}}$

**Varied Amplitude**

- Maximum load $F_{\text{max}}^{(n)}$
- Minimum load $F_{\text{min}}^{(n)}$

**Coupled Balance Analysis**

- S-N based damage accumulation
- Failure reached? Y

**Matrix Crack Injection**

- $\Delta G = G_{\text{max}} - G_{\text{min}}$

**Delamination Mode**

- $\Delta G = G_{\text{max}} - G_{\text{min}}$

**Coupled Fatigue Evolution**

- allowed $dD_{f1}$
- computed fatigue $dD$

**Update Delamination Damage**

- $dN = \min\left\{ dN_{\text{crack max}}, dN_{\text{delamination max}} \right\}$

**Update Matrix Cracks Damage**

- $dN_{\text{crack max}}$
- $dN_{\text{delamination max}}$

**Back to the Beginning with Evolved Structure**
Implementation of Rx-FEM within Abaqus via Its User-Defined Subroutines

Abaqus

Start of Analysis (LOP = 0)

Start of Increment (LOP = 1)

Equilibrium Iterations

End of Increment (LOP = 2)

UEXTERNALDB

(LOP = 0)

(LOP = 1)

(LOP = 2)

UEL

Current DOF

Element Tangent Stiffness Matrix

Load Residuals

Rx-FEM Routines

Read “Rx” Data

Set up External Database

Create Elements

Update Internal Variables

Check Failure Criteria

Write to Database

Check for Cracks

Adjust Elements for Cracks

Calculate Damage

Generate Cohesive Stiffness Matrix
Summary of X-FEM for Abaqus Solution Modules

- Composite Laminate Simulation system
- Fatigue solution module
  - Cohesive damage accumulation (Turon’s model)
    - S-N based matrix properties damage
      - Failure criteria
        - Cohesive crack injection
    - Turon’s fatigue cohesive law
      - Failure criteria
        - Cohesive crack injection
          - VCCT based spring injection
            - Critical initial matrix crack size reached
    - S-N based matrix properties damage
      - Failure criteria
        - Cohesive crack injection
          - VCCT based spring injection
            - Critical initial delamination size reached
    - S-N based Cohesive strength and toughness damage
      - Critical initial cohesive law
        - Crack injection
          - Cohesive law
            - Not implemented yet
              - Need to be enhanced and validated further
              - Long term work

Notes:

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<table>
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<tr>
<th>$E_{11}$ (GPa)</th>
<th>$E_{22} = E_{33}$ (GPa)</th>
<th>$G_{12} = G_{13}$ (GPa)</th>
<th>$G_{23}$ (GPa)</th>
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<td>$\nu_{23}$</td>
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<td>$\sigma_0$ (MPa)</td>
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<td>0.45</td>
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RX-FEM Example: Strength and Damage Prediction of Composite Laminate

RX-FEM Example: Damage Pattern Comparison with Experimental Observation

Load Step N

+45°/90° Ply Interface

90°/-45° Ply Interface

-45°/0° Ply Interface
X-FEM Capability Illustration of Residual Prediction Module
X-FEM Capability Illustration for Fatigue Crack Propagation

\[ \sigma = 100 \text{ MPa} \]

![Diagram showing crack propagation under 100 MPa stress](image)

- 250 mm (initial crack 10 mm)
- 600 mm
- 75 mm
- 500 mm

![Graph showing crack length vs. stress intensity factor](image)

- Crack length (\(2a\)), mm
- Stress intensity factor (\(K_I\), N/mm)

- XFEM
- ASPAN

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Capability Illustration for Mesh Independent Fatigue Crack Propagation within Interface

- \( t = 2.236 \text{ mm, } [45/4-45/4] \)
- \( \sigma_{\text{max}} = 80 \text{ MPa} \)
- \( \sigma_{\text{min}} = 0 \text{ MPa} \)
- \( R_0 = 3.175 \text{ mm} \)
- \( D_0 = 5.425 \text{ mm} \)
- \( \text{W} = 25.4 \text{ mm} \)
- \( \text{L} = 101.6 \text{ mm} \)
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Parameter Analysis for Fatigue Delamination Propagation

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C does not affect the damage patterns
Fatigue Delamination Propagation Process

Case 21

Case 4

N (cycle)

dL (mm)
**S-N based fatigue damage accumulation of strength**

Turon's fatigue cohesive model

**Crack injection**

RF force decreases after crack injection

<table>
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<th>K (N/mm$^3$)</th>
<th>$\sigma_n$ (N/mm$^2$)</th>
<th>$\sigma_s$ (N/mm$^2$)</th>
<th>$G_{lc}$ (N/mm)</th>
<th>$G_{llc}$ (N/mm)</th>
<th>$\eta$</th>
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<tr>
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<td>$C_{ll}$</td>
<td>$m_l$</td>
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Demonstration of Fatigue Damage Accumulation of Laminated Plate

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<th>K (N/mm³)</th>
<th>σₙ (N/mm²)</th>
<th>σₛ (N/mm²)</th>
<th>Gₐ (N/mm)</th>
<th>Gᵢlc (N/mm)</th>
<th>Gᵢlc (N/mm)</th>
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<th>E₃ (N/mm⁶)</th>
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N = 15,470

N = 58,249

N = 61,165

N = 76,721

N = 85,966

N = 88,704

Material: T300/976

6 inch

1.75 inch

[60°/-60°]s ply thickness 0.005 inc

≥175 inch

K (N/mm³) σₙ (N/mm²) σₛ (N/mm²) Gᵢlc (N/mm) Gᵢlc (N/mm) η₁ R E₃ (N/mm⁶)

1.00E+06 60 90 0.2 1 2.239 0 11380

C₁ Cᵢl mᵢ mᵢl Gᵢth-I (N/mm) Gᵢth-II (N/mm) η₂

0.0616 0.0616 4.5 4.5 0 0 2.239

6 inch

1.75 inch

[60°/-60°]s ply thickness 0.005 inc

Material: T300/976

6 inch

1.75 inch

[60°/-60°]s ply thickness 0.005 inc

Material: T300/976

u₁ = 0.5 mm
Capability Illustration for a 2-Ply Plate with a Bolt/Nut Connection and an Interface Bonding (Mixed UEL and Abaqus’ Elements)

Problem Statement

Effective Stress Distribution at Ply Interface

$\varepsilon_{11}$ in $0^\circ$-ply

$\varepsilon_{22}$ in $90^\circ$-ply
Summary and Conclusions

- Implementation both standard X-FEM and RX-FEM with Abaqus for discrete crack description of matrix cracking and delamination.

- Development of VCCT-based delamination propagation model under fatigue loading.

- Implementation of fatigue crack initiation and the fatigue cohesive model for both matrix crack and delamination under cyclic loading.

- Developed a mesh independent crack front tracking via a spring model.

- Constructed the co-simulation framework for matrix cracking and delamination evolution in laminated composites.

- Final goal: an efficient analysis module for failure process simulation of composite laminates under monotonic/cyclic loadings.

- Future investigation of convergence issue associated with user-defined elements under monotonic load.