Numerical Analysis for Impact Behavior of CFRP Composite Structures

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CONTENTS

- Introduction
- Impact Experiment of Composite Plates
- Detection of Composite Damage
- Damage model of Composite material
- Numerical Simulation of Impact Test
- Summary & Conclusions
Composite materials have high specific stiffness and strength.

\[
\frac{E}{\rho} \quad \text{(Specific Stiffness)}
\]

\[
\frac{\sigma_y}{\rho} \quad \text{(Specific Strength)}
\]

Composite materials are widely used for various load carrying structures.

Research Objective

✓ Composite structures are exposed to lots of impacts during construction, operation and repairing process.

✓ Composite materials can be easily damaged by impact load with complex damage modes due to their low-toughness.

✓ Impact damages due to low velocity impact are hard to be detected and reduce composite strength.

✓ Therefore, Impact and composite damages need to be considered in design state and analysis tool is required.

Part I: Experiment

- Impact test of composite plate
- Inspection of impact damages
Impact test of composite plate

- Impact test was performed to investigate the impact response of composite structures.

- Graphite/Epoxy composite plates were fabricated with CU125NS prepreg (Hankuk Carbon Co.) using Autoclave.

- Test Energy: 5J ~ 40J

- Stacking Sequence: [02/902/02/902/02]s

- Dimensions 100mm x 100mm x 2.1mm
Impact test of composite plate

Equipments

- Universal Impact Testing Machine
  INSTRON DYNATUP 9250HV
- Impactor: hemi-sphere 6.5 kg, steel
- Impact Clamping Support Fixture
  - Hydraulic pressure: 350 kPa
- Test temperature: 20°C

Universal impact testing machine

Impactor

\[ r = 6.35 \text{ mm} \]
Impact test of composite plate

Contact force histories at various impact energies

✓ Critical damage appears from 15J
✓ Contact force is suddenly decreased after critical damage.
Impact test of composite plate

![Graph showing Maximum Contact Force vs. Maximum Central Deflection](image1)

- **Maximum Contact Force (kN)**: 2 to 5.5
- **Maximum Central Deflection (mm)**: 4 to 18

![Graph showing Maximum Central Deflection vs. Contact Force](image2)

- **Contact Force (kN)**: 0 to 5
- **Maximum Central Deflection (mm)**: 0 to 15

![Graph showing Impact Energy vs. Critical damage](image3)

- **Impact Energy (J)**: 0 to 40
- **Critical damage**
- **Perforation**
- **Internal Damage**
Impact test of composite plate

Absorbed Energy Ratio = \frac{\text{Absorbed Energy (J)}}{\text{Impact Energy (J)}}

✓ Absorbed energy ratio represents the degree of damage due to impact.
Inspection of impact damage

- Damaged area were inspected with C-scan
- 10MHz frequency signal was used.
  ⇒ overall damage areas were inspected.
Inspection of impact damage

Due to bottom layer delamination

15J

15J

Damage Area (cm²)

Max. Contact Force (kN)

0 5 10 15 20

2 2.5 3 3.5 4 4.5 5 5.5

Area (cm²)
Inspection of impact damage

Damage area without bottom layer delamination

Damage area with bottom layer Delamination

Impact Energy (J)

Damage Area (cm²)
Part II : Numerical Analysis

- Composite Damage model
Impact response and impact damage of composite materials are hard to be predicted because of their complex damage phenomena.

Impact damage of fiber reinforced laminated composite is complicated with several damage modes such as fiber breakage, matrix crack and delamination etc.

Composite damage model based on continuum damage mechanics was developed and implemented in the user subroutine of ABAQUS/explicit, VUMAT.
Composite damage model

✓ Continuum Damage mechanics (CDM) approach was originally developed by Kachanov and Rabotnov.

✓ It assumes that failure of fiber bundle follows the cumulative Weibull distribution function.

\[
\omega = 1 - \exp \left\{ - \frac{1}{m e} \left( \frac{E^0 \varepsilon}{X} \right)^m \right\}
\]

\( \varepsilon \): strain

\( X \): strength

\( E^0 \): initial stiffness

\( m \): shape parameter

✓ It assumes that the material properties are degraded following complementary cumulative distribution function (or survival function)

\[
d = 1 - \omega
\]

Composite damage model

- Some researchers determined the scale parameters with parametric studies.
- For the case of composite materials, $2 \sim 20$ is generally used.
- Shape parameter can be determined by statistical analysis of test data for strength.

- 3 shape parameters were used.
  - For fiber damage: $m_f = 20$
  - For matrix damage: $m_m = 5$
  - For shear damage: $m_s = 5$


- 20: fiber failure, 2: matrix crack, $2 \sim 10$: shear failure


- 10, 20 for fiber and matrix crack
Composite damage model

- Fiber-dir. damage variable
  \[ d_{1}^{(n+1)} = \min \left\{ \exp \left[ -\frac{1}{m_f} e \left( \frac{E_{11}^{0} \varepsilon_{11}}{X} \right)^{m_f} \right], d_{1}^{n} \right\} \]

- Transverse-dir. damage variable
  \[ d_{2}^{(n+1)} = \min \left\{ \exp \left[ -\frac{1}{m_m} e \left( \frac{E_{22}^{0} \varepsilon_{22}}{X} \right)^{m_m} \right], d_{2}^{n} \right\} \]

- Thickness-dir. damage variable
  \[ d_{3}^{(n+1)} = \min \left\{ \exp \left[ -\frac{1}{m_m} e \left( \frac{E_{33}^{0} \varepsilon_{33}}{X} \right)^{m_m} \right], d_{3}^{n} \right\} \]

- Shear-dir. damage variable
  \[ d_{4}^{(n+1)} = \min \left\{ \exp \left[ -\frac{1}{m_s} e \left( \frac{G_{12}^{0} \gamma_{12}}{X} \right)^{m_s} \right], d_{4}^{n} \right\} \]
  \[ d_{5}^{(n+1)} = \min \left\{ \exp \left[ -\frac{1}{m_s} e \left( \frac{G_{23}^{0} \gamma_{23}}{X} \right)^{m_s} \right], d_{5}^{n} \right\} \]
Composite damage model

Constitutive Equation of Composite material

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\tau_{12} \\
\tau_{23} \\
\tau_{31}
\end{bmatrix} =
\begin{bmatrix}
\frac{E_1(1-v_{23}v_{32})}{D} & \frac{E_1(v_{21}+v_{31}v_{23})}{D} & \frac{E_1(v_{31}+v_{21}v_{32})}{D} & 0 & 0 & 0 \\
\frac{E_1(v_{21}+v_{31}v_{23})}{D} & \frac{E_2(1-v_{31}v_{13})}{D} & \frac{E_2(v_{32}+v_{12}v_{31})}{D} & 0 & 0 & 0 \\
\frac{E_1(v_{31}+v_{21}v_{32})}{D} & \frac{E_2(v_{32}+v_{12}v_{31})}{D} & \frac{E_3(1-v_{12}v_{21})}{D} & 0 & 0 & 0 \\
0 & 0 & 0 & G_{12} & 0 & 0 \\
0 & 0 & 0 & 0 & G_{23} & 0 \\
0 & 0 & 0 & 0 & 0 & G_{31}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\gamma_{12} \\
\gamma_{23} \\
\gamma_{31}
\end{bmatrix}
\]

\[D = 1 - v_{12}v_{21} - v_{23}v_{32} - v_{31}v_{13} - 2v_{21}v_{32}v_{13}\]

Stress-strain curves of composite materials in fiber-direction at various shape parameters
Composite damage model

✓ Cohesive zone model was used to represent delamination.

✓ Quadratic nominal strain criterion was used for cohesive zone model.

\[
\left( \frac{\varepsilon_n}{\varepsilon_n^0} \right)^2 + \left( \frac{\varepsilon_s}{\varepsilon_s^0} \right)^2 + \left( \frac{\varepsilon_i}{\varepsilon_i^0} \right)^2 = 1
\]

• Ultimate strain
  t1: 0.005625
  t2: 0.01354
  t3: 0.01354

• Cohesive layer modulus
  Knn : 9.6 Mpa
  Kss : 4.3MPa
  Ktt : 4.3MPa

• Fracture toughness
  Glc : 330 N/m
  GIIc : 800 N/m
  GIIIc : 800 N/m

ABAQUS 6.7 manual
Impact analysis was performed with ABAQUS/explicit and the developed damage model in user material subroutine of ABAQUS/explicit.

Quad model is used to reduce computation time.

Clamping pressure 350kPa was applied on the upper surface of upper jig.

Cohesive zone model was used to represent delamination.
# Composite damage model: material properties

## Material Properties of Composite Plates

<table>
<thead>
<tr>
<th>System</th>
<th>CU125NS (graphite/epoxy) plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>100×100×2.1 mm</td>
</tr>
<tr>
<td>Layup</td>
<td>[0/90/0/90/0/0],</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elastic Moduli</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{11}$</td>
<td>135.4 GPa</td>
</tr>
<tr>
<td>$E_{22}$, $E_{33}$</td>
<td>9.6 GPa</td>
</tr>
<tr>
<td>$G_{12}$, $G_{13}$</td>
<td>4.8 GPa</td>
</tr>
<tr>
<td>$G_{23}$</td>
<td>3.2 GPa</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.31</td>
</tr>
<tr>
<td>$\nu_{23}$</td>
<td>0.52</td>
</tr>
<tr>
<td>$S_{11}$</td>
<td>2930 MPa</td>
</tr>
<tr>
<td>$C_{11}$</td>
<td>1650 MPa</td>
</tr>
<tr>
<td>$S_{22}$</td>
<td>54 MPa</td>
</tr>
<tr>
<td>$C_{22}$</td>
<td>240 MPa</td>
</tr>
<tr>
<td>$S_{12}$</td>
<td>65 MPa</td>
</tr>
<tr>
<td>$S_{13}$, $S_{23}$</td>
<td>65 MPa</td>
</tr>
</tbody>
</table>

Numerical Analysis: conversions test

- Impact energy: 5J
- Without damage model

![Simulation Images](image)

**Contact Force (kN) vs Time (ms)**

- 20x20
- 30x30
- 40x40
- 60x60
- 80x80

**Central Deflection (mm) vs Time (ms)**

- 20x20
- 30x30
- 40x40
- 60x60
- 80x80
Numerical Analysis

Contact force

- **5J**
- **8J**

Central Deflection

- with Damage Model
- without Damage Model
- experiment 1
- experiment 2
- experiment 3
### Numerical Analysis

#### Contact Force

- **10J**
  - **Contact Force (kN)**
  - Time (ms): 0, 5, 10, 15
  - With Damage Model
  - Without Damage Model

- **15J**
  - **Contact Force (kN)**
  - Time (ms): 0, 5, 10, 15
  - With Damage Model
  - Without Damage Model

#### Central Deflection

- **10J**
  - **Central Deflection (mm)**
  - Time (ms): 0, 5, 10
  - Experiment 1
  - Experiment 2
  - Experiment 3
  - Experiment 4

- **15J**
  - **Central Deflection (mm)**
  - Time (ms): 0, 5, 10
  - Experiment 1
  - Experiment 2
  - Experiment 3
  - Experiment 4
Numerical Analysis

Contact force

- 18J
- 20J

Central Deflection

- with Damage Model
- without Damage Model
- experiment 1
- experiment 2
- experiment 3
Numerical Analysis

✓ Comparison of projected damage area between analysis and experiment.

Impact energy 5J

Impact energy 15J
Summary & Conclusions

✓ Impact Tests of composite plates were performed at various impact energies to investigate the impact behaviors and impact damages.

✓ Impact damage was inspected with C-scan to inspect both visible and non-visible impact damages.

✓ Composite damage model based on continuum damage mechanics and maximum failure strain criteria was developed and implemented in the user material subroutine of ABAQUS/explicit.

✓ Impact analysis of composite plate were performed and the impact behaviors and impact damages were compared and the developed damage model was verified.

✓ The developed damage model and cohesive zone model was effective to predict the impact behaviors and impact damage of composite structures subjected to low velocity impact.
Thank you for your attention.