Computationally-efficient multiscale models for progressive failure and damage analysis of composite structures

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Motivation

Extensive penetration of composites for high-performance products

- Customer driven – fuel efficiency, passenger comfort
- Operating cost reduction
- Regulatory driven (ACARE 2010) – reduction in emissions

Moving away from the Black Aluminum approach

- Develop numerical models for composites to mimic physical behavior accurately
- Tackle computational efficiency vs accuracy trade-off

Current state of the art

- Extensive reliance of experimental testing
- Very conservative design approach
- Deficiency in existing design and modeling capabilities – “Black Aluminum approach”

Computational frameworks

- Supplement the testing pyramid with accurate simulation tools – guide testing campaigns
- Physical tests to computational models
  Virtual testing, ICME, Digital Twin programs
- Robust algorithms to interface different physics at different scales
Motivation

Virtual full-scale testing of A350XWB

- Full-scale FEM model
- 68 million DOFs
- Supplement static test campaign

Understanding underlying physics

- Advances in experimental testing
  - Eg: Non-destructive, in-situ imaging [Moffat et al. (2008)]
  - Diversified experimental campaigns

Challenges with virtual testing of composites

Robust and efficient mathematical models

- Physics-based constitutive modeling at relevant scales
- High fidelity, Computationally-efficient numerical models
- Robust interfacing across various models with respective scales
Scope of current research work

Build an efficient and robust set of numerical tools for progressive failure and damage analysis of composite across scales via refined beam models.
Contents

01 Carrera Unified Formulation

02 Nonlinear micromechanical analysis

03 Multiscale analysis

04 Interface modeling - Delamination

05 Impact modeling
Carrera Unified Formulation

1. **Theoretical formulation**

2. Three numerical cases

   A. Failure index evaluation: Demonstrates accuracy and efficiency
   B. Stress Analysis of Adhesively Bonded Joints
   C. Plastic beam bending: Demonstrates effectiveness of physically nonlinear analysis
Carrera Unified Formulation: Hierarchical higher-order 1D models

**1D Truss element**

Kinematic field:

\[
\begin{align*}
u_x(x, y, z) &= u_{x1} \\
u_y(x, y, z) &= u_{y1} \\
u_z(x, y, z) &= u_{z1}
\end{align*}
\]

**Timoshenko beam element**

Kinematic field:

\[
\begin{align*}
&\begin{align*}
&u_x(x, y, z) = u_{x1} \\
u_y(x, y, z) = u_{y1} + u_{y2}x + u_{y3}z \\
u_z(x, y, z) = u_{z1}
\end{align*}
\end{align*}
\]

**CUF beam element**

Kinematic field:

\[
\begin{align*}
&\begin{align*}
&u_x(x, y, z) = u_{x1} + u_{x2}x + u_{x3}z + \cdots \\
u_y(x, y, z) = u_{y1} + u_{y2}x + u_{y3}z + \cdots \\
u_z(x, y, z) = u_{z1} + u_{z2}x + u_{z3}z + \cdots
\end{align*}
\end{align*}
\]

CUF Kinematic field:

\[
u(x, y, z) = F_t(x, z) u(y)
\]

- Different basis functions are employed as \( F_t \) - current work mainly uses Lagrange polynomial.
- Formulated within the context of finite element using standard shape functions.
  \[
u(x, y, z) = N_i(y) F_t(x, z) u_{\tau i}\]
- Formulated as an invariant through Fundamental nuclei – same implementation for different classes of models or materials.
Carrera Unified Formulation: Component-wise modeling

- Lagrange polynomial based function – displacement unknowns only
- Each component of a complex structure is modeled as a beam
- Generalization of LW modeling technique

LW

Assembled structural matrix

CW

CW modeling of reinforced shell structure

Reinforced shell structure

Component-wise approach

Assembled cross-section

10 L-elements
Carrera Unified Formulation

1. Theoretical formulation

2. **Two numerical case**
   - A. Failure index evaluation: Demonstrates accuracy and efficiency
   - B. Stress Analysis of Adhesively Bonded Joints
   - C. Plastic beam bending: Demonstrates effectiveness of physically nonlinear analysis
Failure index evaluation of notched composite specimen (1)

- Laminate sequences: [0/90]
- IM7-8552 material system

**Failure indices evaluated:**
- Hashin failure index
- Delamination index

**Numerical models**
- CUF-CW models
- ABAQUS 3D

<table>
<thead>
<tr>
<th>Model</th>
<th>Load at first ply failure [kN]</th>
<th>Failure mode</th>
<th>DOF</th>
<th>Run time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUF-LW1</td>
<td>1.53</td>
<td>Matrix tension</td>
<td>28,242</td>
<td>19</td>
</tr>
<tr>
<td>CUF-LW2</td>
<td>1.5</td>
<td>Matrix tension</td>
<td>53,346</td>
<td>42</td>
</tr>
<tr>
<td>ABAQUS-1L</td>
<td>2.1</td>
<td>Matrix tension</td>
<td>187,320</td>
<td>42</td>
</tr>
<tr>
<td>ABAQUS-4L</td>
<td>1.8</td>
<td>Matrix tension</td>
<td>1,306,977</td>
<td>602</td>
</tr>
</tbody>
</table>

Transverse stress – through the thickness

---

Failure index evaluation of notched composite specimen

Summary

➢ On average, refined ABAQUS models underpredict failure indices by 42% with respect to CUF models

➢ Effectiveness of standard practice in using 3D linear elements (one element per layer) in capturing accurate stress fields is questionable

➢ CUF stands as an alternate and effective method to produce accurate resolution of stress fields and failure indices with improved computational efficiency

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Stress Analysis of Adhesively Bonded Joints

- Activity undertaken to compare and contrast analytical and efficient numerical models for bonded joints
- Analyzing various joint configuration with varied complexity
- Supplementing the Composite Technology Exploration activity undertaken by NASA

Models
1. Hypersizer – Commercial sizing tool [Mortensen et al. (2002)]
2. Joint Element Designer – semi-analytical tool [Stapleton et al. (2012)]
3. CUF-CW model
4. ABAQUS 3D model (Benchmark)


Stress Analysis of Adhesively Bonded Joints

Peel and shear stress along the top adhesive centerline

\[
\begin{align*}
\sigma_{zz} & (\text{ksi}) \\
\tau_{xz} & (\text{ksi})
\end{align*}
\]
Stress Analysis of Adhesively Bonded Joints

Summary
1. Accurate capturing the stress reversals observed close to the free surface
2. The runtime for all cases were under 110 seconds
3. Traction-free conditions are captured along the free surface
Effectiveness of higher-order 1D models for physically nonlinear problem

Aim
Emphasize on the validation and effectiveness of higher-order model under physically nonlinear regimes

Numerical model
• Plastic beam under bending
• Material model: Isotropic von-Mises plasticity with perfect hardening
• Two classes of CUF models: TE & LE
• Comparison with
  • Analytical solution [Timoshenko et al. (1991)]
  • ABAQUS 3D FEM solution

<table>
<thead>
<tr>
<th>Model</th>
<th>DOF</th>
<th>Displacement at limit load</th>
<th>Plasticity strength factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value [m]</td>
<td>Error (%)</td>
<td>Value</td>
</tr>
<tr>
<td>Analytical</td>
<td>-</td>
<td>4.62</td>
<td>1.50</td>
</tr>
<tr>
<td>ABAQUS (Coarse)</td>
<td>22,590</td>
<td>4.28</td>
<td>7.4</td>
</tr>
<tr>
<td>ABAQUS (Refined)</td>
<td>148,797</td>
<td>4.47</td>
<td>3.4</td>
</tr>
<tr>
<td>CUF-TE4</td>
<td>2,745</td>
<td>4.62</td>
<td>0.03</td>
</tr>
<tr>
<td>CUF-4L9</td>
<td>4,575</td>
<td>4.53</td>
<td>1.9</td>
</tr>
</tbody>
</table>


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Carrera Unified Formulation

Summary

1. Produces accurate stress field at reduced computational cost
2. Powerful numerical tool for physically nonlinear analysis
3. Efficiency vs fidelity trade-off handled pragmatically
Progressive failure capabilities within CUF framework

- Contact modeling
- Micromechanical analysis
- Interface modeling
- Multiscale analysis
- Failure index evaluation
- Nonlinear material models

• Quick & Accurate
• Free-edge analysis

- Low-velocity impact
- Scalable explicit solver

- Concurrent framework
- Highly-scalable – parallel implementation

- CUF Virtual testing platform

- Von-mises material model
- CDM-based progressive failure model (Crack band)

- 3D RVEs
- Nonlinear analysis
- Implemented in NASMAT under fully numerical category

- Delamination
- Debonding

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Micromechanical analysis

1. **Review and Formulation**

2. Three numerical cases
   A. Elastic homogenization
   B. Modeling pre-peak nonlinearity via classical plasticity
   C. Micromechanical progressive failure analysis
Overview

- Integral part of virtual testing framework for hierarchical material systems (Composites, polycrystalline systems)
- Two key aspects:
  - Localization (Down-scaling): Evaluation of local fields within the individual constituents for a given macroscopic load
  - Homogenization (Up-scaling): Computing effective behavior of the representative volume element (RVE)
- Approaches:
  - Analytical: Rules of mixture [Voigt(1889), Ruess (1929)], CCM [Hashin et al. (1964)], Mean-field theories [Mori et al. (1973)]
  - Semi-Analytical: Extension of MFH [Nemat-Nasser et al. (1986)], Method of Cells and its extensions: GMC, HFGMC,
  - Numerical: 2D and 3D FEM based [Sun et al. (1996)], MSG [Yu et al. (2016)], FFT [Moulinec (1997)]

Challenges

- Effectiveness of the method relies on proper constitutive modeling of individual constituents
- Accuracy of method depends heavily of kind of mathematical model employed – Accuracy vs runtime tradeoff
- Scaling to multi-scale framework – enhanced efficiency at lower scales can significantly boost the overall efficiency
Micromechanical formulation within CUF

- CUF-CW technique employed to model heterogenous triply periodic RVE
- Different constituents is degenerated into individual beams
- CW enables displacement continuity across the interfaces automatically
- Periodic boundary condition assumptions – simplification of PBC using CW
- Two nonlinear material models integrated
  - Shear driven plasticity model – Extension of von-Mises J2 theory
  - Progressive failure damage model based on crack band
- Implemented in NASMAT (New NASA multiscale framework) developed at NASA Glenn

Crack band model

- Crack band model - Numerous microcracks coalesce to form larger crack
  - [Bazant (1982), Pineda et al. (2012)]
- Isotropic continuum damage model for matrix – Mode I crack propagation
- Crack is oriented in the local tensile principal stress state
- Energy release rate is scaled with characteristic length to reduce mesh dependency
Micromechanical analysis

1. Review and Formulation

2. **Three numerical cases**
   - A. Elastic homogenization
   - B. Modeling pre-peak nonlinearity via classical plasticity
   - C. Micromechanical progressive failure analysis
Linear elastic homogenization

Dehomogenization of randomly distributed fiber composite under transverse loading

Normal transverse stress $\sigma_{xx}$

CW discretization of RVE

CUF-CW | DOF: 19,080
Runtime: 18s

ABAQUS 3D | DOF: 91,305
Runtime: 324s

Effective moduli of periodical cellular structure

Architecture of hexagonal honeycomb

CW discretization of RVE – 18L9

Predicted transverse Young’s modulus

<table>
<thead>
<tr>
<th>CUF-CW</th>
<th>FEM 3D</th>
<th>G-A MMM (Gibson et al.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0504</td>
<td>0.0498</td>
<td>0.0485</td>
</tr>
</tbody>
</table>

von-Mises stress contour $\sigma_{vm}$

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Modeling pre-peak nonlinearity via classical plasticity (1)

- Assumption: microdamage and inelastic material behavior in matrix is modeled similar to dislocation motion in metals
- Framework is able to experimental data points are input for post yield stress (Piece-wise interpolation within the data points)

Nonlinear shear behavior of unidirectional composites

- Experimental comparison of in-plane shear response of three material systems:
  - (a) IM7-8552, (2) HTA-6376 and (c) E-Glass-MY750
- Cross-section of RVE modeled as a square-packed
- Calibrated elastic and plastic hardening properties are used

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Randomly distributed fiber RVE under transverse tension

- Loading: Transverse tension
- Material models:
  - Fiber: Transversely isotropic elastic
  - Matrix: Isotropic J2 plasticity with linear hardening
- Numerical models
  - CUF-LE
  - ABAQUS 3D

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Micromechanical progressive failure analysis (1)

- Uni-directional E-Glass/MY 750 Epoxy composite under transverse tension
- Scanning electron microscope image show brittle like behavior characterized by matrix cracking [Gamstedt et al. (1999)]

- Material model:
  - Fiber: Elastic
  - Matrix: Isotropic crack band model

- Numerical model:
  - CUF-CW – 265L9 & 276L9
  - 3D FEM model

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Randomly distributed fiber RVE under transverse tension

- Tensile stress vs strain

<table>
<thead>
<tr>
<th>Model</th>
<th>DOF</th>
<th>Ultimate global stress [Mpa]</th>
<th>Runtime [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUF-CW (265L9)</td>
<td>19,080</td>
<td>46.15</td>
<td>36</td>
</tr>
<tr>
<td>CUF-CW (276L9)</td>
<td>24,843</td>
<td>45.71</td>
<td>48</td>
</tr>
<tr>
<td>ABAQUS-3D</td>
<td>91,305</td>
<td>51.11</td>
<td>108</td>
</tr>
</tbody>
</table>

Micromechanical progressive failure analysis (2)

Damage progression at various global strains (Gray: Fiber, Blue: undamaged matrix, Red: Damaged matrix)

<table>
<thead>
<tr>
<th>Model</th>
<th>Ultimate global stress [Mpa]</th>
<th>Strain at ultimate stress [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMC</td>
<td>54.6</td>
<td>0.0031</td>
</tr>
<tr>
<td>HFGMC</td>
<td>56.8</td>
<td>0.0031</td>
</tr>
<tr>
<td>FE-2D</td>
<td>51.3</td>
<td>0.0027</td>
</tr>
<tr>
<td>CUF-CW</td>
<td>59.7</td>
<td>0.0032</td>
</tr>
</tbody>
</table>

Square-packed RVE under transverse tension

Comparison of CUF-CW against literature solutions

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Micromechanical analysis

Summary

1. High-fidelity with great computational efficiency
2. Handle varying measures of nonlinearity accurately
3. Ideal candidate for computationally intensive application such as concurrent multiscale and impact analysis
Multiscale analysis

1. **Review and Formulation**

2. Three numerical cases
   
   A. Stiffness prediction of multi-directional laminates
   B. Linear multiscale analysis of open-hole specimen with randomly distributed large RVE
   C. Nonlinear analysis of open-hole specimen under tension
Continuum-based constitutive modeling well suited only for overall response of structures

Macroscale constitutive modeling accounts for heterogeneity at a given material point through implicit mathematical formulation

In Hierarchical structure, localized phenomena are heavily influenced by lower-scale features (Eg: Fiber distribution in composites) – macroscale constitutive modeling not suitable for nonlinear analysis

Within multiscale framework, material points are interfaced with explicit heterogenous definitions

Various coupling schemes are adopted:

- Hierarchical – One-way coupling
- Concurrent – Two-way coupling
- Synergistic – Blended approach
Multiscale analysis: Literature review

- Multiscale method based on classical homogenization technique initiated by Hill and its derivatives [Hill (1965), Huang et al. (1994)]
- Micromechanics toolbox based on Method of Cells and its derivatives (GMC/FHGMC/HOTFGM) - (New NASA Multiscale framework - NASMAT) [Aboudi et al. (2013), Naghipour et al. (2017)]
- Multiscale computational framework based on closed form solutions using CCM and GSCM method [Zhang et al. (2014)]
- FE-based multiscale models initiated by Feyel and coworkers for nonlinear analysis [Feyel et al. (2000)]
- Commercial codes such as DIGIMAT utilizes mean-field methods and its extensions [DIGIMAT (2008)]
- Exhorbitant computational costs addressed through
  - Parallel implementations – OpenMP/MPI/CUDA [Fritzen (2014)]
  - Reduced-order modeling based on Proper Orthogonal Decomposition (POD) or Proper Generalized Decomposition (PGD) [Chinesta et al. (2010)]
Multiscale analysis: Challenges

- Accuracy of predictions rely heavily on high-fidelity modeling at sub-scales
- Cost trade-off: Analysis time (long computer runs) vs Accuracy
- Scalability of multiscale algorithms to solve complex problems (Impact, full-scale structures etc.)
- Lack-of wide-spread adoption

[Aboudi et al. (2013)]
Computationally efficient concurrent multiscale based on CUF (1)

- Fully nested – concurrent framework
- Efficiency is derived at both scales using CUF models
- Parallel implementation- highly scalable (Hybrid OpenMP-MPI)
- Framework can handle
  - Multiple classes of RVE
  - Nonlinear material models
- Full micro tangent matrix developed through perturbation method
- Handles combinations of multiple structural models
  - 1D
  - 2D
  - 3D

Concurrent CUF framework

Computationally efficient concurrent multiscale based on CUF (2)

Consistent macroscopic tangent matrix computation

- Perturbation technique based on forward different approximation [Miehe and Koch (2002)]
- Computed by applying six infinitesimally small perturbation strains on the current macroscopic strain
- Perturbed stress can be computed as
  \[
  \delta \sigma = C_{\delta e} \delta e \\
  \delta \sigma^{n+1} = \sigma(e^{n+1} + \delta e, H^{n+1}) + \delta(\epsilon^{n+1}, H^{n+1})
  \]
- Each micro call involves 7 bvp solution (1 – macro stress and 6 – tangent matrix)
- Modified Newton-Raphson method adopted – tangent computed only at beginning of each load increment

Flowchart for concurrent CUF framework

Parallelization strategy: Hybrid OpenMP-MPI


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Multiscale analysis

1. Review and Formulation

2. Three numerical case
   A. Stiffness prediction of multi-directional laminates
   B. Linear multiscale analysis of open-hole specimen with randomly distributed large RVE
   C. Nonlinear analysis of open-hole specimen under tension
Multiscale analysis: Numerical Example 1

- Material system: IM7-8552
  - Fiber volume fraction: 65%

- Macro specimen interfaced with a square-packed RVE

- Tensile and Compressive stiffness prediction for three layups
  - $[0/45/90/-45]_{2s}$
  - $[60/0/60]_{3s}$
  - $[30/60/90/30/-60]_{2s}$

- Comparison with experimental and literature solutions

### Stiffness prediction of multi-directional laminates

<table>
<thead>
<tr>
<th>Model</th>
<th>Experimental</th>
<th>MAC/GMC</th>
<th>NCYL</th>
<th>CUF: 1D-1D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[0/45/90/-45]_{2s}$</td>
<td>48.3</td>
<td>49.1 (1.66%)</td>
<td>50.3 (4.14%)</td>
<td>49.4 (2.28%)</td>
</tr>
<tr>
<td>$[60/0/60]_{3s}$</td>
<td>48.8</td>
<td>48.9 (0.20%)</td>
<td>51.1 (4.71%)</td>
<td>50.44 (3.36%)</td>
</tr>
<tr>
<td>$[30/60/90/30/-60]_{2s}$</td>
<td>32.4</td>
<td>33.7 (4.01%)</td>
<td>34.5 (6.48%)</td>
<td>33.25 (2.62%)</td>
</tr>
</tbody>
</table>

All units in GPa. Quantities in parenthesis represent error with respect to experimental result.

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Linear multiscale analysis of open-hole specimen with randomly distributed large RVE

Two multiscale models

1. **1D-1D** (Macro and micro model: CUF beam)
2. **1D-3D** (Macro: CUF beam and micro: 3D FE)

<table>
<thead>
<tr>
<th>Model</th>
<th>Macro model</th>
<th>Micro model</th>
<th>Runtime [s]</th>
<th>Memory requirement [MB]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DOF</td>
<td>No. of GP</td>
<td>DOF</td>
<td>No. of GP</td>
</tr>
<tr>
<td>1D-1D</td>
<td>4,140</td>
<td>2,736</td>
<td>13,642</td>
<td>9,540</td>
</tr>
<tr>
<td>1D-3D</td>
<td>31,524</td>
<td>61,008</td>
<td>9.6</td>
<td>42.7</td>
</tr>
</tbody>
</table>

Multiscale analysis: Numerical Example 3

Nonlinear analysis of open-hole specimen under tension

Two multiscale models

1. **1D-1D** (Macro and micro model: CUF beam)
2. **3D-1D** (Macro: 3D FEM and micro: CUF beam) – Coarse & Refined

<table>
<thead>
<tr>
<th>Model</th>
<th>Macro model</th>
<th>Runtime [hh:mm]</th>
<th>Memory requirement [MB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D-1D</td>
<td></td>
<td>01:54</td>
<td>2.02</td>
</tr>
<tr>
<td>3D-3D (Coarse)</td>
<td></td>
<td>05:27</td>
<td>7.28</td>
</tr>
<tr>
<td>3D-3D (Refined)</td>
<td></td>
<td>08:25</td>
<td>8.75</td>
</tr>
</tbody>
</table>

Multiscale analysis: Numerical Example 3

Nonlinear analysis of open-hole specimen under tension

Inelastic strain contour plot at various time instances at both scales

Comparison of inelastic strain contour plots

Multiscale analysis

Summary

1. Efficient concurrent multiscale framework
2. Nonlinearity at lower scale are accurately and efficiently scaled up
3. On average, 3x faster runtime and 6x memory efficient wrt. 3D FE models
Progressive delamination analysis

1. **Cohesive formulation within CUF**
2. Numerical case
   A. Multiple delamination in composite specimen
Progressive delamination analysis: Overview

- Delamination – one of the most **predominant failure** in laminated composite structure

- Main causes: run-way debris impact, tool-drop during maintenance,
  
  high interlaminar stresses around material (e.g.: ply-drop) and geometric discontinuities (e.g.: free-edge)

- Two main numerical approaches:
  
  - **Cohesive zone models** [Dugdale (1960), Barenblatt (1962)]
    
    Cohesive fracture concept
  
  - **Virtual crack closure technique** [Rybicki and Kanninen (1977)]
    
    Based on linear elastic fracture mechanics
    
    Computationally cheap – restricted to problems to predefined cracks

- Precursor to precise delamination analysis: **Accurate transverse fields.**
Progressive delamination analysis: Challenges

- Accurate stress resolution requirement dictates the need of computationally intensive FE models
  - Judicious scaling of penalty stiffness and cohesive strength [Turon et al. (2007)]
  - Discrete cohesive zone modeling approach [Xie and Waas (2006)]

- Appropriate constitutive modeling of the cohesive surface
  - Updated mixed-mode cohesive law accounting for mode ratios [Joseph et al. (2018)]

- Extremely refined mesh near the cohesive zone
  - Efficient isometric implementations using B-splines and NURBS [Hosseini et al. (2015), Nguyen et al. (2014)]

- Convergence issues in tracing the equilibrium path
  - Viscous regularization [Gao et al. (2004)]
  - New class of arc-length solvers for fracture problems [Alfano et al. (2003), Gutierrez (2004)]

- Scalability to largescale structures is still computationally infeasible
Cohesive formulation within CUF

- Cohesive kinematics introduced within Component-wise modeling paradigm

- Three new types of cohesive expansion functions are introduced
  - CS4 (linear)
  - CS6 (Quadratic)
  - CS8 (Cubic)

- Cohesive displacement opening can be formulated as:

\[ \mathbf{u}^{+} = F_{T} N_{i} \mathbf{u}_{T,i}^{+}, \quad \mathbf{u}^{-} = F_{T} N_{i} \mathbf{u}_{T,i}^{-}, \quad [\mathbf{u}] = F_{T} N_{i} (\mathbf{u}_{T,i}^{+} - \mathbf{u}_{T,i}^{-}) \]
Cohesive formulation within CUF

Constitutive modeling

- Continuum damage mechanics based formulation [Simo et al. (1987), Turon et. Al.(2006)]
- Quadratic initiation criteria [Cui et al. (1992)]
- Propagation based on mixed-mode law based on Camanho and coworkers’ work (2003)

Dissipation-based arc length solver

- Developed by Gutierrez for geometrically linear fracture problem [Gutierrez (2004)]
- Path-following constraint based on global energy release rate

\[ g = \frac{1}{2} f^{ext}_T (\lambda_0 \Delta \mathbf{u} - \Delta \lambda \mathbf{u}_0) - \Delta \tau \]

- Total energy dissipation is a global quantity — no apriori selection of degrees of freedom
- Requires algorithmic switching for pure elastic branches in equilibrium curve
Progressive delamination analysis

1. Cohesive formulation within CUF
2. **Numerical case**
   A. Multiple delamination in composite specimen
Multiple delamination in composite specimen

- Experimental study undertaken by Robinson et al. (2000)
- Exhibits complex equilibrium path
- Elements are cross-section features and non-homogeneous 1D elements

<table>
<thead>
<tr>
<th>Model</th>
<th>DOF</th>
<th>Total number of increments</th>
<th>Total number of iterations</th>
<th>Analysis time [hh:mm]</th>
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<tbody>
<tr>
<td>CUF-CW: 12L9-4CS6</td>
<td>56,376</td>
<td>229</td>
<td>897</td>
<td>1:47</td>
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<tr>
<td>3D FEM - Coarse</td>
<td>56,133</td>
<td>213</td>
<td>835</td>
<td>1:25</td>
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<tr>
<td>3D FEM - Medium</td>
<td>111,537</td>
<td>298</td>
<td>1173</td>
<td>4:44</td>
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<tr>
<td>3D FEM - Refined</td>
<td>150,660</td>
<td>300</td>
<td>1188</td>
<td>7:15</td>
</tr>
</tbody>
</table>

Kaleel I., Petrolo M., Carrera E., Novel structural models for the progressive delamination of composite structures. (Under review) 2019.

Kaleel, Ibrahim - Computationally-efficient multiscale models for progressive failure and damage analysis of composite structures (Torino, 2019)
Delamination in composites

Multiple delamination in composite specimen: Damage progression

Kaleel I., Petrolo M., Carrera E., Novel structural models for the progressive delamination of composite structures. (Under review) 2019.

Kaleel, Ibrahim - Computationally-efficient multiscale models for progressive failure and damage analysis of composite structures (Torino, 2019)
Progressive delamination analysis

Summary

1. Accurate out-of-plane resolution leads accurate and efficient delamination propagation
2. Capture complex equilibrium path accurately
Impact modeling

1. Contact formulation within CUF
2. Numerical cases
   A. Rectangular block impact
   B. Rod impact
Impact modeling: Formulation

- Numerical modeling of impact – Computationally intensive
- Complexity arises from
  - Global contact detection (E.g: Bounding dox algorithm, bucket sort)
  - Contact discretization (E.g.: Node-to-node, node-to-surface, surface-to-surface)
  - Contact enforcement (Penalty or Lagrange multiplier)
  - Contact solver (Implicit and Explicit formulation)
- Beam based contact formulation by Wriggers and coworkers [Wriggers et al. (1997), Zavarise et al. (1997)]

Contact formulation within CUF

- Normal contact geometrical constrained in CUF formulation
  \[ g_N = (x_2 - x_1) \cdot n_1 \geq 0 \]
  \[ g_N = \left( \sum F_t N_i x_2 - \sum F_t N_i x_1 \right) \cdot n_1 \geq 0 \]

- Two classes contact discretization are implemented
  - Node-to-Node
  - Node-to-surface

- Contact enforcement achieved through
  - Penalty method
  - Lagrange multiplier method

- Parallel nonlinear solvers
  - Explicit - CDS
  - Implicit – Newton-Raphson based

Kaleel, Ibrahim - Computationally-efficient multiscale models for progressive failure and damage analysis of composite structures (Torino, 2019)

Nagaraj M. H., Kaleel I., Carrera E., Petrolo M., Contact analysis of laminated structures including transverse shear and stretching. (Under review) 2019.
Impact modeling

1. Contact formulation within CUF

2. **Numerical cases**
   A. Rectangular block impact
   B. Rod impact
**Impact modeling: Numerical results**

**Block impact**
- Linear elastic blocks
- Initial velocity imposed on impacting body
- Parallel explicit solver with node-to-node contact discretization

**Rod impact**

Displacement-time response

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Nagaraj M. H., Kaleel I., Carrera E., Petrolo M., Contact analysis of laminated structures including transverse shear and stretching. (Under review) 2019.

Kaleel, Ibrahim - Computationally-efficient multiscale models for progressive failure and damage analysis of composite structures (Torino, 2019)
Impact modeling

Summary

• Initial assessment affirms the applicability of CUF models of impact
Outcome

01. Developed a computationally efficient nonlinear tool for composite analysis

02. Various modes of nonlinear phenomena of composites across scales such as pre-peak nonlinearity, progressive failure, delamination are addressed using numerical tool

03. Virtual testing framework showcases multi-fold efficiency in terms of analysis time and memory requirements

04. Scalable multiscale implementations bridges the physically nonlinear behavior across scales

05. Integration of in-house developed tools with commercial software such as ABAQUS
Summary

**Computational models**
- Efficient multiscale models for progressive failure and damage analysis of composite structures (Torino, 2019)
- Micromechanics & Mesoscale modeling
- Fast and reliable failure index evaluation of meso-scale coupons
  - High-fidelity micromechanics framework capable of handling varying nonlinearity
  - Average computational savings: Runtime: 3x & Memory: 5x

**Constitutive modeling**
- Concurrent multiscale framework
  - Nonlinearity driven at lower scales and up-scaled
  - Average computational savings: Runtime: 3x & Memory: 6x

**Theory of structures**
- Interface & Impact modeling
  - Accurate resolution of transverse fields and highly scalable
  - Complex delamination propagation are captured
  - Average computational savings: Runtime: 4x & Memory: 2.7x

**Micromechanics & Mesoscale modeling**
- Convergence of models on complex assemblies
- Interface & Impact modeling
- Concurrent multiscale framework
- Nonlinearity driven at lower scales and up-scaled
- Average computational savings: Runtime: 4x & Memory: 5x
Journal Publication (12)


11. Nagaraj M. H., Kaleel I., Carrera E., Petrolo M. (2019), Contact analysis of laminated structures including transverse wise shear and stretching. (Under review)


Book Chapter (1)


# Training Activities/External activities

## Internal Training

**ScuDo Courses:**
1. Hard skill course: 149 Hrs
2. Soft skill course: 41 Hrs

**Master thesis supervision:**
1. MSc. Students - 2
2. Exchange student - 1

## External Research Activities

1. **Visiting Scholar at Purdue University** (West Lafayette, USA)
   - Host supervisor: Prof. Wenbin Yu, School of Aeronautics & Astronautics, Purdue University
   - Duration: 1 month

2. **Visiting Scholar at University of Washington** (Seattle, USA)
   - Host supervisor: Prof. Anthony M Waas, Chair, William E Boeing Department of Aeronautics and Astronautics, University of Washington
   - Duration: 4 months

3. **Visiting PhD student at MSc Software Company & e-Xstream Engineering, (Turin, Italy)**
   - Host supervisor: Mr. Daniele Catelani, Mr. Matteo Giugno
   - Duration: 4 months (Part-time basis)

4. **Visiting researcher at Multiscale and Multiphysics Modeling (LMS) Branch, NASA Glenn Research Centre** (Cleveland, USA)
   - Host supervisor: Dr. Evan Pineda
   - December 2018

## External Training

1. Workshops – 8
2. Seminars – 8
3. Conference presentations - 9

## Additional research projects

1. Project INTE PoliTO-Purdue University
2. Project COMPOSELECTOR
3. NASA-MUL² collaboration
Acknowledgment

This research work has been carried out within the project FULLCOMP (FULLy analysis, design, manufacturing, and health monitoring of COMPosite structures), funded by the European Union Horizon 2020 Research and Innovation program under the Marie Sklodowska-Curie grant agreement No. 642121.

Authors would also like to acknowledge the computational resources provided by HPC@POLITO (http://hpc.polito.it).
EXTRA SLIDES
ABAQUS-MUL² Integration
Integration Step #3: Output/Visualization

Kaleel, Ibrahim - Computationally-efficient multiscale models for progressive failure and damage analysis of composite structures - NASA GRC - December 14, 2018
Automatic Integration: Abaqus – CUF- NASMAT

- No extra coding was needed for Abaqus integration
- Only light debugging
- Demonstrates NASMAT “plug and play” capability
- Solution computed using multiple cpus