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

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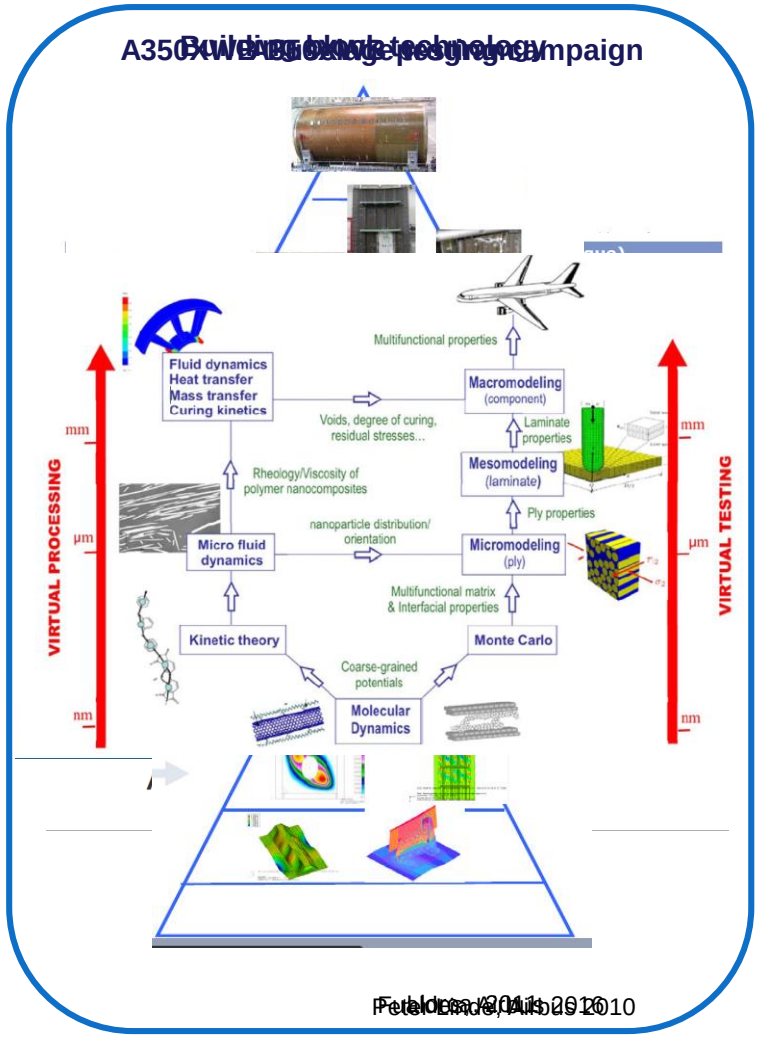
Motivation



Extensive penetration of composites for high-performance products

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

Current state of the art

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

Moving away from the Black Aluminum approach

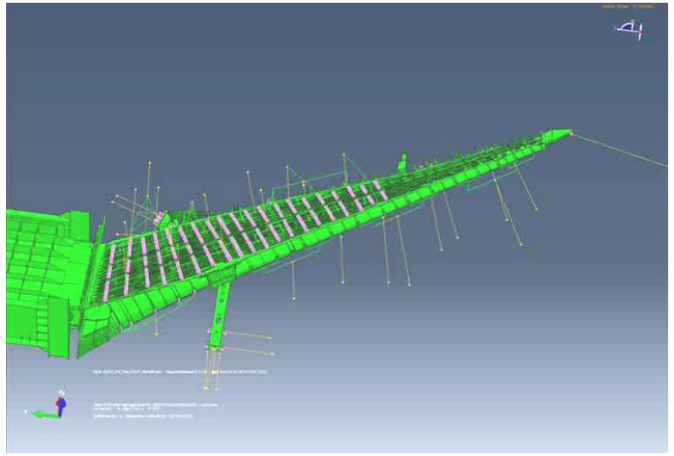
- Develop numerical models for composites to mimic physical behavior accurately
- Tackle computational efficiency vs accuracy trade-off

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

Fualdes, Airbus 2016

Challenges with virtual testing of composites

Understanding underlying physics

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

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

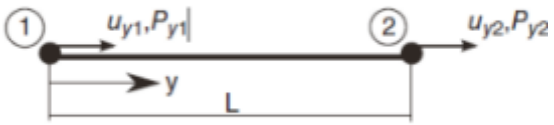
Contents

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

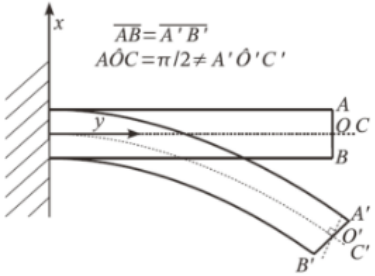
1D Truss element



Kinematic field:

$$u_x(x,y,z) = u_{x1}$$
$$u_y(x,y,z) = u_{y1}$$
$$u_z(x,y,z) = u_{z1}$$

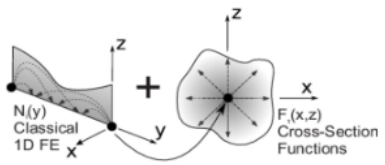
Timoshenko beam element



Kinematic field:

$$u_x(x,y,z) = u_{x1}$$
$$u_y(x,y,z) = u_{y1} + u_{y_2}x + u_{y_3}z$$
$$u_z(x,y,z) = u_{z1}$$

CUF beam element



Kinematic field:

$$u_x(x,y,z) = u_{x1} + u_{x_2}x + u_{x_3}z + \cdots$$
$$u_y(x,y,z) = u_{y1} + u_{y_2}x + u_{y_3}z + \cdots$$
$$u_z(x,y,z) = u_{z1} + u_{z_2}x + u_{z_3}z + \cdots$$

CUF Kinematic field: $u(x,y,z) = F_\tau(x,z)\, u(y)$

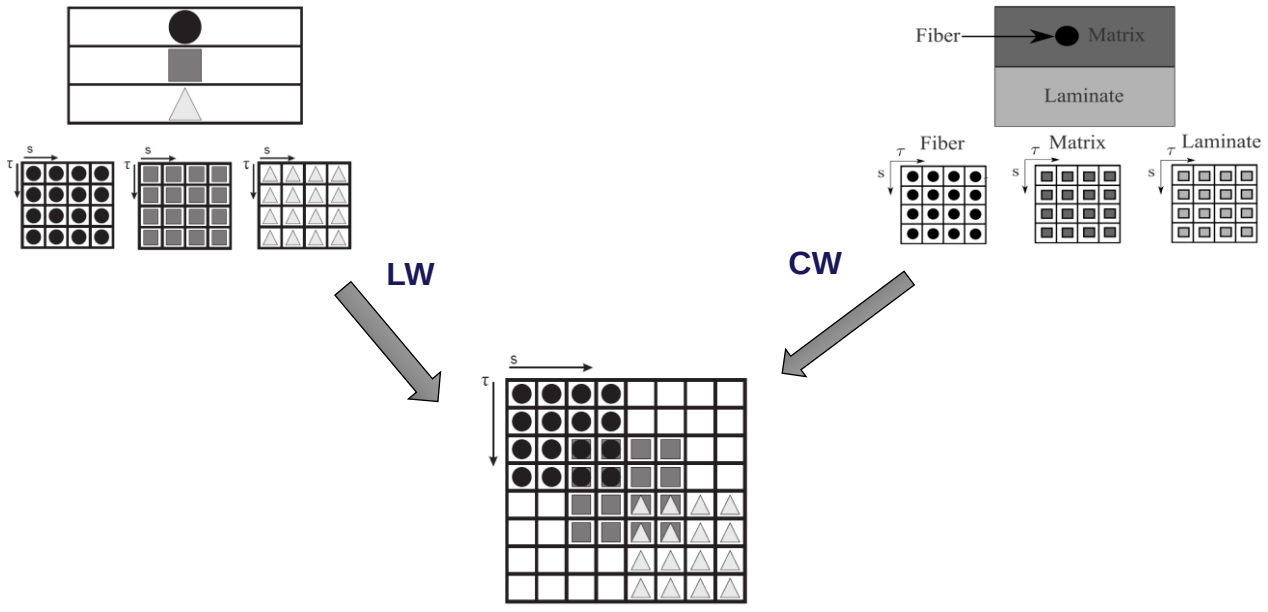
- Different basis functions are be employed as F_τ - current work mainly uses Lagrange polynomial
- Formulated within the context of finite element using standard shape functions

$$u(x,y,z) = N_i(y) F_\tau(x,z)\, u_{\tau i}$$

- Formulated as an invariant through Fundamental nuclei – same implementation for different classes of models or materials

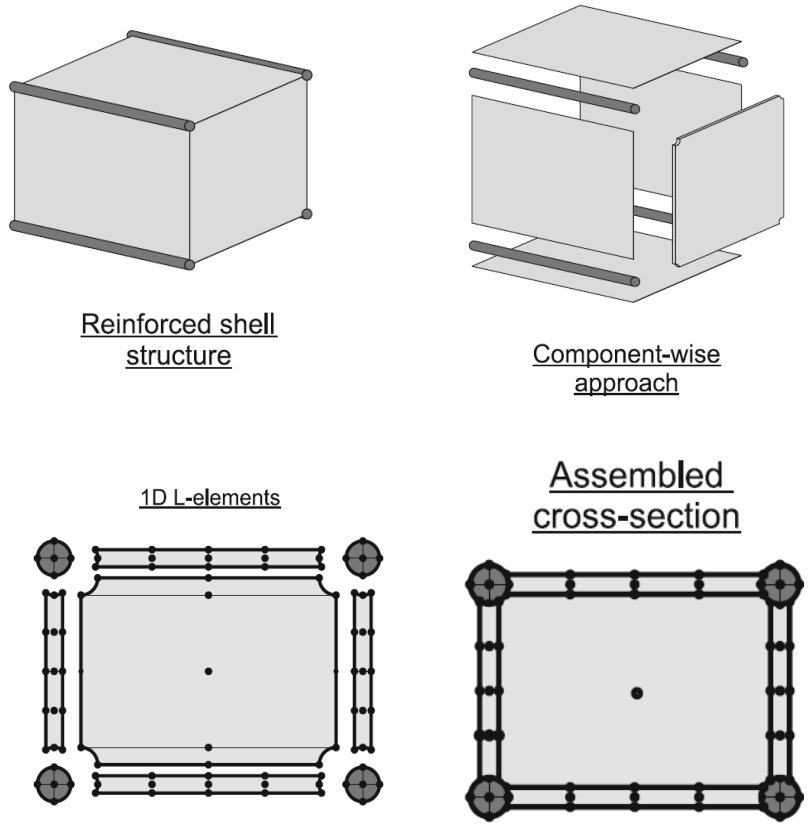
Carrera Unified Formulation: Component-wise modeling

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



Assembled structural matrix

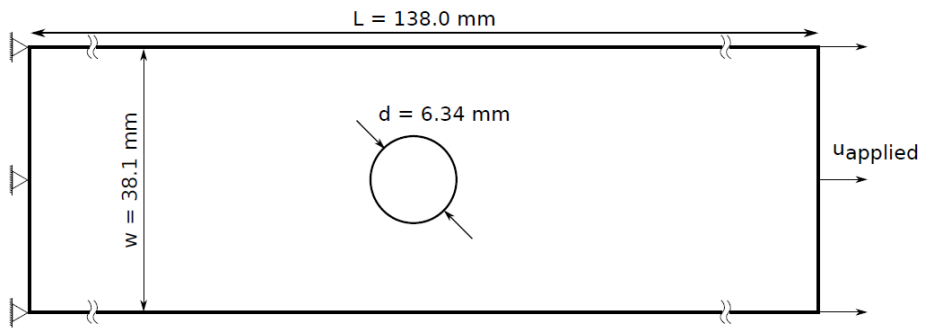
CW modeling of reinforced shell structure



Carrera Unified Formulation

1. Theoretical formulation
2. **<u>Two numerical case</u>**
   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: $[0/90]_s$
- IM7-8552 material system

Failure indices evaluated:

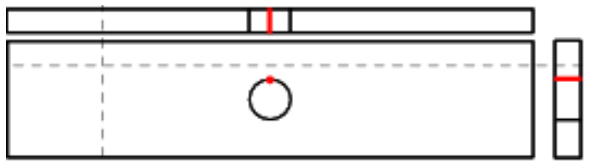
- Hashin failure index
- Delamination index

Numerical models

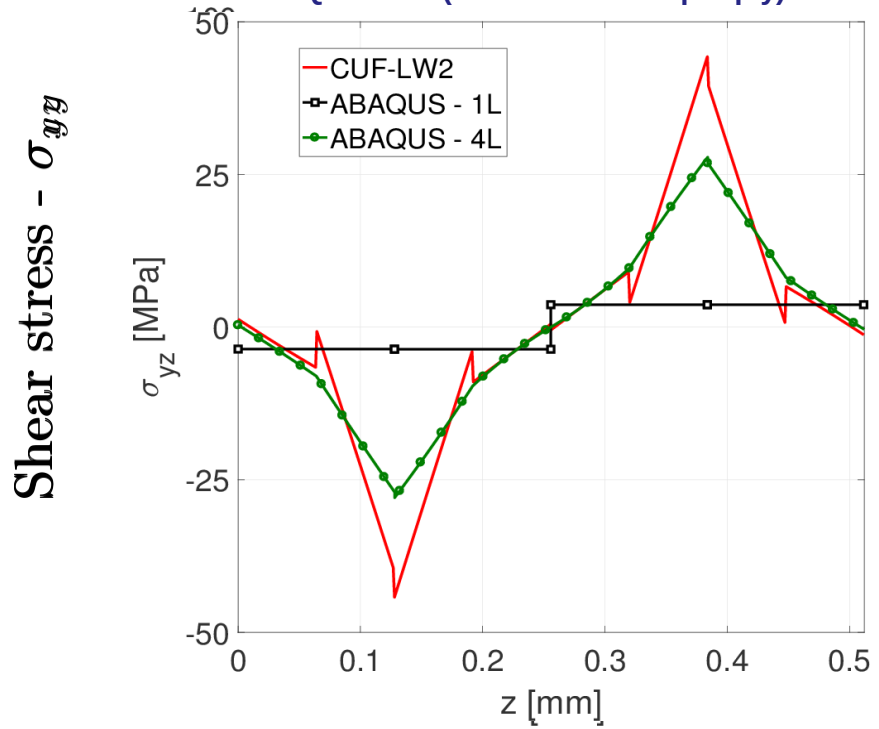
- CUF-CW models
- ABAQUS 3D

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

Transverse stress – through the thickness



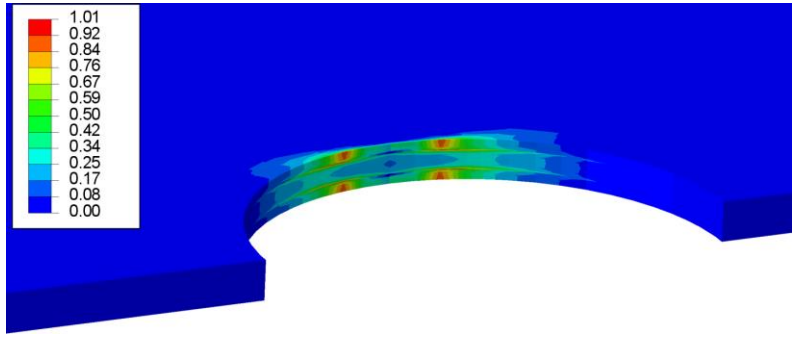
CUF-LW2 (Two 1 per ply) vs ABAQUS – 1L (One linear element per ply) vs ABAQUS – 4L (4 linear element per ply)



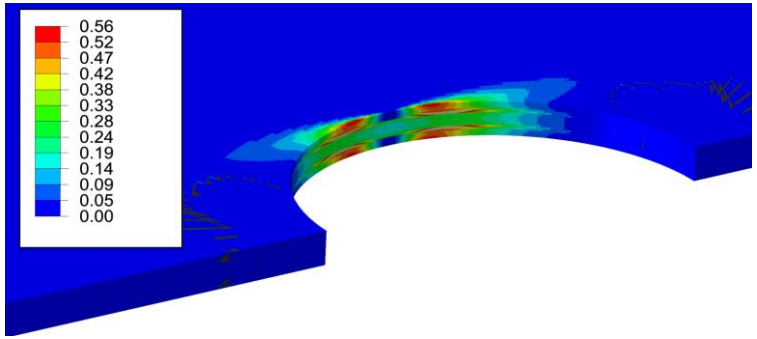
de Miguel A.G., Kaleel I., Nagaraj M. H., Petrolo M. Pagani A., Carrera E. (2018), Accurate evaluation of failure indices of composite layered structure via various FE models", Composite Science and Technology 167:174-189

Failure index evaluation of notched composite specimen (2)

Matrix tension failure index

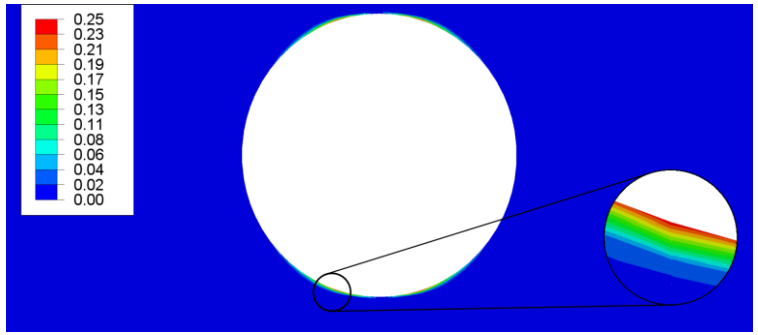


CUF-2L

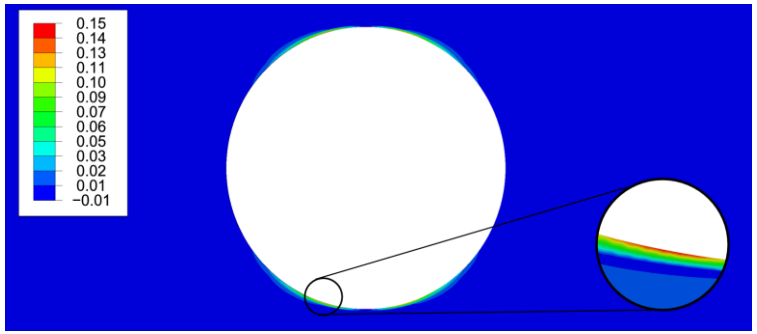


ABAQUS-4L

Delamination index



CUF-2L



ABAQUS-4L

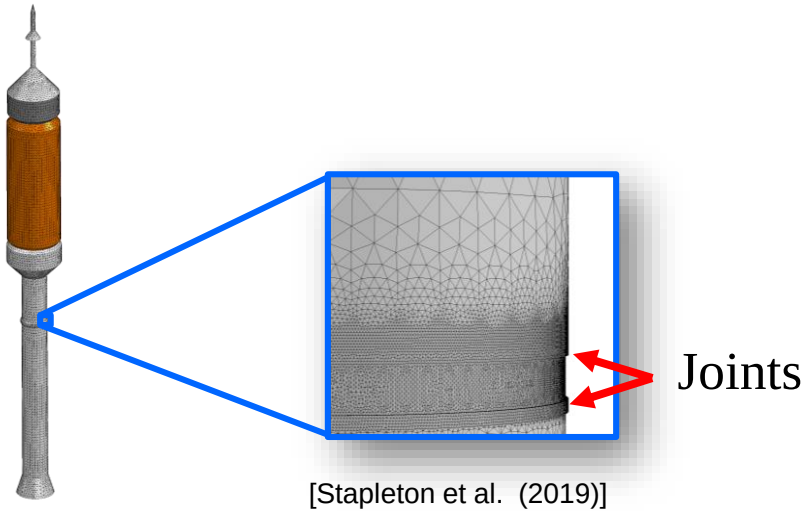
Summary

- On average, refined ABAQUS models underpredicts 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

de Miguel A.G., Kaleel I., Nagaraj M. H., Petrolo M. Pagani A., Carrera E. (2018), Accurate evaluation of failure indices of composite layered structure via various FE models", Composite Science and Technology 167:174-189

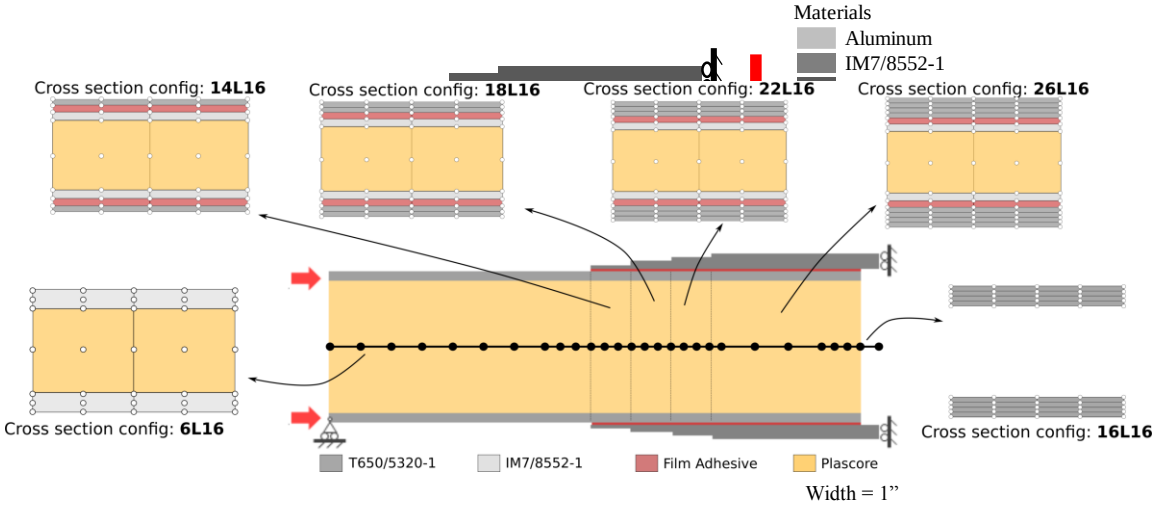
Stress Analysis of Adhesively Bonded Joints

- 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



[Stapleton et al. (2019)]

Bonded joint geometry, material & boundary conditions

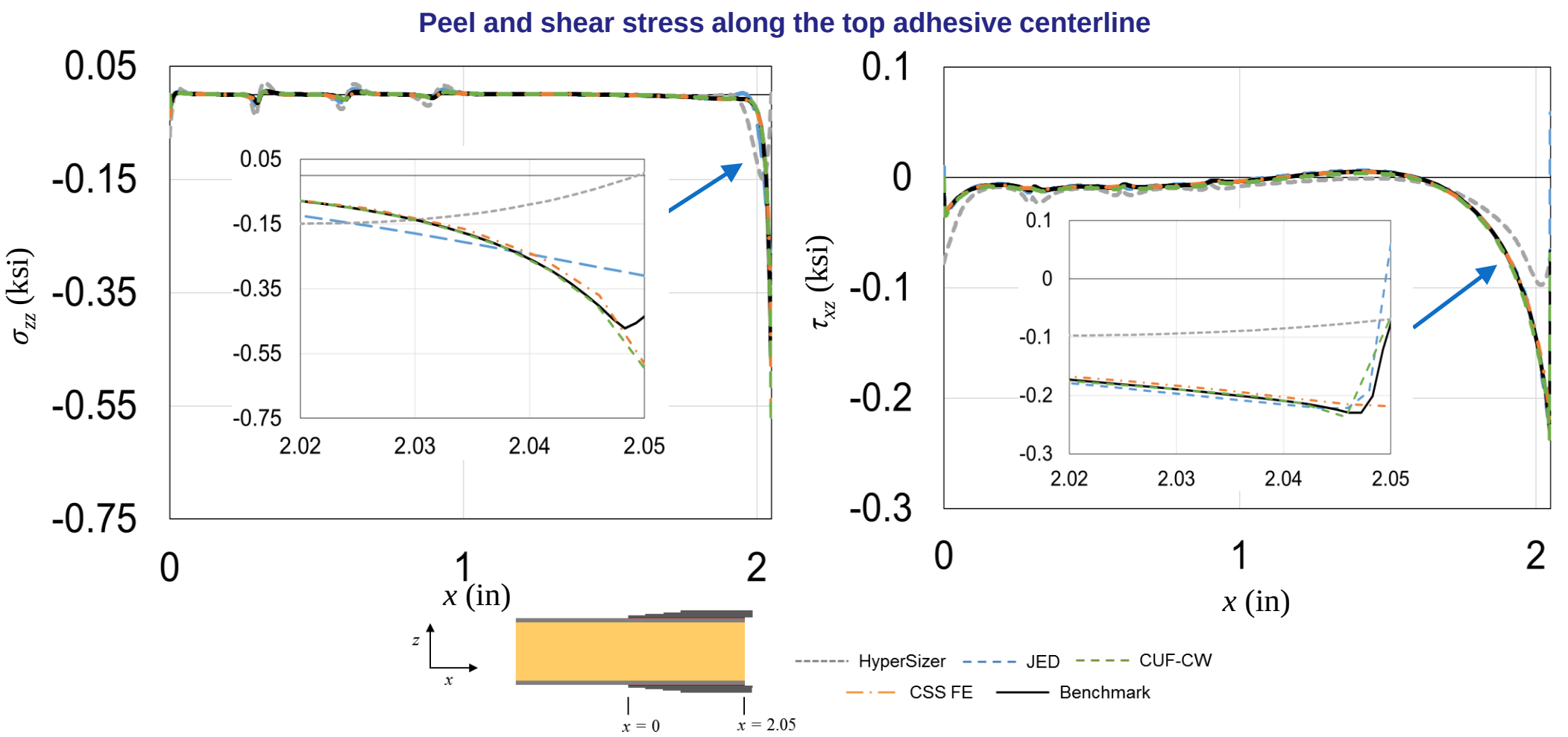


Models

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)

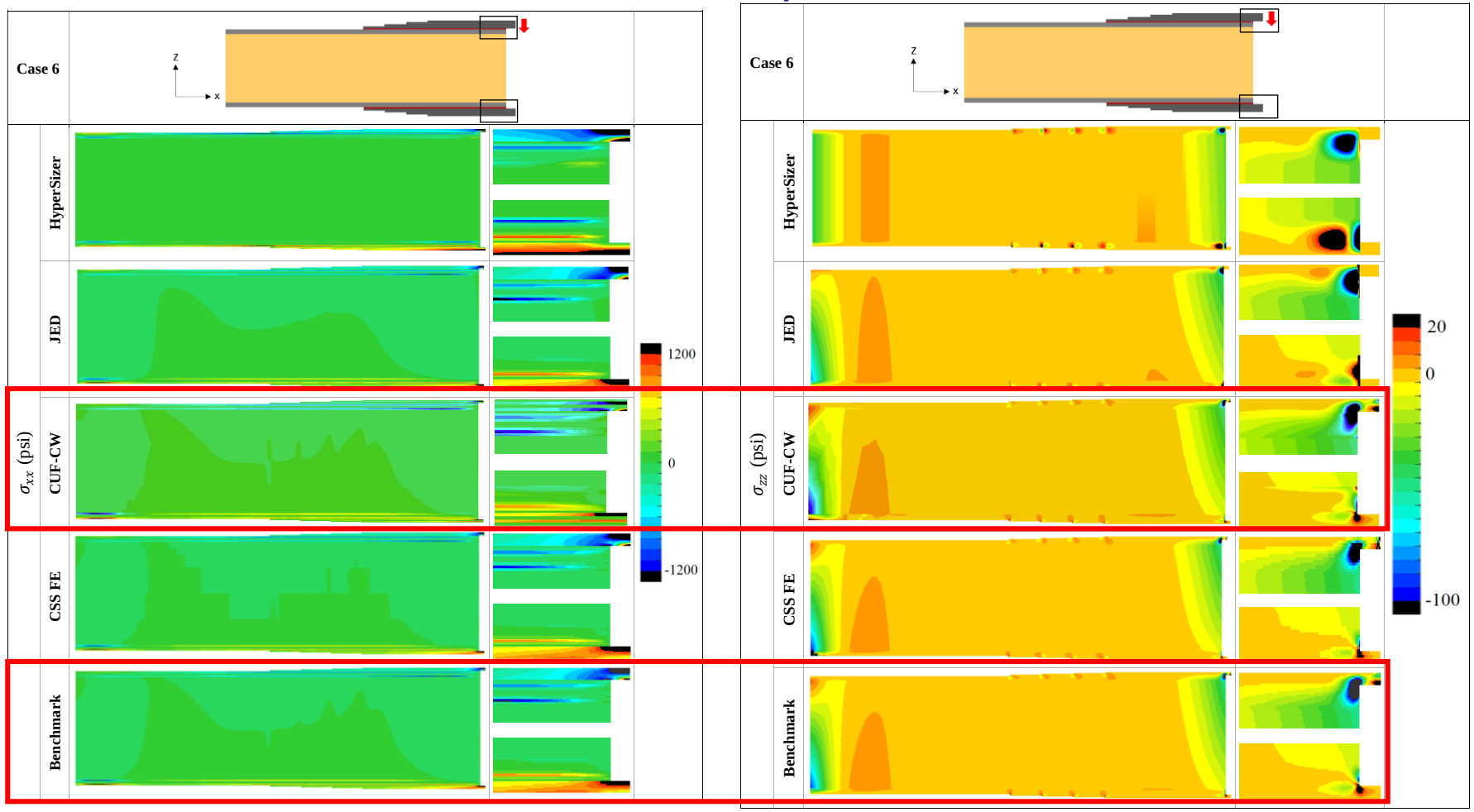
Stapleton S. E., Stier B., Jones S., Bergan A., Bednarcyk B. A., Kaleel I., Petrolo M., Carrera E. (2019), “A Critical Assessment of Design Tools for Stress Analysis of Adhesively Bonded Joints” (Under work)

Stress Analysis of Adhesively Bonded Joints



Stress Analysis of Adhesively Bonded Joints

Stress contour plots



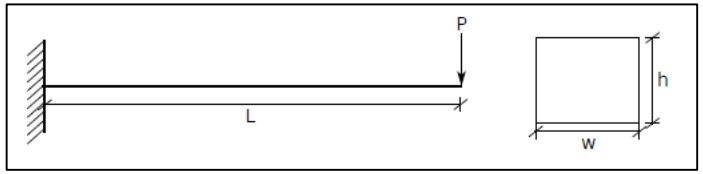
Summary

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



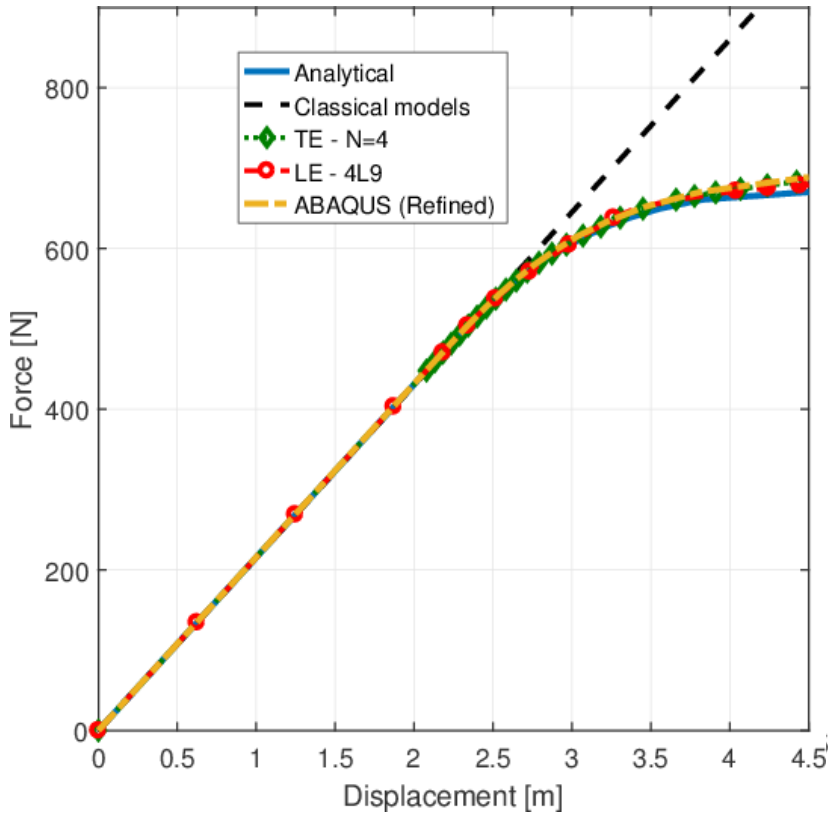
Numerical model

- 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

Model	DOF	Displacement at limit load		Plasticity strength factor	
		Value [m]	Error (%)	Value	Error (%)
Analytical	-	4.62	-	1.50	-
ABAQUS (Coarse)	22,590	4.28	7.4	1.55	3.6
ABAQUS (Refined	148,797	4.47	3.4	1.54	2.4
CUF-TE4	2,745	4.62	0.03	1.52	1.3
CUF-4L9	4,575	4.53	1.9	1.52	1.3

Load–displacement curve

Analytical vs Classical models vs CUF models (LE & TE) vs ABAQUS 3D



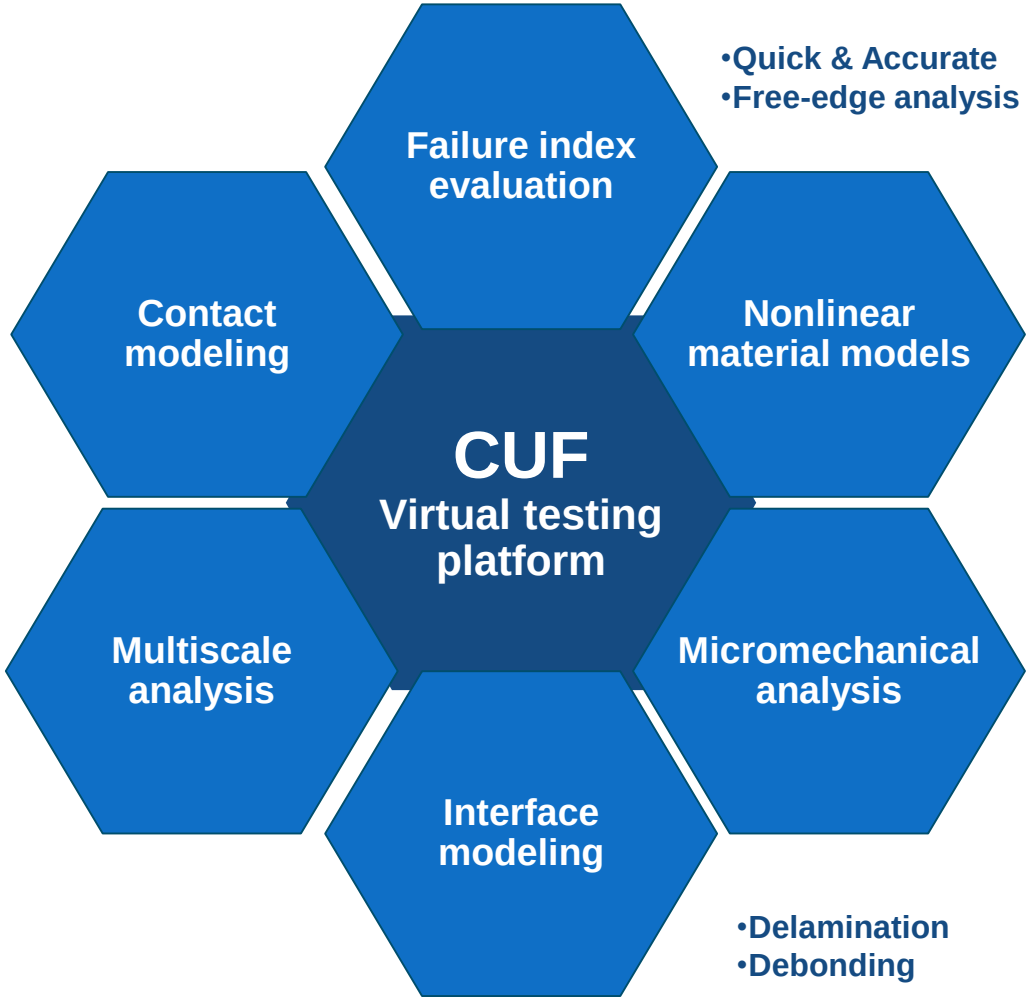
Carrera E., Kaleel I., Petrolo M. (2017), “Elastoplastic analysis of compact and thin-walled structures using classical and refined beam finite element models”, Mechanics of Advanced Materials and Structures

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



- Quick & Accurate
- Free-edge analysis

- Low-velocity impact
- Scalable explicit solver

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

- Concurrent framework
- Highly-scalable – parallel implementation

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

- Delamination
- Debonding

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

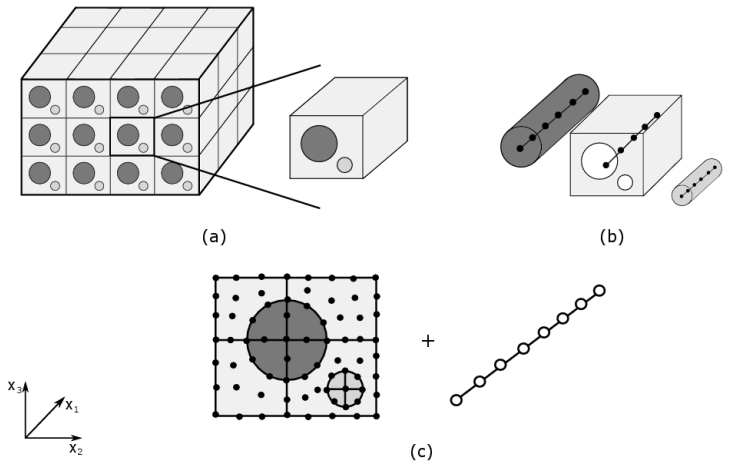
Overview

- 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

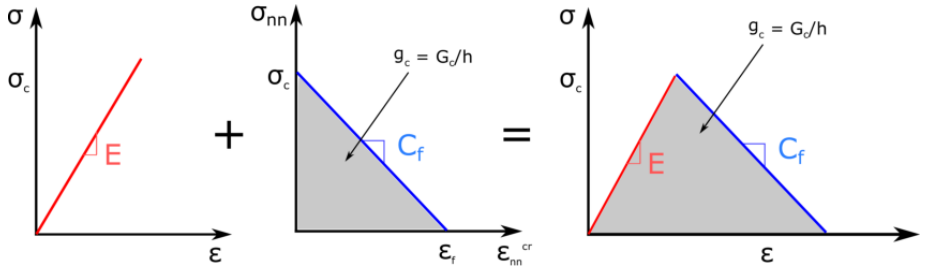
- Effectiveness of the method relies on proper constitutive modeling of individual constituents
- Accuracy of method depends heavily of kind of mathematical model employed – Accuracy vs runtime tradeoff
- Scaling to multi-scale framework – enhanced efficiency at lower scales can significantly boost the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

Kaleel I., Petrolo M., Waas A.M., Carrera E. (2017), "Computationally efficient, high-fidelity micromechanics framework using refined 1D models", Composite Structures 181:358-367.

Micromechanical analysis

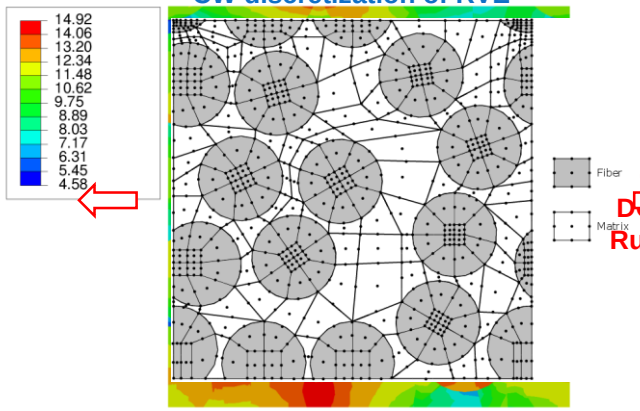
1. Review and Formulation
2. **Three numerical cases**
   A. Elastic homogenization
   B. Modeling pre-peak nonlinearity via classical plasticity
   C. Micromechanical progressive failure analysis

Linear elastic homogenization

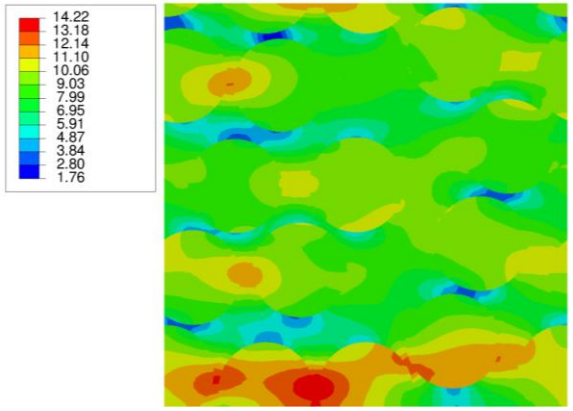
Dehomogenization of randomly distributed fiber composite under transverse loading

Normal transverse stress σ_{xx}

CW discretization of RVE



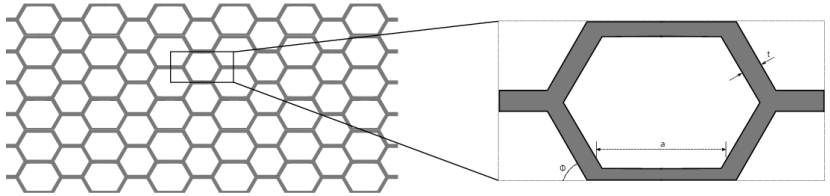
CUF-CW
DOF: 19,080
Runtime: 18s



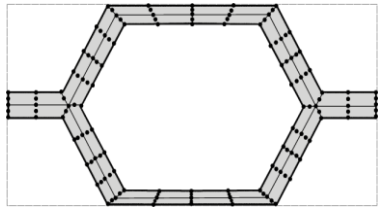
ABAQUS 3D
DOF: 91,305
Runtime: 324s

Effective moduli of periodical cellular structure

Architecture of hexagonal honeycomb



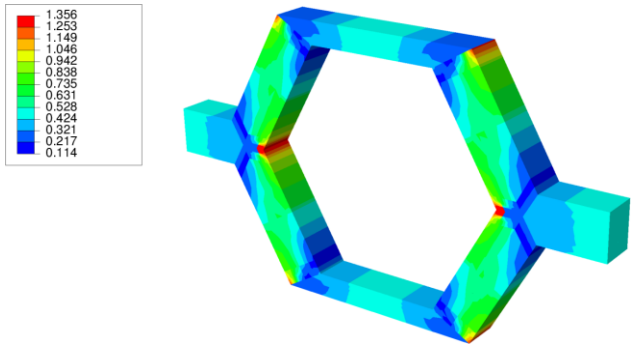
CW discretization of RVE – 18L9



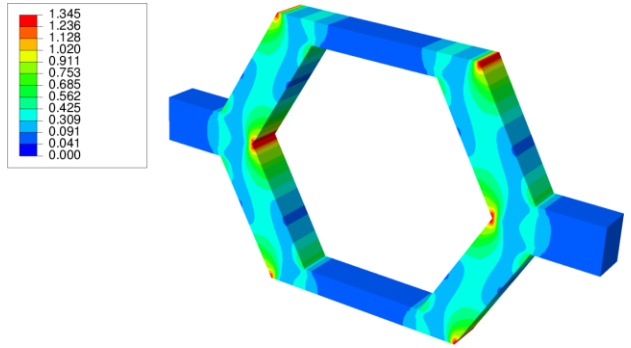
Predicted transverse Young's modulus

CUF-CW	FEM 3D	G-A MMM (Gibson et al.)
0.0504	0.0498	0.0485

von-Mises stress contour σ_{vm}



CUF-CW | DOF: 6,993



ABAQUS | DOF: 79,104

Kaleel I., Petrolo M., Waas A.M., Carrera E. (2017), "Computationally efficient, high-fidelity micromechanics framework using refined 1D models", Composite Structures 181:358-367.

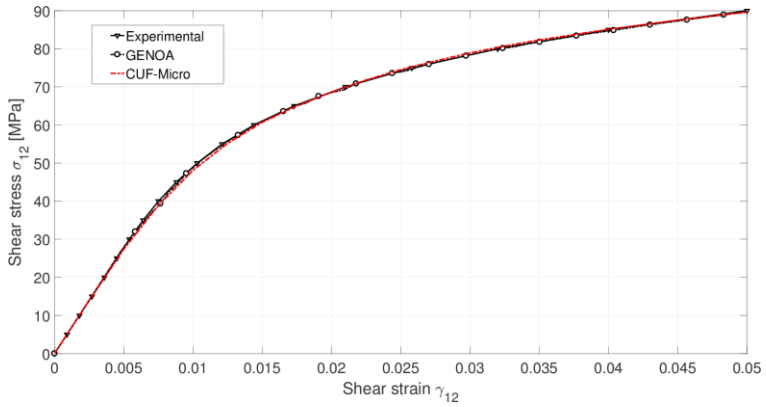
Modeling pre-peak nonlinearity via classical plasticity (1)

- 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)

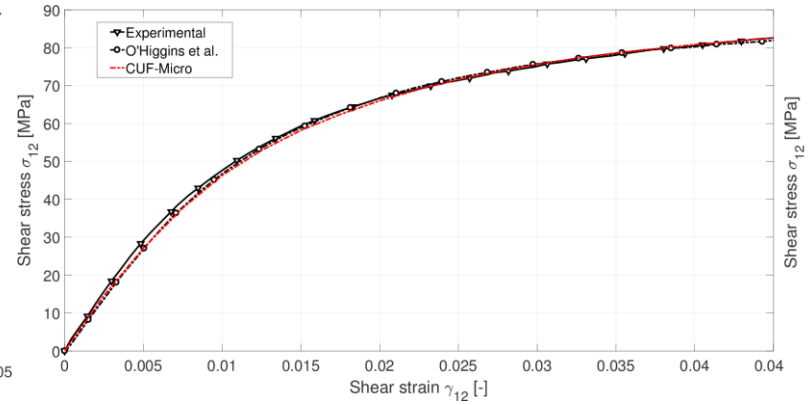
Nonlinear shear behavior of unidirectional composites

- Experimental comparison of in-plane shear response of three material systems:

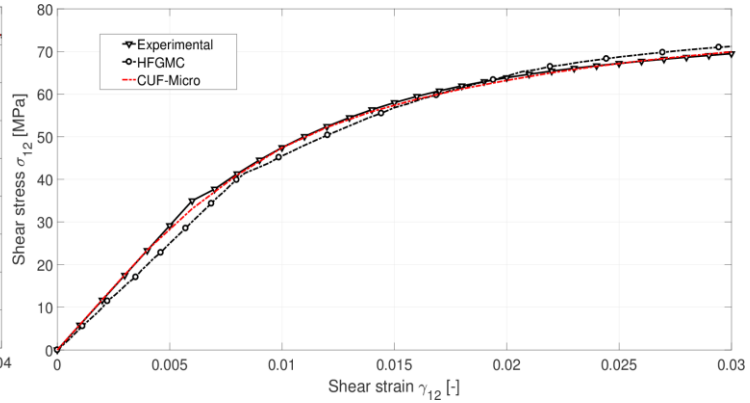
  (a) IM7-8552, (2) HTA-6376 and (c) E-Glass-MY750
- Cross-section of RVE modeled as a square-packed
- Calibrated elastic and plastic hardening properties are used



IM7-8552



HTA-6376



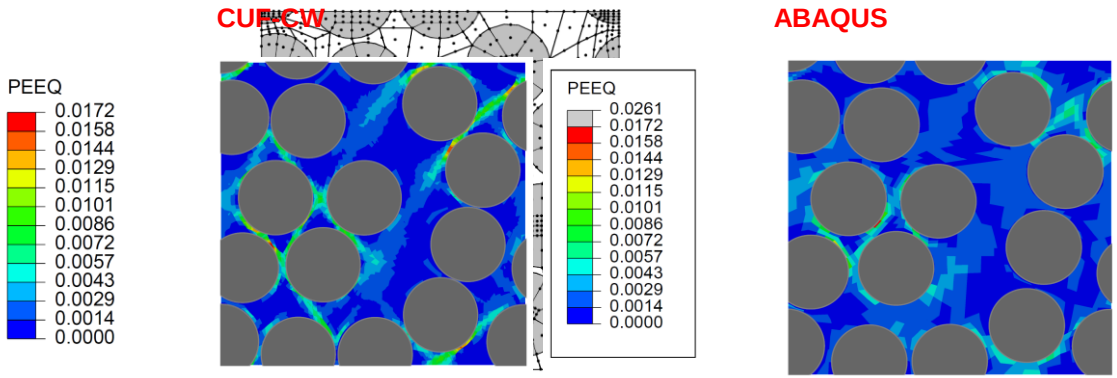
E-Glass-MY750

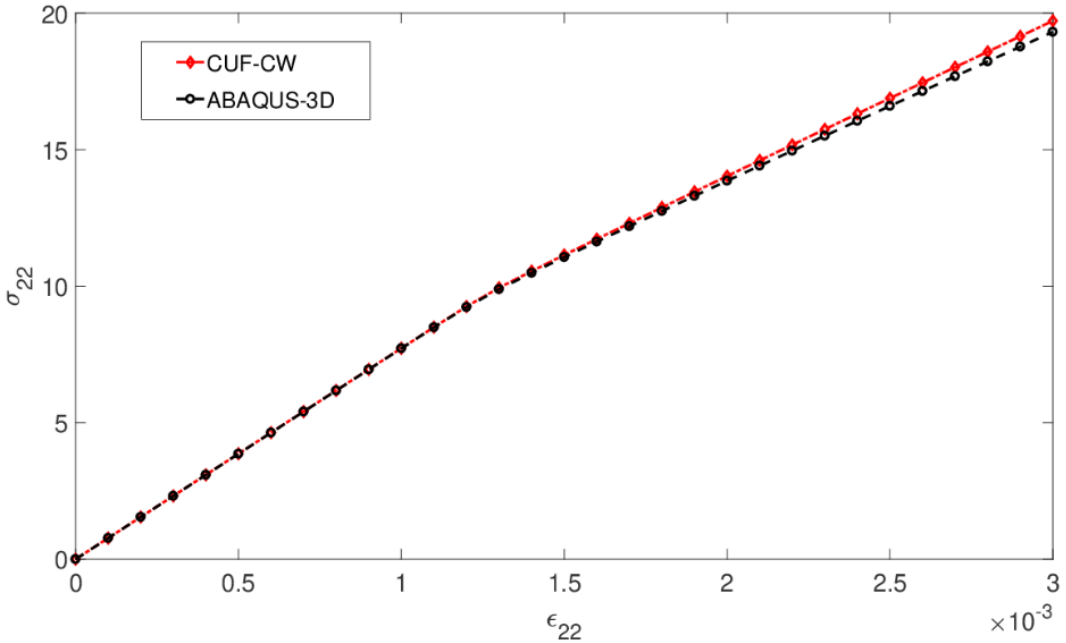
Kaleel I., Petrolo M., Carrera E., Elastoplastic and progressive failure analysis of fiber-reinforced composites via an efficient nonlinear microscale model. Aerotecnica Missili & Spazio - 97:103.

Modeling pre-peak nonlinearity via classical plasticity (2)

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





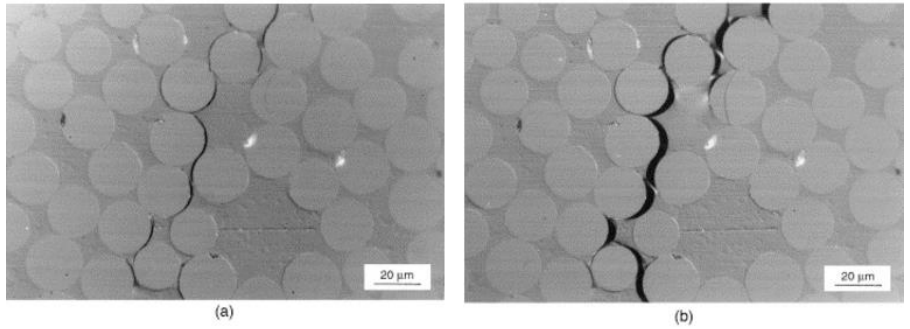
Model	DOF	No. of GP	Runtime [s]	Average iters per incr
	~6.7x	~10.4x	~3.7x	
CUF-CW	13,644	9,540	1,109	4
ABAQUS-3D	91,305	99,060	4,034	4

Kaleel I., Petrolo M., Carrera E., Elastoplastic and progressive failure analysis of fiber-reinforced composites via an efficient nonlinear microscale model. Aerotecnica Missili & Spazio - 97:103.

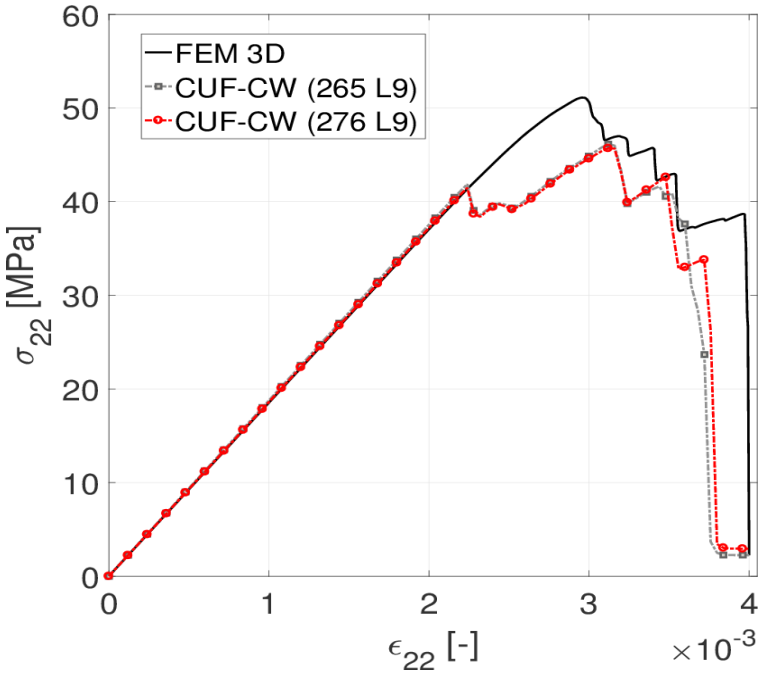
Micromechanical progressive failure analysis (1)

Randomly distributed fiber RVE under transverse tension

- 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

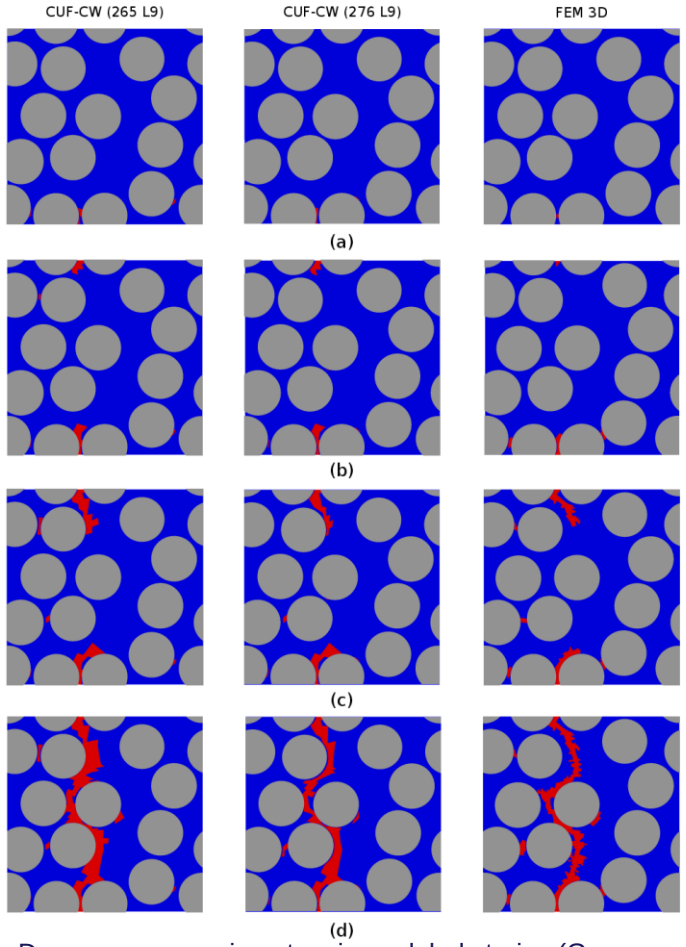


Tensile stress vs strain

Model	DOF	Ultimate global stress [Mpa]	Runtime [min]
CUF-CW (265L9)	19,080	46.15	36
CUF-CW (276L9)	24,843	45.71	48
ABAQUS-3D	91,305	51.11	108

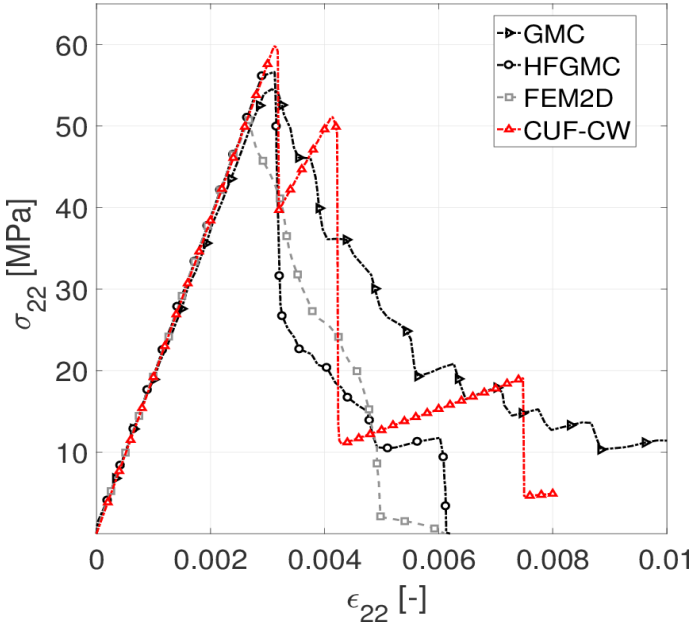
Kaleel I., Petrolo M., Waas A. M., Carrera E. (2017), Micromechanical Progressive Failure Analysis of Fiber-Reinforced Composite using Refined Beam Models. ASME. J. Appl. Mech. 85(2):021004-021004-8

Micromechanical progressive failure analysis (2)



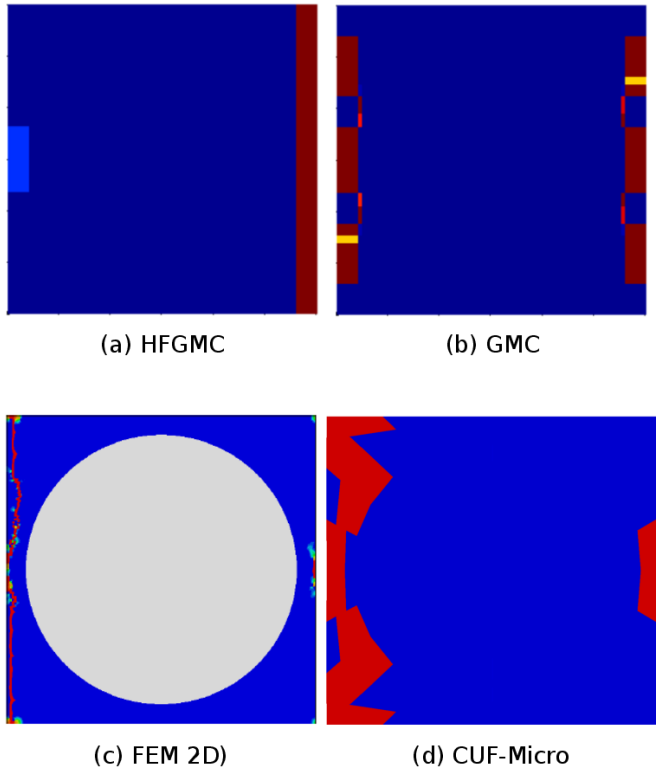
Damage progression at various global strains (Gray: Fiber, Blue: undamaged matrix, Red: Damaged matrix)

Square-packed RVE under transverse tension



Model	Ultimate global stress [Mpa]	Strain at ultimate stress [-]
GMC	54.6	0.0031
HFGMC	56.8	0.0031
FE-2D	51.3	0.0027
CUF-CW	59.7	0.0032

Comparison of CUF-CW against literature solutions



(Pineda et al. 2012)

Kaleel I., Petrolo M., Waas A. M., Carrera E. (2017), Micromechanical Progressive Failure Analysis of Fiber-Reinforced Composite using Refined Beam Models. ASME. J. Appl. Mech. 85(2):021004-021004-8
Kaleel I., Petrolo M., Carrera E., Elastoplastic and progressive failure analysis of fiber-reinforced composites via an efficient nonlinear microscale model. Aerotecnica Missili & Spazio - 97:103.

Micromechanical analysis

Summary

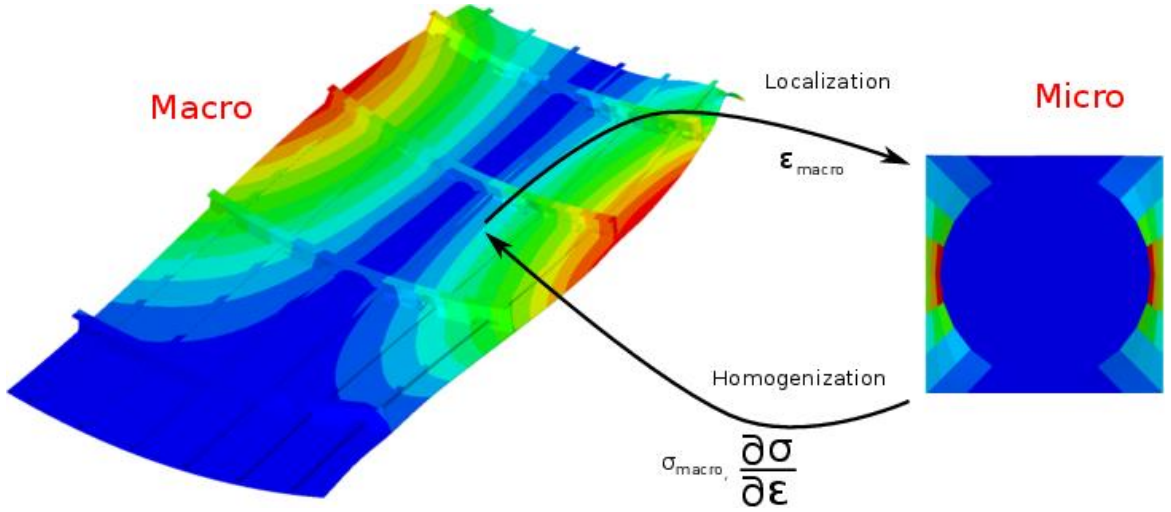
1. High-fidelity with great computational efficiency
2. Handle varying measures of nonlinearity accurately
3. Ideal candidate for computationally intensive application such as concurrent multiscale and impact analysis

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

Multiscale analysis: Overview

- 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



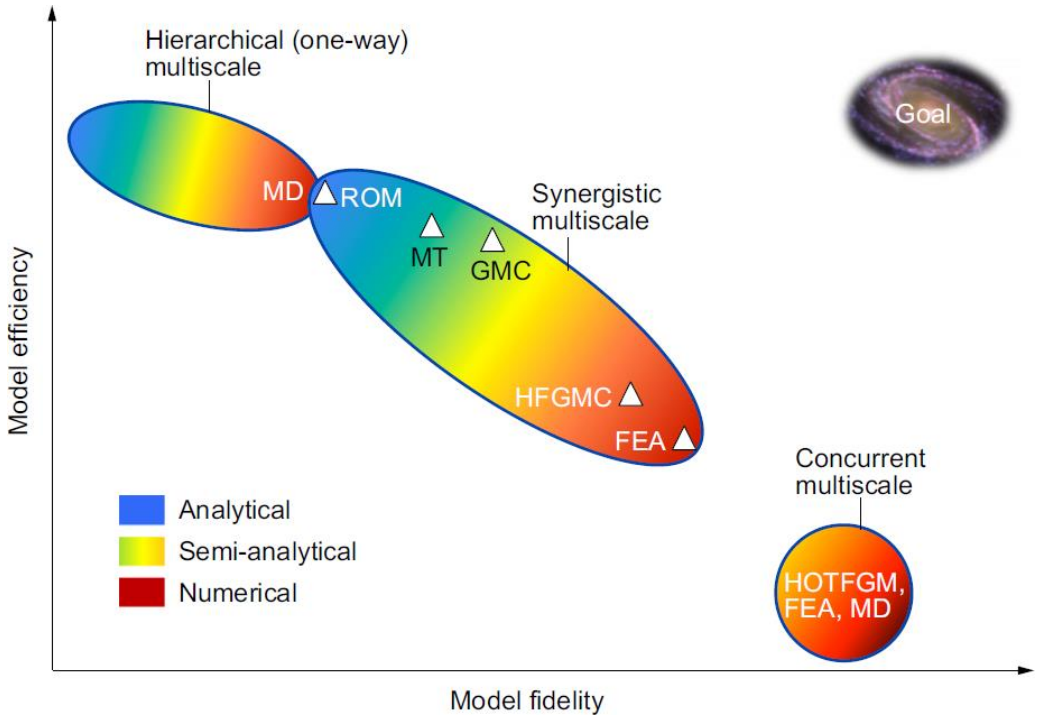
Concurrent coupling scheme

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 intitated by Feyel and coworkers for nonlinear analysis [Feyel et al. (2000)]
- Global-local LATIN-based methods for failure analysis of composites by Ladeveze and coworkers [Ladaveze et al. (2001), Allix et al.]
- Commercial codes such as DIGIMAT utilizes mean-field methods and its extensions [DIGIMAT (2008)]
- Exhorbitant computational costs addressed through
  - Parallel implmentations – 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



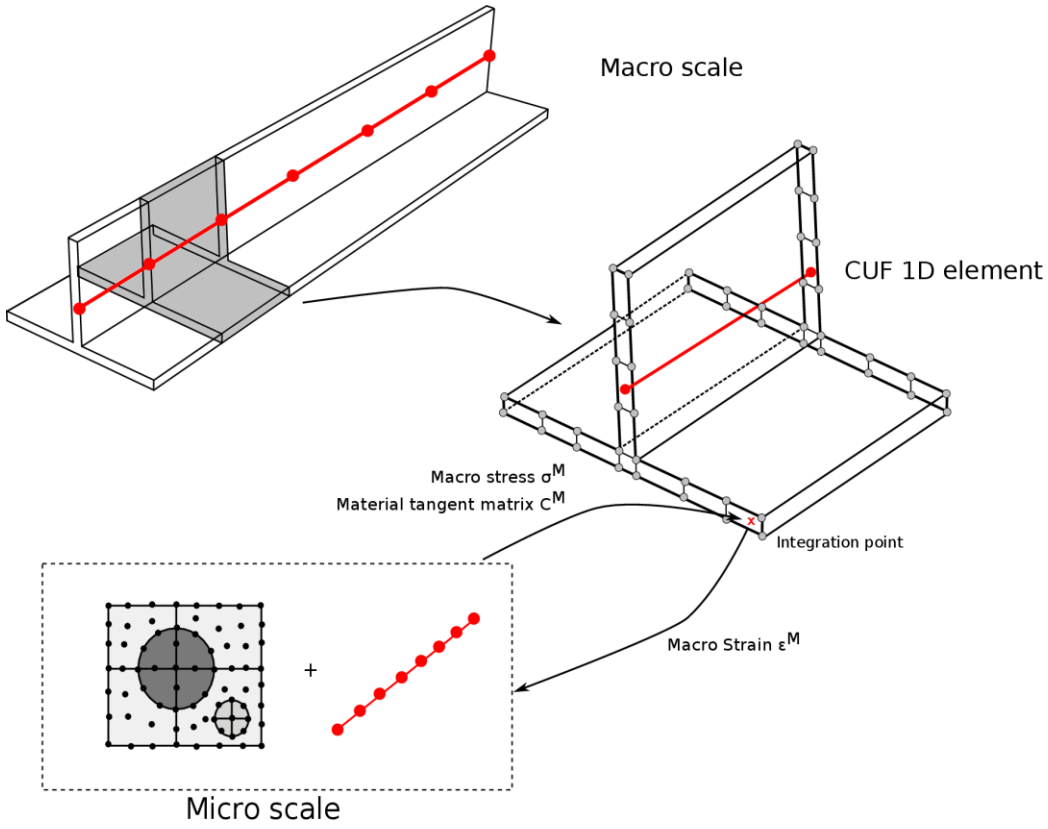
[Aboudi et al. (2013)]

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



Kaleel I., Petrolo M., Carrera E., Waas, A. M, A computationally efficient concurrent multiscale framework for the linear analysis of composite structures. (Submitted) 2018.

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

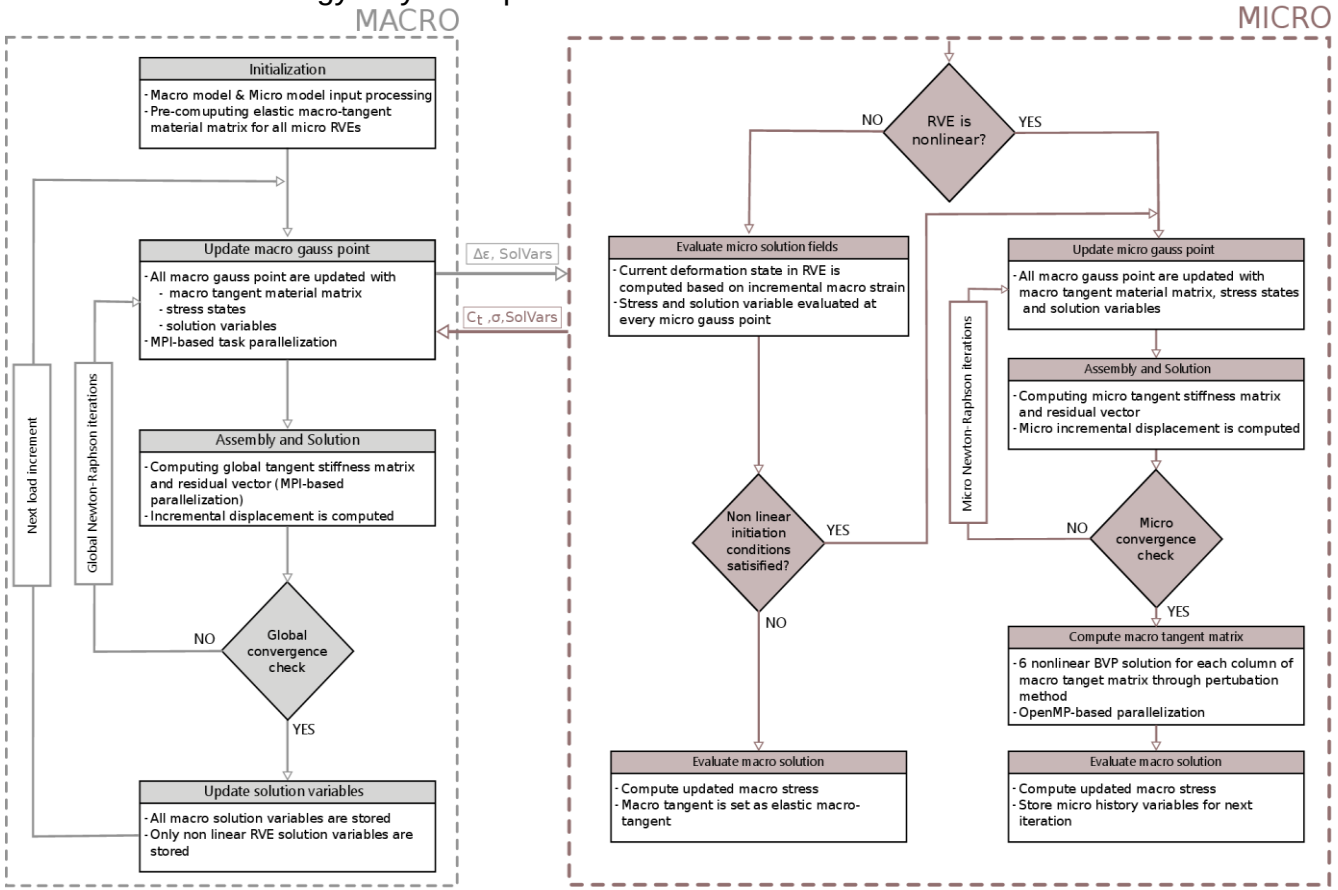
$$\delta\boldsymbol{\sigma} = \mathbf{C}_{\delta\boldsymbol{\epsilon}}\delta\boldsymbol{\epsilon}$$

$$\delta\bar{\boldsymbol{\sigma}}^{n+1} = \bar{\boldsymbol{\sigma}}(\boldsymbol{\epsilon}^{n+1} + \delta\boldsymbol{\epsilon}, \mathbf{H}^{n+1}) + \delta\mathbf{H}) - \bar{\boldsymbol{\sigma}}(\boldsymbol{\epsilon}^{n+1}, \mathbf{H}^{n+1})$$

- 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



Kaleel I., Petrolo M., Carrera E., Waas, A. M, A computationally efficient concurrent multiscale framework for the nonlinear analysis of composite structures. (Submitted) 2018.

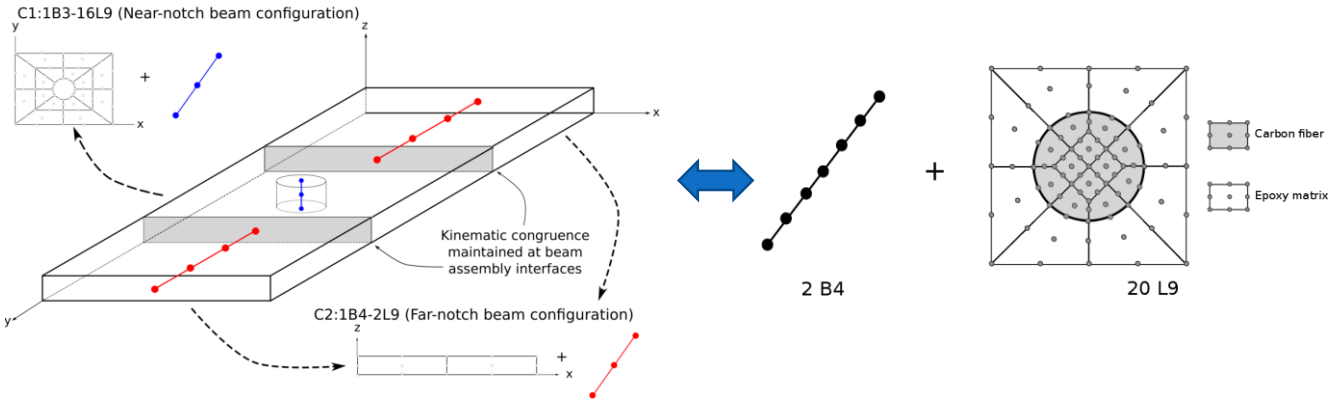
Multiscale analysis

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

Stiffness prediction of multi-directional laminates

- 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



Macro model: Open hole specimen **Micro model: Square-packed RVE**

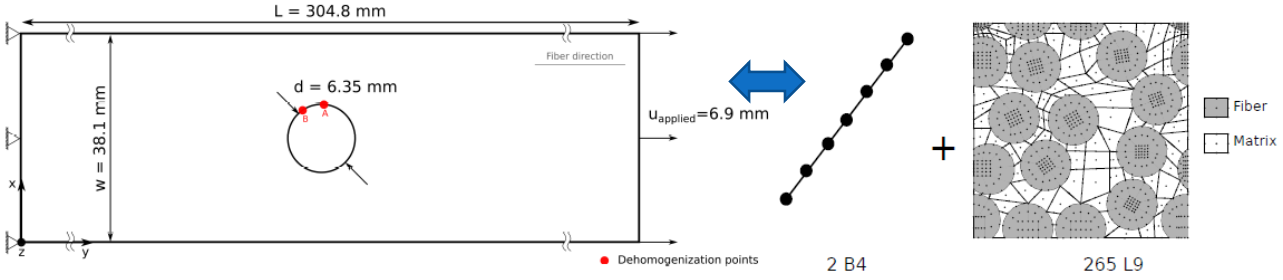
Model	Experimental	MAC/GMC	NCYL	CUF: 1D-1D
$[0/45/90/-45]_{2s}$	48.3	49.1 (1.66%)	50.3 (4.14%)	49.4 (2.28%)
$[60/0/60]_{3s}$	48.8	48.9 (0.20%)	51.1 (4.71%)	50.44 (3.36%)
$[30/60/90/30/-60]_{2s}$	32.4	33.7 (4.01%)	34.5 (6.48%)	33.25 (2.62%)

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

Kaleel I., Petrolo M., Carrera E., Waas, A. M, A computationally efficient concurrent multiscale framework for the linear analysis of composite structures. (Submitted) 2018.

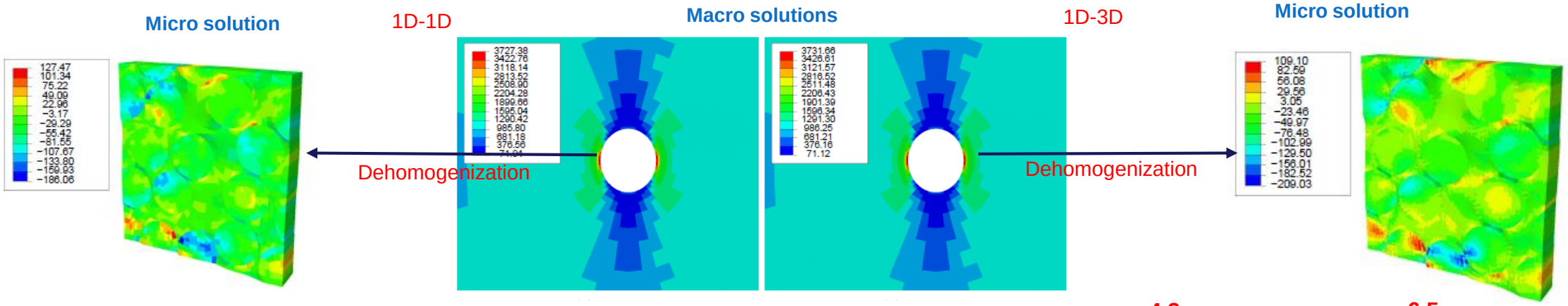
Multiscale analysis: Numerical Example 2

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)



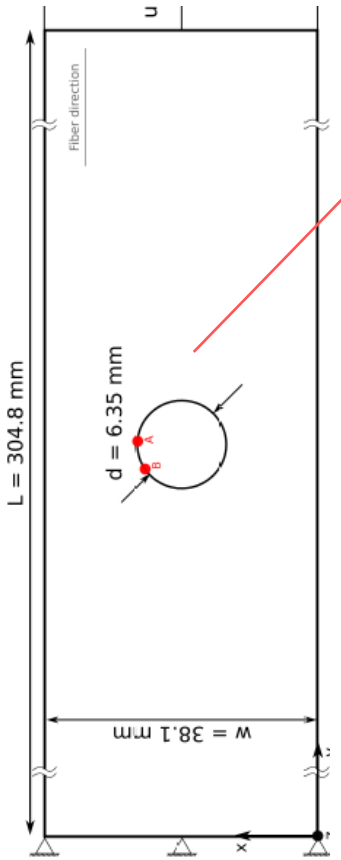
~4.2x ~6.5x

Model	Macro model		Micro model		Runtime [s]		Memory requirement
	DOF	No. of GP	DOF	No. of GP	Without local fields	With local fields	[MB]
1D-1D	4,140	2,736	13,642	9,540	3.0	10.1	1.5
1D-3D			31,524	61,008	9.6	42.7	9.8

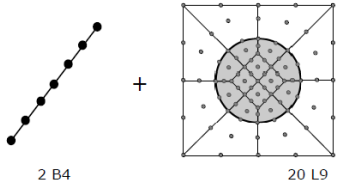
Kaleel I., Petrolo M., Carrera E., Waas, A. M, A computationally efficient concurrent multiscale framework for the linear analysis of composite structures. (Submitted) 2018.

Multiscale analysis: Numerical Example 3

Nonlinear analysis of open-hole specimen under tension



Micro model

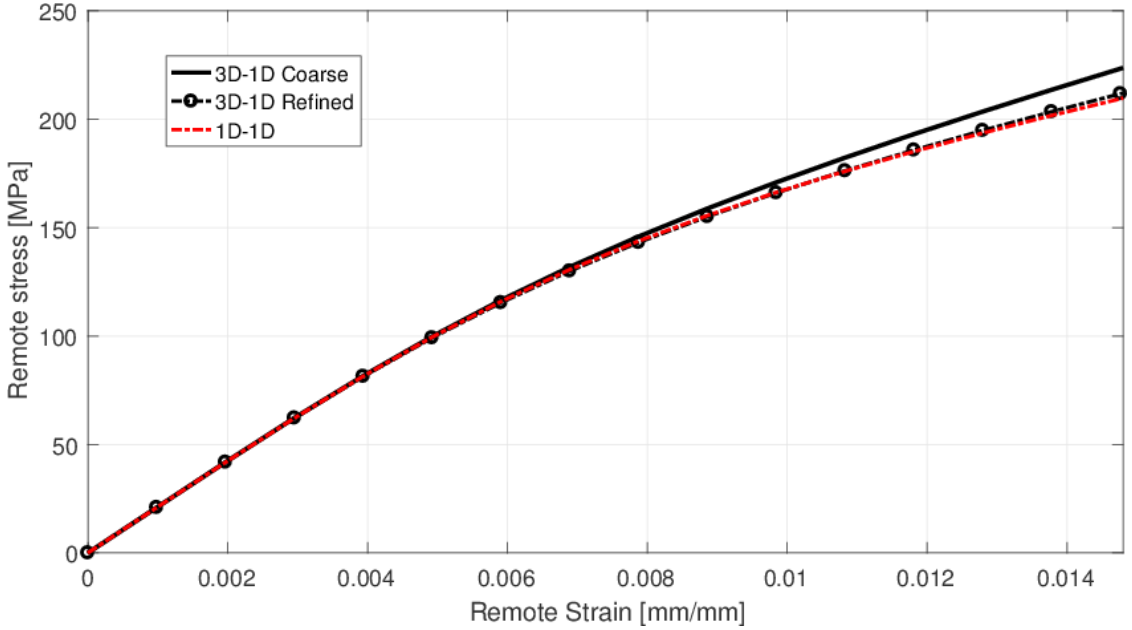


Fiber : Elastic

Matrix: **J2 plasticity theory**

Two multiscale models

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



Model	Macro model		Runtime ~4.1x	Memory requirement ~4.3x
	DOF	No. of GP	[hh:mm]	[MB]
1D-1D	2,655	2,664	01:54	2.02
3D-3D (Coarse)	3,450	6,336	05:27	7.28
3D-3D (Refined)	4.650	8,704	08:25	8.75

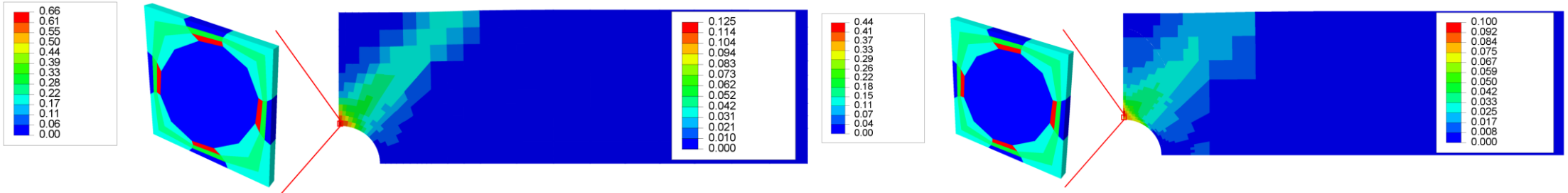
Kaleel I., Petrolo M., Carrera E., Waas, A. M, A computationally efficient concurrent multiscale framework for the nonlinear analysis of composite structures. (Submitted) 2018.

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



1D-1D **1D-3D (refined)**

[6] Kaleel I., Petrolo M., Carrera E., Waas, A. M, A computationally efficient concurrent multiscale framework for the nonlinear analysis of composite structures. (Submitted) 2018.

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

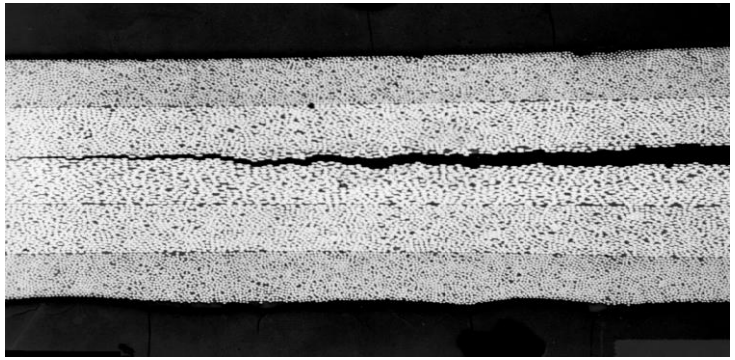
  discontinuities (e.g.: free-edge)
- Two main numerical approaches:
  - Cohesive zone models [Dugdale(1960), Barenblatt (1962)]

    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.

Delamination in an epoxy carbon short beam shear test [Martinez et al. (2015)]



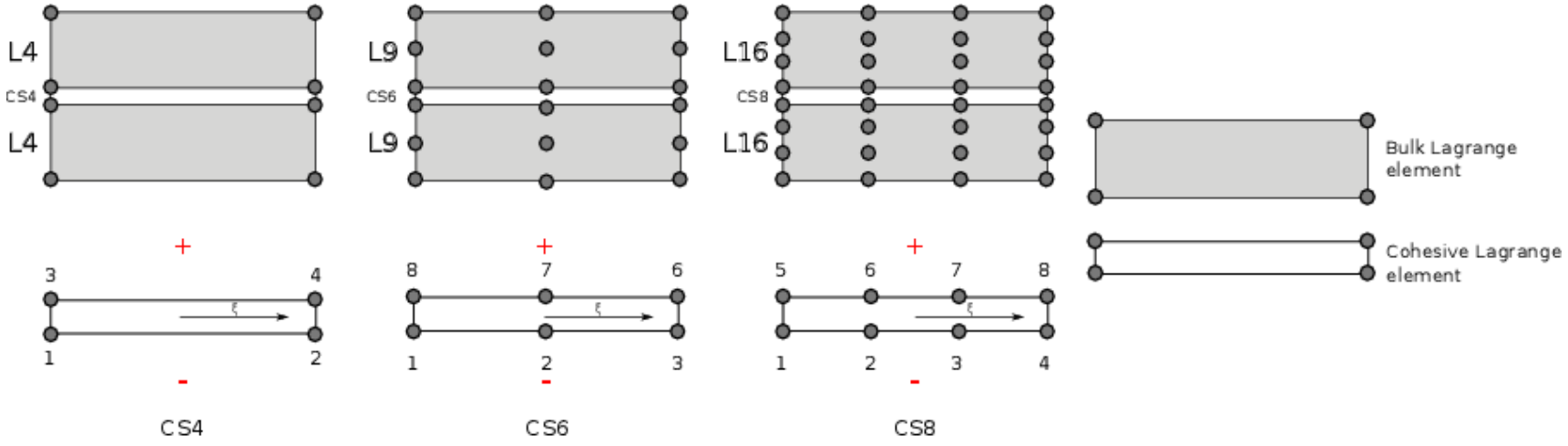
Free edge delamination in Graphite-Epoxy laminate [Crossman et al. (1982)]

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

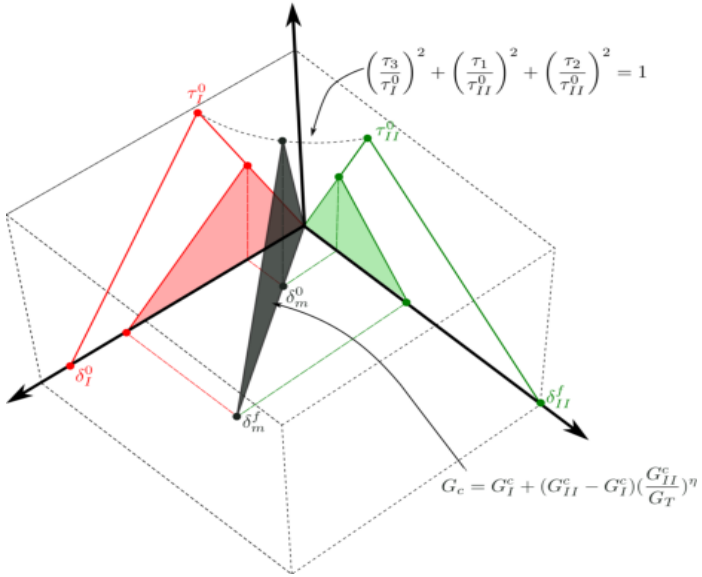


- Three new types of cohesive expansion functions are introduced
  - CS4 (linear)
  - CS6(Quadratic)
  - CS8 (Cubic)
- Cohesive displacement opening can be formulated as:

$$\mathbf{u}^{+} = F_{\tau} N_i \mathbf{u}_{\tau i}^{+}, \qquad \mathbf{u}^{-} = F_{\tau} N_i \mathbf{u}_{\tau i}^{-}, \qquad [[\mathbf{u}]] = F_{\tau} N_i \left(\mathbf{u}_{\tau i}^{+} - \mathbf{u}_{\tau i}^{-}\right)$$

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

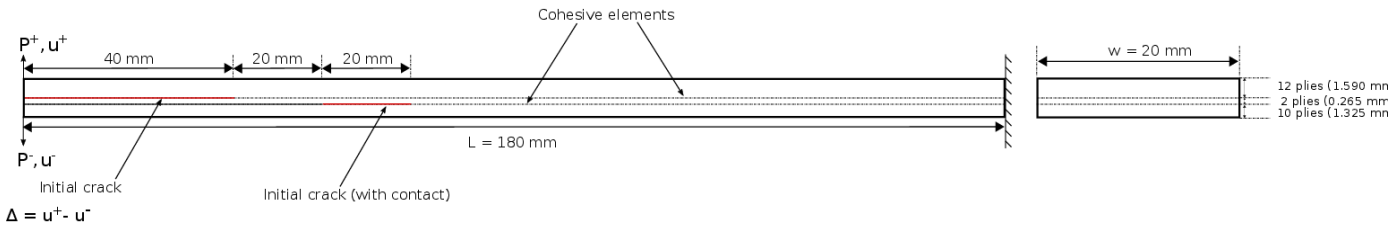
$$g = \frac{1}{2}\mathbf{f}_{ext}^T(\lambda_0 \Delta\mathbf{u} - \Delta\lambda\mathbf{u}_0) - \Delta\tau$$

- 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

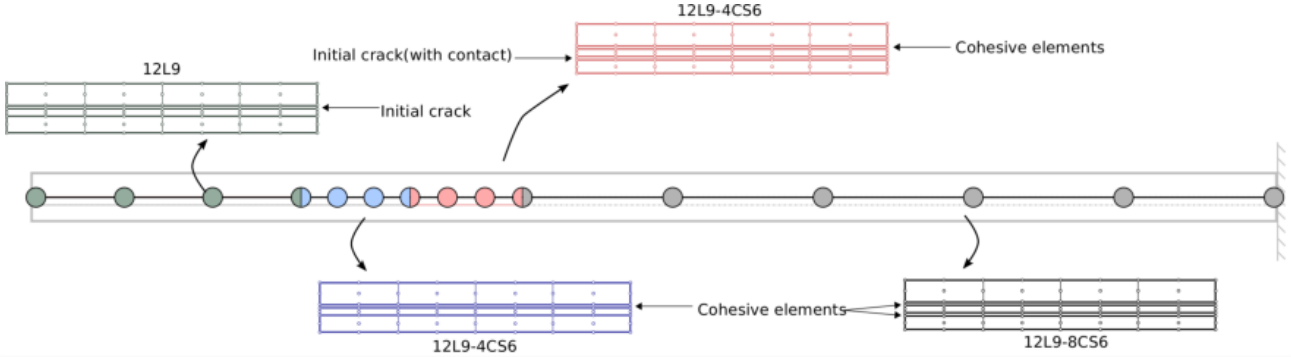
1. Cohesive formulation within CUF
2. **Numerical case**
   A. Multiple delamination in composite specimen

Multiple delamination in composite specimen



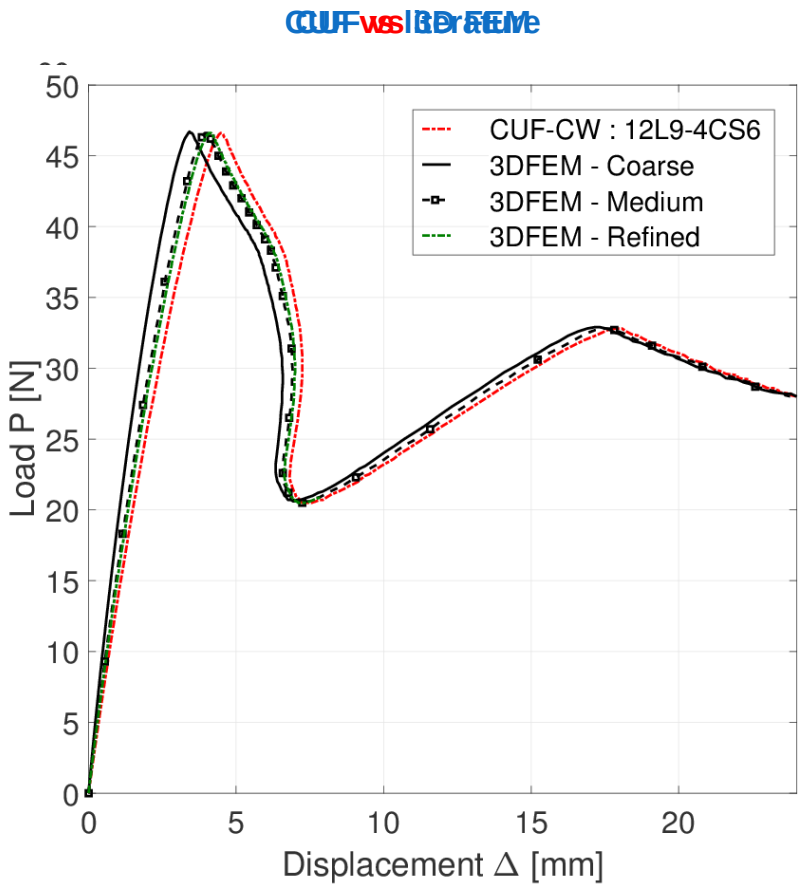
- Experimental study undertaken by Rybinson et al. (2009)
- Exhibits complex equilibrium path

Early modeling elements are cross-section features and non-homogeneous 1D elements



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

~4x



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

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 (Eg: 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

$$\mathbf{g}_N = (\mathbf{x}_2 - \mathbf{x}_1) \cdot \mathbf{n}_1 \geq 0$$

$$\mathbf{g}_N = (\sum F_\tau N_i \mathbf{x}_2 - \sum F_\tau N_i \mathbf{x}_1) \cdot \mathbf{n}_1 \geq 0$$

- 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

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

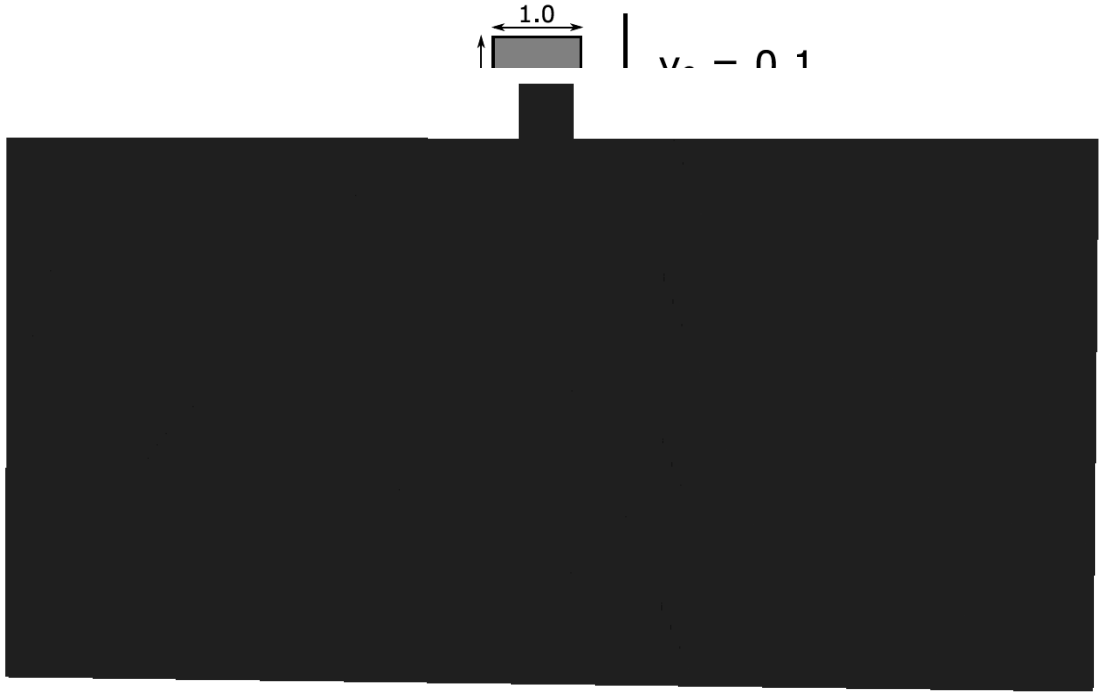
Impact modeling

1. Contact formulation within CUF
2. **Numerical cases**
   A. Rectangular block impact
   B. Rod impact

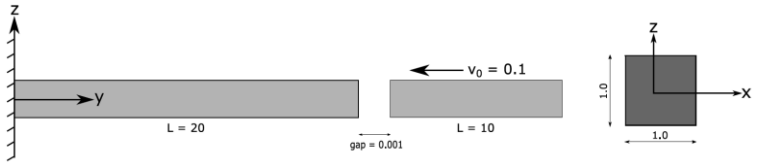
Impact modeling: Numerical results

Block impact

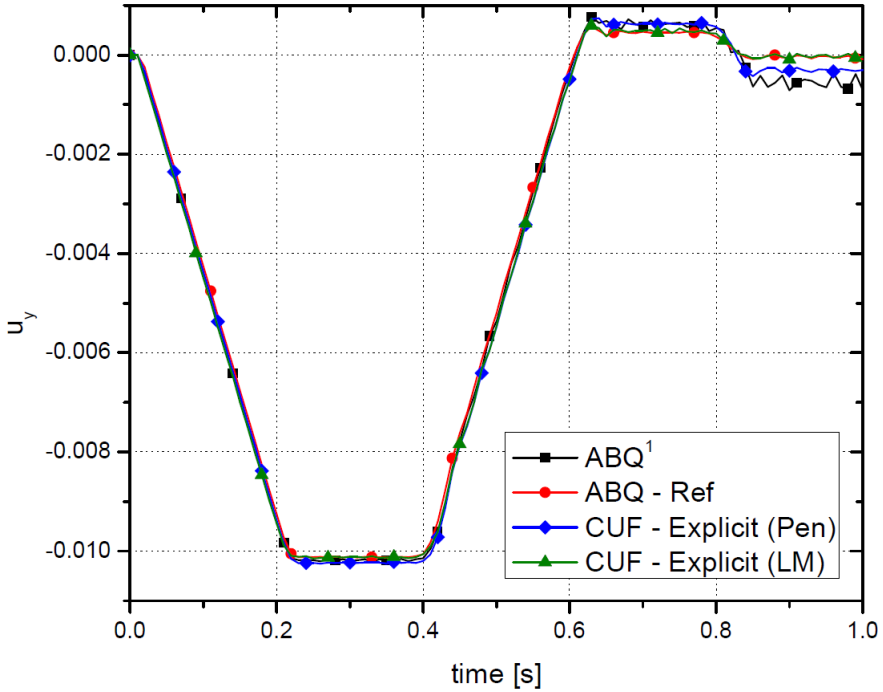
- Linear elastic blocks
- Initial velocity imposed on impacting body
- Parallel explicit solver with node-to-node contact discretization



Rod impact



Displacement-time response



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

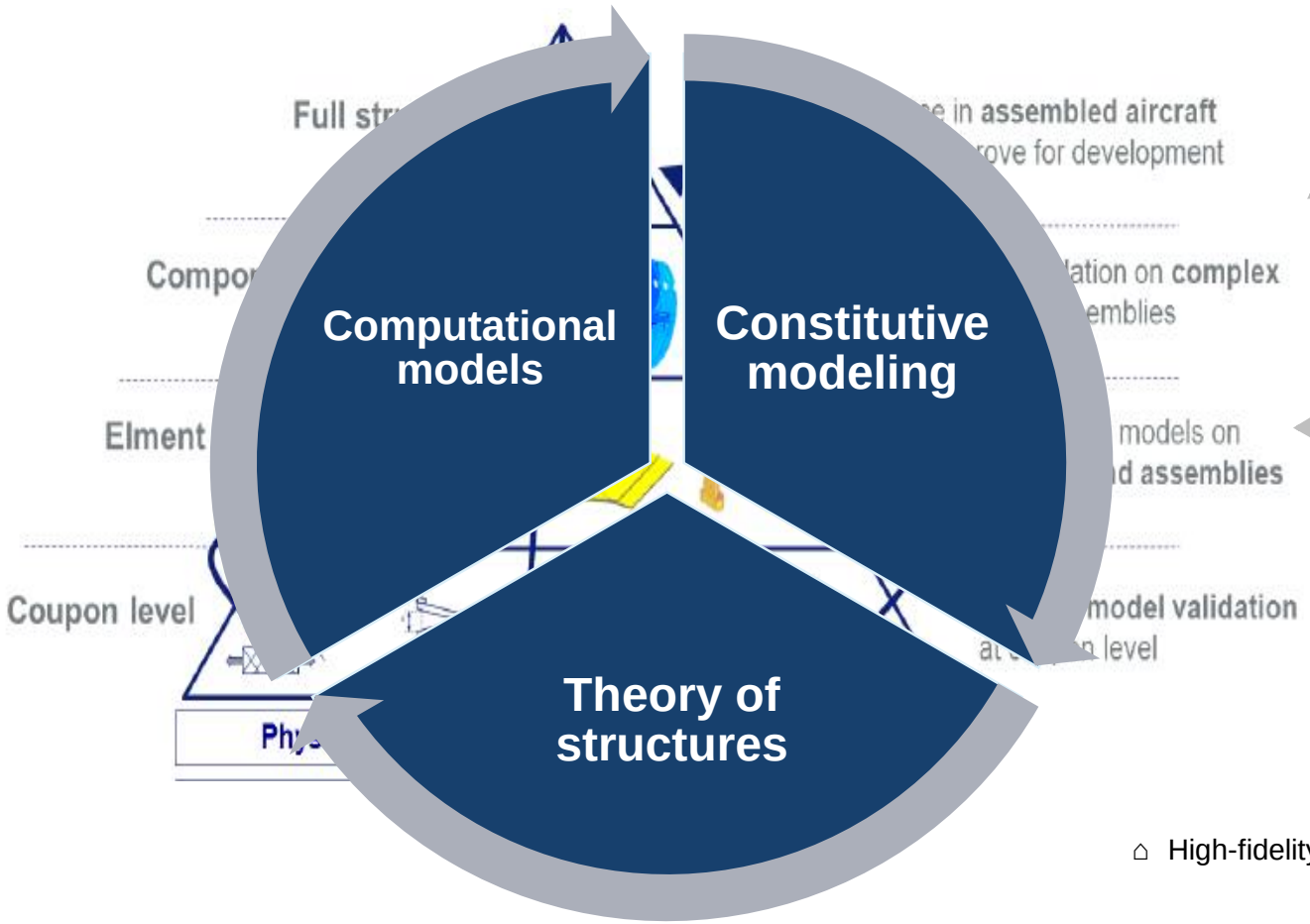
02 Various modes of nonlinear phenomena of composites across scales such as pre-peak nonlinearity, progressive failure, delamination are addressed using numerical tool

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



Interface & Impact modeling

- Accurate resolution of transverse fields and highly scalable
- Complex delamination propagation are captured

Average computational savings : Runtime: 4x & Memory: 2.7x

Multiscale modeling

- Concurrent multiscale framework
- Nonlinearity driven at lower scales and up-scaled

Average computational savings : Runtime: 3x & Memory: 6x

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

Journal Publication (12)

1. Kaleel I., Petrolo M., Waas A. M., Carrera E. (2017), “Micromechanical Progressive Failure Analysis of Fiber-Reinforced Composite using Refined Beam Models”. ASME. J. Appl. Mech. 85(2): 021004-021004-8
2. Kaleel I., Petrolo M., Waas A.M., Carrera E. (2017), "Computationally efficient, high-fidelity micromechanics framework using refined 1D models", Composite Structures 181:358-367.
3. Carrera E., Kaleel I., Petrolo M. (2017), “Elastoplastic analysis of compact and thin-walled structures using classical and refined beam finite element models”, Mechanics of Advanced Materials and Structures .
4. Petrolo M., Kaleel I., Pietro G. D., Carrera E. (2018), "Wave propagation in compact, thin-walled, and layered beams using refined finite element models” International Journal for Computational Methods in Engineering Science and Mechanics 19(3):207-220
5. Petrolo M., Nagaraj M. H., Kaleel I., Carrera E. (2018), "A global-local approach for the elastoplastic analysis of compact and thin-walled structures via refined models", Computers and Structures 206:54-65.
6. de Miguel A.G., Kaleel I., Nagaraj M. H., Petrolo M. Pagani A., Carrera E. (2018), Accurate evaluation of failure indices of composite layered structure via various FE models”, Composite Science and Technology 167:174-189
7. Kaleel I., Petrolo M., Carrera E. (2018), "Elastoplastic and progressive failure analysis of fiber-reinforced composites via an efficient nonlinear microscale model", Aerotecnica Missili and Spazio 97(2):103-110
8. Kaleel I., Petrolo M., Carrera E., Waas A.M. (2019), " A computationally efficient concurrent multiscale framework for the linear analysis of composite structures " (Under review)
9. Kaleel I., Petrolo M., Carrera E., Waas A.M. (2019), "A computationally efficient concurrent multiscale framework for the nonlinear analysis of composite structures" (Under review)
10. Kaleel I., Petrolo M., Carrera E. (2019), "Efficient progressive delamination analysis in composite structures via component-wise models", (under review)
11. Nagaraj M. H., Kaleel I., Carrera E., Petrolo M. (2019), Contact analysis of laminated structures including transverse shear and stretching. (Under review)
12. Stapleton S. E., Stier B., Jones S., Bergan A., Bednarcyk B. A., Kaleel I., Petrolo M., Carrera E. (2019), “A Critical Assessment of Design Tools for Stress Analysis of Adhesively Bonded Joints” (Under review)

Book Chapter (1)

1. Kaleel I., Petrolo, M., Carrera, E., Waas, A. M. (2019) “On the effectiveness of higher-order one-dimensional models for physically nonlinear problems in in “Advances in Predictive Models and Methodologies for Numerically Efficient Linear and Nonlinear analysis of Composites”, PoliTO Springer Series

Conference Proceedings (14)

1. Kaleel I., Nagaraj M. H., Petrolo M., Carrera E., Waas A.M. (2018), "An efficient multiscale virtual testing platform for composite via component-wise models", In: Proceedings of the American Society for Composites - Thirty-Third Technical Conference, Seattle, WA (USA), 24-26 September 2018.

2. Kaleel I., Petrolo M., Carrera E. (2018), “Computationally efficient interface modeling in fiber-reinforced composites through displacement-based componentwise approach”, In: Proceedings of the American Society for Composites – Thirty- Third Technical Conference, Seattle, WA (USA), 24-26 September 2018.

3. Carrera E., Kaleel I., Nagaraj M. H., Petrolo M. (2018), "A Virtual Testing Framework for the Analysis of Damage in Composite Structures", In: Proceedings of the 13th World Congress in Computational Mechanics, New York (USA), 22-27 July 2018.

4. Kaleel I., Nagaraj M. H., Petrolo M., Carrera E. (2018), “Contact modeling within displacement-based refined one-dimensional beam models”, In: Proceedings of the First International Conference on Mechanics of Advanced Materials and Structures, Turin (Italy), 17-20 June 2018.

5. Kaleel I., de Miguel A. G., Nagaraj M. H., Pagani A. Petrolo M., Carrera E. (2018), “A component-wise formulation for virtual testing of composites”, In: Proceedings of the First International Conference on Mechanics of Advanced Materials and Structures, Turin (Italy), 17-20 June 2018.

6. Kaleel I., Petrolo M., Carrera E., Giugno M., Linari M. (2018), “Micromechanics based multiscale modeling for nonlinear analysis of fiber-reinforced composites using DIGIMAT”, In: Proceedings of the First International Conference on Mechanics of Advanced Materials and Structures, Turin (Italy), 17-20 June 2018.

7. Kaleel I., Petrolo M., Carrera E. (2017), "Advanced Structural Models for Numerical Simulation of Delamination in Laminated Structures", In: Proceedings of International Conference on Composite Materials and Structures, Hyderabad (India), 27-29 December 2017.

8. Kaleel I., Petrolo M., Carrera E., Waas A.M. (2017), "Micromechanical progressive failure analysis of fiber-reinforced composite using refined beam models", In: Proceedings of the ASME 2017 International Mechanical Engineering Congress and Exposition (IMECE2017), Tampa, FL (USA), 3-9 November 2017.

9. Carrera E., Pagani A., Petrolo M., de Miguel A.G., Kaleel I. (2017), "Component- Wise method for macro-meso-micro modelling and failure analysis of composite structures", In: Proceedings of the American Society for Composites - Thirty-second Technical Conference, West Lafayette, IN (USA), 23-25 October 2017.

10. Carrera E., Kaleel I., Petrolo M. (2017), "Numerical simulation of failure in fiber reinforced composites", In: Proceedings of the XXIV International Conference of the Italian Association of Aeronautics and Astronautics, AIDAA 2017, Palermo-Enna (Italy), 18-22 September 2017.

11. Kaleel I., Petrolo M., Carrera E., Waas A. (2017), "Efficient high-fidelity two-scale computational model for progressive failure analysis of fiber reinforced composites via refined beam models", In: Proceedings of the 6th ECCOMAS Thematic Conference on the Mechanical Response of Composites: COMPOSITES 2017, Eindhoven (Netherlands), 20-22 September 2017.

12. Kaleel I., Maiarú M., Petrolo M., Carrera E., Waas A. (2017), "Fast two-scale computational model for progressive damage analysis of fiber reinforced composites", In: Proceedings of the 25th Annual International Conference on Composite/Nano Engineering, ICCE-25, Rome (Italy),16-22 July 2017.

13. Carrera E., Kaleel I., Petrolo M. (2016), "Progressive Damage Analysis of Composite Structures via One-Dimensional Carrera Unified Formulation", In: 19th International Conference on Composite Structures (ICCS19), Porto (Portugal), September 5-9, 2016.

14. Petrolo M., Carrera E., Kaleel I. (2016), "Efficient Component-Wise Finite Elements for the Dynamic Response Analysis of Metallic and Composite Structures”, In: 1st International Conference on Impact Loading of Structures and Materials (ICILSM 2016), 23 May 2016, Torino, Italy.

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 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-MUL^2 collaboration

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

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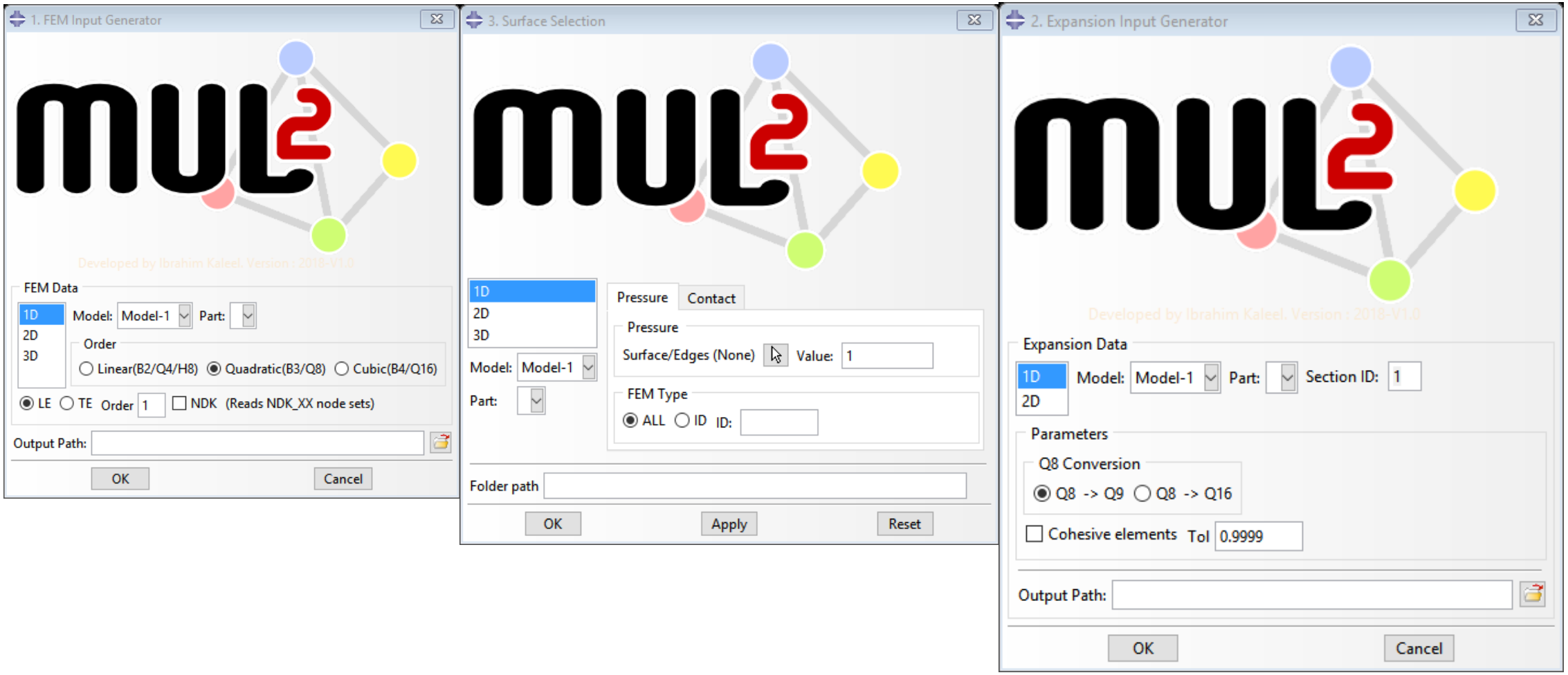
This research work has been carried out within the project FULLCOMP (FULLy analysis, design, manufacturing, and health monitoring of COMPosite structures), funded by the European Union Horizon 2020 Research and Innovation program under the Marie Sklodowska-Curie grant agreement No. 642121.

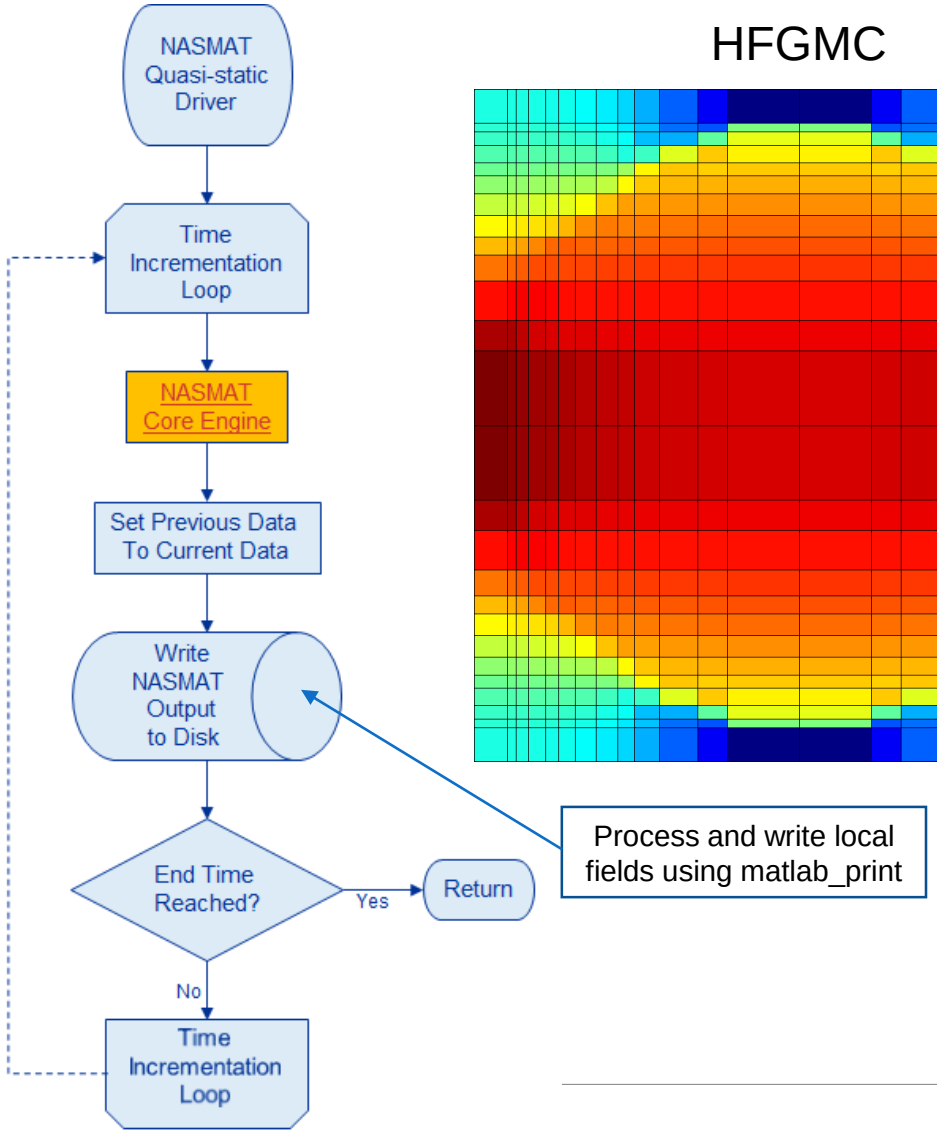
Authors would also like to acknowledge the computational resources provided by HPC@POLITO (http://hpc.polito.it).

EXTRA SLIDES

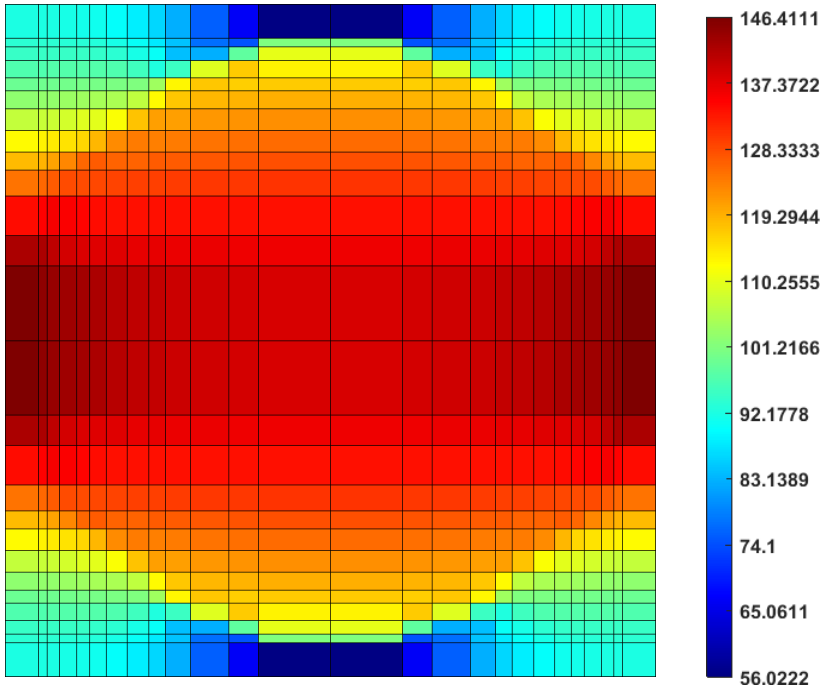
ABAQUS-MUL^2 Integration



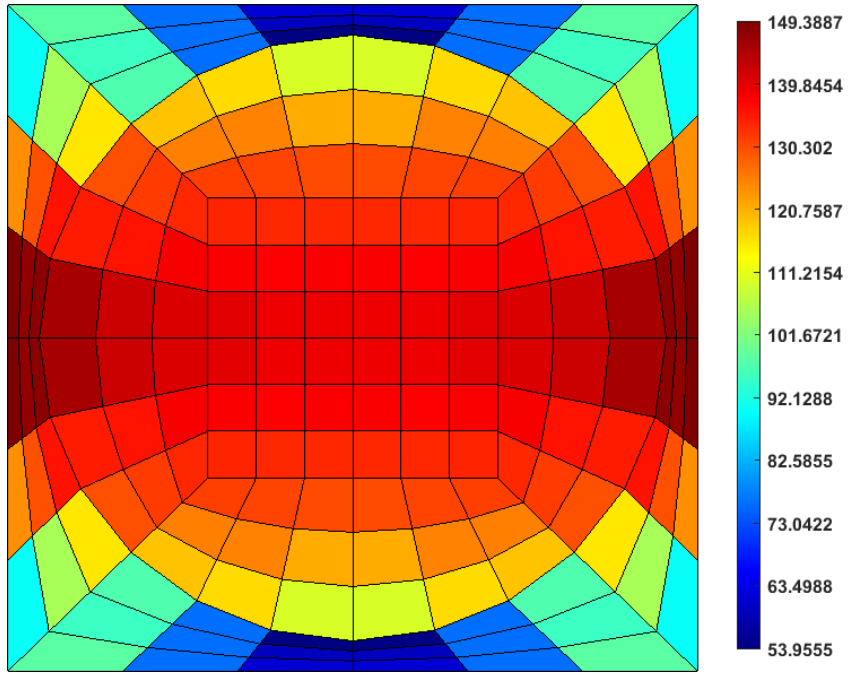
Integration Step #3: Output/Visualization



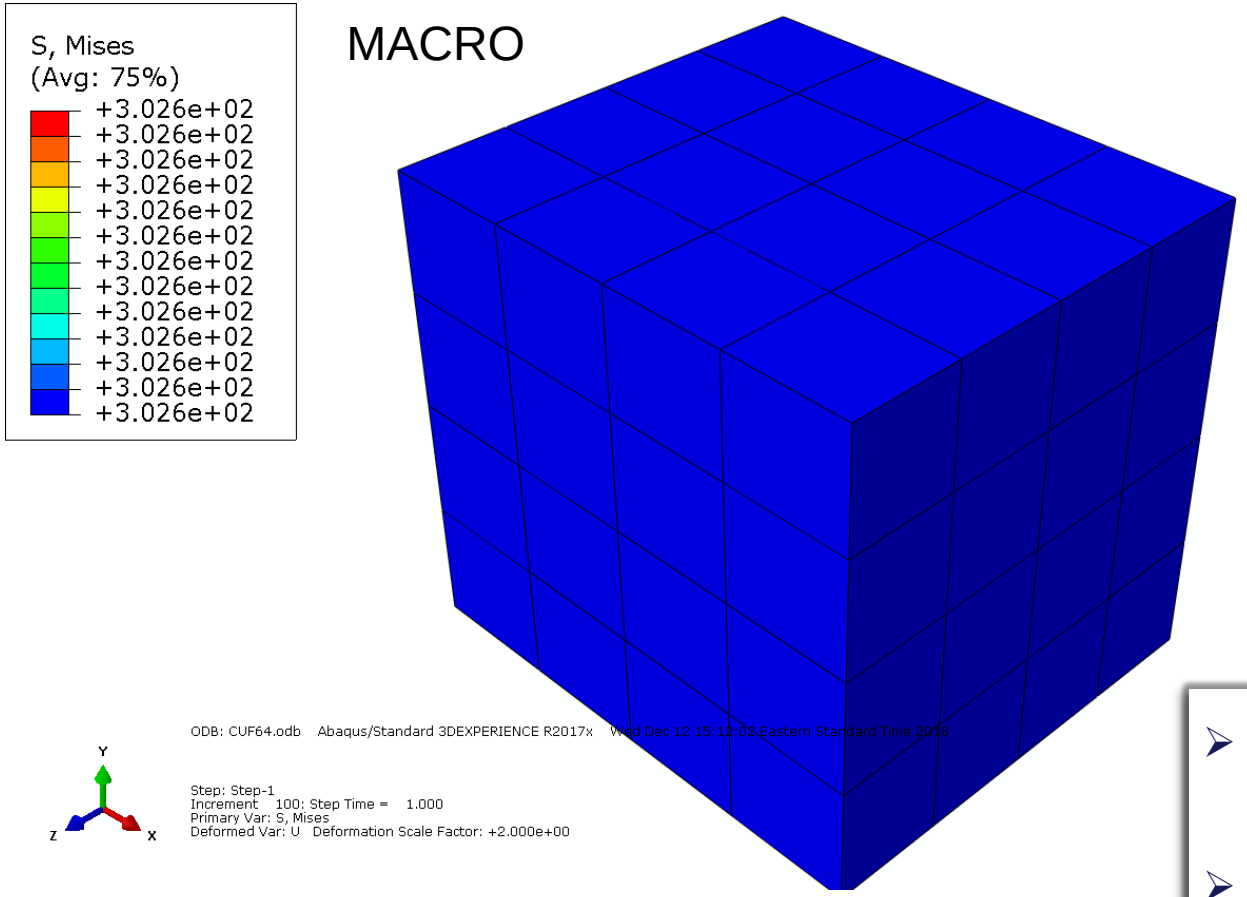
HFGMC

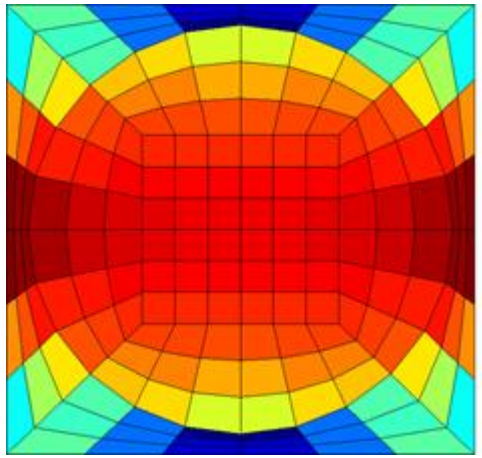


CUF



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