Application of Digital Element Approach in Fabric Mechanics and Composite Mechanics

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Oct.26, 2016

Composites Laboratory

Objectives

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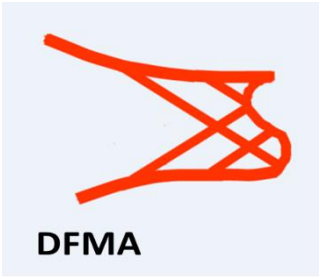
1. Generate a structural similitude of fiber-level micro-geometries for various textile fabrics: 2-D or 3-D woven fabrics, 2-D or 3-D braided composites
2. Simulate textile process to calculate fiber damage during manufacturing process
3. Create composite micro-geometry for micro-scale composite analysis
4. Simulate the textile composite molding process
5. Determine fabric strength (Static or dynamic)
6. Develop fabric mechanics software: Digital Fabric Mechanics Analyzer (DFMA)



CONCEPTS OF DIGITAL ELEMENT ANALYSIS

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- **Digital Fiber:**
  A flexible one-dimensional component with a constant cross section: similitude of fiber

- **Digital Yarn:**
  a bundle of digital fibers: similitude of yarn
  (Assumptions: Iso-length or Iso-stress)

- **Contact of digital fibers:**
  Support Compression and friction

- **Static and dynamic analysis**

  Static: Micro-geometry, Quasi-static deformation

  Dynamic: Impact load and impact strength analysis such as ballistic penetration problem

Digital Fiber

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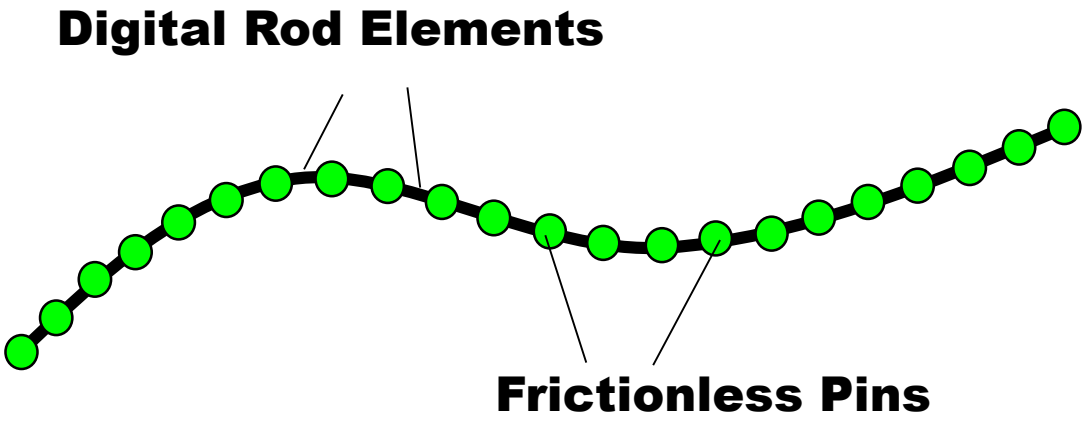

Digital fiber: Physical representation of fiber

(Similitude of fiber)

A flexible one-dimensional component with a circular cross-section, such as a fiber.

Digital Yarn Assembly

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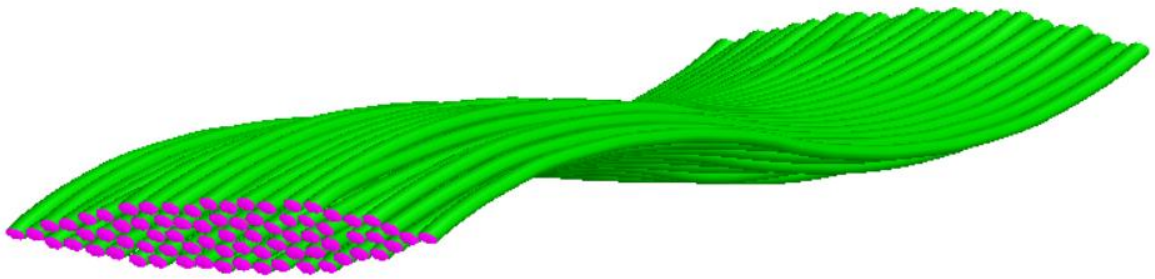
A digital yarn is composed of many digital fibers. Physically, a yarn is composed of hundreds or thousands of fibers. In simulations, 19-50 digital fibers might be sufficient to represent yarn cross section.



Yarn: Similitude of yarn, (Assembly of digital fibers)

Assumption: Iso-length

CONTACT OF DIGITAL FIBERS

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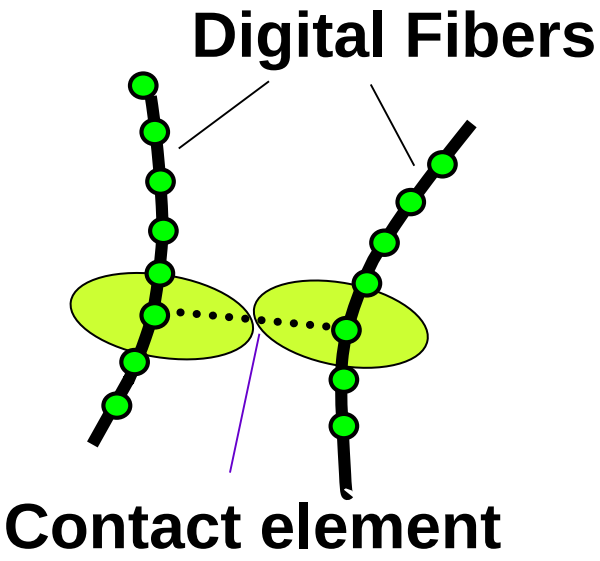

As the distance between two fibers is smaller than digital fiber diameter, a contact element will be placed between two nodes. If the two fibers separate, the contact element will be removed.

Micro-geometry of Unit-Cell

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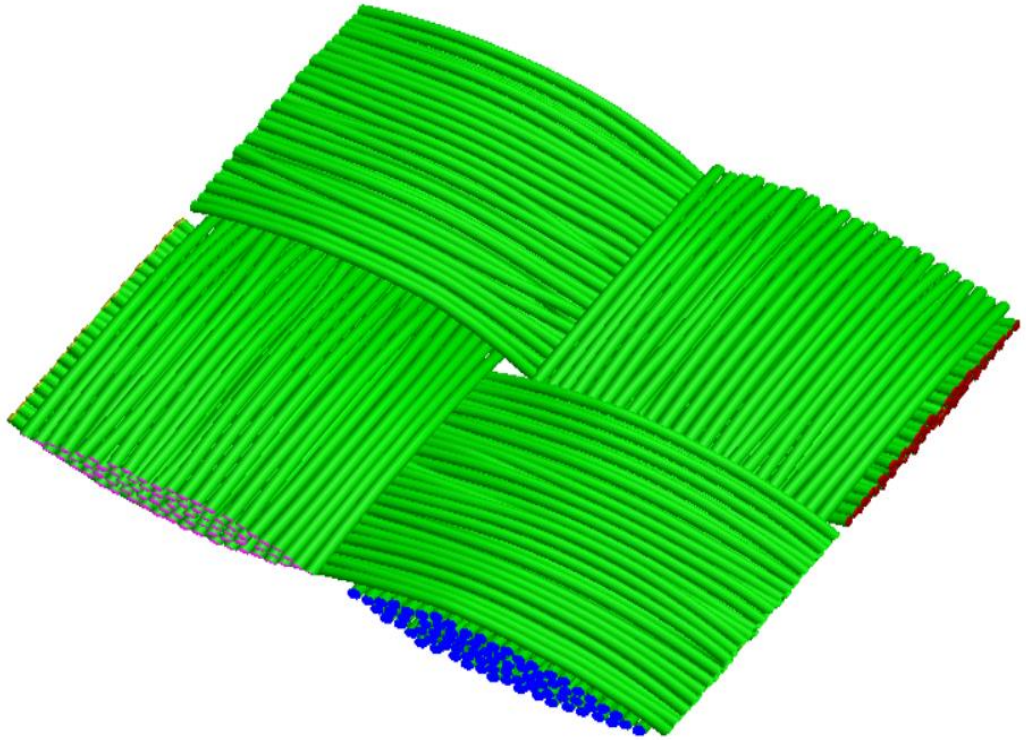

Unit cell geometry can be derived by:

1. **Simulate 2-D weaving process**
2. **Apply tension to unit-cell topology and minimize potential energy**

Unit Cell Micro-Geometry

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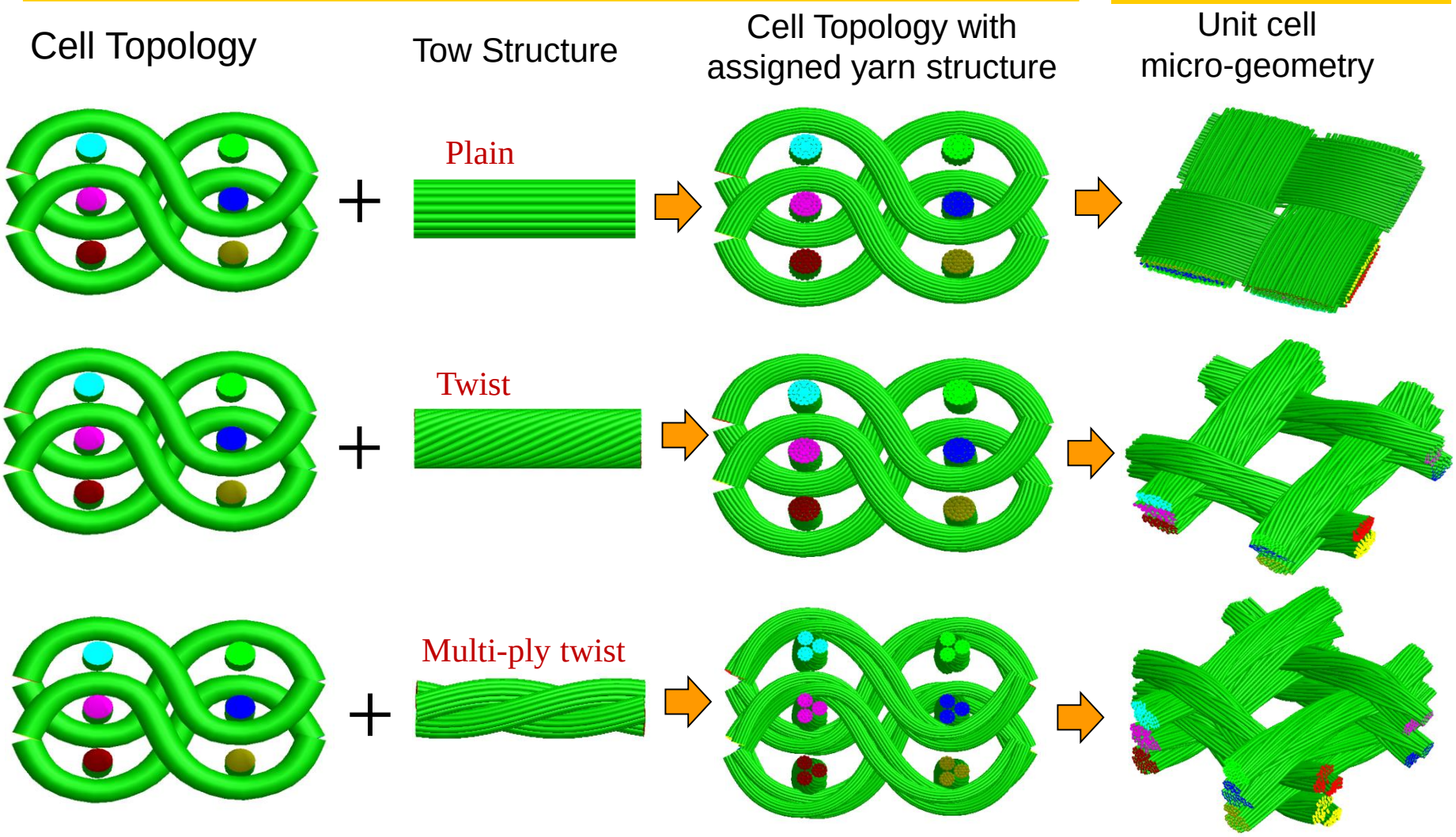

Micro-geometry is determined by dynamic relaxation approach with periodic boundary conditions.

Iso-length and Iso-stress Assumptions

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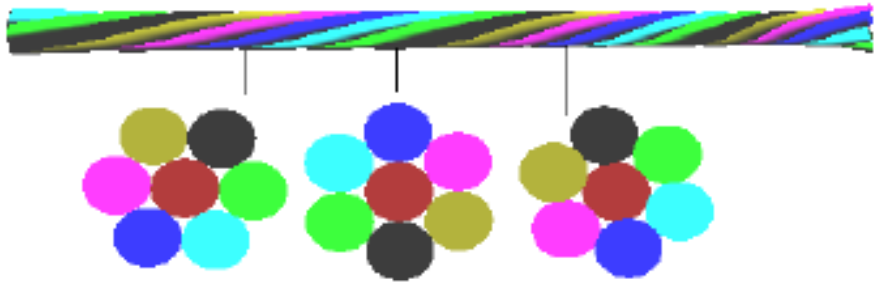
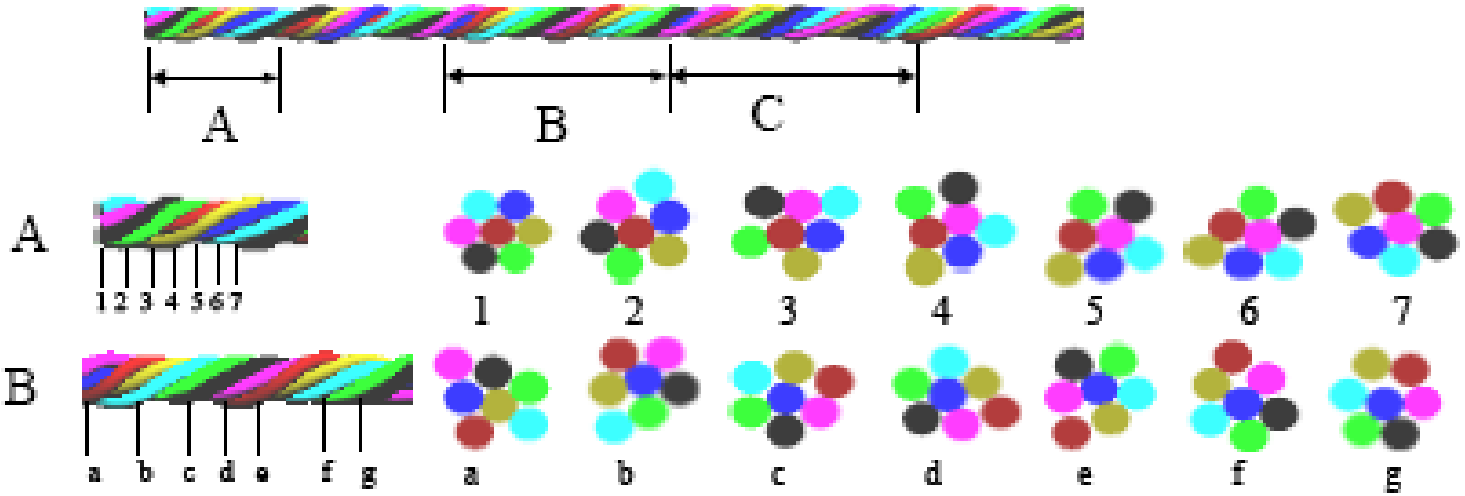
Iso-stress twist simulation:



Iso-length twist simulation:



Applications

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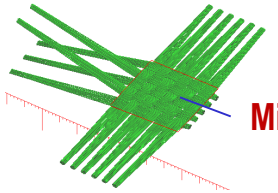
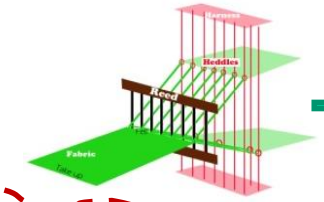
- Textile process simulation

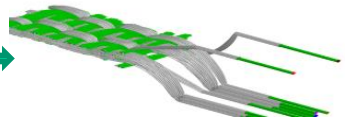
  Static Simulation (Weaving)



Micro-geometry

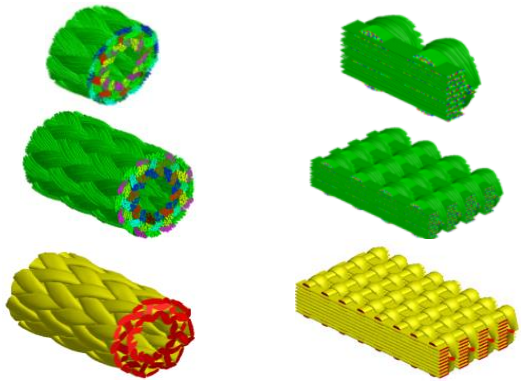
  Dynamic Simulation (Weaving+ Beat-up)





Micro-geometry & Fiber damage

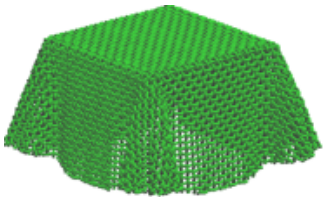
- Dynamic relaxation with periodic boundary conditions (DFMA: Fabricmechanics.com)
  - Unit cell fiber-level micro-geometry
  - Assembly of unit cells ⟹ Fabrics
  - Yarn Geometry



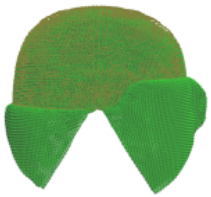
- Fabric stress analysis
  - Static Analysis: fiber stress, fabric deformation, fabric strength, fabric damage
  - Dynamic Analysis

Impact

Drape



Molding



Questions

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1. How many digital fibers are required to generate a structural similitude of the yarn in a fabric.

2. Can the digital element simulation provide

   – accurate micro-geometry of textile fabrics,
   – accurate fabric deformation, and,
   – accurate stress and strength ?

This presentation:

Case Study (Some examples)

Software Development (DFMA)

Example 1: Yarn Path Comparison for 3-D braided composite preform

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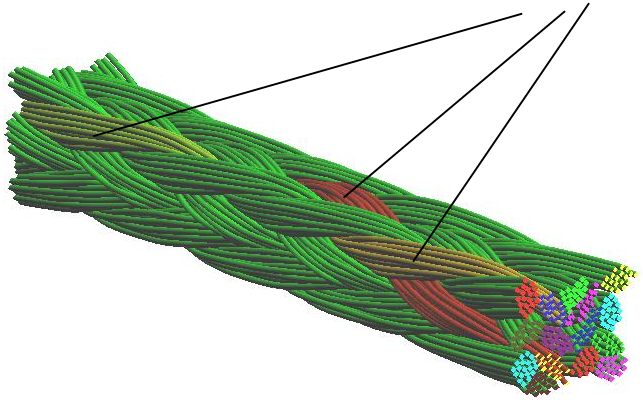
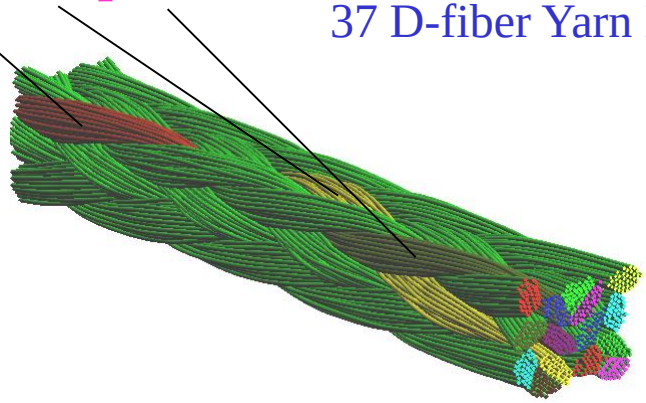
19 D-fiber Yarn Model

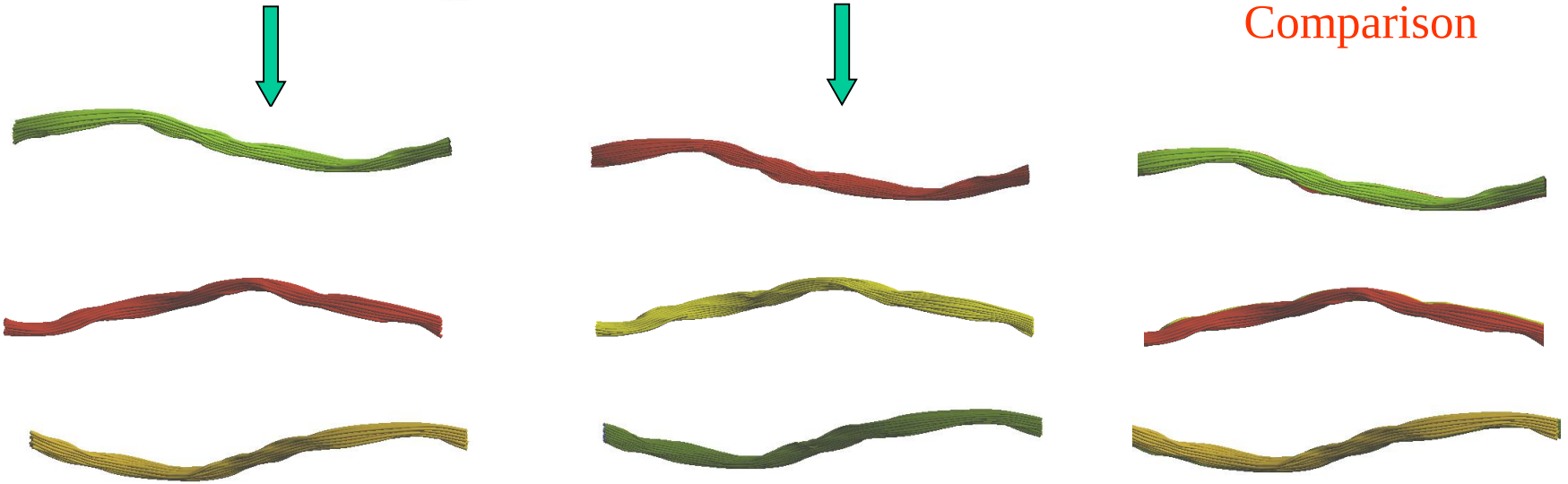
Selected yarn path

37 D-fiber Yarn Model





Comparison



Almost identical

Example 1: Cross-Section Comparison (3-D braiding)

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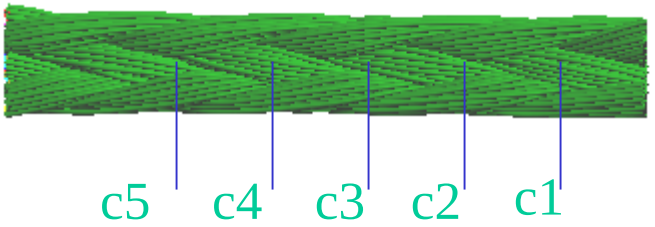
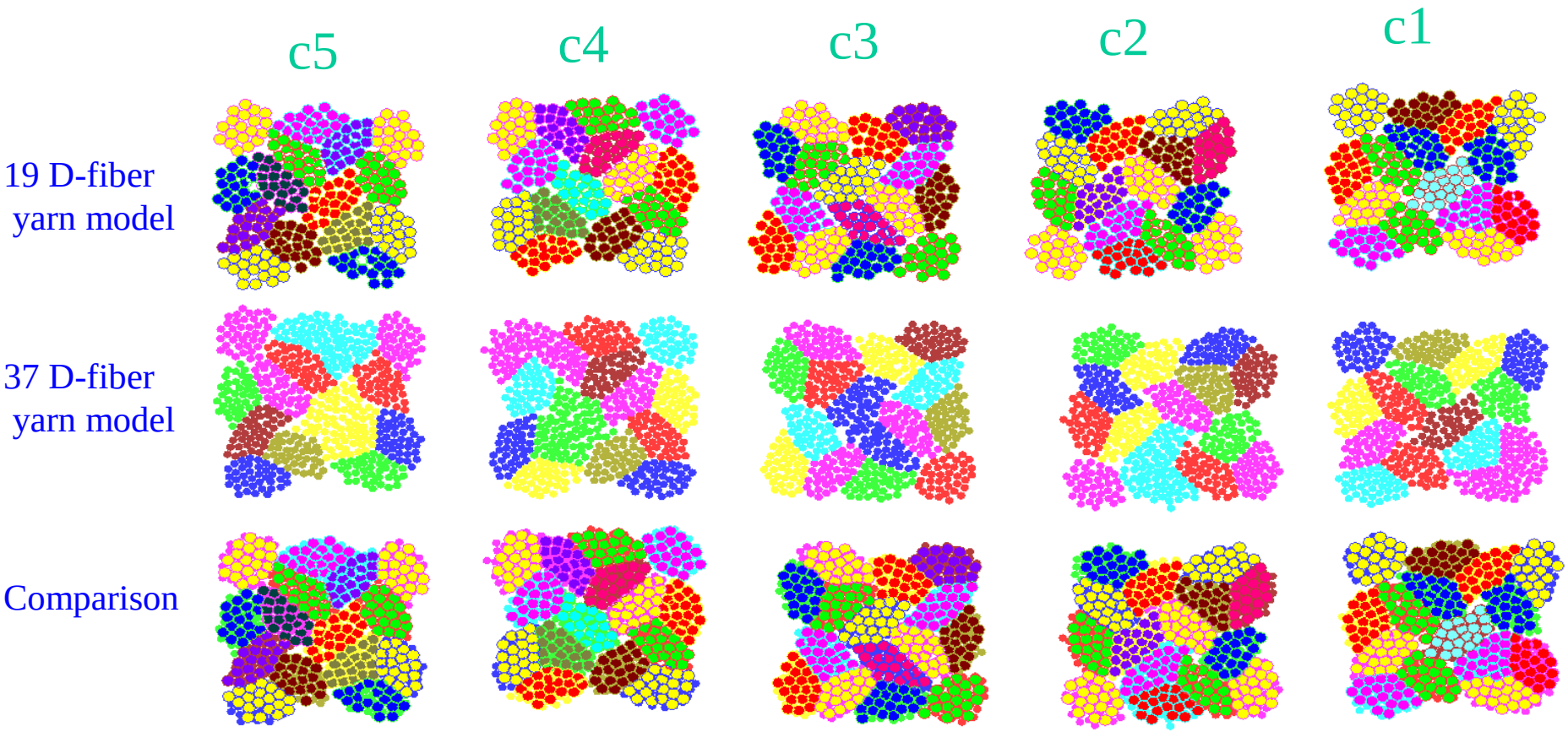
Selected yarn cross-section





Example 1: Comparison of Cross-section(3-D braided fabric)

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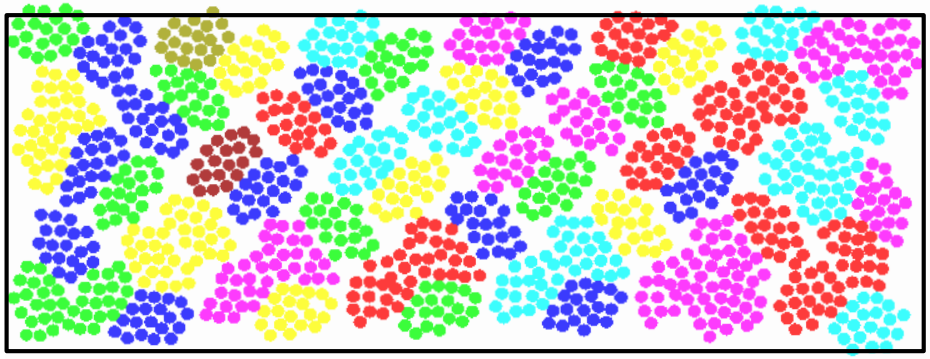

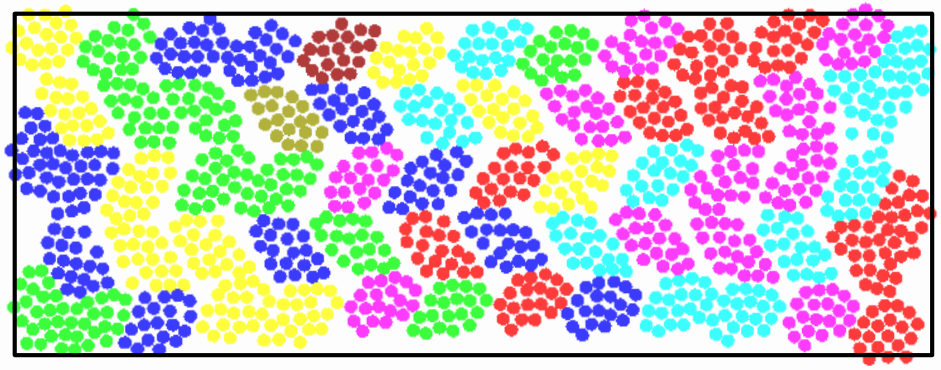

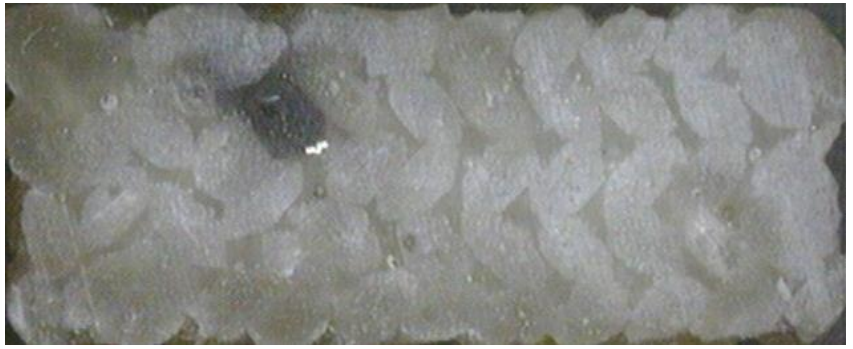

Example 2 Low velocity impact test (Double blind test-simulation comparison)

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Target: Hexcel Style 706

Shapes: Circular, Square

Dimension: 10”

Material properties:

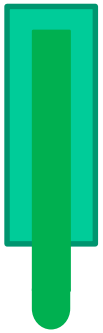
E_{11}=84.62GPa, E_{22}=1.34GPa, Su=3.88GPa

Boundary : Fixed

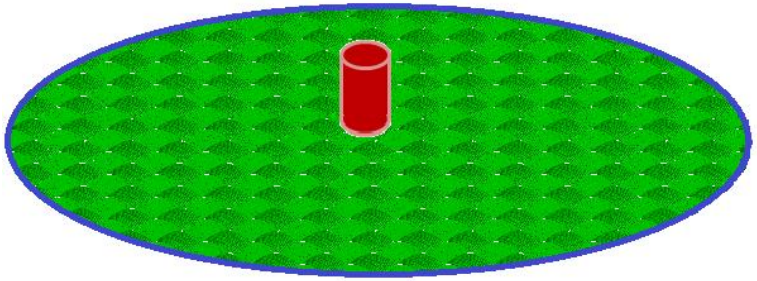
Impact Speed: 22.2m/s

Projectile mass: 104g

Projectile:



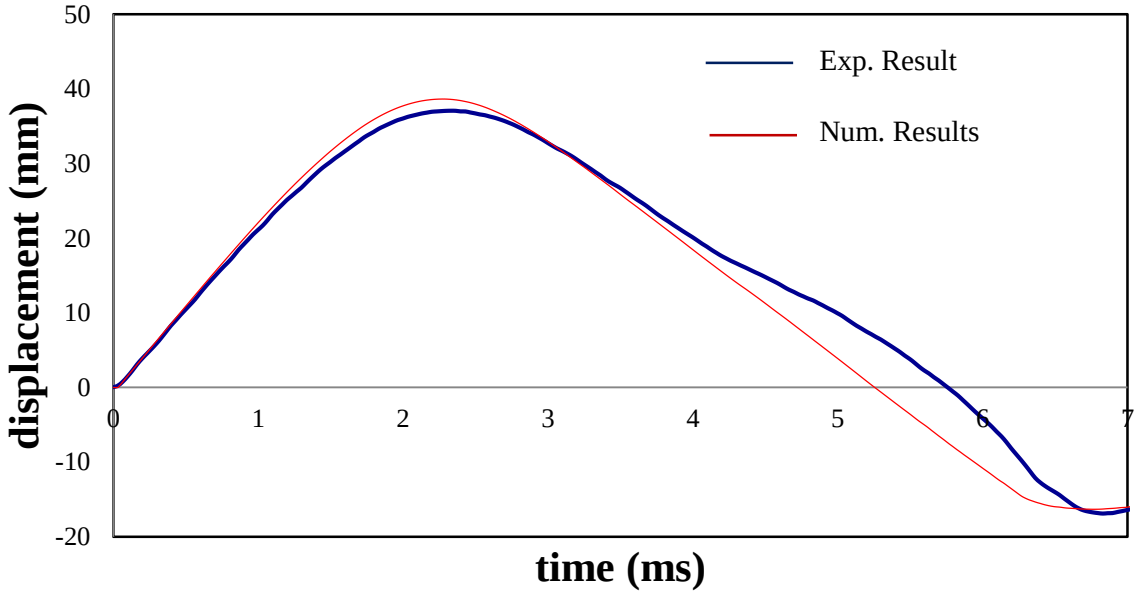
Simulation Model



10” in diameter

1. Weerasooriya, Tusit, C. Allan Gunnarsson, and Paul Moy, "Measurement of Full-Field Transient Deformation of the back surface of a Kevlar KM@ fabric during impact for material model validation," ***Proceedings of the 2008 International Congress and Expositions on Experimental Mechanics and Applied Mechanics. Orlando, Florida, 2008.***

Accuracy analysis: on displacements



Double blind test comparison!

1. Weerasooriya, Tusit, C. Allan Gunnarsson, and Paul Moy, "Measurement of Full-Field Transient Deformation of the back surface of a Kevlar KM@ fabric during impact for material model validation," ***Proceedings of the 2008 International Congress and Expositions on Experimental Mechanics and Applied Mechanics. Orlando, Florida, 2008.***

Example 2: Deflection History Comparison - Tusit Weerasooriya Tests

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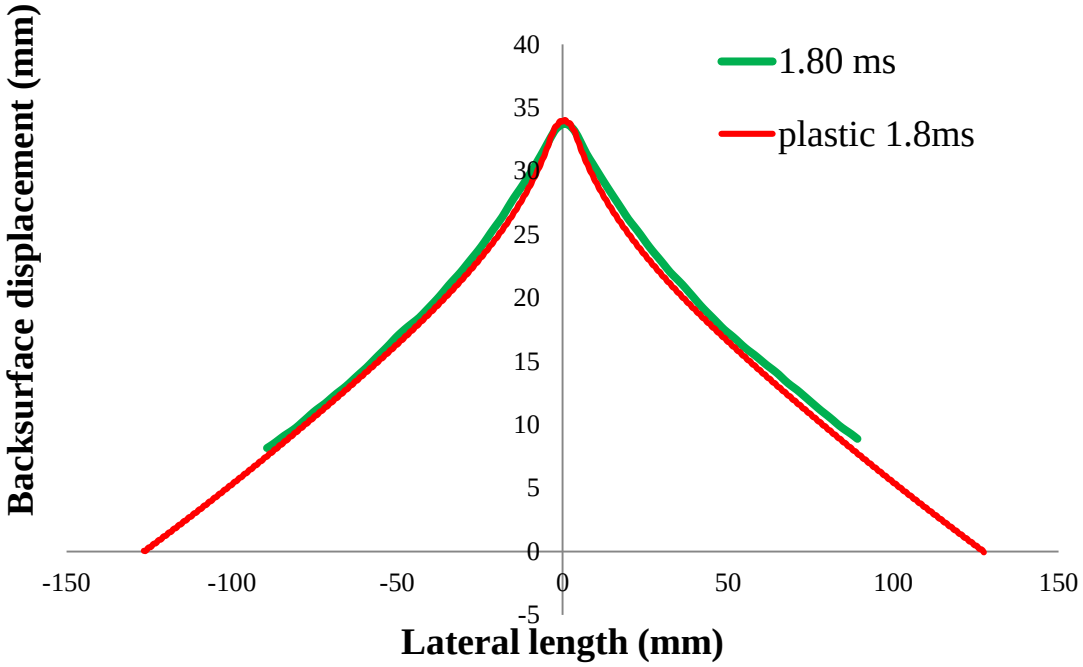

Discussions:

- **Fabric profile shape derived from DEA is close to experimental results**

Example 3: Convergence of DEA in Ballistic Penetration Simulation

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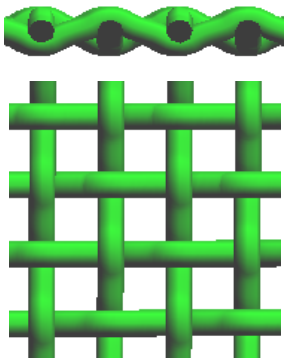
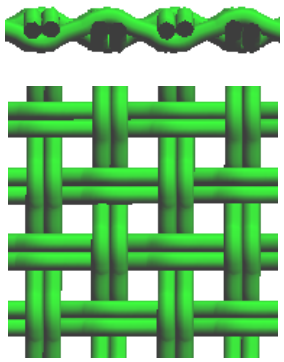
Fabrics : Kevlar KM2, 34x34 yarns per inch, 600 denier, area density 180g/m^2
Numbers of digital fibers per yarn: 1, 2, 5, 7, 14, 19, 25, 37
Fabric dimension: 1.3”x1.3”, 2” x 4”, 4” x 4”
Element Length: 0.5 x fiber diameter
Bullet information: Diameter=0.22”, mass=0.62g

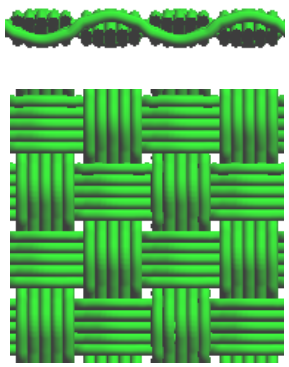
Geometrical models:



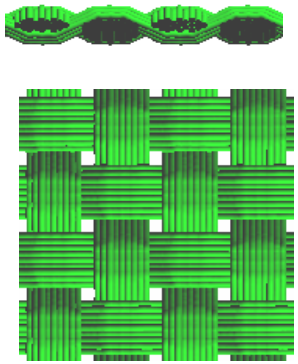
1 digital fiber yarn model



2 digital fiber yarn model



5 digital fiber yarn model



19 digital fiber yarn model

Example 3: Mesh Analysis: Fabric: 2”x 4”

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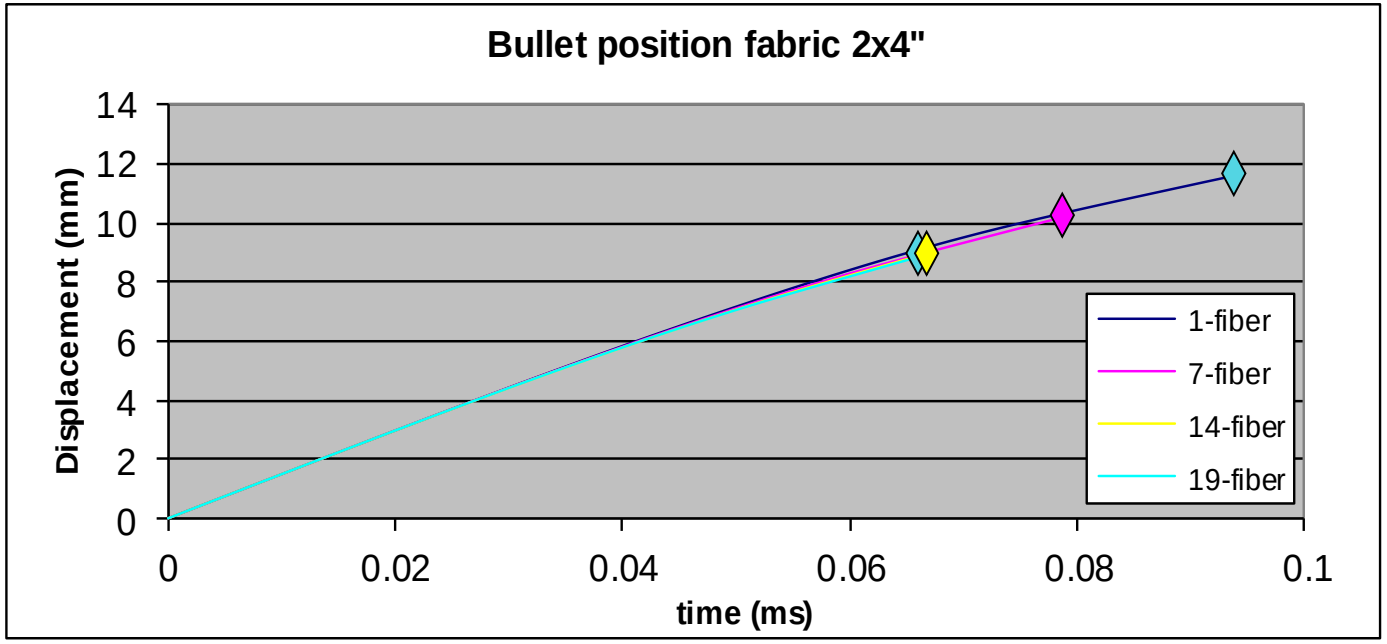
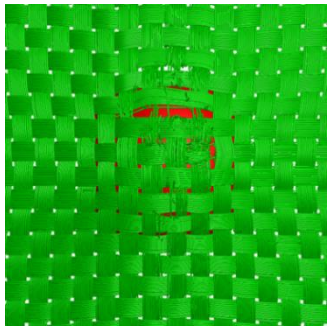
- **Striking velocity is 150 m/s, no dumping, full constrain**

No fibers	1 fiber	7 fibers	14 fibers	19 fibers
V-residual (m/s)	83.2	99.26	109.35	109.61





Example 3 Mesh Analysis:Fabric: 2”x 4”

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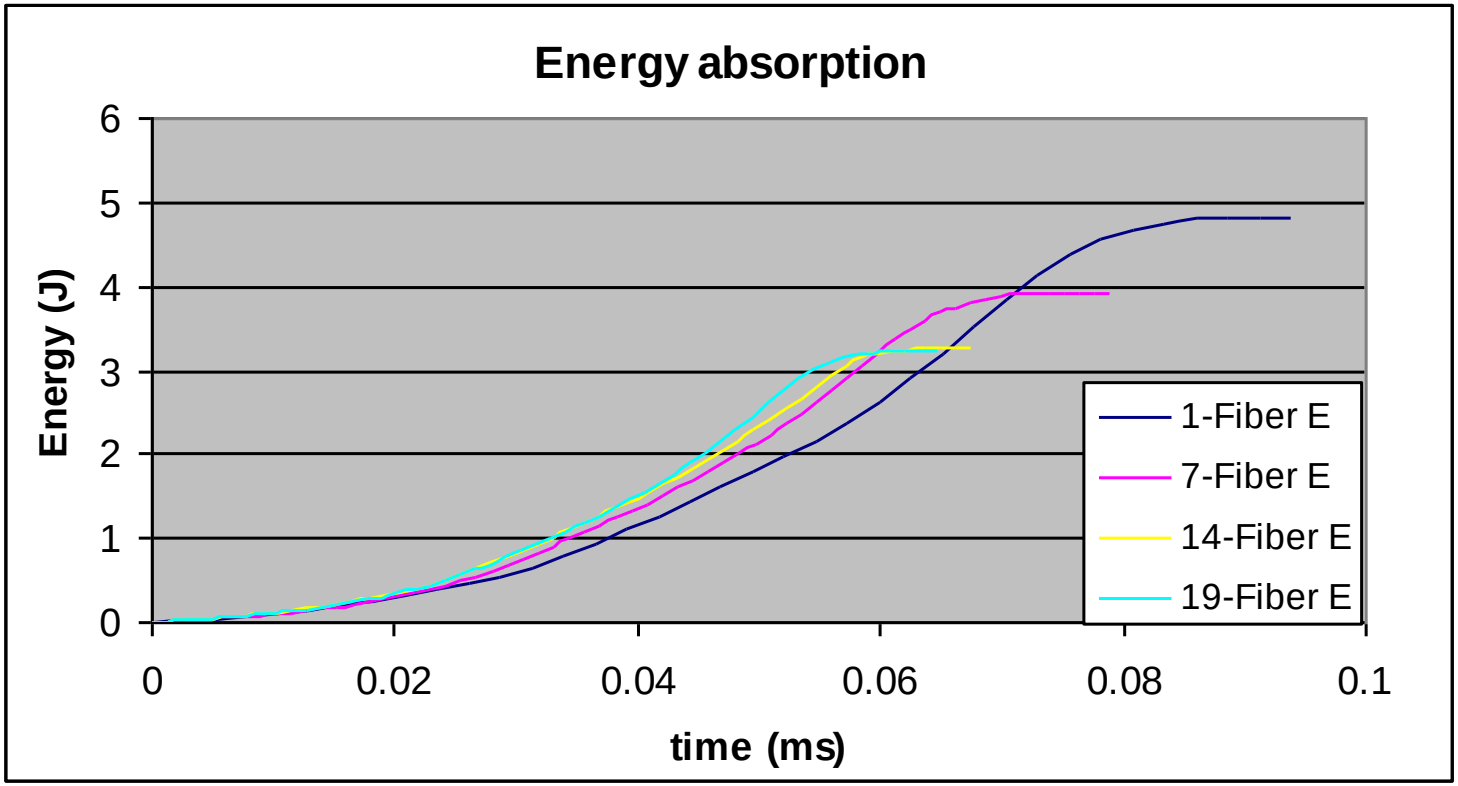

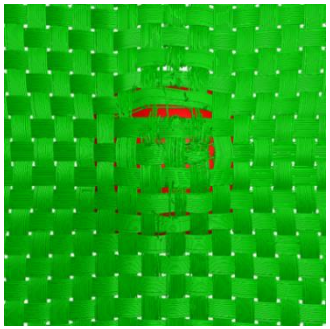

Mesh analysis shows that 19 fibers per yarn would be sufficient to analyze the penetration process of Hexcel 706 fabrics using spherical projectile.

Example 4: Strength Analysis for Fabric used in high pressured hose

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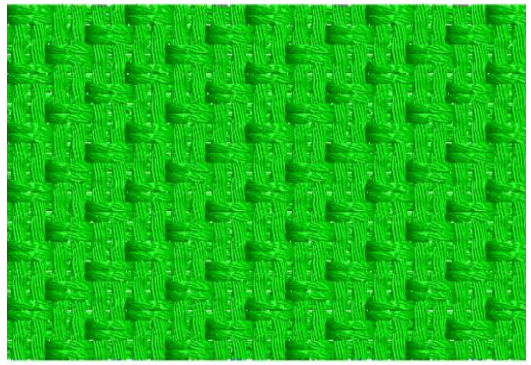
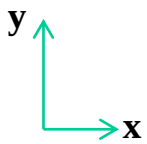
$u_y=0$

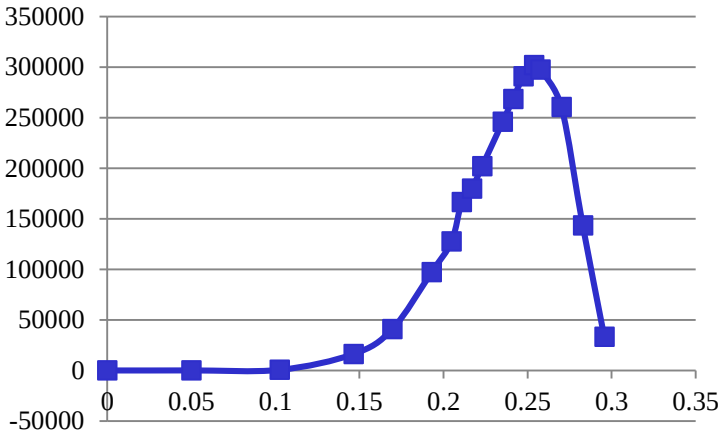


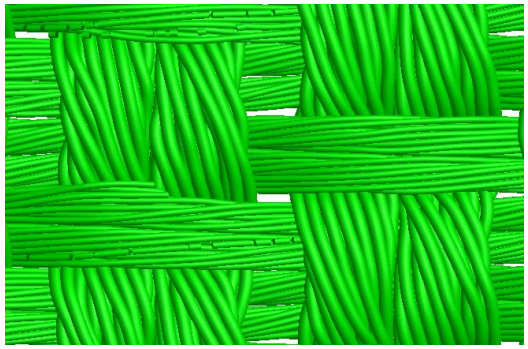
$u_y=0$



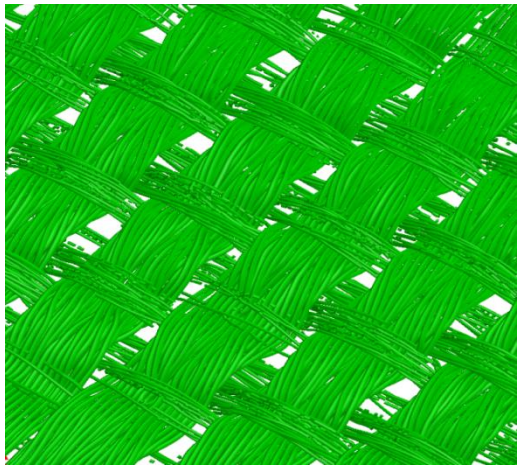
Boundary Load

N_l - ε_l relations





Failure begins



Massive Fiber failure

Hose Strength: Exp.: 603 psi, Num.: 633 psi

Example 5:
Airplane Engine Blade Preform and Final Product

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Near-net shape fabric as woven
(composite preform)

Net-shape composite

Step 1: Generate preform geometry as woven
Step 2: Compare micro-geometry derived from numerical simulation to microscopic picture
Step 3. Simulate the molding process to derive the geometry of final product

Topology of the Engine Preform

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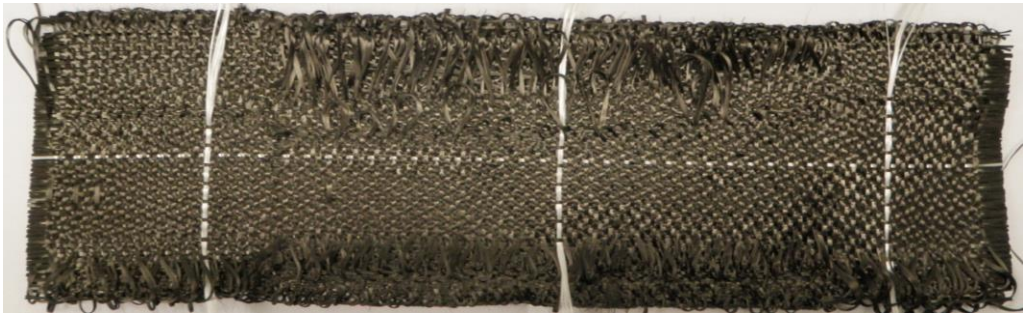
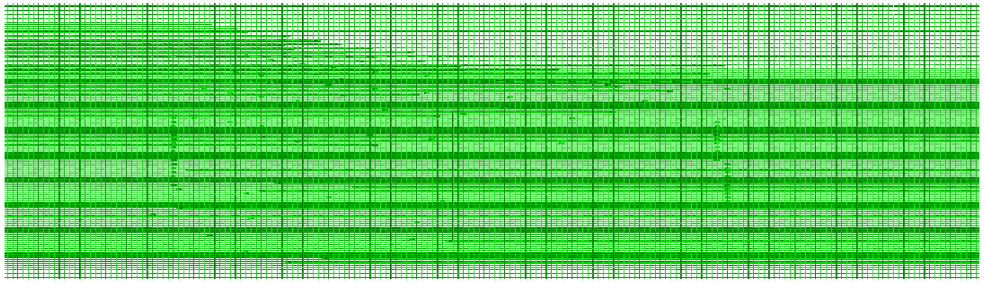
Sample



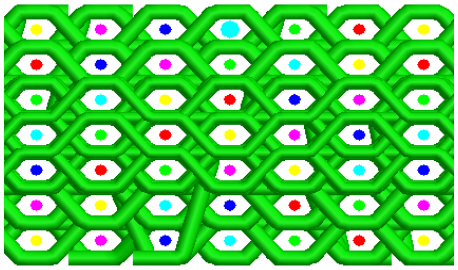
Dimension:10x3.3x0.16 in^3
Total yarns: nearly 2000
Fibers per yarn: 3k, 6k

Topology

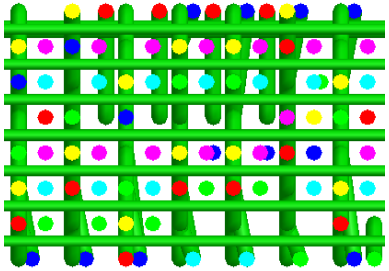
Weft
Warp



Topology local views



Front view



Side view

Detailed Geometry of the Engine Blade as Woven

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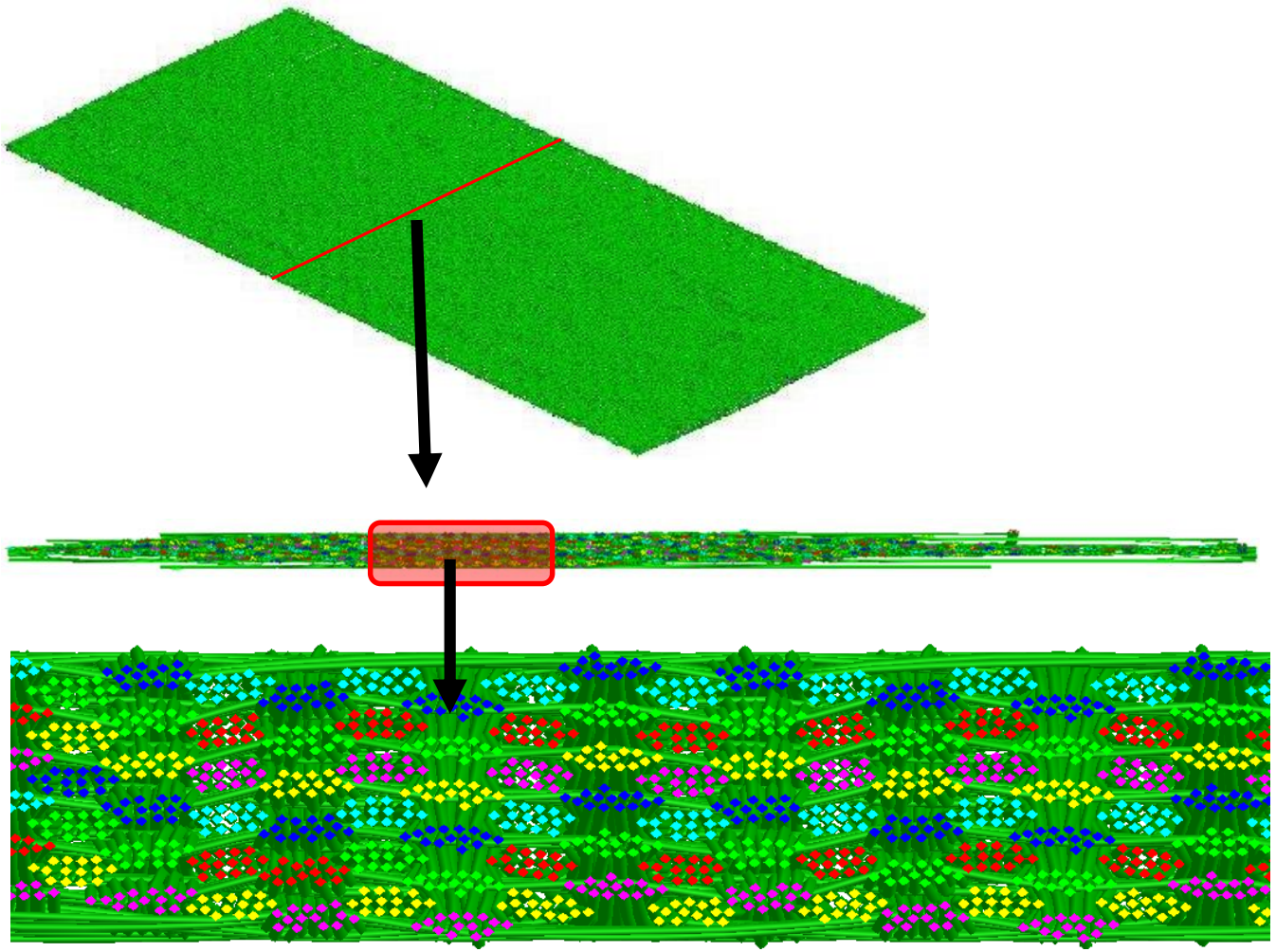
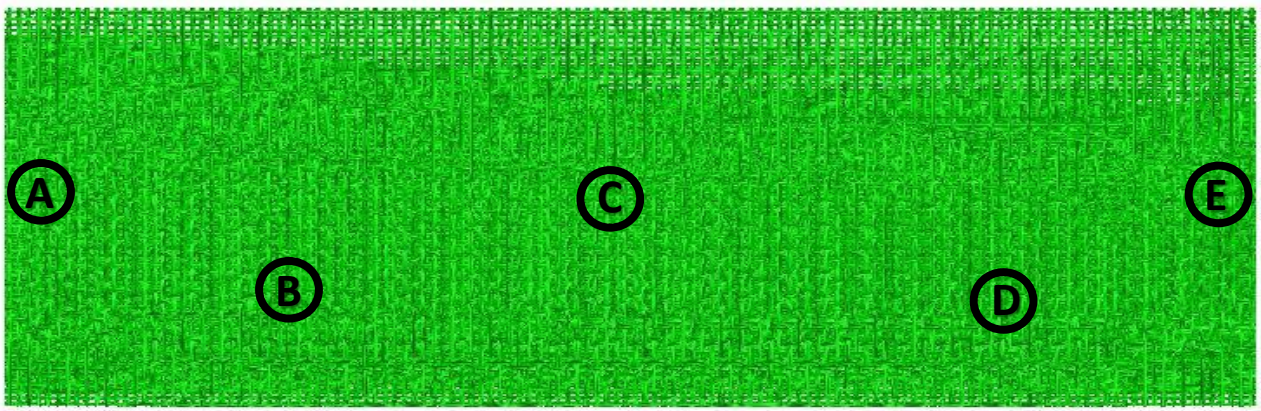
3-D View

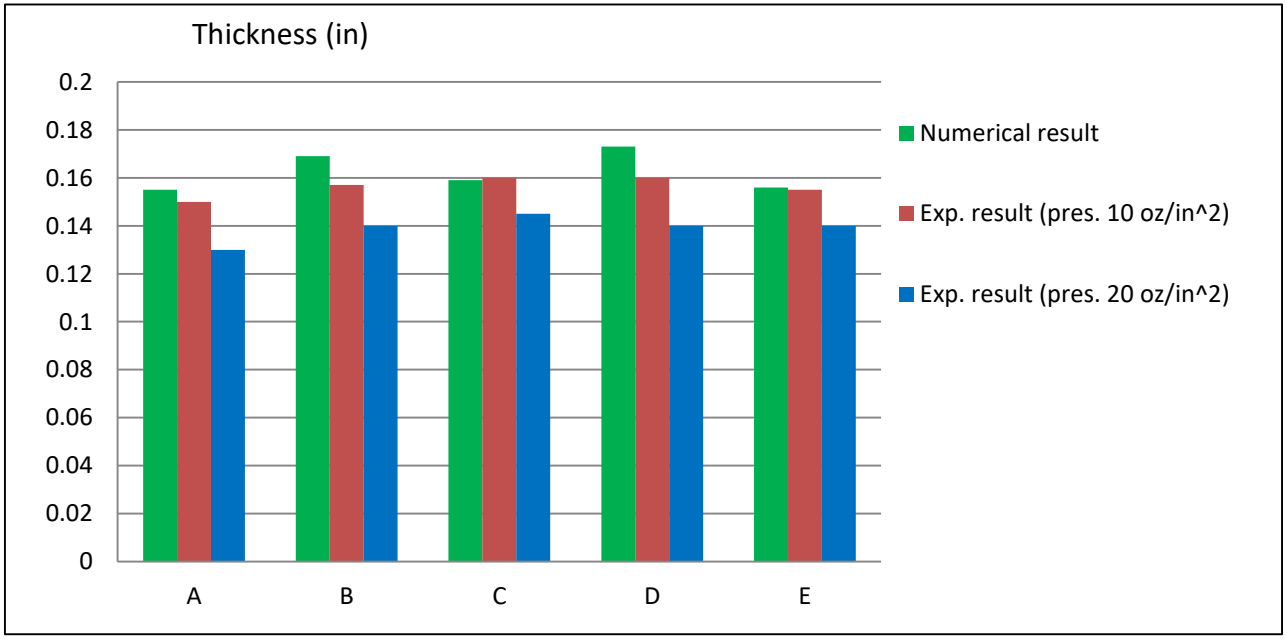
Section View

Detail



Thickness Comparison with Experimental Results





Yarn Pattern Comparison

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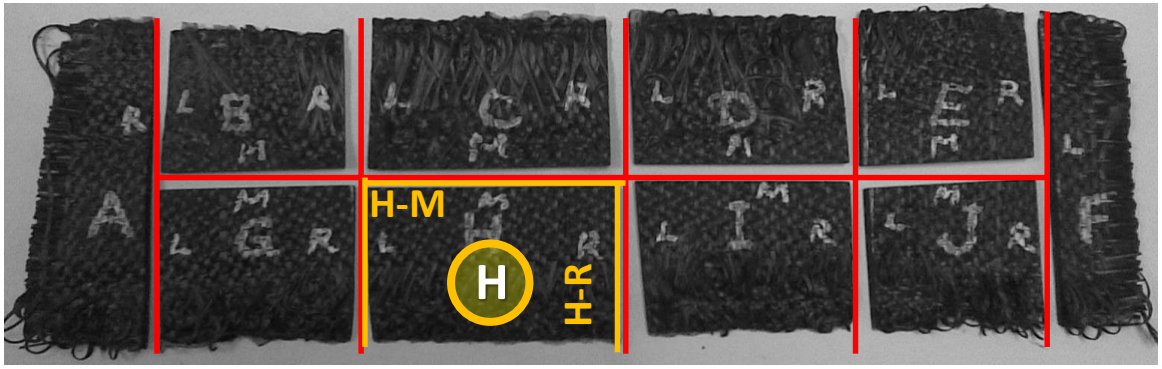
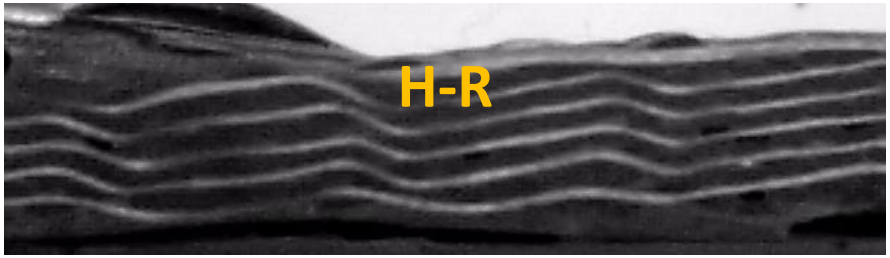
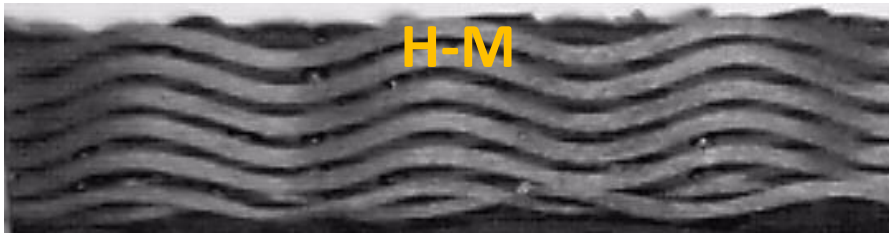
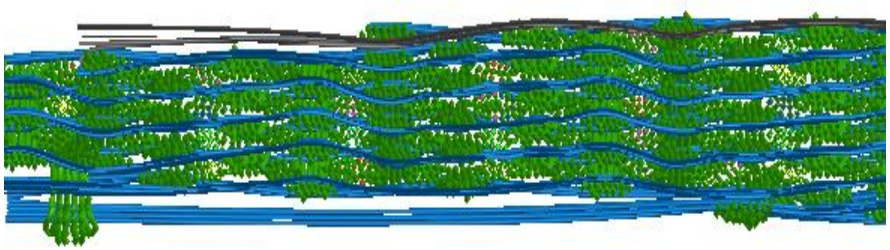


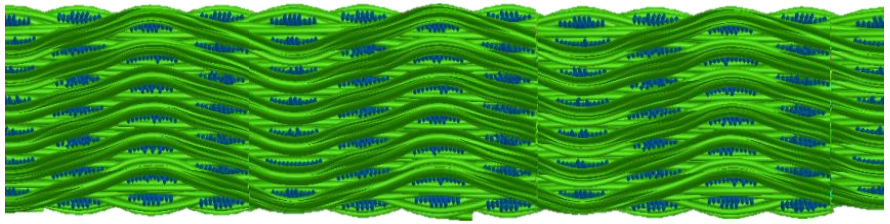
Top view (surface)







Weft section view

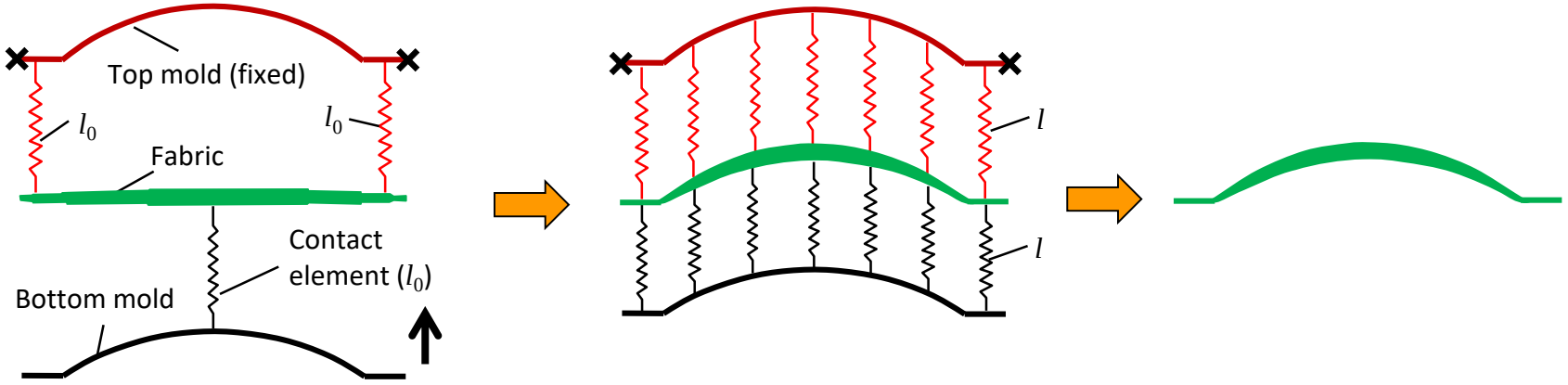


Warp section view

Molding Process

Resin Transfer Molding

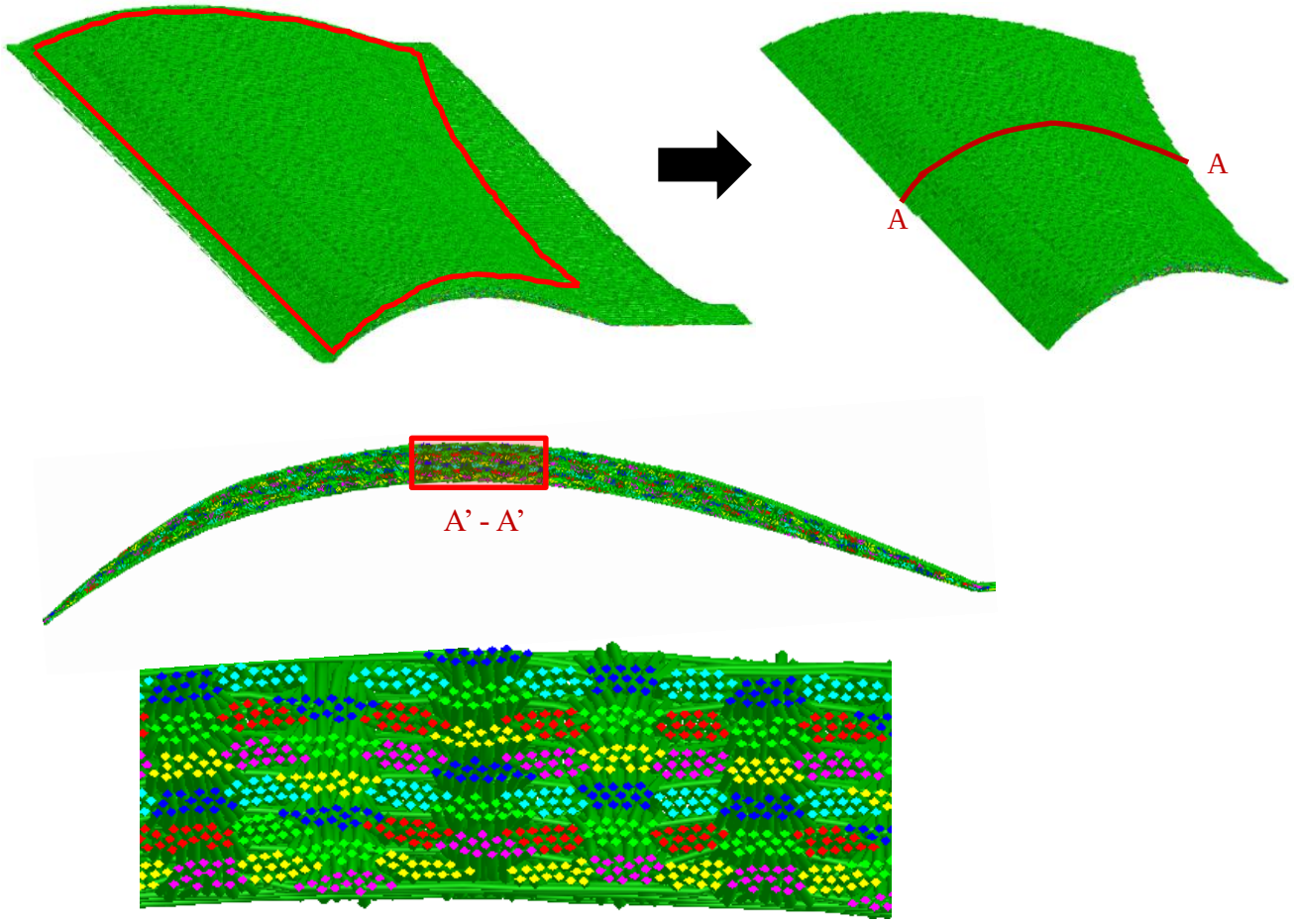
Illustration of Molding Process Simulation



Molding Process Model:

Top mold surface:	fixed
Bottom mold surface:	move upward

Trim the boundary: Net shape of the component



Software Structure

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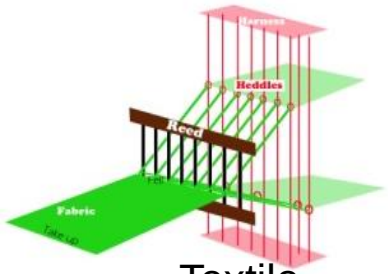
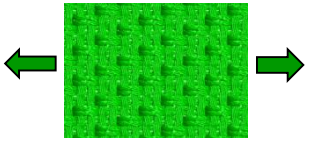
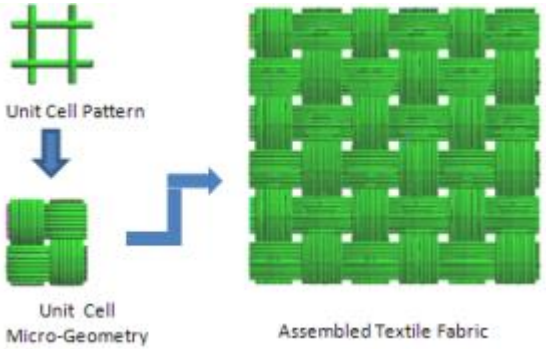


Textile Process Simulator

Main Solver (DFMA)

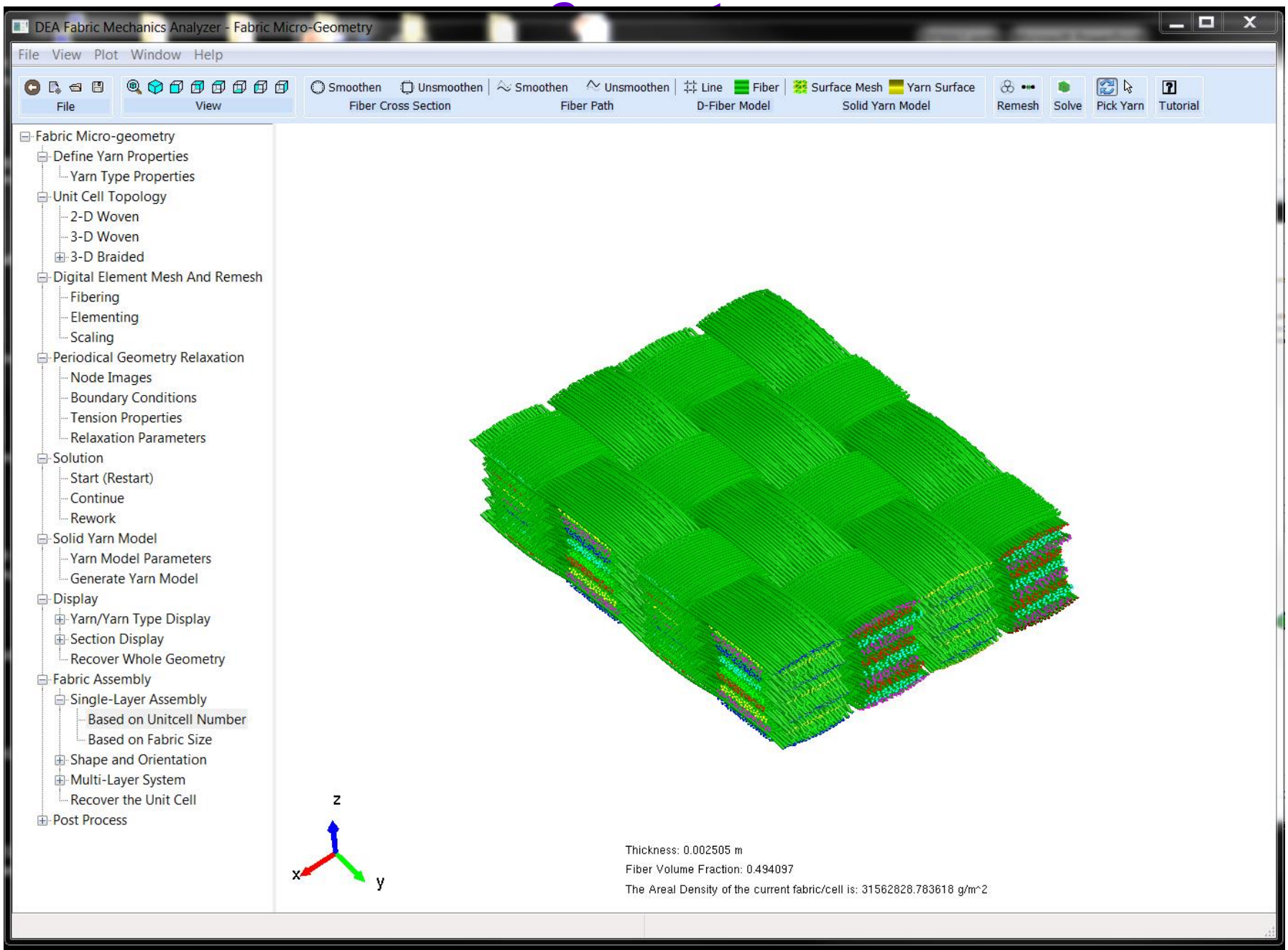


Stress, strength deformation, impact, molding, draping analysis



Determine Fabric Micro-Geometry

Function 1: Interface for Fabric Micro-



Unit Cell Micro-Geometry

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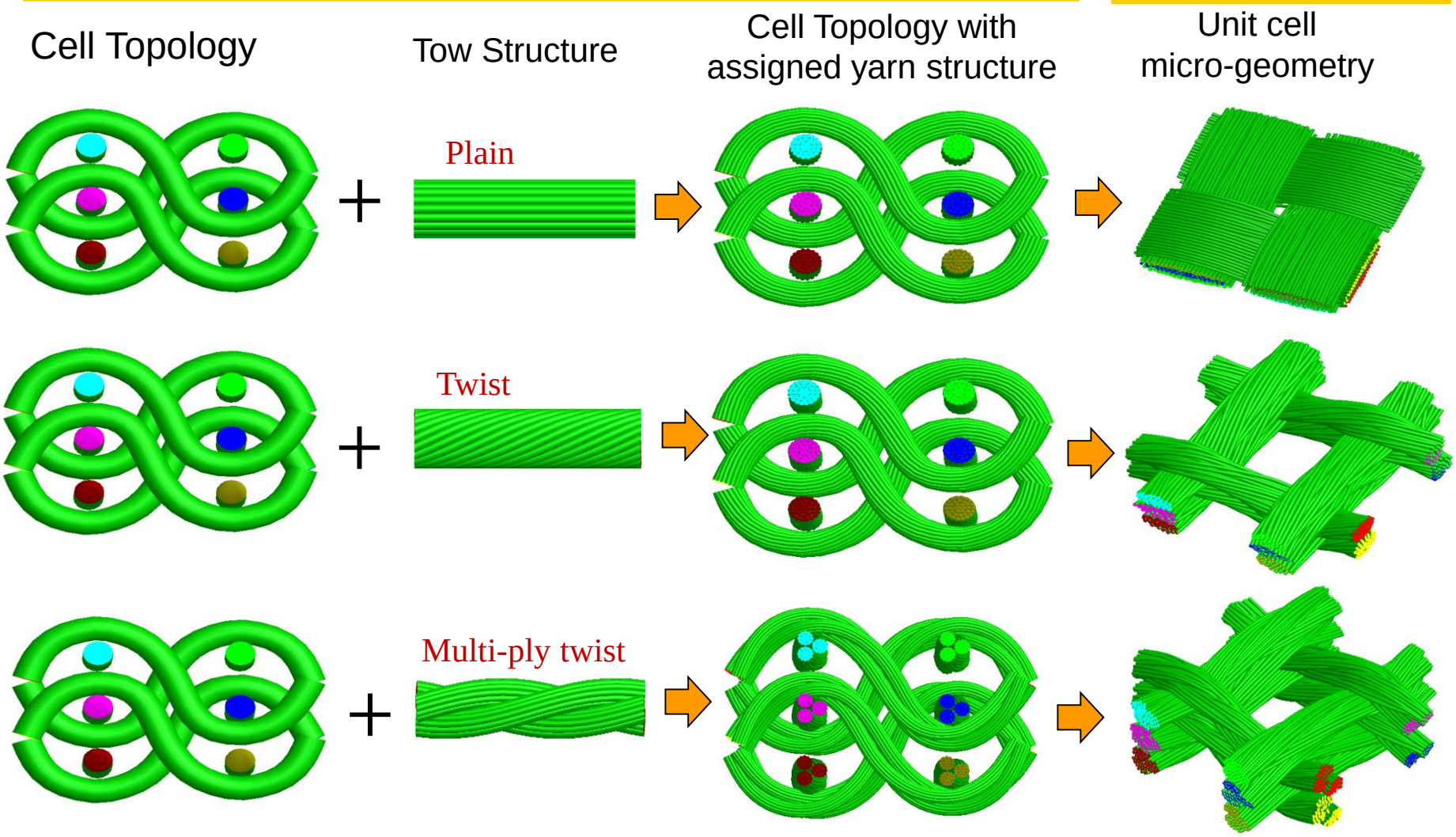

Micro-geometry is determined by dynamic relaxation approach with periodic boundary conditions.

Uniform Fabric Assembly

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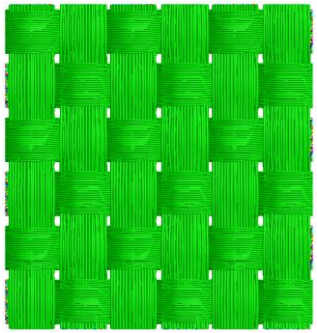
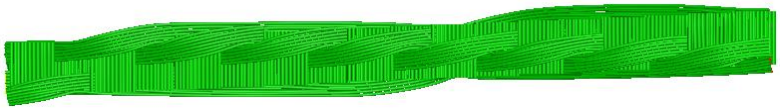
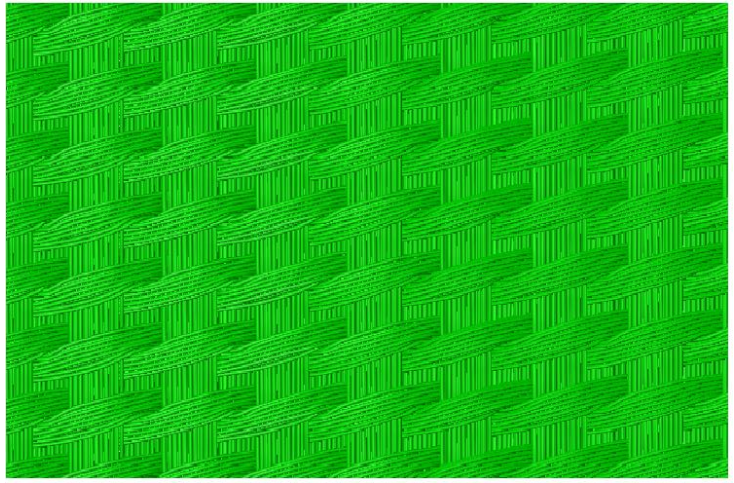
Assembly



Rectangular unit cell



Non - rectangular unit cell
(Angle-interlock)



Hybrid Unit Cell Assembly

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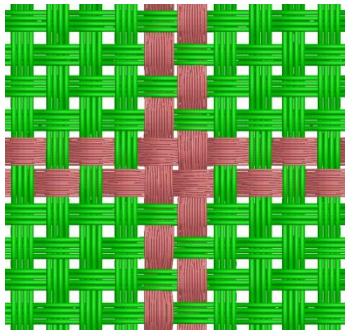
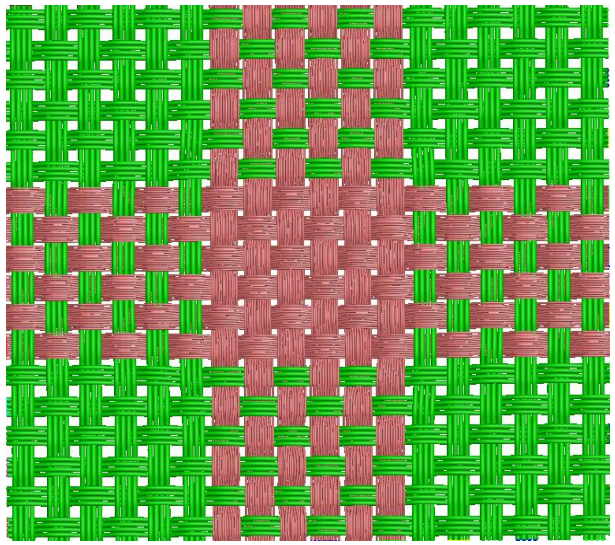


Representative Structures

Assembly



Expanded Fabrics

The representative structure of a fabric is not the unit cell of the fabric. It contains all cells required to assemble a hybrid fabric.

Fabric Surface comparison

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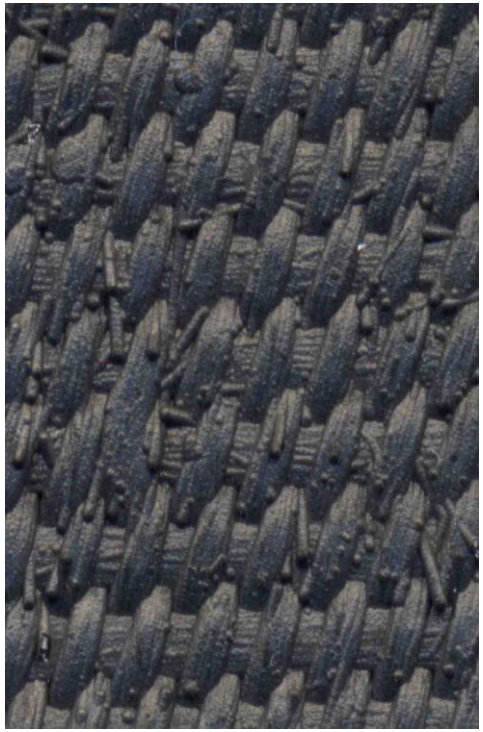
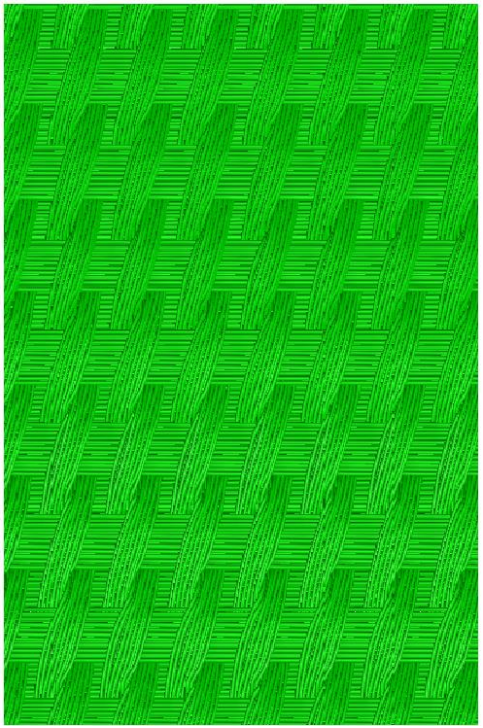
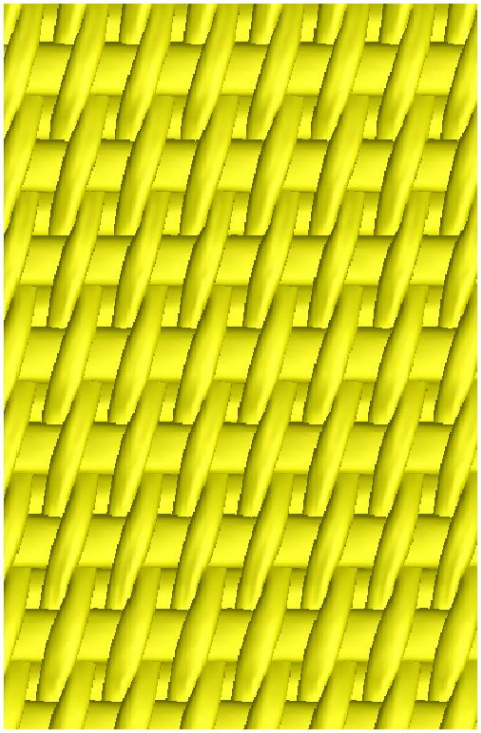


Microscopic picture

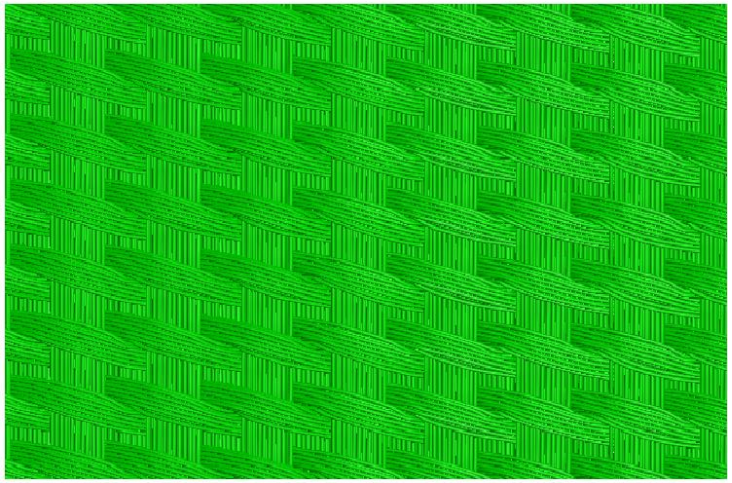


Assembly with fiber mode



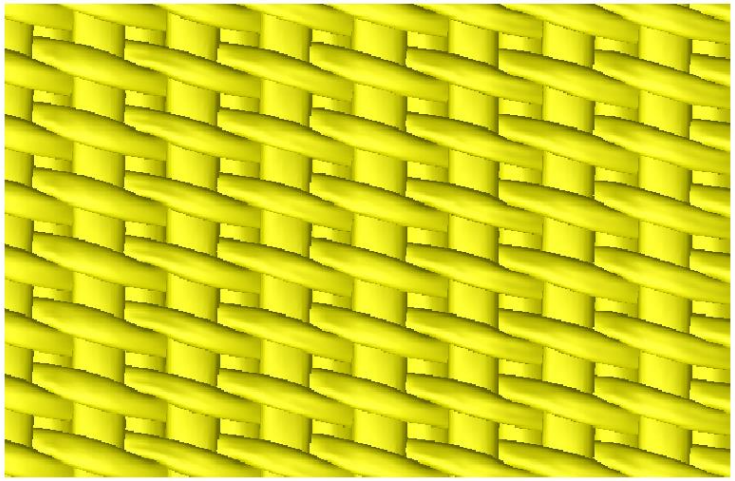
Assembly with solid yarn mode

Output format



Fiber mode

For fiber-level micro-mechanics analysis



Yarn mode

Yarn level geometry can be read by ANSYS, Pro-E or other commercial software. It can be used for yarn-level micro-mechanics analysis.

Various Fabric Micro-Geometries

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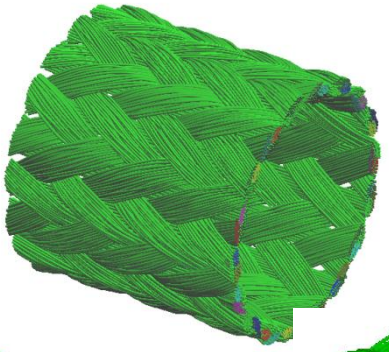
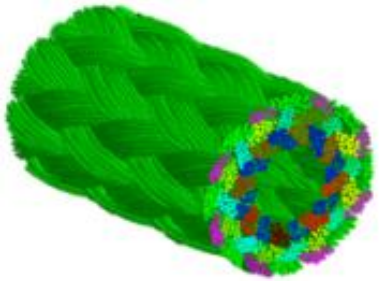
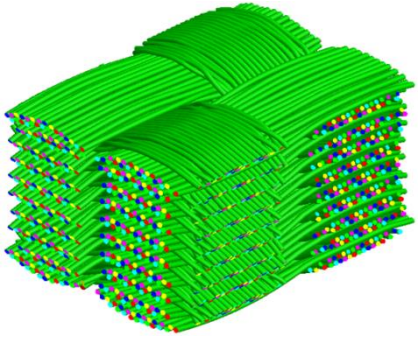
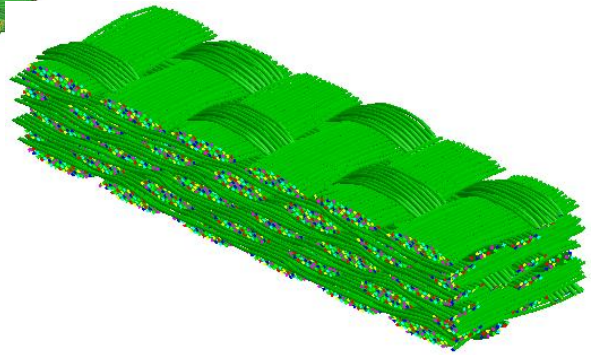
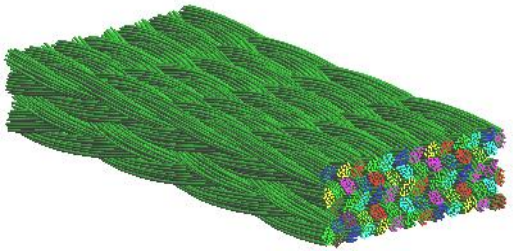
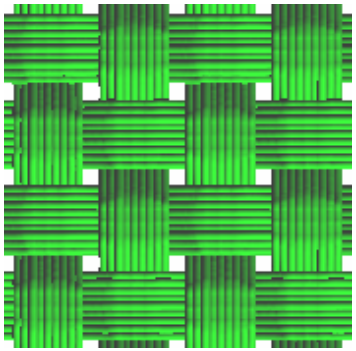
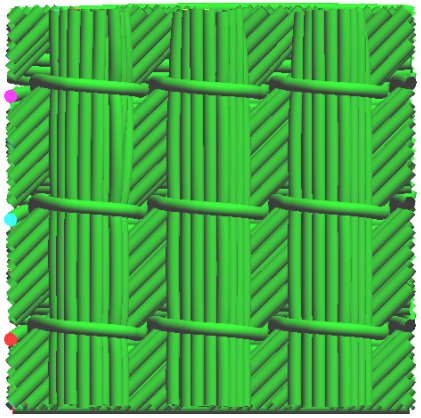
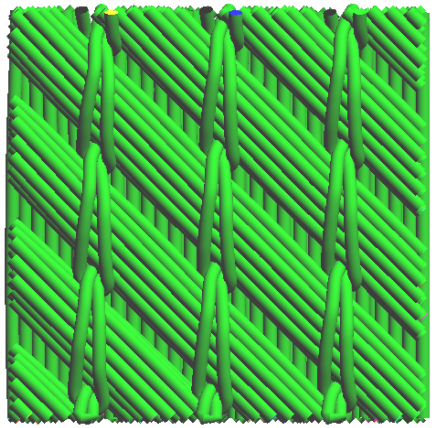
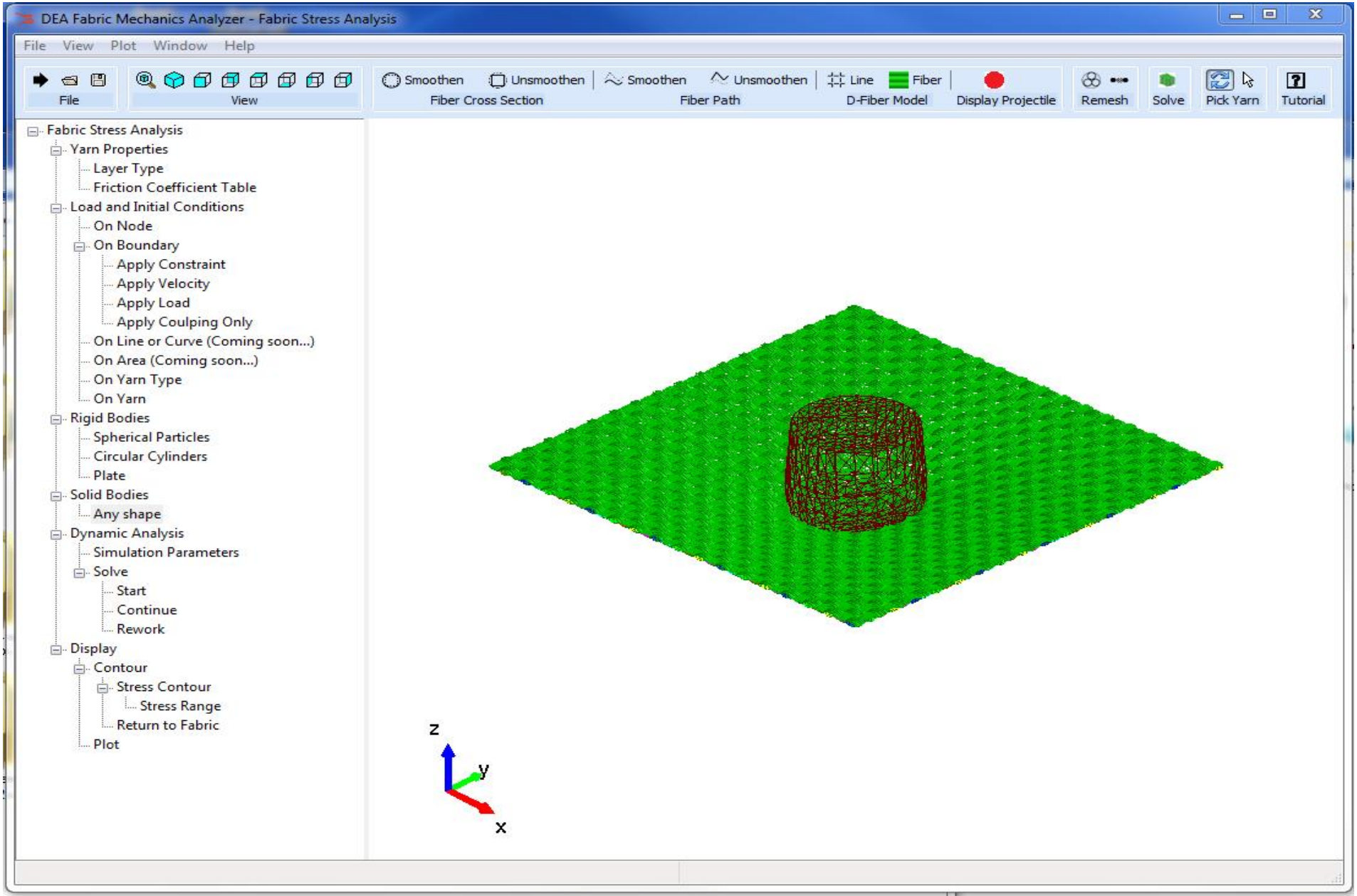









Function 2: Stress, Deformation, Impact Analysis



Main Solver Structures

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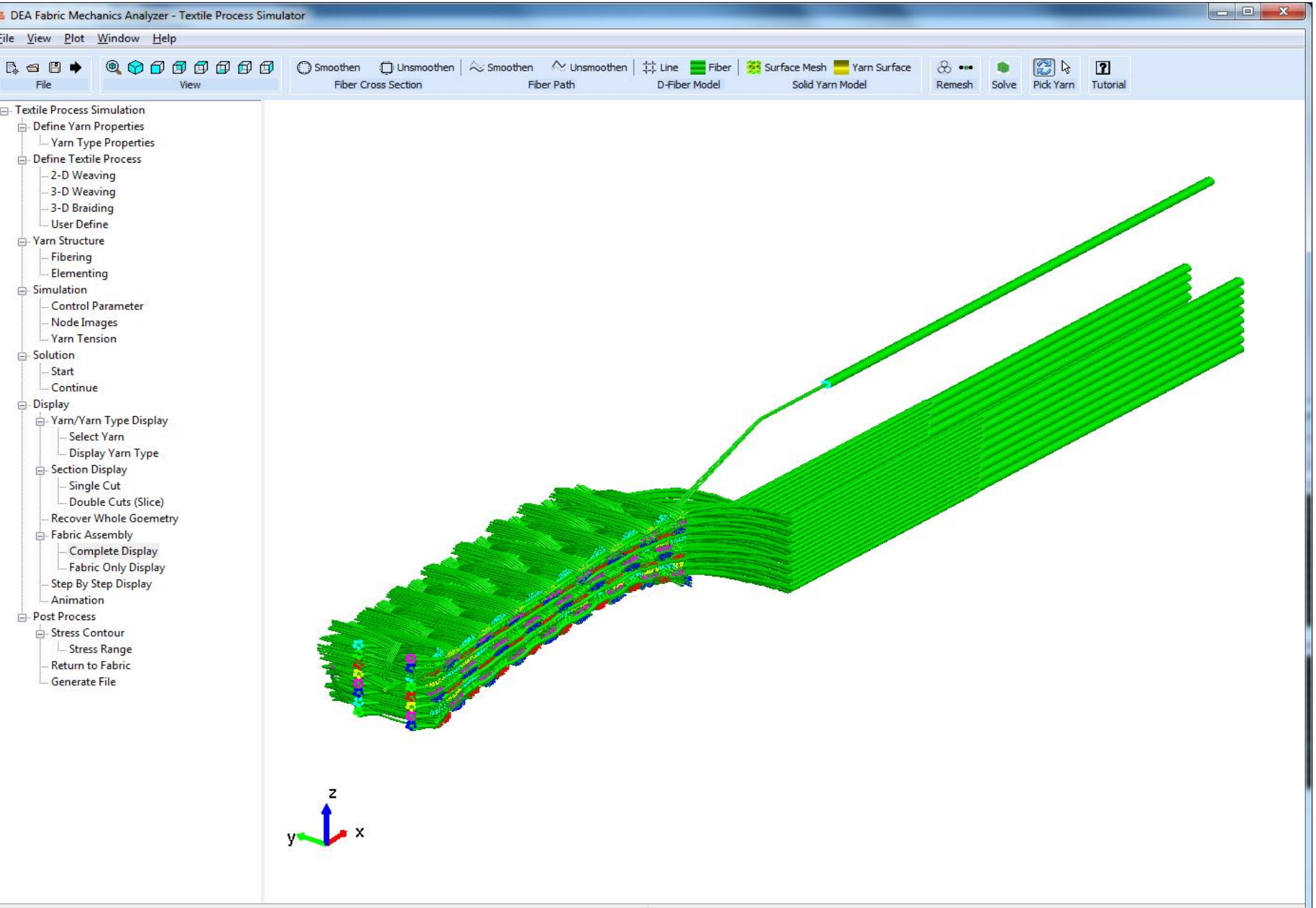
1. The software consists of a DEA solver (For fabric analysis) and a FEA solver (for continuum body analysis). In each step, the interacts between the fabric and the other continuum body are searched. The contact force applied to both fabric and other continuum body are modeled.

2. Material domain used in this software can consists:

   - ❖ Fabric (Single fabric or multiple fabrics)
   - ❖ Particles with diameter
   - ❖ Rigid body with arbitrary shape
   - ❖ Deformable continuum body

3. The software can be used for stress, strength, deformation, impact, draping and molding analysis.

Part 3: Weaving Process Simulator



3D WEAVING MACHINE STRUCTURE AND WEAVING PROCESS SIMULATION

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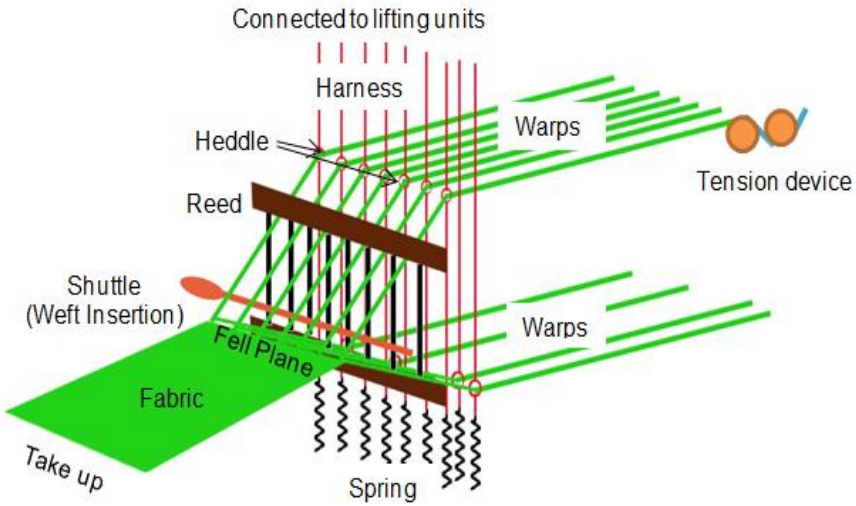

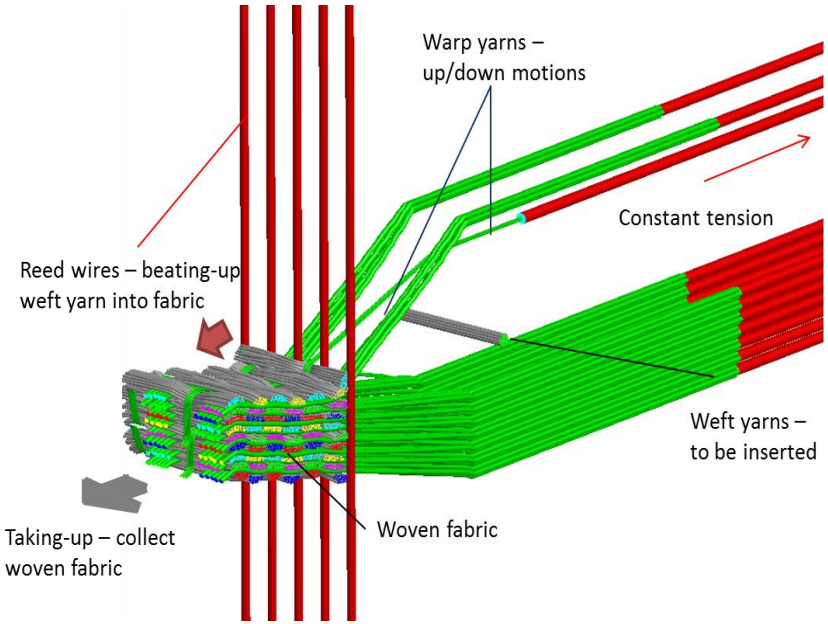

Machine structure → **Process simulation**

Applications

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1. Effect of weaving kinetics, such as yarn tension, beat-up velocity, take up frequency, inter-fiber friction, reed-fiber friction, on fabric thickness, unit cell length and unit-cell width.
2. Analyze fiber damage during the weaving process. The beat-up velocity and reed-fiber friction can play important role on the fiber damage. Fiber damage could affect the fabric strength and composite strength.
3. We have collaborated with 3-D weaving company to design 3-D weaving machine for 3-D armors. The simulator is used to calculate the beat-up load applied to the 3-D weaving machine. It will guide company for the design of new machine.
4. It can also be used to simulate braiding processes.

Software Version

K-State Composites Laboratory

- Window based version:
  - Have a user friendly graphic interface
  - Have pre-processor and post processor
  - Used open-mp (parallel code with shared memory) and C++ language.
- Cluster based version:
  - Use MPI and C++ language
  - Can be used for large scale simulation
  - Have to use the window-based version for pre- and post- processors
- Working in progress:
  - Connect the window based code to cluster
  - Parallel post-processor
  - One can use window based code to connect cluster and create a friendly environment for cluster simulation

PC version can be downloaded from: www.fabricmechanics.com

Questions?

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Thank You !