Nonlinear Multi-Scale Modeling of Aerospace Composites Materials & Structures

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Material Challenges

- Manage Material Data
  - Generate Data (Cost & Time of Test)
  - Manage, Trace, Protect (IP)
  - Comply (Regulation)

- Model (composite) Materials, part & systems
  - Nonlinearity: Progressive damage & failure
  - Anisotropy
  - Heterogeneity
  - Process dependency
Systems ↔ Parts ↔ Materials

- Use Actual System (IP protected)
- Use Actual Part (IP Protected)
- Use Actual Material Model (IP Protected)

Event n ↔ Event 1

Mat 1 ↔ Mat n
Exploiting Materials in Systems Design

Test Data → Fit/Excel → MaterialCenter → 3rd Party DB's

characterization

Materials Management
e-Xstream, The material modeling company

- Software & Engineering company 100% focused on advanced material modeling.
- Founded in 2003
- A team of 30 (+ 4 TBH)
- 2 offices in Europe + MSC
- Hybrid sales channel
- 200+ major customers
- CAGR_{04-11} of 56%
- An MSC Software Company (Sep 2012)

MSC Software Global Reach

- +1000 Employees
- Diversified Global Revenue Distribution
- Diversified Industries
- 20 Countries
- R&D in 5 countries

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Customers

✉ Material Suppliers
  ✓ Plastics
  ✓ Composites,…

✉ Automotive
  ✓ OEMs
  ✓ Tier 1

✉ Aerospace
  ✓ Aero Structures (OEMs)
  ✓ Aero Engines

✉ Electric & Electronic
  ✓ Electronic Appliances:
    ✓ Electric : Connectors, transformers

✉ Defense

✉ Medical Devices
DIGIMAT, The material modeling platform

Is

✓ The nonlinear multi-scale material modeling platform

Used by

✓ Material Engineers
✓ Structural Engineers

At

✓ Material Suppliers
✓ Tier 1 (Material Users/Any Industry)
✓ OEM (Material Users/Any Industry)

For

✓ Material Engineering
✓ Accurate & Efficient FEA of “Composite” Structures
DIGIMAT Material Engineering

Input

Homogenization

Output

Stress vs Strain

Fiber orientation

Input

RVE Generator

Output

<σ_r

matrix> vs <σ_r

fibers> vs <σ_r

matrix>

Input

Reverse Engineering

Output

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Nonlinear MicroMechanics

Mean Field

Global behavior

Localization

Averaging

Local phase behavior

Finite Element

\[ \Delta \varepsilon_r = \langle \Delta \varepsilon(x) \rangle_r = H_r : \Delta E \]

\[ \Delta \bar{\sigma} = \bar{c}(c_r) : \Delta \bar{\varepsilon} \]

\[ \Delta \sigma_r = c_r : \Delta \varepsilon_r \]
Process ↔ Material ↔ Structure

**Material Processing**
- Injection molding
- Compression molding
- D-LFT

**Material Microstructure**
- Chopped fibers
- Nano, ...

**Material Characteristics**
- Mechanical
- Thermal
- Electric, ...

**Structural Performance**
- Stiffness
- Strength
- Fatigue, ...

**Material Processing**
- Drapage,
- AFP,
- PCM
- HP-CRTM

**Material Microstructure**
- Continuous fibers: UD/Woven
- Nano, ...

**Material Characteristics**
- Mechanical
- Thermal
- Electric, ...

**Structural Performance**
- Stiffness
- Fatigue, ...
Nonlinear Multi-Scale Modeling

Carbon Fiber
- $E_1 = 220$ GPa
- $E_2 = 15$ GPa
- $G_{12} = 22$ GPa
- $\nu_{23} = 0.2$, $\nu_{12} = 0.2$
- $S_{\text{max}} = 5,400$ GPa

Fibers Stress
- Fully Coupled NL MicroMech

Matrix Strain
- Constituent Prop Process Effect
- Real MicroStr Micro Failure
Motivation for Multi-Scale Modeling
Continuous Fibers/Draping

Carbon Fiber
E_1 = 220,000 MPa
E_2 = 15,000 MPa
G_{12} = 22,000 MPa
\nu_{23} = 0.2
\nu_{12} = 0.2

Failure
Epoxy

Failure
CF
Nonlinear Multi-Scale Modeling

Input

Interfaces

Result

Microstructure & Macro Strain

Macro Stress & Stiffness Matrix

Micro stress, strain, failure
Case Studies
MATERIAL ENGINEERING

Promising Material Candidates

Improved MF Modeling

Composite behavior

Constituents’ Behavior

Constituents’ Behavior

Strong, 2-Way Coupling

Moldflow

3D-SIOMA

Moldex3D

3D TIMON

APMEDI

Draping

Inj. Molding

digimat-MX

digimat to CAE

digimat-CE

digimat-FC

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# Mechanical: Stiffness Matrix of CFRP

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<th>Epoxy M18 + YSH-50A</th>
<th>E1 (GPa)</th>
<th>E2 (GPa)</th>
<th>n12</th>
<th>n23</th>
<th>G12 (GPa)</th>
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</table>

## Carbon HM / Epoxy

![Graph showing the relationship between Transverse Modulus E2 (GPa) and Fiber Volume Ratio (-)](chart.png)

**Source:** e-xstream engineering, 2011 – CONFIDENTIAL
Thermal Conductivity

- Materials: thermal conductivity (isotropic)
  - Kerimid 601: 0.23 W/mK
  - Al₂O₃: 30.7 W/mK

- 2-phase Microstructure: Kerimid matrix with Al₂O₃ fibers
  - Matrix: Kerimid
  - Inclusions: Al₂O₃ fibers
    - Volume fraction: from 0.0 to 0.4
    - AR = 6
    - Orientation: random in xy-plane (Random2D)
Electric : Electric Conductivity

∞ Materials : electrical conductivity (isotropic)
  ▪ PE: 2.5 E-14 S/cm
  ▪ Carbon: 50 S/cm (effective particle*)

∞ Microstructure : 2-phase
  ▪ matrix: PE
  ▪ inclusions: Carbon
    • VF: 0 → 50%
    • AR: 1, 5.5 & 33
    • Orientation: Random3D

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* value obtained from composite with inclusion volume fraction → 1.0 [Cai]
Defects generated in the material during processing
✓ Can eventually lead to failure of the composite
Curing of CFRP

- delamination
- higher stress of fiber matrix interface between layers
- alternation of shrinking behavior at the border of laminate layers
"DIGIMAT enables us to perform in depth studies of complex and realistic microstructures. As an invest into the future we base our simulation approach on the DIGIMAT software, both for our research and the education of a new generation of simulation engineers who will be experts in the modeling of materials."

Prof. Vasily Ploshikhin, Airbus endowed chair for Integrative Simulation and Engineering of Materials and Processes (www.isemp.de)
Case Studies

MATERIAL ENGINEERING
Aero Structure: Barely Visible Damage CFRP

- 4-side clamped plate:
  - Width: 4 in. (100 mm)
  - Length: 6 in. (150 mm)

- Lay-up sequence:
  - [45/90/-45/0]_s
  - 24 layers of UD
  - Total thickness: 4.8 mm

- Materials:
    - Longitudinal Young’s modulus: 228 000 MPa
    - Transverse Young’s modulus: 6220 MPa
    - Transverse shear modulus: 7600 MPa
    - Tensile strength: 4278 MPa
  - Epoxy 15 parts Bisphenol A-epichlorhydrine, 2 parts tri-ethylenetetramine (source: Rensselaer Polytechnic Institute, Troy, New York)
    - ElastoPlastic behavior:
      - Young’s modulus: 1300 MPa
      - Yield stress: 22.5 MPa
      - Isotropic exponential hardening
  - Microstructure:
    - Unidirectional fibers
    - Volume fraction of fibers = 57%
**Aero Structure:** Barely Visible Damage in CFRP (Accumulated Plastic Strain in Epoxy Matrix)
Bird Impact on Composite Belly Fairing

**Carbon Fiber**

\[ E_1 = 220 \, 000 \, \text{MPa} \]
\[ E_2 = 15 \, 000 \, \text{Mpa} \]
\[ G_{12} = 22000 \, \text{MPa} \]
\[ v_{23} = 0.2 \]
\[ v_{12} = 0.2 \]

**Epoxy**

Failure

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Bird Impact: Composite Belly Fairing
Macro & Micro Failure Indicators

Failure indicator in Epoxy matrix

Layer 1

- 1.003E+00
- 8.918E-01
- 7.805E-01
- 6.691E-01
- 5.577E-01
- 4.463E-01
- 3.350E-01
- 2.236E-01
- 1.122E-01
- 8.223E-04

No result
Aero Engine: Ti/SiC Compressor Blade

Turbine Blade: Centrifugal Cyclic Loading

Material: Matrix: Ti- ElastoPlastic
Reinforcements: SiC – Elastic
Short Fibers/Oriented
Outlook

Materials

- Long Fibers Thermoplastics
- Woven Composites

Performance

- Fatigue
  - Chopped Fiber
  - Continuous Fiber
- Creep

Physics (longer term)

- More focus on electric conductivity

Source: Lomov & Al.
CONCLUSIONS
Digimat’s Holistic Multi-Scale Modeling

Materials
- Chopped Fibers: Short/Long
- Continuous Fibers
- Fillers

Physics
- (Thermo)-Mechanical
- Thermal
- Electric

Manufacturing
- Injection
- Draping
- Compression

Performance
- Stiffness
- Strength
- Fatigue

Technology
- Linear/Nonlinear
- Mean Field/FEA
- Micro/Hybrid
e-Xstream is the “Composite” in:

Design & Process of **Composite** Products