MULTISCALE MODELING OF MULTIFUNCTIONAL POLYMER COMPOSITES

Thomas E. Lacy Jr., P.E. (GA/MS)
Professor
Department of Aerospace Engineering
Mississippi State University
T.E. Lacy: Background

- **Education:**
  - PhD, ME, Georgia Institute of Technology, 1998
    - NASA GSRP Fellow
  - MSME, Georgia Institute of Technology, 1992
  - BSME, University of New Mexico, 1983

- **~Ten years aerospace industry experience:**
  - The BDM Corporation
  - Boeing (Peacekeeper Missile Program, 767, KC-135)
  - Northrop (B-2)
  - McDonnell Douglas (A-12, YF-23 ATF)
  - Lockheed (L-1011)
  - GTRI Aerospace Laboratory (MH-53J)

- **Areas of interest:** Computational solid mechanics, damage tolerance of metallic & composite aircraft structures, fatigue, fracture, design of experiments

- **Miscellaneous:**
  - Fellow, ASME
  - Associate Fellow, AIAA
  - Chair, Emerging Technologies Division, American Society for Composites, 2009-2012
  - Founding University Partner, NASA Glenn Multiscale Analysis Center of Excellence
  - Scientific Advisor for *Golf Magazine*
  - Recipient, 2009 SAE Ralph R. Teetor Educational Award
  - Member, BCoE’s Academy of Distinguished Teachers
  - National Institute for Aviation Research Faculty Fellow (Wichita State U.)
  - Licensed Professional Engineer (GA, MS)
Multiscale Modeling of Thermoset Composites
(DoE, FAA, NASA)

Goal: Develop multiscale analysis/design methodology for predicting structure, properties, evolution, and failure of fiber reinforced composite materials.

Nanoscale

MD

Arnold et al. (2009)
Numerical Estimates of the Compressive Strength of Impact-Damaged Sandwich Composites (FAA)

(Y. Hwang)
Motivation

- Develop physically-motivated large scale nonlinear finite element models to predict progressive failure and CAI residual strength (ABAQUS) based upon NDI estimates of damage

\[ R_c \]

\[ \text{Experiment} [7] \]

\[ \text{Maximum Stress} \]

\[ \text{Maximum Strain} \]

\[ \text{Tsai-Wu} \]

\[ \text{Initiation of first-ply failure} \]

\[ \frac{1180}{\text{lbf/in}} \]

\[ \frac{1350}{\text{lbf/in}} \]

\[ \frac{1}{\text{Nlbf/in}} \]

\[ \frac{P}{y} \text{ in} \]

\[ \frac{P}{y} \text{ in} \]

\[ \text{Experimental} \]

\[ \text{FEA: Progressive Failure} \]
UAV Ultra-Light Sensor Platform (Army SMDC)

PI: D. Lawrence
Collaborators: R. Sullivan, M. Rais-Rohani, T. Lacy, et. al
Ultra-Light UAV Sensor Platform

- Develop a low cost ultra-light UAV sensor platform for future military/civilian requirements
  - 72-hour endurance target

- Based on proof-of-concept sailplane vehicle

- UAV structure constructed from oven-cured carbon fiber epoxy prepreg

- Tasks
  - Perform flight/ground/launch loads analysis
  - Perform structural analysis/FEA (ABAQUS)
  - Perform wing & fuselage/tail proof testing
  - Perform wing & fuselage/tail vibration testing

- GOAL: Development of a multi-functional MSU UAV for “near space” missions
UAV Testing/ Simulation
(Y. Hwang, Y. Yamada)

- Full scale wing/fuselage vibration and ultimate load testing
- Structurally Complete 3-D Finite Element Models
  - Composite material stack-up, sandwich construction, ply drop offs
  - 200+ material property regions (Wing)
  - Weight of adhesive, non-structural masses
Molecular Dynamics (MD) Simulations of Thermoset Composites (DoE)

(C. Jang, S. Nouranian)

**Goal:** Develop analysis/design methodology for predicting the interfacial shear strength of vinyl ester resin/graphene surface using MD simulations

Nanofiber Morphology  Crosslinked network  Graphene pullout

RRV Algorithm for crosslinking
Multiscale Modeling (DoE, NASA)
MD + Micromechanics (EC-MAC) + MAC/GMC
(T. Ricks, J. Yu, C. Jang, S. Nouranian)

Molecular Scale → Nano/Micro Scale → Macro Scale

MD simulation

Micromechanics (MTM & SCM)

MAC/GMC

Woven Polymer Matrix Composite with MAC/GMC
Modified Mori-Tanaka Method

- Multiple inhomogeneities problem: Different nanoreinforcements with coating
- Multi-Phase Problem: Simulate voids, agglomerates, carbon clusters, etc.

**Solid** silica nanospheres ($E_s = 24$ GPa) in epoxy ($E_m = 3.27$ GPa),

- Tensile test data
- Zhang et al. (2006), tensile test data

**Hollow** glass nanospheres ($E_s = 70.2$ GPa) in polyester ($E_m = 4.89$ GPa),

- Tensile test data
- Huang and Gibson (1993), tensile test data

$D_s = 42 \pm 21$ nm, $t_w = 0.84$ nm

0.00 “Egg shell types” 0.05

Volume Fraction of Solid

Normalized Effective Modulus

(Volume Fraction of Heterogeneities)
Effective Properties of Composites Containing Multiple Heterogeneities II
(J. Yu, T. Ricks, A. Adil)

**Hollow & Wavy** VGCNFs \((E_F = 960 \text{ Gpa}, R/R_o = 0.5)\) in vinyl ester \((E_m = 3.155 \text{ GPa})\)

1: **Hollow** only
2: Hollow + **Waviness** \((h/\lambda=0.054)\)
3: Hollow + Waviness + **Voids** \((c_v = c_f)\)
4: Hollow + Waviness + **Voids** \((c_v = 500 \cdot c_f^2)\)

Viscosity: Nonlinear (quadratic function)

*Electrical Conductivity* Estimates using EC-MAC
(J. Yu, T. Ricks, A. Adil)

Modified Micromechanics (MTM & SCM)

- **Multiple inhomogeneities problem:** Thermal properties, *electrical properties*
- **Multi-Phase Problem:** Simulate voids, agglomerates, carbon clusters, etc.

VGCNF ($\sigma_{(1)} = 10000$ S/cm)
in epoxy ($\sigma_{(0)} = 1.0E-10$ S/cm),
Ardanuy *et al* (2011), Electrical conductivity data

SWNT ($\sigma_{(1)} = 5.1E + 4$ S/ m)
in polystyrene ($\sigma_{(0)} = 1.0E - 4$ S/ m),
Ramasubramaniam *et al* (2003), Electrical conductivity data

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A Stochastic, Multiscale Modeling Methodology for Composite Materials (NASA)  
(T. Ricks)

- Developed a methodology to perform progressive failure analysis of MMCs using FEAMAC
- Assigned fiber strengths to RUC at random based on 2-Parameter Weibull CDF
- Assigned RUCs at random to elements within ABAQUS

- Use of no strength distribution gives non-physical, symmetrical failure behavior, over-prediction of strength
- Use of a strength distribution gives random failure behavior throughout specimen, much better prediction of strength
Hypervelocity Impact Testing (NSF, NASA)
(J. Warren, S. Offenberger)

• Danger to spacecraft/satellites due to micro-meteoroids and orbital debris
  - Average velocities: 10-20km/s

• Two stage light gas gun
  - Velocity range: 3-7km/s
  - 1mm diameter projectiles

• Develop multifunctional sandwich composite space shielding
  - Structural performance/ permeability barrier/ radiation shielding/ impact mitigation


Magnification: 911 X
Damage Tolerance of Multifunctional Composite Structures (NASA)
(T. Ricks)

- Possible loss of mission critical functionality while retaining structural integrity

**Materials**
- Piezoelectrics
- Nanomaterials
- Aerogels
- Shape Memory Alloys

**Applications**
- Vibration/ Noise Control/ Sonic Fatigue
- Morphing
- Lightning Strike
- Structural Health Monitoring
Future Direction: Use of Multifunctional Composite Materials in Advanced Vehicle Designs (NASA)
(T. Ricks)

GOAL: Facilitate materials and/or structural design by providing insight into relationships between material configuration and damage that lead to improved damage tolerance characteristics

Lightweight
Temperature Resistant
Multipurpose
Impervious to Environment

Fatigue Resistance
Vibration Mitigation
Structural Health Monitoring

Stealth

Low-Cost
Energy Absorbing
Acoustic Management

Load Carrying Capability
Damage Tolerant
Power Storage (PSC)
Lightning Strike Resistant