Composite Structures-
Modeling, FEA, Optimization and Diagnostics

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Refined Higher Order Displacement Field: Accounts for variations in transverse shear stresses through thickness

\[
\begin{align*}
    u &= u_0 + z \psi_x - \frac{4z^3}{3h^2} \left( \frac{\partial w_0}{\partial x} + \psi_x \right) \\
    v &= v_0 + z \psi_y - \frac{4z^3}{3h^2} \left( \frac{\partial w_0}{\partial y} + \psi_y \right) \\
    w &= w_0
\end{align*}
\]

\( u_0, v_0, w_0 \) denote the displacements of a point \((x, y)\) on the mid-plane and \( \psi_x, \psi_y \) represent the rotations of normal to the mid-plane about the y and x axes, respectively.
Composite Aircraft Wing

Aircraft wing (box beam) modeled using refined higher order theory of composite laminates

\[
\begin{align*}
    u &= u_0 + z \psi_x - \frac{4z^3}{3h^2} \left( \frac{\partial w_0}{\partial x} + \psi_x \right) \\
    v &= v_0 + z \psi_y - \frac{4z^3}{3h^2} \left( \frac{\partial w_0}{\partial y} + \psi_y \right) \\
    w &= w_0
\end{align*}
\]
Design Optimization

**Multidisciplinary Optimization** - Structural (weight; failure), aeroelastic (flutter), and aerodynamic (L/D) objectives/constraints

**Design variables** – Ply orientations, laminate thickness, wing sweep, PZT actuator thickness
Computational Modeling of Nanocomposite (sponsored by US Army; collaborator - Ahmadi)

- Develop simulation based design for nano-composites
- Determine constitutive relation and load-displacement diagram for nano-structured glass fibers
- Model nano-composite with randomly oriented glass fibers

RVE Approach
Modeling of the entire fiber
Over one hundred million nodes
Use a representative volume element (RVE)

3-D representation of RVE
Constitutive Relationship and Load-Displacement Diagram

- Six independent engineering constants obtained for the glass fiber (orthotropic material)
- Modeling of glass fiber under nano-indentation load using adaptive meshing

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\tau_{23} \\
\tau_{13} \\
\tau_{12}
\end{bmatrix} = \begin{bmatrix}
19.643 & 10.614 & 5.144 & 0 & 0 & 0 \\
10.614 & 19.643 & 5.144 & 0 & 0 & 0 \\
5.144 & 5.144 & 33.311 & 0 & 0 & 0 \\
0 & 0 & 0 & 7.185 & 0 & 0 \\
0 & 0 & 0 & 0 & 7.185 & 0 \\
0 & 0 & 0 & 0 & 0 & 2.437
\end{bmatrix}
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\gamma_{23} \\
\gamma_{13} \\
\gamma_{12}
\end{bmatrix}
\] (Gpa)

\begin{figure}
\centering
\includegraphics[width=\textwidth]{graph.png}
\caption{Graph showing load-displacement diagram for different models of glass fiber.}
\end{figure}
Composite Modulus for Randomly Oriented Fibers

RVE for modeling composite (S and L are calculated by sensitivity analysis for aligned fibers)

RVE stresses under longitudinal load

RVE modeling for different capsule orientations

\[ E_{\text{random}} = \int_{0}^{\pi/2} E(\alpha)f(\alpha)d\alpha \]

\[ f(\alpha) = 2.6329 \left( \frac{\alpha}{0.79} \right)^{1.08} e^{-\left( \frac{\alpha}{0.79} \right)^{2.08}} \]

Weibull’s distribution function for fiber orientation
FEA - Automotive Component
(sponsored by Magna Powertrain)

1 Million elements - shell (quad and triangular) and solid (hexagonal, tetrahedral)
Material- metal and composite
Rear Part - Stress Contours
Nonlocal Elasticity (collaborator- Ahmadi)

- **Current FEM**
  - (In macro scale) cannot model the atomic scale
  - Uses Classical Elasticity
  - Cannot model high frequency waves
- **Nonlocal Elasticity**
  - Can implement the atomic scale length (even in macro scale modeling)
  - Gives close match with atomic dispersion

\[ t_{kl}(x) = \int_{\nu} \alpha(|x' - x|)\sigma_{kl}(x')d\nu' \]
Nonlocal Elasticity Results

- Developed second order approximation based nonlocal theory for modeling nano-composites
- Resulting stress distribution produces force and moment identical to detailed FEM
- Proposed method gives correct wave propagation behavior for nano scale structures
- Classical (local) elasticity fails to give correct moment values; not capable of modeling high frequency wave propagation
Composite Failure Analysis & Testing
(Sponsored by NYSERDA/MAS Composites)
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(Sponsored by NYSERDA/MAS Composites)

- Random (short-) fiber composite
- Predicted modulus and strength correlated with experimental data
Smart Structures Lab

Scanning Laser Vibrometer
Advanced Signal Processing

Analysis of STS-41 Vibrations

Hilbert-Huang Transform

STFT Analysis

Magnitude, g/Hz

Frequency, Hz

Time, s
Adaptive Predictive Control for Vibration Suppression

Two mode operation: adaptive prediction and control
Experimental Setup

Original Structure

Plate Added Structure

Tip Mass Added Structure
Response to combined sine wave disturbance (original structure)

RMS reduction = 94% for NAPC, 86% for AGPC
Responses to tip mass attachment during experiment

RMS reduction = 83% for NAPC, 72% for AGPC
Integrated Structural Health Monitoring

Diagnostics (Integrated Structural Health Monitoring) is a critical enabling technology for advanced, high performance composite structures

- Integrate NDE functionality into structure
  - Provide complete damage information (location, presence, type, severity)
  - Real-time capability (continuous inspections)
  - Ability to monitor entire structure, not just accessible portion

- Benefits
  - Condition-Based Maintenance (Large potential for time and cost savings)
  - More efficient structural designs
Vibration Based ISHM

- Active research area
- Advanced sensors available
- Several methods investigated at Clarkson
  - Modal analysis (frequencies & mode shapes)
  - Hilbert-Huang Transform (nonlinear, non-stationary data)
  - Time Series Analysis (AR, ARX models)
  - POD/SVD based algorithm
Diagnostics of Composite Structures

- Impact damage (BVID) of composite structures is a big concern; damage detection procedure required to monitor structures.
- Developed diagnostic method based on Proper Orthogonal Decomposition of vibration signals.
- Dynamical invariants (POMs) used as damage indicators.
Composite Diagnostics

- Carbon epoxy plate, 254x127x 2mm, [0/90]4s lay-up, AS4/3506-1 material
- Modeled using 1056 SOLID46 layered ANSYS elements
- Excitation applied at tip (root fixed); First 2 bending modes with 25% random noise added; Acceleration of plate limited to ~2g
- Impact damage simulated by reducing stiffness of selected elements (approx 9% of plate area damaged)
Lamb Wave Based Diagnostics for Composites (sponsored by AFOSR)

Variations between the two responses indicates presence of damage

Response for healthy case must be known
Modified Time Reversal Method

Baseline free method

Significant reduction in actuation hardware
Lamb Wave Experimental Setup

Actuation signal
Tone burst
• 20 kHz
• 9.5 cycles
Damage Index Values (Path 1-2)
Damage Index Values (Path 1-3)
Damage Index Values (Path 2-3)
Results (Signal Path 1-2)
Lamb wave based diagnostics

- Results show that modified time reversal method identifies damage
  - Presence
  - Location
  - Severity
- Baseline (healthy) data for test specimen not needed