MACHINE LEARNING APPROACH FOR PREDICTION OF FIBER ORIENTATION DISTRIBUTION IN MOLDED COMPOSITES

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Digital Twins to Advance High-Rate Manufacturing Methods

- Compression molding of discontinuous fiber forms, such as “chopped prepregs” is a cost efficient manufacturing method of complex shaped geometries.

- Development of material & process technologies aimed at enabling high-volume production of thermoplastic composites requires:
  - Fundamental understanding of process-structure-property-performance relationships:
    - Origin of mechanical properties
    - Mechanisms of progressive damage accumulation
  - Integrated design solutions for manufacturing & performance:
    - Variability in the manufacturing process & performance characteristics
    - Anticipation of failure modes
PPMC Material System

- Prepreg platelets contain carbon fiber reinforced with polymer
- Prepreg is a transversely isotropic material
- PPMC fills a niche – it allows greater fiber volume fraction and fiber length, yet is formable into geometrically complex parts
- PPMC parts require time intensive inspection due to their stochastic local orientation states
- PPMC are beneficial as they are strong, stiff and light, and can be produced via high-throughput manufacturing processes such as compression molding
Varying Scales of molded platelet Applications

Example (Aerospace)
Compression Molded Parts

Liftgate Inner (Ford):
Dow’s Vorafuse™

Thermoplastic Blocker Door
Motivation

• Establishing rapid non-destructive evaluation of the fiber orientation distribution (FOD):
  • Identification of the faulty components, areas of concern, inconsistencies in the resulting FOD
  • Development of the digital thread process by identifying the unique manufacturing signature embedded into the components meso-structure
  • Inspection techniques that readily allow structural analysis
Fiber Distribution

- Individual platelet boundaries visible in grey image
- Surface fiber orientation is not representative of the fiber orientation throughout the thickness
PPMC Plate Simulation

• PPMC virtual plate, subdomains shown in different colors (a)

• Fiber orientation distribution tensor (FOD) described by Advani and Tucker is plotted over the plate (c)
  • Only the $a_{11}$ and $a_{12}$ terms are required to describe a PPMC with a 2D random material orientation state

• The probability density of $a_{11}$ and $a_{12}$ are shown (d)
PPMC Non-Uniform Deformation Fields

- Due to stochastically varying nature intrinsic to PPMC, non-uniform deformation fields will develop as a result of temperature change.
- Local strain fields of the plate are also non-uniform.
Problem Solution

- Digimat software is used to construct 2D random PPMC morphologies in a 5” x 5” plate
- ABAQUS software is used to perform finite element analysis (FEA) uniform temperature differential simulation
- Entire process is automated via python scripting
- 2000 simulations were performed to generate the dataset for the study
- Each simulation had 25 smaller 32x32 pixel patches extracted so as to increase the size of the dataset (Figure 3)
• U-Nets in this study were evaluated with root mean squared error (RMSE) and mean absolute error (MAE) loss functions
Dataset

- Smaller patches were extracted from each plate and used for U-Net training
- Different patch sizes were used during training, and corresponding U-Net performance was evaluated
Datasets Used in Study

<table>
<thead>
<tr>
<th>Patch Size (pixels)</th>
<th>32²</th>
<th>80²</th>
<th>160²</th>
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</thead>
<tbody>
<tr>
<td>Train X dataset shape (pixels)</td>
<td>(35000,32,32,6)</td>
<td>(5600,80,80,6)</td>
<td>(1400,160,160,6)</td>
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<tr>
<td>Train Y dataset shape (pixels)</td>
<td>(35000,32,32,2)</td>
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<td>Validation X dataset shape (pixels)</td>
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<td>Validation Y dataset shape (pixels)</td>
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</table>
• Majority of model learning occurs within first 1000 epochs
• Model trained with 32x32 input patches and RMSE achieved lowest test dataset loss of 0.066
Results
Results

• Model captures trend, yet still oversmoothed
Results

• Model can detect embedded region with global $a_{11c} = 0.75$

• The model detects this patch yet underpredicts the high $a_{11}$ values observed

• This is expected as higher $a_{11}$ values are less frequent in the training dataset
Conclusions

• The trained U-Net can accurately predict the local through-the-thickness FOD terms with 6.6% error
• This error is attributed to over-smoothing of the FOD term predictions
• The U-Net overpredicts values near the mean dataset value, but underpredicts less commonly occurring values
• The U-Net can accurately detect regions of fiber bias
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• The authors acknowledge the support of the Batten College of Engineering Technology Multidisciplinary Research Seed Grant
<table>
<thead>
<tr>
<th>Loss metric</th>
<th>Patch Size (pixels$^2$)</th>
<th>Patches extracted per plate</th>
<th>Epochs</th>
<th>Epoch of saved parameters</th>
<th>Training Time (hrs)</th>
<th>MAE (training)</th>
<th>RMSE (training)</th>
<th>MAE (test)</th>
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