Data-driven in-situ characterization of microscale properties of composite materials

PI: James Ratcliffe (james.g.ratcliffe@nasa.gov)

Co-PIs: Nelson Carvalho (nelson.carvalho@nasa.gov), David Wagner (david.wagner-1@nasa.gov),

Saikumar Yeratapally: (saikumar.yeratapally@nianet.org), Ed Glaessgen (e.h.glaessgen@nasa.gov)

Collaborators: Caglar Oskay (caglar.oskay@vanderbilt,edu) and Mike Czabaj (m.czabaj@utah.edu)

Executive Summary

The objective of this research is to measure microscale properties of composite materials, aiming to characterize the coefficient of thermal expansion, elastic moduli, residual stresses, and their spatial variation, in a composite material at the microscale. This objective is being accomplished via a data-driven inverse approach that uses a computational framework to determine the (micro-scale) properties. Key accomplishments in this research are (1) development of the computational framework, (2) design and manufacture of micro-scale test articles, and (3) development of experimental approach that acts as the empirical benchmark to the computational property determination framework.

Background

Micromechanics models of composite materials offer the possibility of relating the behavior of structure composed of composites to the properties and behavior of the constituents of the composite, potentially highlighting issues of material behavior that are unresolvable by macroscopic homogenized techniques. These models rely on microscale morphology information and spatial distribution of material properties to predict mesoscale behavior. The material properties used in these studies are generally based on bulk data, which are known to differ from their microscopic values. Moreover, spatial distribution of material properties is caused by defects occurring at lower length scales, selective distribution of fillers and other toughening as a function of material heterogeneity, all remain unresolved in a microscale model. There is no framework capable of characterizing these properties and their spatial variability, since microscopic, full-field strain measurement has not been possible until recently, and no technique exists to establish microscopic stress-strain relationships. The innovation in the present work involves a computational inverse material property determination approach driven by data obtained from microscopic ‘benchmark’ experiments. This framework will provide microscopic material properties (and their spatial distributions), providing empirical input for micromechanics analyses and enhanced understanding of mechanical material behavior.

Plan and Objectives

The plan of this research consists of the following two parallel tracks: (1) development of microscopic experiments in which blocks of composite material are subjected to mechanical, thermal and a combined thermal-mechanical loading with the resulting deformation of the composite material constituents being documented during an experiment and (2) development of a computational approach for simulating the thermal-mechanical response of composite materials at the microscale such that individual fibers and surrounding matrix are resolved in the resulting analysis. Data obtained from the microscopic experiments are used as benchmarks to assess accuracy of the simulations with adjustments to input properties. The project objective is to measure microscale properties of composite materials, aiming to characterize the coefficient of thermal expansion, elastic constants, residual stresses, and their spatial variation in a composite material at the microscale. These project deliverables are aimed at bridging the current gap in state-of-the-art micromechanical approaches that rely on bulk property information.

Partnerships

The project included two partnerships in this project: (1) A Vanderbilt University team, via a cooperative agreement with the National Institute of Aerospace, developed the inverse computational approach for determination of microscale material properties and (2) A University of Utah team helped to develop the microscopic experimental techniques that form part of the data-driven inverse framework and conducted preliminary pathfinder experiments, including measurement of mechanical properties of the matrix material used in the composite material system considered in this project. Both teams played a significant role in the planning of the project, including the research plan, objectives, and deliverables.

Results/knowledge gained via list of accomplishments and highlights

This project has yielded a first-of-a-kind framework for determining microscale mechanical and thermal properties of composite materials via an experimental data-driven inverse computational method. Specific results are outlined below.

- Composite material plates and neat matrix material plaques manufactured and subset of plates and plaques fabricated into test specimens. This activity is performed to document the differences between the in-situ (in composite) and neat (homogeneous) properties of the matrix.
- Developed a fiber template matching (FTM) technique to provide displacement data from microscopic experiments. This technique offers improved accuracy over digital-image correlation (DIC), since it relies on movements of single speckles (fiber centroids), whereas DIC requires a small subset of fibers to determine displacements.
- Established inverse identification framework to characterize the matrix properties (elastic and coefficient of thermal expansion) at the micro- and meso- scales using FTM data. This framework provides a “direct” approach to obtain microscopic properties without resorting to property correlations (e.g., nanoindentation hardness to modulus).
- Performed assessment of error tolerance of the framework and demonstrated robustness of the approach to measurement error. This activity demonstrated the robustness of the framework in view of uncertainty in FTM and load measurements.
- In the process of extending the inverse identification framework to characterize the spatial variability and uncertainty in the material properties, which are present in many composites systems. This activity ensures that sufficient information is available in FTM measurements such that the framework is accurate and robust when more parameters need to be identified.

Technology Maturation Opportunities

Application, validation, and computational performance testing of the inverse identification framework are immediate technology advancing next steps. A present aerospace industry trend is to increase aircraft production rates, with the risk of increases in material property variability. The current technology could be applied to determine sources of variability early in the development phase of a materials development program. The technology therefore aligns with an ARMD Transformative Tools and Technologies (TTT), Revolutionary Vertical Lift Technologies (RVLT) and the High Rate Composites Manufacturing (HiCAM) projects, wherein increased material performance, safety, and reliability of composite structures are critical for meeting project objectives.