Uncertainty Management in Analysis and Optimization of Multiscale Composite Materials

by

Varun Sakalkar

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Examining Committee:

Prabhat Hajela, Thesis Adviser

Kristin Bennett, Member

Nikhil Koratkar, Member

Achille Messac, Member

Rensselaer Polytechnic Institute
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ABSTRACT

Analytical and computational modeling is at the very core of designing high performance composite structural systems for aerospace applications. The behavioral response available from such models is used to provide the ‘what if’ input to the design process. There is concern that inherent modeling errors, if not quantified appropriately, can introduce significant deviations in the behavior of the physical system from predicted values. Composite structures, with distinctly different failure modes and patterns from homogeneous material systems, are particularly vulnerable to this deficiency. Failure in composite structures is typically obtained from mechanistic models of damage that span length scales ranging from the material constituent level to component or macro structural level. Each level of modeling has uncertainties which influence the behavioral response used to guide design decisions.

Thus, a major objective of this thesis is a systematic examination of mechanistic models of damage to identify the major sources of uncertainty in their predictive capabilities. Of specific interest in this study will be the adaptation of the transformation field analysis (TFA) approach to model the onset and progression of damage in composite materials at various length scales. The presence of uncertainties at multiple length scales requires development of models that describe the propagation of uncertainty across the scales. As shown in this thesis, the quantification of uncertainty in a multiscale analysis poses an attendant cost for computational design. To overcome this, approximate models for stress response based on Polynomial Chaos Expansion (PCE) and Support Vector Machine (SVM) are shown to reduce the computational cost. Also, a Radial Basis Function (RBF) based neural network is shown to provide a computationally efficient and high fidelity approximation for the strain response from the TFA model.

This research also seeks to develop a consistent methodology for modeling uncertainty and risk in the simulation-based optimal design of composite structural systems. In a deterministic design approach, these models are linked to formal mathematical methods of optimization. Such an approach, however, is deemed inadequate, as it fails to account for the various sources of uncertainty in predictive capabilities of the behavior model. A key aspect of this research was to develop a

framework to represent the risk related to various failure modes, not all of which are equally critical to system integrity. This framework, referred to as state transition approach, has been used to develop rational metrics for optimizing system performance, with focus on characterization and management of uncertainties over the operational life of the structural system. A "system effectiveness" metric is proposed to gauge the life of a composite system based on the failure modes predicted by the TFA model. The inclusion of this metric as part of a non-deterministic optimization framework is also pursued and results indicate the efficacy of proposed technique over conventional methods.

This research also focuses on utilizing the hierarchical nature of the multiscale TFA models for damage initiation and propagation. The adaptation of multiscale models in optimization is especially amenable to a multilevel decomposition based design strategy. In this context, this research examines how uncertainty can be quantified and propagated in generic hierarchical structures for the design of risk tolerant systems.

Major contributions of the research include a) new approximation strategies to include the effects of uncertainty in a computationally efficient predictive model, b) rational metrics for quantifying performance with focus on characterization and management of uncertainties over the operational life of the structural system, and, c) a novel decomposition based optimization methodology for handling uncertainty in the optimal design of hierarchical structural systems.