Unified Multiscale Model Considering Wave Effects in Composite Materials

Luke B. Borkowski

Adaptive Intelligent Materials & Systems (AIMS) Center
School for Engineering of Matter, Transport and Energy
Arizona State University, Tempe, Arizona, 85287-6106, USA
Luke.Borkowski@asu.edu

ABSTRACT

Although current ultrasonic wave propagation techniques have been proven effective in detecting and characterizing damage in composite materials, their capabilities have been limited since the interactions of ultrasonic stress waves at the microscale have been neglected. To address these issues, a unified modeling approach including elastic wave effects in composite materials is proposed. The developed methodology will be used to investigate the sensitivity of nonlinear wave propagation to microscale damage. The model will provide an improved understanding of the effects of damage initiation, growth, and evolution and their interaction with wave propagation within systems of various materials and subjected to several loading conditions. The proposed research also has broader effects, as the use of a comprehensive and efficient multiscale model will reduce the number of nondestructive evaluation experiments necessary to detect damage in complex composite structures and will be a useful element in prognostics and health management to predict the remaining useful life of critical components.

1. STATEMENT OF PROBLEM

High performance, light-weight composites are increasingly being used in applications ranging from engine fan casings to structurally loaded members. However, since a damage event will compromise the integrity of the composite structure and possibly lead to ultimate failure, the assurance of structural reliability is a critical issue. Diagnostic methods that look primarily for nonlinear phenomena such as wave distortion by creation of harmonics and multiplication of waves of different frequencies have a strong potential in damage detection. The higher harmonics associated with ultrasonic wave propagation will affect the stresses at the microlevel and exemplify small scale damage. Therefore it is important to account for the ultrasonic harmonic effects at the constitutive level.

To address these issues, a unified modeling approach including elastic wave effects in composite materials is proposed. Since damage initiates at the microscale, a physics-based multiscale model, capable of capturing the initiation of damage and propagating this information across the length scales, will be used. Nonlinear elastic wave spectroscopy (NEWS) will be incorporated into a higher-order micromechanics theory to investigate the effect of wave propagation and attenuation across multiple length scales. The developed methodology will be used to investigate the sensitivity of nonlinear wave propagation to microscale damage. It is expected that the proposed research will lead to more robust and reliable prognostics and health management techniques for characterizing damage and estimating the remaining useful life in anisotropic materials and structures. The following are the specific objectives of the proposed research:

a. Develop an approach to integrate the effect of nonlinear wave propagation, including ultrasonic, to characterize in situ damage in complex composites
b. Characterize the thermo-mechanical effects of acoustic waves on microlevel material stresses
c. Develop attenuation models to investigate the effect of high frequency ultrasonic waves on very small scale damage
d. Conduct experiments to validate and further refine the modeling techniques

2. APPROACH

An integrated approach that couples the material's heterogeneous microstructure with nonlinear wave propagation will be developed. The physics based model will bridge multiple length scales in order to capture the effect of various forms of damage on the wave propagation, attenuation, and reflection at the smallest length scale possible. The developed modeling tools will be useful to predict the global, local, and remaining useful life of complex composites, and will be useful in prognostics and health management and NDE.

This comprehensive multiscale modeling framework, interfaced with the software suites ABAQUS and MAC/GMC, will be used for the analysis and characterization of a variety of weave patterns, materials, and complex geometric configurations under various loading conditions. The methodology will be useful to characterize multiscale damage including interfacial damage, intratow cracking, and intratow delamination. This will result in a firmer understanding of the effects of damage initiation, growth, and evolution and their interaction with wave propagation within the material system.

A modification of the Cartesian-based higher-order theory for functionally graded materials that enables the thermoinelastic analysis of materials with spatially varying microstructures in three orthogonal directions, developed by Aboudi et al. (Aboudi et al., 1999), will be utilized to model the wave effects, from the micro to macroscale, in composite materials of periodic microstructures without periodic boundary conditions. This modeling strategy couples the material's heterogeneous microstructure with the structural global analysis, avoiding the problematic use of the standard micromechanical approach (Aboudi et al., 1999). By utilizing this higher-order theory for functionally graded materials, the problematic issue of wave interaction at the interfaces within the composite structure's repeating representative volume elements will be avoided.

Within the physics-based multiscale model, the stress tensor will be decomposed into three parts at both the micro and global scale: the mechanical stress term due to external loading, thermal stress term due to thermal loading, and harmonic stress term due to ultrasonic wave excitation. The mechanical and thermal stress terms will be calculated using the higher-order theory micromechanics at the global scale and the constitutive models at the lower scale. The harmonic stress term will be obtained from the ultrasonic elastic wave excitation. Furthermore, material degradation information due to damage will be captured from the multiscale modeling which will affect the ultrasonic wave propagation through damage affected zones and consequently affect the harmonic stress term.

The developed theory and model will be incorporated into the MAC/GMC code to investigate wave interactions, from low to high frequencies, with damage in composite materials ranging from the micro to macroscale. MAC/GMC is an efficient and accurate multiscale analysis technique that has already proven its capabilities and is adequate to model composites at the micro and mesoscale levels (Bednarcyk, 2000). If local nonlinear effects, such as damage, debonding, and inelasticity must be captured, the micromechanics theory must provide access to the local stress and strain fields throughout the composite. The family of micromechanics theories, known collectively as the Generalized Method of Cells (GMC) provides semi-closed form expressions for the effective constitutive behavior of a composite material, including nonlinear effects which can be modeled internally based on the local fiber and matrix stress and strain fields (Aboudi, 1996; Pindera et al., 1999). A subroutine will be developed to link the commercially available finite element software ABAQUS to the micromechanics code MAC/GMC. This subroutine will contain the multiscale model and allow quick setup and configuration to mimic the validation of experiments.

Experimental validation is a critical module in this proposed research. The experimental validation will be conducted for various scales of damage as well as wave interactions across multiple length scales. By using the results of the experiments to continuously calibrate and correlate the multiscale model, this testing will verify the accuracy of the code in determining the ultimate failure for a composite structure and its effect on wave propagation and provide feedback for further improvements of the code. To verify the ability of the developed model to detect, localize, and characterize various sizes and types of damage, damages will be introduced onto the composite plate and NEWS techniques will be used for the damage prognosis.

3. PROGRESS TO DATE

Although the proposed research is in its beginning stages, much progress has been made. Currently, work has been conducted toward submission of a conference paper for the International Workshop on Structural Health Monitoring. For this work, a model has been developed to investigate the capability of detecting a small delamination in a carbon fiber stiffened panel using a piezoelectric actuator and Fiber Braggs grating sensor system. In addition to the model, test specimens have been fabricated and prepared for experiments.

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