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A model based bayesian solution for characterization of complex damage scenarios in aerospace composite structures

H. Reed [a,*], Cara A.C. Leckey [b], A. Dick [a], G. Harvey [c], J. Dobson [d,e]

[a] Thornton Tomasetti - Weidlinger Applied Science, 40 Wall St. 19th Fl., New York, NY 10005, United States
[b] NASA Langley Research Center, Hampton, VA 23681, United States
[c] PZFlex, 19200 Stevens Creek Blvd, Suite 100, Cupertino, CA 95014, United States
[d] PZFlex, 6th Floor South Suite, 39 St Vincent Place, Glasgow, United Kingdom
[e] Centre for Ultrasonic Engineering, University of Strathclyde, Glasgow, United Kingdom

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ABSTRACT

Ultrasonic damage detection and characterization is commonly used in nondestructive evaluation (NDE) of aerospace composite components. In recent years there has been an increased development of guided wave based methods. In real materials and structures, these dispersive waves result in complicated behavior in the presence of complex damage scenarios. Model-based characterization methods utilize accurate three dimensional finite element models (FEMs) of guided wave interaction with realistic damage scenarios to aid in defect identification and classification. This work describes an inverse solution for realistic composite damage characterization by comparing the wavenumber-frequency spectra of experimental and simulated ultrasonic inspections. The composite laminate material properties are first verified through a Bayesian solution (Markov chain Monte Carlo), enabling uncertainty quantification surrounding the characterization. A study is undertaken to assess the efficacy of the proposed damage model and comparative metrics between the experimental and simulated output. The FEM is then parameterized with a damage model capable of describing the typical complex damage created by impact events in composites. The damage is characterized through a transdimensional Markov chain Monte Carlo solution, enabling a flexible damage model capable of adapting to the complex damage geometry investigated here. The posterior probability distributions of the individual delamination petals as well as the overall envelope of the damage site are determined.

1. Introduction

In the past decade a number of industries, including aerospace and automotive, have increased the use of light-weight composite materials for structural and non-structural components [1]. Carbon fiber reinforced polymer (CFRP) composites are extensively used in aerospace components. This expanded use of composites leads to unique nondestructive evaluation (NDE) challenges since defects which are specific to layered composites (i.e., did not exist in heritage metallic parts) can occur during the manufacture and curing of components. Additionally, damage to composites can occur post-curing in a manufacturing or in-service setting. Common defects/damage in CFRP components include delaminations, fiber waviness (marcelling) and wrinkling, microcracking and porosity [2–4]. Delamination damage due to impact and/or in-service loading can occur as a complex three-dimensional (3D) volumetric geometry with individual delaminations existing at different ply depths through the composite thickness. The defects that commonly occur in CFRPs may lead to no visible indication on the composite surface, thus appropriate NDE methods are required for defect detection and characterization.

Ultrasonic inspection is one of the most widely used NDE approaches applied to composites in both manufacturing and in-service settings. Traditional ultrasonic inspection approaches commonly applied to composites include pulse-echo and through-transmission scanning. Guided wave methods are also highly applicable for inspection of plate-like composite laminates [5–8]. Simulation of ultrasonic wave behavior in composites can significantly aid in the development and application of damage characterization methods. The simulation of the wave interaction with materials/defects is commonly referred to as the forward modeling problem. The inverse modeling problem entails the use of models/simulation to estimate the defect characteristics which

* Corresponding author.
E-mail address: hreed@thorntontomasetti.com (H. Reed).

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caused a measured experimental signal, and involves making comparisons between simulated and experimental data. NASA has unique needs for light-weight advanced materials for aerospace applications, including manned spaceflight applications which have strict safety, durability, and reliability requirements. Advancing the state-of-art in forward and inverse modeling for the purpose of improved defect detection and characterization in advanced materials (such as composites) is highly relevant to NASA's aerospace missions.

In recent years there is a growing literature on the use of ultrasonic modeling tools (mostly Finite Element (FE) based tools) for simulation of the physics of wave propagation and scattering in composites. Recent authors reporting forward model simulation of ultrasound in composites includes Ng and colleagues who implemented 3D FE, using LS-DYNA as the FE solver, to study guided wave scattering from delaminations in a quasi-isotropic composite laminate [9]. Ng et al. assume homogeneous orthotropic material properties for each ply and accounted for the individual ply rotations of the layup [9]. They simulated scattering from simple circular geometry delaminations located at a single ply depth. Singh et al. report using COMSOL FE software to simulate guided waves in a composite laminate with homogenized material properties through the thickness (i.e., individual ply layers were not simulated). Guided wave interaction with a simulated conical shaped defect representing impact damage was studied [10]. Leckey et al. used a custom 3D finite integration code to study guided wave propagation in composite laminates (simulating each ply layer) and incorporated a realistic damage geometry using X-ray computed tomography data of impact induced delamination damage [11]. More recently, Murat et al. report using a custom FE code to simulate guided wave propagation in a cross-ply composite laminate and study guided wave interaction with a square shaped delamination [12].

There are significantly fewer reports in published literature addressing the ultrasonic inverse problem for defect characterization in composites. Roberts and Holland recently reported use of a Green's function based analytical approach for model-based inversion of pulse-echo ultrasound data of delamination defects in composites laminates [13]. Fahim et al. considered a cost function (i.e. an optimization problem) as the inverse solution to characterize delamination damage features through the use of a semi-analytic model of the wave propagation forward problem [14]. Bochud et al. model the composite damage in each layer as a reduction of Young's modulus and studied various signal processing techniques for use in an inverse problem [15].

Bayesian model-based inverse methods for damage characterization were originally developed in the field of civil engineering to determine damage in structural models [16,17]. Beck and Au [17] demonstrate Bayesian updating methods effected through Markov Chain Monte Carlo to determine the reliability of a dynamic moment resisting frame structural model. Bayesian methods have also recently been used to identify damage through the use of guided waves. Ng [18] demonstrated the use of guided waves in a beam-like structural model within a Bayesian framework to characterize damage through a hybrid particle swarm optimization. He and Ng [19] implemented a Bayesian method to determine the number of delaminations in a composite laminate by simulating the guided waves in a spectral finite element model. By including a bias-correction function in their analysis, Vanli and Jung [20] were able to achieve good damage prediction accuracy of a composite panel with a Lamb-wave sensing system, modeled with a finite element model.

In this work a finite element simulation is implemented to model guided wave propagation in composite laminates and wave interaction with delamination defects. A model-based inversion approach using Markov Chain Monte Carlo (MCMC) method is combined with the FE modeling and is applied to ultrasonic wavefield data from a composite laminate containing impact induced delamination damage. This work differs from prior work in that the number of delaminations in the composite laminate are not assumed know *a priori*; rather, the inverse problem will determine the sufficient number of delamination petals to characterize the damage. Prior to the application of the inversion method to the real delamination case, a material characterization study is performed. Numerous factors can lead to differences between simulation and experiment. For composite materials a primary factor can be differences between the ideal ply level material properties (provided by a manufacturer or found through destructive testing) and the properties of a cured as-manufactured specimen [11]. A comparison between the FE simulation and experimental data is performed for a pristine unidirectional laminate to more closely characterize the as-manufactured composite material properties. Section 2 describes the mathematical approach used in the forward and inverse modeling, along with the wavenumber domain method that is used to compare the simulation data to experimental wavefield data. Section 3.2 discusses the results of the material characterization step. In Section 3.3 the MCMC method is then applied to a single delamination case to verify that the approach works for a simple defect scenario. Application of the inverse model method to the wavefield data recorded in experiment for the complex delamination case is then reported in Section 3.4.

2. Problem description

2.1. Forward problem

The wave propagation problems investigated here are implemented in the commercial explicit finite element software PZFlex [21], utilizing 3D, 8-node linear continuum elements. The forward problem entails simulating wave propagation and interaction with delamination damage in a composite laminate. The domain of the problem corresponding to the delaminated quasi-isotropic specimen is given in Fig. 3. The composite laminate is comprised of 26 ply layers with a layup of $[(0/45/-45/90)_3]_s$. To build up the entire composite laminate in the finite element model, the material tensor of a single ply is computed in a reference orientation (such as along the 0° fiber direction of the top ply shown in Fig. 3), and the material tensors of the ply layers at differing ply angles are computed by rotating the material tensor by the appropriate rotation transformation operator. In this work, we assume that a single ply layer containing fibers and resin can be accurately modeled as a single anisotropic material (with transverse anisotropy for the cases studied in this work). However, due to variations in fiber volume ratio, overall specimen thickness, and fiber waviness and warping (i.e. where fibers do not run along the intended direction), accurately predicting the homogenized anisotropic material properties for the ply layer is difficult. An approach for addressing as-manufactured laminate property variations from the idealized properties will be discussed in Section 3.2.

The composite laminate in this work is excited by a 12.7 mm (0.5 in.) diameter piezoelectric transducer, modeled in this work by applying a displacement boundary condition to the finite element nodes corresponding to the transducer location. The excitation function was selected to match the corresponding experimental case, as discussed in Section 3.1. The response of the laminate to the excitation considered here is the time history out-of-plane velocity data recorded at the finite element nodes on the top surface of the composite laminate. While the entire displacement and stress time history (in-plane and out-of-plane) is modeled within the laminate in the FE simulation, we only consider the response that is captured in the experimental wavefield