Journal of Sound and Vibration 414 (2018) 110–125

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Wave propagation modeling in composites reinforced by randomly oriented fibers

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ARTICLE INFO

Article history:
Received 6 July 2017
Received in revised form 30 October 2017
Accepted 9 November 2017

Keywords:
Randomly oriented fibers
Wave propagation
Spectral element method
Composites

ABSTRACT

A new method for prediction of elastic constants in randomly oriented fiber composites is proposed. It is based on mechanics of composites, the rule of mixtures and total mass balance tailored to the spectral element mesh composed of 3D brick elements. Selected elastic properties predicted by the proposed method are compared with values obtained by another theoretical method. The proposed method is applied for simulation of Lamb waves in glass-epoxy composite plate reinforced by randomly oriented fibers. Full wavefield measurements conducted by the scanning laser Doppler vibrometer are in good agreement with simulations performed by using the time domain spectral element method.

1. Introduction

Randomly oriented fiber composites have many applications due to easy of manufacturing and good reinforced mechanical properties (stiffness, durability and impact resistance). However, because of the complicated structural and mechanical features involved, randomly distributed fiber composites remain one of the most difficult to ng materials. The problem is particularly complex in case of wave propagation modeling in randomly oriented fiber composites. Solving this problem on the multiscale level is prohibitive due to high computational cost. Another option is numerical modeling of each fiber inclusion in the matrix by separate finite element and solving the problem in macro-scale. Such model is very accurate, but it is computationally inefficient due to a large number of degrees of freedom. On the other hand, micromechanics continues to be the forefront of analysis of composite materials and can be useful for this application.

Anomalies of Lamb waves propagating in elements of structures can be utilized in structural health monitoring (SHM) systems. Lamb wave are mechanical waves propagating in thin-walled structures. Due to the fact, that complexity of Lamb waves regarding the number of propagating modes increases with frequency, most often only fundamental modes are used for SHM, namely A0 and S0. A0 mode has antisymmetric character corresponding to bending behavior of plates whereas S0 mode has symmetric character corresponding to compression and extension. At the same frequency, A0 mode has a shorter wavelength and has lower phase and group velocity than S0 mode [1].

In order to use model assisted signal processing methods for damage identification, it is indispensable to have an accurate model. So far most of the research work on Lamb wave modeling has been devoted to isotropic [2–4] or orthotropic materials [5–10] (mostly composite laminates reinforced by uniform unidirectional fibers). However, full wavefield simulation of

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https://doi.org/10.1016/j.jsv.2017.11.015

propagating waves in randomly oriented fiber composites has not been reported so far, except an attempt by the authors [11]. Consequently, the present paper extends and improves the approach presented in Ref. [11].

One of the best methods for wave propagation modeling excited by a piezoelectric transducer is the time domain spectral element method [1]. It utilizes high-order shape functions, namely Lagrange polynomials, which are spanned on Gauss-Lobatto-Legendre points. Hence, spectral element nodes coincide with quadrature points used in numerical integration. The method is suitable for wave propagation modeling in composite materials and has the same flexibility as conventional finite element method, but it is computationally much more efficient. It is mostly due to the diagonality of mass matrix and application of explicit solver. The computation time can be further reduced by parallel implementation on GPU cards [12].

The spectral element method was introduced by Patera in 1984 for laminar flows [13]. However, the method has found many other applications over the years. Zak et al. [1] rediscovered the method in 2006 in the context of structural health monitoring. They presented certain results of the analysis of wave propagation in isotropic panel with damage in the form of an open crack. In 2007 Kudela et al. [6] applied plate spectral element for analysis of wave propagation behavior in composite laminates. Kim et al. [2] as well as Kudela et al. [3], presented a 3D solid spectral element for wave propagation analysis in isotropic media with the capability to model piezoelectric actuators and sensors. Lonkar and Chang [7] introduced a layered 3D spectral element for improved laminate modeling accuracy. Recently Rekatsinas and Saravanos [14] developed a layerwise theory for thick laminated composite strips with piezoelectric actuators and sensors and an associated explicit time domain spectral finite element with the aim to provide robust, accurate and fast simulations of the transient coupled electromechanical wave response. It should be noted that despite significant progress in the development of the time domain spectral element method it is still challenging to model accurately high frequency multimodal character of Lamb waves propagating in thin composite plates.

Experimental investigations reveal that elastic wave propagation pattern is significantly affected by randomly oriented fibers which cause additional reflections and change the wave front. Such behavior cannot be modeled by using effective elastic mechanical constants for the whole lamina because it leads to the circular wave front characteristic for isotropic materials as it is in case of Manera [15] and Pan [16] rule of mixtures (ROM). Both Manera and Pan models require as an input only volume fraction of reinforcing fibers. Manera [15] derived equations for elastic constants using the laminate analogy approach. This approximate theory gives lower effective values of Young's modulus of short fiber composites than the standard Halpin-Tsai equations [17]. A neat and straightforward theoretical model which derives the relationship between overall system fiber volume fraction and the fiber area fraction at a cross-section of the composite has been developed by Pan [16]. Due to the simplicity of model by Pan and good overall agreement of predicted elastic constants with experimental values, this model is used for comparison purposes in the current study.

The effective mechanical properties of a composite elastic plate can be determined numerically. The prediction procedure consists in replacing a probabilistic approach to the problem (size and shape of inclusions, distribution of inclusions, physical properties of materials, inter-phase contacts between inclusions) by a conventional computation in the structure represented by the representative volume element (RVE). The prediction of mechanical properties of linear elastic heterogeneous materials through a homogenization process, where the material can be idealized as being effectively homogenous in the RVE might be cumbersome because the probability distribution function of reinforcing fibers is usually not known. Additionally, it is difficult to estimate appropriate size of the RVE. Effective properties come from asymptotic expansions (see Refs. [18] and [19]), in which the parameter is the ratio of the size of inclusions to the size of the structure in static approach or the size of inclusions to the wavelength in dynamic approach (or wave propagation). The problem is that Lamb waves phenomenon has multimodal character [20]. It means that many modes can propagate at the same time and each mode has a different wavelength. Effective elastic properties are generally evaluated by finite element analysis [21]. It should be noted that the investigation of the dimensions of the RVE used in the finite element analysis is a key issue from which representativeness, efficiency, and validity of the numerical modeling strongly depend on [22].

Excellent review of micromechanics is given in Hashin [23]. It is out of the scope of this introduction to summarize all homogenization methods. The general conclusion is that an appropriate modeling technique of material properties requires a compromise between accuracy of results and low cost of calculation. The latter one is especially important in case of Lamb wave propagation problem. Hence, the elastic constants should be time-independent, but there should be random variation in space to capture local effects of propagating waves. However, due to computation time constraints in the authors' opinion, the whole problem should be solved only on macroscale level.

This research aims to adopt the time domain spectral element method for modeling of elastic wave propagation phenomenon in randomly oriented fiber composites. Due to the complexity of the problem, the mesh density must be kept as low as possible. Hence, an automated iterative method for volume fractions assignment to mesh nodes is proposed based on the modified ROM. It is shown that based on the proposed approach local interaction of Lamb waves with fibers is well captured. To the best authors' knowledge, such simulation results have not been reported so far.

The structure of the paper is as follows. Following the introduction, the problem statement is described. Next numerical method for prediction of elastic constants of the randomly oriented fiber reinforced composite is proposed. In the numerical examples section, volume average elastic constants are compared with the Pan ROM theory [16] and full wavefield analysis is performed. Finally, it is presented a qualitative comparison of modeled full wavefield of propagating elastic waves at the surface of randomly oriented fiber composites with experimental measurements by scanning laser Doppler vibrometer (SLDV).