Composite Structures 206 (2018) 484–498

Contents lists available at ScienceDirect

Composite Structures

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

Lamb wave interaction with composite delamination

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ARTICLE INFO

Keywords:
Time domain spectral finite element method
Lamb waves
Ultrasonic
Composite
Damage detection
Delamination

ABSTRACT

Elastic guided wave based evaluation is useful to detect delamination in composites. This paper reports a detailed account of guided wave interaction with delamination in laminated composites modeled using time domain spectral finite element (TSFE) method. Wave scattering due to different delamination positions is studied. Wave field near the delamination in different layer-wise positions is investigated, which is useful to further characterize and correlate the far field wave packet carrying the parametric signature of delamination. Off-axis delamination in composite laminate creates an asymmetry in the elastodynamic stress transfer. It leads to wave mode conversions. Sensitivity of the delamination to the wavelengths is studied. The outcome of this study indicates potential possibilities to use frequency-wavelength information to discriminate various sizes of delamination. Energy of the scattered waves and dissipation/conversion of the wave energy due to the defects depend on the resonance characteristics of the sub-laminates. Wave scattering effect due to length-wise multiple delaminations and edge delamination is also analyzed. The resonance patterns in the signals are analyzed with reference to the defect quantification problem.

1. Introduction

Due to their simple, low-cost and energy efficient fabrication, laminated composites have a wide range of applications in various industries, especially in aerospace industries. The specific stiffness and strength of composite structures are of great advantages over those of metallic structures. However, composites are sensitive to impact loads. Even a low velocity and low-intensity impact can initiate matrix cracks which eventually may lead to delamination. Thus, delamination is one of the most common type and vulnerable defect in a laminated composite structure which can grow and affect the mechanical properties and structural integrity. Mitigating these defect initiations via complex fabric architecture based reinforcements dramatically increase the manufacturing complexity and the cost and the technologies required to do this is currently at an early stage. So, it is important to detect a delamination at its earliest stage. Delamination grows in an interfacial plane; therefore, the presence of this type of defect cannot be identified by visual inspections. Ultrasonic C-scan, X-ray tomography etc. are the traditional non-destructive evaluation methods which can detect a delamination accurately. But these methods require an entire structural component to be accessible, which is not always possible due to various difficulties involved in disassembly and reassembly of structural components. Other techniques involving global structural vibration are also used in defect detection. These techniques can be classified into two categories - modal vibration based technique and guided wave based technique. Modal vibration based techniques [1–3] make use of the various modal parameters, which includes natural frequencies, mode shapes etc. to detect the defect. Any deviation in the relevant structural parameters indicates the presence of a possible defect(s) and can be solved as a structural parameter identification problem. But defect like small delamination causes an insignificant change in the dynamic stiffness of the structure at high-frequency vibration modes. Therefore, modal vibration based techniques are not capable of detecting defects that are of small size compared to the size of the structural component. That limitation is overcome with the help of high frequency guided wave based techniques. In the guided wave based techniques the wave generated from an actuator travels through the structure. Defect is identified by analyzing the received signal by the transducers at one or multiple locations. High frequency (ultrasonic) guided waves have advantage that it can travel a long distance without showing much attenuation [4]. Hence defects can be detected and monitored with a relatively small number of transducers. Moreover, it has a guided nature that it follows the structural boundaries even if where there is a curvature or joints and hence an ability to bring defect signature from a hidden location [5]. Guided wave based defect interrogation in plate or beam-like structures had been investigated by several researchers [6–9].

Higher-order modes of waves and near-field components participate

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https://doi.org/10.1016/j.compstruct.2018.08.072
Received 17 April 2018; Received in revised form 10 August 2018; Accepted 27 August 2018
Available online 29 August 2018
0263-8223/

in the scattering due to a defect in a structure. Therefore, one requires an accurate computational scheme to model wave propagation and use such information in defect detection and identification. Various methods such as finite difference method [10], boundary element method [7,11], and finite element method [12,13] had been used in modeling wave propagation in structures. Modeling wave propagation using those methods requires very fine mesh to capture the effect of all the higher-order modes and hence those methods become computationally expensive. That limitation can be overcome by using higher-order interpolation of wave field with a spectral convergence property. Two types of spectral methods, one is the Frequency Domain Spectral Finite Element (FSFE) method and the other is the Time domain Spectral Finite Element (TSFE) method, have been reported to model the wave propagation in structure efficiently.

One kind of frequency domain spectral finite element method was proposed by Doyle [14], which uses characteristics in frequency and wavenumber space to construct the element shape functions. Its application in one-dimension and semi-infinite layered media problems were reported [15–18]. The method has been successfully applied to various waveguides, semi-infinite and membrane problems, and also for modeling wave propagation in more complex structural components using finite element mesh and wave enrichment [19]. On the other hand, time domain spectral finite element method [20–23] is similar to the conventional finite element method but it uses a high-order orthogonal polynomial such as Chebyshev or Legendre polynomials as the interpolation basis functions and the nodal distributions are based on the roots of those polynomials. The method has been employed to modeling wave propagation in structure by several researchers. Dauksher et al. [24] employed Chebyshev polynomial as the basis function in their TSFE formulation and investigated acoustic wave propagation in 1-D and 2-D domains. They studied the accuracy and effectiveness of various schemes of mass matrix diagonalization. Later, using the same formulation they studied the 2-D elastostatic and elastodynamic problems [25]. Kudela et al. [26] modeled the 1-D elastic wave propagation in rods and beams and studied various aspects of wave propagation characteristics. Kudela et al. [27] studied transverse wave propagation in a composite plate. Zak [28] formulated Chebyshev polynomial based spectral finite element and investigated the symmetric and anti-symmetric Lamb wave propagation in a plate structure. Sridhar et al. [29] applied Chebyshev spectral method to study the wave propagation in an anisotropic, inhomogeneous structure and they have shown the efficiency of spectral method in terms of convergence and computer memory. Zak et al. [30] formulated another spectral finite element method based on Legendre polynomial to investigate the in-plane wave propagation in an isotropic plate structure with a fatigue crack. Zak and Krawczuk [31] demonstrated the efficiency of spectral interpolation functions in comparison with the shape functions used in Hermite polynomial finite element method and discussed various computational aspects affecting the accuracy of numerical solutions concerning with wave propagation.

Several studies were found in literature investigating wave interaction with delamination in composite laminate. Wang et al. [1] modeled a delamination considering the delaminated region with split-beam layers and studied the vibration response of the delamination without contact effect. Mujumdar and Suryanarayan [2] improved this solution further by imposing constraint condition such that the delaminated part cannot have overlap but they ignored the possibility of delamination opening. Farris and Doyle [32] used Timoshenko beam approximation to study the wave propagation in a beam with delamination assuming the sub-laminates as two separate waveguides. Alleyne and Cawley [9] studied the Lamb wave interaction with a variety of defects and investigated the sensitivity of various Lamb wave modes to a defect using finite element analysis and verified their results with experimental results. Guo and Cawley [11] established that Lamb waves can be used to detect the delamination in a laminate using simple transducer configuration used in the pulse-echo method and observed that the wave interaction with delamination depends on the through-thickness position of the delamination. Al-Nassar et al. [6] used finite elements with mode expansion to model the Lamb wave scattering effect due to geometric and material irregularities in an isotropic infinite plate. Cho and Rose [33] combined a boundary element method and mode superposition technique and developed a hybrid boundary element method to investigate the Lamb wave characteristics and mode conversion. Ramadas et al. [34] studied the effect of fundamental anti-symmetric mode (A_0) wave on symmetrically located delamination in a composite laminate using both experimental approaches as well as the finite element simulation. They studied the multiple mode conversion due to wave interaction with two ends of the delamination and captured the responses of both reflected A_0 waves as well as mode converted S_0 waves (fundamental symmetric). They further extended their study of asymmetrically located delamination in a laminate [35].

Hayashi and Endoh [7] modeled guided waves in a beam using hybrid boundary element method and explained that the presence of a delamination in a beam produces two waveguides like effect in the delamination region [8] and that the wave characteristics in the two sub-laminate are different if the delamination is not in the mid-plane. Investigation shows that multiple reflections occur due to the wave interaction with delamination tips. Delamination position and size significantly influence the reflected and transmitted powers. Wang and Rose [36] modeled composite beam with delamination using Timoshenko beam approximation, where delaminated region is considered as split beam. They studied the wave interaction with delamination and determined the power of reflected and transmitted wave. Mahapatra and Gopalakrishnan [37] studied the scattering of Lamb waves with delamination in the laminated composite beam with asymmetric ply stacking using frequency domain spectral finite element method. Nag et al. [38] and Mahapatra et al. [15] studied the effect of variation in delamination length and layerwise position on the wave scattering and determined the reflected and transmitted power for various delamination configurations. Their study also demonstrated the sensitivity of excitation frequency to the size of the delamination and analyzed the effect of multiple delaminations on the response and spectral power flow characteristics.

Wave propagation in the defect region can create local resonance which has an important implication in defect detection. Local resonance based defect characterization have been studied by several researchers. Rokhlin [39] studied the Lamb wave diffraction from finite crack parallel to the surface where the local resonance effect on the wave scattering was addressed. Klepka et al. [40] used the local resonance phenomena for detection of impact damage in a laminate where they showed that the response can be enhanced by exciting the structure at a particular resonance frequency.

Anisotropic nature of the composite enables one to make a structure stronger in specific directions of maximum loading. This way the structural design can be optimized based on the load carrying requirements. Suitable load carrying structural design is made by taking different ply orientations [41]. However, ply stacking sequence plays a major role in delamination initiation [42,43]. In the case of unidirectional ply stacking, there is less possibility of delamination initiation under loading. On the other hand, for a cross-ply laminate, there is a higher possibility to develop an inter-laminar crack in the interface of two adjacent cross plies due to the inter-laminar stress development. Delamination can initiate in different layers depending on the loading conditions. Dynamic stress localization under an impact loading can cause delamination at some other places with respect to where the impact load is applied. Matrix cracking is a precursor to initiation of delamination. Multiple delaminations created by low-velocity impact at the bottom surface of a thin laminate creates reverse pine tree like shape [44]. In the case of impact loading on a thick laminate, matrix crack can appear at the top surface and delamination can spread from the top to the bottom layers with increasing size. For a fixed support, there is a high possibility of delamination initiation near the fixed edge