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A novel dynamic stress analysis in bimaterial composite with defect using ultrasonic wave propagation

Ran Li [a], Toshiaki Natsuki [b], Qing-Qing Ni [b,c,*]

[a] Interdisciplinary Graduate School of Science and Technology, Shinshu University, Tokida, Ueda 386-8576, Japan
[b] Department of Functional Machinery & Mechanics, Shinshu University, Tokida, Ueda 386-8576, Japan
[c] Key Laboratory of Advanced Textile Materials and Manufacturing Technology, Ministry of Education, Zhejiang Sci-Tech University, Hangzhou, China

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ABSTRACT

A new method to evaluate dynamic stress distribution of composite materials is presented using ultrasonic wave propagation analysis. In this method, a two-dimensional bimaterial composite with elliptical defect is modeled by using finite element analysis software. Based on elastic wave propagation analysis, the deformation and dynamic stress fields against different material properties are simulated. As the material properties change, the stress distribution at free edge and interface also change causing different stress wave propagation behavior. By investigating the dynamic stress distribution, the interaction of stress singularities at free edge, mode conversion at interface and wave propagation is clarified. The simulation results show that ultrasonic wave propagation analysis is a convenient and effective way to evaluate the correlation between material properties, stress singularities and dynamic internal stress distribution in composite materials.

1. Introduction

Composite materials, such as carbon fiber or glass fiber reinforced plastics (FRP), have been applied practically in various fields, such as aircraft, space and other structural fields, owing to their excellent characteristics of light-weight, high rigidity ratio and so on. As the application of composite materials in load-bearing structure increases, it is considerably important to understand the characteristics of dynamic stress distribution and the influence of stress singularities when the composite material is under dynamic loading. Due to the free edge, interface and the presence of defects, the applied dynamic loading may cause complicated stress distribution and difficult to characterize the interactions between them. Thus, no well-defined method for characterization of dynamic stress distribution in composite materials has been proposed.

On the other hand, it is well known that ultrasonic wave technology is an effective way for non-destructive evaluation of material characteristics [1–7] and internal damage status in fiber-reinforced composite materials. Since the ultrasonic wave propagation is based on elastic wave theory it should be corresponding to the dynamic stress fields. The wave intensity, amplitude and other characteristics may vary with the material properties, interface behavior and defect shape/size, so that the characterization of wave propagation can be used to study the dynamic variation of internal stress fields in composite materials.

Many investigators have studied the characteristics of ultrasonic wave propagation in composites experimentally and theoretically. Saches [8] reviewed the relative development of quantitative ultrasonic measurements and presented examples of applications of these methods. Rokhlin [9] discussed two potential ultrasonic techniques for characterization of fiber–matrix composites, confirmed that the elastic properties can significantly affect the ultrasonic propagation. By using finite element method, Datta [10] proposed a two dimensional plane strain finite element model to deal with the mode conversion and scattering due to the presence of flaws. By using a computational procedure for multiple wave scattering, Biwa [11] dealt with the ultrasonic propagation and the quantization of attenuation.

In the present paper, based on the wave propagation and its correspondence relationship with stress fields, we discussed both the scattering wave propagation behaviors and dynamic internal stress redistribution considering the free edge, interface, defect and material properties. The advantage of the present method is to take all of these factors together into account. We hope to clarify the influence mechanism of all of scattering waves, such as

* Corresponding author at: Department of Functional Machinery & Mechanics, Shinshu University, Tokida, Ueda 386-8576, Japan.
E-mail address: niqq@shinshu-u.ac.jp (Q.-Q. Ni).

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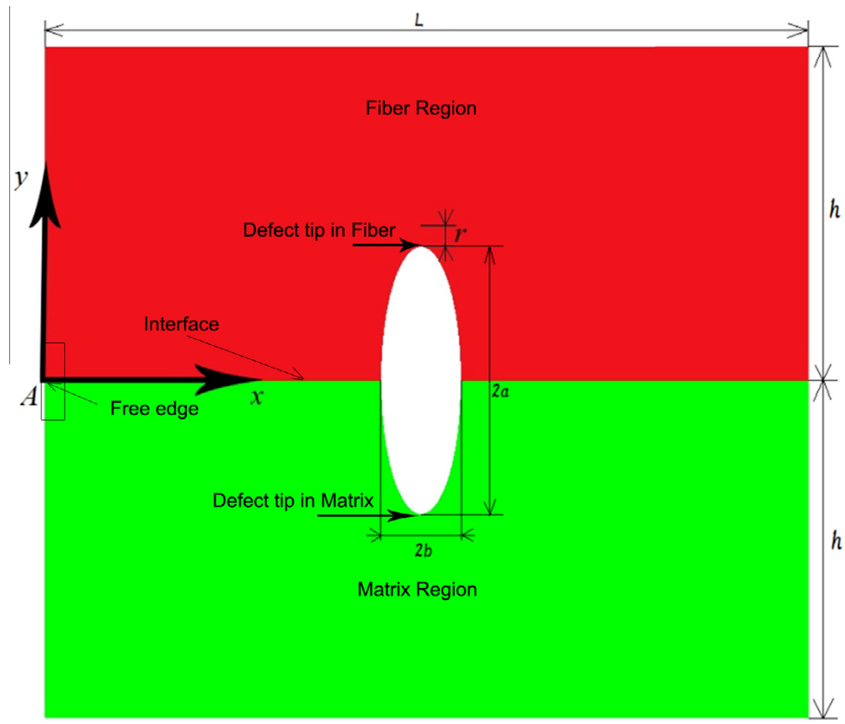

Fig. 1. Model of bimaterial composite with a defect.

Table 1
Material parameters used for analysis.

Materials	Fiber	Resin	Defect
Density (kg/m^3)	2400	1200	0
Longitudinal velocity (m/s)	6000	3000	0
Transverse velocity (m/s)	3500	1850	0
Loss (db/m)	0	0	0

reflection, wave mode change, attenuation, on the internal stress redistribution. This is a new try to investigate the dynamic stress distribution simply and quickly from the viewpoint of wave propagation.

Here, a two layered bimaterial composite model with an transverse elliptical defect is analyzed by time-domain finite element analysis of ultrasonic wave propagation, under a time-harmonic longitudinal incident wave, and the complicated ultrasonic wave propagation. Based on the direct correspondence between waveform and internal stress fields in the material, the dynamic internal stress distribution is visualized and analyzed. The characterization of internal dynamic stress distribution varying with material properties, and the influence of stress concentration at free edge and interface on the ultrasonic propagation are clarified. The results of stress concentration factors at defect tips in different material regions also indicate the validity of the present analysis. Through the above, the correlation between internal stress fields and ultrasonic wave characterization is clarified, and the effectiveness of ultrasonic wave propagation as a novel dynamic stress analysis is confirmed.

2. Ultrasonic wave equations of motion

When an ultrasonic wave propagates in a material, from Hooke's law, the stress–strain relationship for two-dimensional plane strain in an isotropic media is written as follows [12]:

$$\sigma = c\varepsilon \tag{1}$$

$$c = \begin{bmatrix} \lambda + 2\mu & \lambda & 0 \\ \lambda & \lambda + 2\mu & 0 \\ 0 & 0 & \mu \end{bmatrix} \tag{2}$$

$$\sigma = [\sigma_{xx} \quad \sigma_{yy} \quad \sigma_{xy}]^T \tag{3}$$

$$\varepsilon = [\varepsilon_{xx} \quad \varepsilon_{yy} \quad \varepsilon_{xy}]^T \tag{4}$$

where λ and μ are lamé constants, and the T superscript denotes the transposition.

The ultrasonic wave equations of motion for two-dimensional plane strain in an isotropic media are:

$$\left.\begin{array}{l} \frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{xy}}{\partial y} = \rho\frac{\partial^2 u_x}{\partial t^2} \\ \frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} = \rho\frac{\partial^2 u_y}{\partial t^2} \end{array}\right\} \tag{5}$$

where, the first term on the left-hand side of the Eq. (5) corresponds to a longitudinal wave, and the second term corresponds to a transverse wave. ρ is density. For each of the wave fields, the displacement is given in terms of two displacement potentials ϕ and ψ via the Helmholtz decomposition.

$$u_x = \frac{\partial\Phi}{\partial x} + \frac{\partial\Psi}{\partial y} \quad u_y = -\frac{\partial\psi}{\partial x} + \frac{\partial\phi}{\partial y} \tag{6}$$

From Hooke's law, the $\sigma_{xx}, \sigma_{yy}, \sigma_{xy}$ can be rewritten as:

$$\frac{\sigma_{xx}}{2G} = -\frac{\partial^2\Phi}{\partial y^2} + \frac{1}{2}\kappa^2\left\langle\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2}\right\rangle + \frac{\partial^2\psi}{\partial x\partial y} \tag{7}$$

$$\frac{\sigma_{yy}}{2G} = -\frac{\partial^2\Phi}{\partial x^2} + \frac{1}{2}\kappa^2\left\langle\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2}\right\rangle - \frac{\partial^2\psi}{\partial x\partial y} \tag{8}$$

$$\frac{\sigma_{xy}}{2G} = \frac{\partial^2\Phi}{\partial x\partial y} - \frac{\partial^2\psi}{\partial x^2} + \frac{1}{2}\left\langle\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2}\right\rangle \tag{9}$$