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Evaluation of the Fiberglass-Reinforced Plastics Interfacial Behavior by using Ultrasonic Wave Propagation Method

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Abstract:

In this paper, ultrasonic wave propagation in three phases (3P) of composite materials was investigated. The simulation was conducted by *PZFlex* analysis code, a time domain finite element program. The reflection and transmission characteristics with different shapes of middle layer between glass fiber and epoxy resin are investigated in order to understand basic ultrasonic behavior of energy dispersion and transmission in the middle layer. The relationship between impedance in middle layer and ultrasonic propagation characteristics is discussed. As a practical approach to the practical composite materials, the SFC (single fiber composite) model is proposed with a middle layer between fiber and matrix. Moreover, the influence of the middle layer with different debonding failure regions and failure directions is taken into account. As a result, the influence of the fiber/matrix interface, the geometrical size of middle layer and its physical property on wave propagation was clarified. When the debonding failure existed in the middle layer between fiber and matrix, its influence on ultrasonic motion pattern and the characteristics of energy propagation were understood. The complicated propagation behavior resulted from reflection, transmission, multi-reflection and dispersion due to the existence of debonding failure at the fiber/matrix interface was visualized. With these results, it is indicated that an approach based on ultrasonic technology is possible for the evaluation of interfacial behavior in 3P composite materials with a middle layer existed between fiber and matrix. With these results, it is indicated that an approach to the evaluation of interfacial behavior in 3P composite materials is possible.

Keywords: ultrasonic wave, energy propagating behavior, interface debonding, finite element method, impedance, interphase, fiber-reinforced composite

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, because of their excellent characteristics of light-weight, high rigidity ratio and so on. Despite the outstanding characteristics of composite materials, the damages, such as cracks in matrix, fiber breakage and debonding between fiber and matrix are easy to occur in practical application. The occurrence or progress of these damages depends deeply on the interfacial behavior between fiber and matrix. The recent researches[1)] have shown that introduction of the middle layer between fiber and matrix may improve the interfacial property and then it will play an important role on the performance of composite materials since the components of the middle layer generally are of both the senses of fiber and matrix and will have a good bonding force to both of fiber and matrix. This leads to that the evaluation of the behavior of middle layer between fiber and matrix becomes indispensable for the development of composite materials. However, the behavior of the middle layer between fiber and matrix is hard to be evaluated directly by visual inspection technology from the material surface or just by mechanical tests. Thus, a method to evaluate the damage status or the mechanical behavior of a middle layer between fiber and matrix is necessary.

It is well known that ultrasonic wave technology is an effective way for non-destructive evaluation of material characteristics[2-8)] and internal damage states in fiber-reinforced composite materials. When an ultrasonic wave propagates through a middle layer, not only the transmitted and reflected waves but also the multi-reflections occur. The phase angle and other wave characteristics may vary with the change of the mechanical property in the middle layer. These factors make the ultrasonic wave propagation in the composite materials with middle layer, three phase (3P) composite materials, be very complicated. Here, the time domain finite element analysis (*PZflex*, a newly developed analysis code[6-8)]) is used to clarify the characteristics of ultrasonic wave in 3P composite materials. The reflection and transmission characteristics with different shapes of middle layer between glass fiber and epoxy resin are investigated in order to understand basic ultrasonic behavior of energy dispersion and transmission in the middle layer. The relationship between impedance in middle layer and ultrasonic propagation characteristics is discussed. For the practical composite materials with fibers embedded in matrix, the influence of the middle layer with different debonding failure regions and failure directions is compared. With the simultaneous visualization of ultrasonic wave propagation, the role of the middle layer between fiber and matrix is made clearer. With these investigations, an approach to the evaluation of interfacial behavior in 3P composite materials is proposed.

2. Ultrasonic Wave Equations of Motion

Consider a middle layer between fiber and matrix in a 3P composite material. Two dimensions analysis is conducted as shown in Fig. 1 for three types of middle layer. When an ultrasonic wave propagates in these models, from Hooke's law, the stress-strain relationship for two-dimensional plane strain in an isotropic media is written as follows [9]:

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

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

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

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

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 as follows:

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

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. If the longitudinal wave velocity c_L and transverse wave velocity c_T are introduced the ultrasonic wave equations of motion for two-dimensional plane strain can be rewritten by

$$\begin{Bmatrix} c_L{}^2 \dfrac{\partial^2 u_x}{\partial x^2} + c_T{}^2 \dfrac{\partial^2 u_x}{\partial y^2} + (c_L{}^2 - c_T{}^2)\dfrac{\partial^2 u_y}{\partial x \partial y} \\ c_L{}^2 \dfrac{\partial^2 u_y}{\partial y^2} + c_T{}^2 \dfrac{\partial^2 u_y}{\partial x^2} + (c_L{}^2 - c_T{}^2)\dfrac{\partial^2 u_x}{\partial x \partial y} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial^2 u_x}{\partial t^2} \\ \dfrac{\partial^2 u_y}{\partial t^2} \end{Bmatrix} \tag{6}$$

In the case of a plane advancing wave, the following formula is used to calculate for the oscillating energy generated by the ultrasonic wave per unit time.[10]

$$I = \frac{p^2}{\rho c} \tag{7}$$

3. Analysis results

3.1 Analysis model of single fiber composite model with middle layer

As mentioned previously, the introduction of the middle layer between fiber and matrix is one way to improve the interfacial property and then develop high performance of composite materials. Figure 5 shows a single fiber composite (SFC) model with a middle layer. Considering the main factors in the practical composite materials, only the physical property and the damage status, such as debonding failure, are investigated in this section. The influence of the acoustic impedance, debonding size and its position in the middle layer are mainly discussed. In the model as shown in Fig.1, an elastic fiber with a middle layer around it is embedded in a finite viscoelastic matrix, i.e., the attenuation of matrix is taken into account. The debonding region in the middle layer is defined by the angle 2δ and its position is represented the direction of angle θ. For the case of 2δ=0˚, it implies that all fiber are completely bonded to the matrix, while for the extreme case of δ=180˚, the fiber are fully separated from the matrix and that means a cavity layer. A circular glass fiber is embedded in the center of the epoxy matrix. The size of the model is

20λ×20λ accompanying with the fiber diameter of d=4λ and the middle layer thickness of 1λ. An incident longitudinal wave of 100 MHz is used and the other input data is in Table I. Boundary conditions are assumed to be the PML absorption boundary.

3.2 Influence of the impedance in middle layer

Four kinds of acoustic impedance in the middle layer as listed in Table I are used to discuss its influence on the characteristics of ultrasonic wave for the SFC model. The data of acoustic impedance for the middle layer are referred according to the practical composite materials in reference [2], the glass fiber with a coated layer reinforced epoxy resin. For these four different values of impedance in the middle layer, Fig.2 shows the curves of normalized transmission energy (a) and normalized reflection energy (b), respectively.

In Fig. 2(a), it is shown that there are two parts in the curves of the normalized transmission energy. The lower part of the transmission energy with earlier arrival time resulted from fiber and middle layer region, while the higher part of the transmission energy with later arrival time are generated due to transmission of the incident wave through the matrix region. For the latter, the magnitude of the transmission energy is much larger that the former one since there is no reflection occurs in the matrix region. Consider the different impedance Z_0 in the middle layer, it is obvious that when the Z_0 becomes small in the order of Z_{01}, Z_{02}, Z_{03} and Z_{04}, the peak transmission energy in the lower energy part corresponding to the fiber and middle layer region reduces in the same order, while the order for the peak transmission energy in the higher energy part corresponding to the matrix region becomes complicated. The reason for this maybe is due to the dispersion of waveform at the interface.

In Fig. 2(b), the reflection energy for four different values of impedance in the middle layer shows that when the Z_0 becomes small in the order of Z_{01}, Z_{02}, Z_{03} and Z_{04}, the peak reflection energy in both lower energy part and higher energy part of the curves increases in the same order, except the peak energy for Z_{02} in the lower part. The peak reflection energy in the lower energy part almost disappeared for Z_{02} since the value of Z_{02} is near to that for glass fiber and so that there is no obvious reflection occurs at the interface between the middle layer and glass fiber.

3.3 Influence of debonding failure in middle layer

The debonding failure in the middle layer is represented by two parameters, the angle 2δ for the size of debonding region and the directional angle θ for its position around the circle of the middle layer. Two debonding regions are assumed asymmetrically in the middle layer.

Figure 3 shows the normalized reflection energy and normalized transmission energy for different positions of debonding region when the debonding size and the impedance are kept same as 2δ=30˚and Z_0=Z_{01} in Table I. One energy peak is observed in the curves of reflection energy, while two energy peaks are observed in the curves of transmission energy. As stated in previous section, the lower energy peek is contributed by the ultrasonic wave through the fiber and middle layer region, while the higher energy peek resulted from the ultrasonic wave propagation in the matrix region. Thus, here only the former is discussed for the comparison of influence of the debonding failure in the middle layer. In the case of the angle θ =0˚, i.e., the debonding region is just right to the incident wave, the normalized peak reflection energy (Fig. 3(a)) is 0.052, which is about 5 times of the value for θ =45˚ or θ =90˚. The peak reflection energy for both θ =45˚ and θ =90˚ is almost same with the value of 0.012. The reason maybe is that the incident angle in these two cases is larger than critical full reflection angle and full reflection occurs at the debonding regions. However, in Fig. 3(b), the normalized transmission energy curves are quite different with the change of debonding positions. The peak transmission energy in the lower energy part increases in the order of θ =0˚, θ =45˚ and θ =90˚. Looking at the debonding positions in Fig.1, it is confirmed that the analysis result is reasonable.

When the debonding position is kept as θ =45˚ and the debond region 2δ changes from 0˚ (no damage) to 180˚ (cavity middle layer), both reflected wave and transmitted wave exhibits different behavior. Figure 4(a) shows the normalized reflection energy and normalized transmission energy with different debonding regions. In the region of 2δ=0˚~90˚ the curve of reflection energy increases slowly, while it becomes sharp during 2δ=90˚~135˚. After that the reflection energy is almost kept constant due to the left side of the middle layer becomes full cavity. The relationship between transmission energy and the debonding angle is shown in Fig. 4(b). With the increment of the debonding angle, the normalized transmission energy reduces dramatically. However, during 2δ=135˚~180˚ the transmission energy is near to zero. With these results, it is confirmed that reflection energy and transmission energy of ultrasonic wave during wave propagation have a deep dependence on debonding region in the middle layer between fiber and matrix.

3.4 Visualization of ultrasonic wave with different interfaces

Figure 5 shows the series of propagation patterns of ultrasonic wave for three models with different interfaces: (Fig. 5.1) a single glass fiber is embedded in epoxy resin but no middle layer; (Fig. 5.2) a single glass fiber is embedded in epoxy resin and with a middle layer between glass fiber and epoxy resin but without debonding failure; (Fig. 5.3) a single glass fiber is embedded in epoxy resin and with a middle layer between glass fiber and epoxy resin and with two debonding region of 2δ=30 at the positions of θ =45˚. Observing the motion pattern and the wave crests of both reflected and transmitted wave at each propagation time, it is obvious that the propagation behaviors in these three models are quite different. In Figs. 5.1 and 5.2, when a wave motion arrived at the interface between the fiber and the matrix, part of the wave is reflected as a secondary source wave, and at the same time a dispersion wave is generated. The other part of the wave was transmitted and multi-reflection takes place around the glass fiber. In the model with debonding region (Fig. 5.3), the reflection also occurred in the debonding region. The wave motion pattern is symmetrical in Figs. 5.1 and 5.2 without debonding failure, while it was asymmetrical due to the existence of debonding region (see Fig. 5.3). The debonding region may reflect the wave earlier than other places and enable the wave to propagate through the debonding area to the surroundings. With these results, the influence of fiber and debonding failure on propagation and dispersion of an ultrasonic wave in a 3P composite material could be understood well.

4 Conclusions

In this paper, ultrasonic wave propagation in 3P composite materials was investigated in model cases of composite materials made of fiber, matrix and a middle layer existed between fiber and matrix. The influence of the fiber/matrix interface, the geometrical size of middle layer and its physical property on wave propagation was clarified. When the debonding failure existed in the middle layer between fiber and matrix, its influence on ultrasonic motion pattern and the characteristics of energy propagation are investigated in detail. The complicated propagation behavior resulted from reflection, transmission, multi-reflection and dispersion due to the existence of debonding failure at the fiber/matrix interface was visualized. With these results, it is indicated that an approach based on ultrasonic technology is possible for the evaluation of interfacial behavior in 3P composite materials with a middle layer existed between fiber and matrix.

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Table I. Material parameter used for analysis

Materials series	Epoxy	Glass	Interphase	Interphase	Interphase	Interphase
Impedance	Z_1	Z_2	Z_{01}	Z_{02}	Z_{03}	Z_{04}
Density (kg/m^3)	1200	2400	1600	1400	1200	1100
Longitudinal velocity (m/s)	3000	6000	4500	2570	2000	1500
Transverse velocity (m/s)	1500	3000	2250	1280	1000	750
Loss (dB/cm)	1.2	0	0	0	0	0
Incidence frequency MHz)	100					

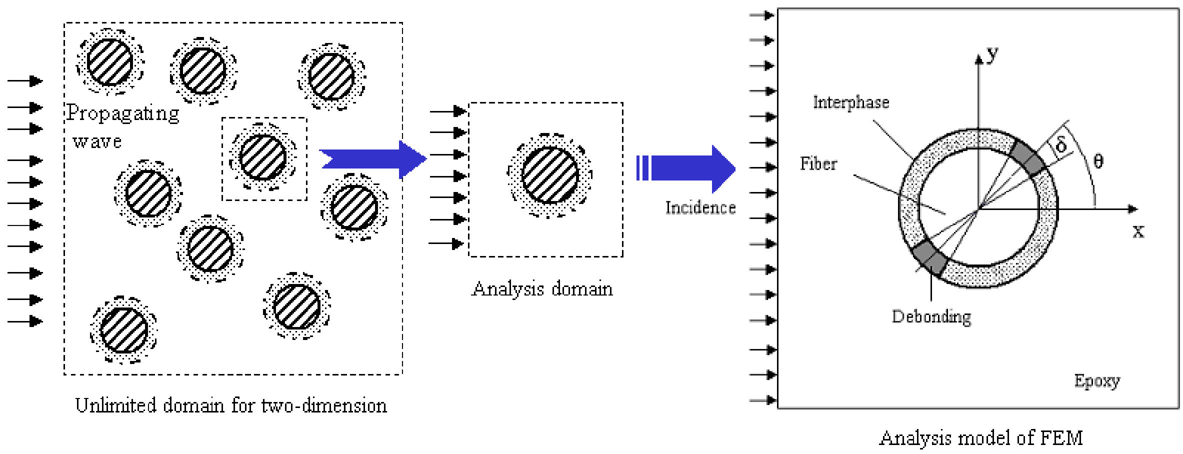
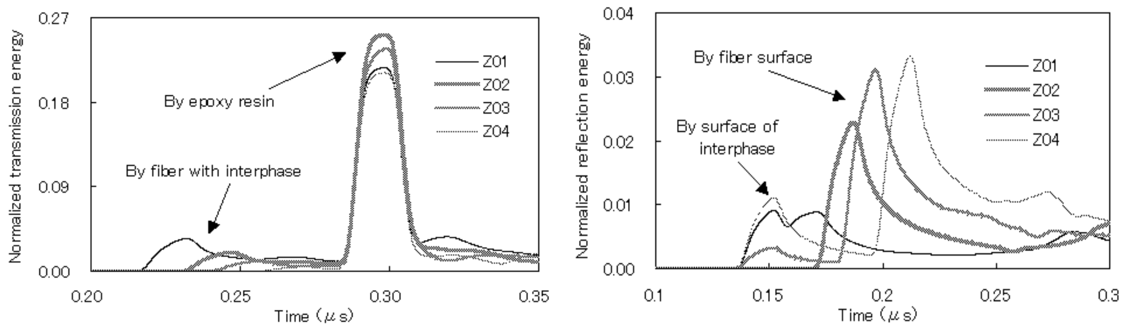
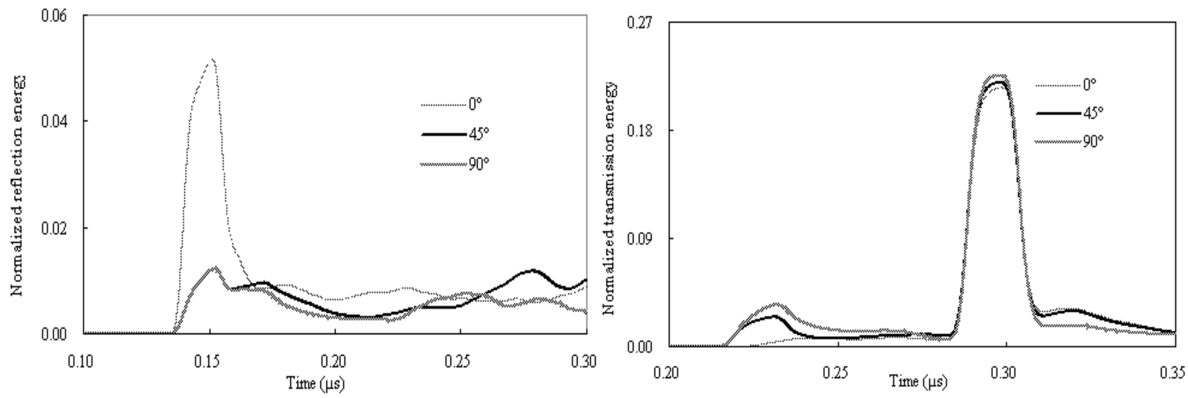


Fig. 1. Computational model for the investigation of the effect of middle layer in 3P composite materials with debonding failure; model size 20λ×20λ, radius of fiber 4λ, thickness of middle layer 1λ.



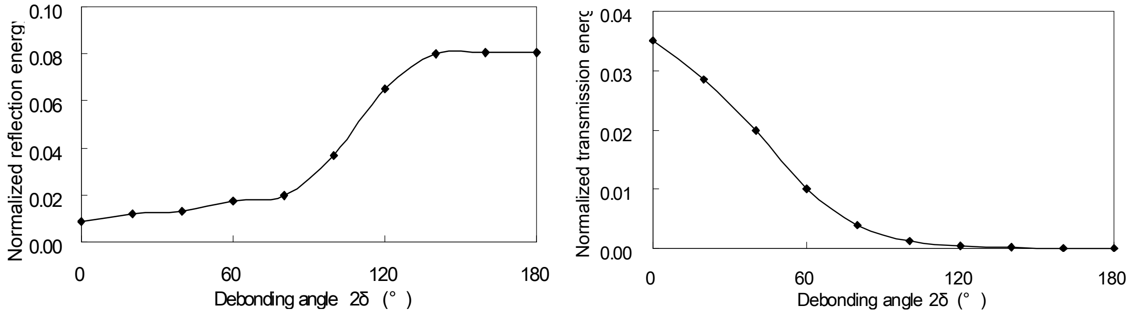
(a) (b)

Fig. 2. Normalized transmission energy (a) and normalize reflection energy (b) with propagation time for different acoustic impedances in the middle layer.



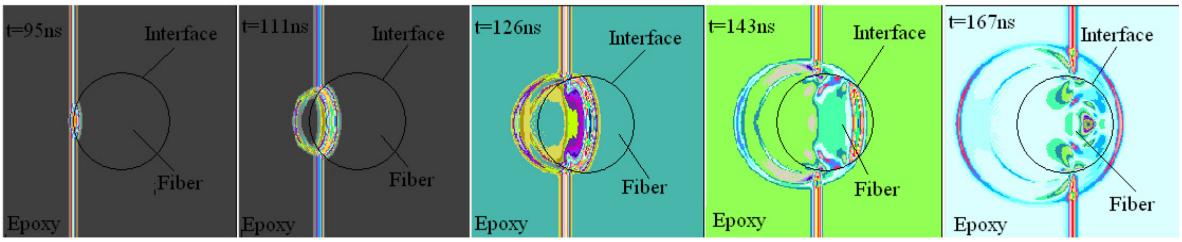
(a) (b)

Fig. 3. Normalized reflection energy (a) and normalized transmission energy (b) with propagation time for different debonding positions at θ=0˚, 45˚, 90˚ under 2δ=30˚.



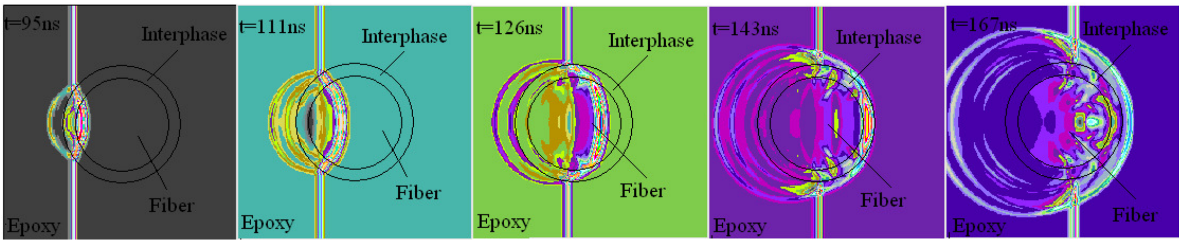
(a) (b)

Fig. 4. Normalized reflection energy (a) and normalized transmission energy (b) with propagation time for different debonding region 2δ from 0˚(no debonding) to 180˚(cavity middle layer) under θ=45˚.



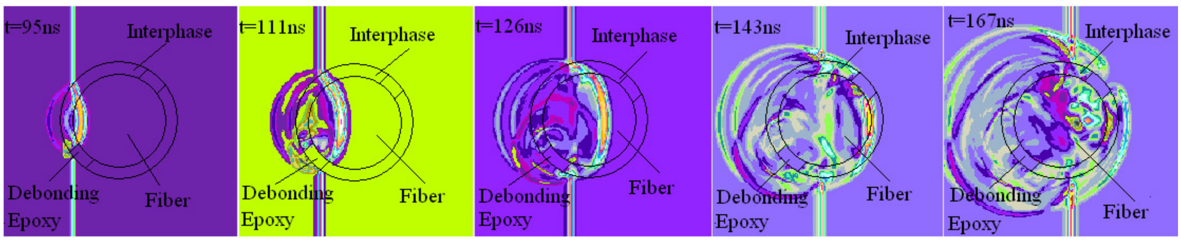
(a) (b) (c) (d) (e)

Fig. 5. 1



(a) (b) (c) (d) (e)

Fig. 5. 2



(a) (b) (c) (d) (e)

Fig. 5. 3

Fig. 5. Ultrasonic wave motion patterns for three interfacial models under propagation time t=95ns, 111ns, 126ns, 143ns and 167ns, respectively. Fig. 9.1 for that a single glass fiber is embedded in epoxy resin but no middle layer; Fig. 9.2 for that with a middle layer between glass fiber and epoxy resin but without debonding failure; Fig. 9.3 for that with a middle layer and two debonding regions of 2δ=30 at the positions of θ =45˚.