EFFECTS OF REFLECTION AND REFRACTION OF ULTRASONIC WAVES ON THE

ANGLE BEAM INSPECTION OF ANISOTROPIC COMPOSITE MATERIAL*

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INTRODUCTION

Nondestructive testing of composite materials by ultrasonic techniques has several specific features resulting from strong material anisotropy and inhomogeneity. This requires reexamination of old testing methodologies and development of new ones. The latest developments in this direction were recently reviewed by Henneke and Duke [1] and by Bar-Cohen [2].

One of the basic physical concepts in ultrasonic NDE is reflection-refraction of ultrasonic waves on a plane interface. Even the simplest testing procedure requires knowledge of elastic wave reflection and transmission coefficients, refraction angles, and mode conversion [3]. While simple and well-documented for testing of isotropic materials [3], refraction-reflection phenomena for anisotropic materials are much more complicated from both physical interpretation and technical calculation points of view. In the analysis of the angle beam inspection method for composite materials, one first has to address the problem of wave propagation through the interface between the immersion medium and the composite material. For example, there is a water-composite interface in the immersion technique and perspex-composite interface in the contact method. Slip boundary conditions must be selected in the second case. Furthermore, for multidirectional plies of fibers, the reflection and transmission of ultrasonic waves from one unidirectional ply to another with a different orientation may be considered. From this list, only the problems of liquid-composite interfaces have been given some attention in a different context [4,5,6].

The objective of this paper is to analyze reflection and refraction phenomena between coupling media containing an ultrasonic transducer and the composite material, and between layers with different fiber orientations in the composite material, both in immersion and contact variants of ultrasonic tests. For our calculations, we will use a general algorithm [7,8], which was recently developed for analysis of wave interaction with the interface between two generally anisotropic media. This algorithm was slightly modified to take into consideration slip interfaces between solids, and if needed, liquid media.

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The basic structural unit of an advanced composite material is a uni-
directional lamina. In such a lamina, fibers are oriented in a single
direction, parallel to the lamina surface. A multidirectional composite
material is designed by forming layers with several unidirectional laminas
and orienting these layers in desirable directions. If the thickness of the
unidirectional layers is greater than the ultrasonic pulse length, the trans-
mission from layer to layer can be considered as transmission through an
interface between two composite semispaces with different fiber orientations.
Therefore, study of ultrasonic wave propagation through the interface between
the immersion medium where the ultrasonic transducer is placed and the uni-
directional composite lamina, and through the interface between differently
oriented laminas has quite general implications.

Fig. 1 illustrates the case under consideration, where the ultrasonic
wave is incident from the upper semispace onto a unidirectional composite
medium. The plane of incidence, in general, may be rotated from the fiber
direction. The upper medium may be liquid, solid isotropic, or another uni-
directional media with different fiber orientation.

It was shown in our previous paper [7] that for characterization of wave
reflection and refraction on an interface, it is very convenient to use
energy flow relations for determination of reflection and transmission
coefficients

\[ t^a, r^a = \frac{U_3^a}{U_3^0} \] (1)

where \( U_3 \) is the projection of the vector of this energy flux on the normal to
the interface (axis 3 in this case), the superscript \( a \) characterizes the type
of reflected or transmitted mode, and the superscript \( o \) relates to the inci-
dent wave. \( t \) and \( r \) are the energy flow transformation factors; they char-
acterize the redistribution of the incident energy flux between different
reflected and refracted modes. The direction of the energy flux vector \( \vec{U} \)
coincides with the direction of the group (ray) velocity \( \vec{U}_g \). Equation 1
can be written in this form:

\[ t^a, r^a = \left( \frac{A^a}{A^0} \right)^2 \frac{\rho_a (\vec{V}_g^3)^a}{\rho_o (\vec{V}_g^3)^o} \] (2)

where \( A^a \) and \( A^0 \) are relative amplitudes of the displacements, \( \rho \) is the den-
sity, and \( \vec{V}_g^3 \) is the projection of the group velocity on the normal to the
interface. Equation 2 leads immediately to this important conclusion: when
the energy of the transmitted wave (or group velocity) is oriented parallel
to the interface \( (\vec{V}_g^3)^a = 0 \), the transmitted coefficient equals zero inde-
pendent of the direction of the wave vector. For complete discussion of this
critical angle problem, refer to the authors' previous papers [7,8] and the
work of Henneke [9].

The usefulness of the energy transmission coefficient is illustrated in
Fig. 2 where \( A_0 \) and \( A_T \) are amplitudes of the incident and transmitted waves.
If the transmitted wave is completely reflected back, it will be received in
the upper medium with coefficient \( A_T \). The energy transmission coefficient in
one direction is equal to the forward-backward transmission through the
interface for amplitude values and equal to the amplitude reflection coeffi-
cient \( R \) for the case shown in Fig. 2. The same energy transmission coeffi-
cient will be equal to the amplitude transmission coefficient through the
plate between two identical media (transmission through two interfaces).
Fig. 1. Position of the plane of incidence relative to fiber direction.

Material parameters used in this study were selected from the paper of Kriz and Ledbetter [10]. They are listed in Table 1. Several angles of rotation of the incident plane relative to the fiber direction (Fig. 1) were considered: 0°, 30°, 45°, 70°, and 90°. The angle of incidence was varied in the 0° - 90° range. Due to paper length limitations, we consider only several typical examples of the calculations.

TABLE 1. Elastic constants in GPa and density in g/cm³ for graphite-epoxy composite material.

<table>
<thead>
<tr>
<th>c_{11} = c_{22}</th>
<th>c_{33}</th>
<th>c_{12}</th>
<th>c_{13} = c_{23}</th>
<th>c_{44} = c_{55}</th>
<th>c_{66} = (c_{11} - c_{12})/2</th>
<th>\rho</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.6</td>
<td>144</td>
<td>7.0</td>
<td>5.47</td>
<td>6.01</td>
<td>3.3</td>
<td>1.61</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

The unidirectional graphite-epoxy composite material can be considered as transversely isotropic. In such a material, three elastic waves can propagate in an arbitrary direction: quasi-longitudinal, quasi-transverse, and pure transverse. The displacements of all three waves must be orthogonal. In the plane of incidence, coincident with the fiber direction (θ = 0° where θ is the angle of rotation, see Fig. 1), the pure transverse wave will have displacement perpendicular to the plane of incidence independent of the angle of propagation in this plane, so it may be called SH wave. The second transverse wave will be a quasi-SV wave. The phase velocity of the SH wave is less than the velocity of the SV wave. Only in the direction of fibers do both speeds have the same value. In this plane of incidence, mode conversion occurs only to the two transmitted waves, quasi-longitudinal and quasi-SV, at any angle of incidence from the liquid or isotropic solid. The same situation occurs when the plane of incidence is θ = 90°; this is the plane of isotropy (plane perpendicular to the fiber direction). The SV wave has displacement laying in this plane, and therefore has displacement perpendicular to the fiber direction. The SH wave will have displacement in the fiber direction and will be faster than the SV wave. If the angle of rotation is continuously changed, one will observe that the slow pure transverse wave which is SH in the plane of fibers (θ = 0°) becomes an SV wave at θ = 90° and vice-versa for the quasi-transverse wave.
Fig. 3. Energy reflection and transmission coefficients for liquid/composite interface.
At an arbitrary rotation angle (θ ≠ 0° or 90°), neither of these waves will have SV or SH character, and both of them will have displacement components in and out of the plane of incidence. So we distinguish them as fast (with higher speed) which will be quasi-transverse and slow which will be pure transverse.

Due to deviation of the displacement of all three waves from the plane of incidence for an arbitrary rotation angle, the incident wave from liquid or isotropic solid will be converted on the interface to three transmitted waves. This is illustrated in Fig. 3 for angles of rotation 45° and 70°. It is seen that for the 45° incident plane, there exist three critical angles for the quasi-longitudinal and both quasi-transverse waves, while for 70°, only two critical angles exist since the speed of the slow wave becomes less than the speed in the water. Another interesting observation is that the positions of the first and second critical angles move in opposite directions on the incident angle axis when the angle of rotation changes.

In the upper part of the figures for the transmission coefficient, the angles of refraction both for the ray (ultrasonic beam) and the wave vector are shown. Therefore, these scales give the angle of deviation of the ultrasonic beam from the wave normal. The ultrasonic beam deviates not only in the plane of incidence, but out of the plane also. This is illustrated for a quasi-longitudinal wave in Fig. 4 for rotation angle 45°. From this figure, one can see that the beam of the quasi-longitudinal wave tends to deviate to the fiber direction (out of plane component is close to 45°) and strongly deviates toward the material surface even at small angles of incidence (closer to the fiber direction). As shown in Fig. 3, when the wave vector has a refraction angle βt(w.v) equal to 23°; the angle of refraction for the beam βt(ray) is equal to 72° (deviation in the plane of incidence can be around 50°, Fig. 4). These very large deviations in composite materials were observed experimentally [11,12]. If the ultrasonic beam for the quasi-longitudinal wave tends not to penetrate to the material (deviates to the surface), the ultrasonic beam for the fast quasi-transverse wave at rotation angle 45° behaves differently. At small angles of incidence, it very strongly deviates from the wave normal, compare the angle for the wave normal βf(w.v) = 6.9° and the refracted angle for the beam βf(ray) = 52.1°. At larger angles of incidence, the ray refraction angle decreases and becomes less than the wave normal angle. The deviation angle of the slow transverse wave is positive. For rotation angle 70°, the angle of deviation for the fast quasi-transverse wave does not change sign.

Fig. 4. Angle of deviation of group velocity from wave normal for quasi-longitudinal wave.
For modeling of angle beam contact transducers, slip boundary conditions must be selected on the interface. These conditions consist of continuity of the normal displacement and stresses on the interface and vanishing of the tangential stress components. Physically such boundary conditions correspond to a thin, low-viscosity liquid layer on the interface [13].

The case for an angle beam contact transducer (perspex wedge) is illustrated in Fig. 5. The plane of incidence is rotated by $45^\circ$ from the fiber direction. First, it is useful to note the very high transmission at normal incidence (the parameters of materials are very similar in this direction). For the material parameters under study, only one critical angle for the quasi-longitudinal wave may be observed. As in the case of the water-composite interface, at the critical amplitude, the reflection coefficient sharply reaches unity. It seems that unity of the reflection coefficient at the critical angle is a general property for liquid-solid interfaces and solid-solid interfaces with slip boundary conditions. The results of the calculations for the same pair of materials but with rigid boundary conditions are shown in Fig. 6. The reflection coefficient for this case is about ten times less at the critical angle and does not tend to unity. Another interesting difference from the slip boundary conditions case is that the SH reflected wave appears in the reflected field, but the slow transverse wave disappears in the transmitted field.

The dependence of the critical angle on the rotation angle is shown in Fig. 7. It changes from about $17^\circ$ in the fiber direction to $70^\circ$ in the direction perpendicular to the fiber.

Two examples for reflection transmission on a composite-composite interface are shown in Fig. 8 and Fig. 9. The case of incident plane coincident with the fiber direction in the upper medium and $45^\circ$ rotated in the lower medium is shown in Fig. 8. First of all, it is useful to note the relatively higher reflection coefficient for the longitudinal wave above $20^\circ$ incident angle. Note also, the very strong deviation of the ultrasonic beam

![Diagram](image-url)

**Fig. 5.** The reflection and transmission coefficients for the perspex/composite interface. Slip boundary conditions.
Fig. 6. The reflection coefficient for the perspex/composite interface in a case of rigid boundary conditions.

Fig. 7. The dependence of the critical angle on the rotation angle.

Fig. 8. Energy reflection and transmission coefficients for $0^\circ/45^\circ$ composite interface.

such that the reflected beam is very close to the interface (this deviation is greater than for the $45^\circ$ rotated plane). There is no deviation of the reflected beam from the plane of incidence. The conversion to the quasi-transverse reflected wave is very small. All three waves appear in the transmitted spectrum while the quasi-longitudinal wave is dominant.

The inverse situation is shown in Fig. 9. Here the upper medium is a $45^\circ$ rotated composite and in the lower medium, the fibers lie in the incident plane. The critical angle phenomenon is observed in this case for the trans-
mitted quasi-longitudinal wave. The general rule in both cases is that below 15° incident angle, very small reflection and mode conversion occur for the quasi-longitudinal wave when it crosses interfaces in the multidirectional composite. On the other hand, beam deviation from the wave normal is very significant even at these small angles.

REFERENCES

6. A. H. Nayfeh, these Proceedings.