

ANALYTICAL ULTRASONICS FOR EVALUATION OF COMPOSITE MATERIALS RESPONSE

PART I: PHYSICAL INTERPRETATION

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The prediction of the mechanical performance of engineering structures made from composite materials is an issue receiving great attention from designers, builders, and users of these items. The need for nondestructive evaluation techniques and procedures to fulfill the requirements for such predictive capabilities is obvious. Ultrasonics, and in particular, analytical ultrasonics, is one NDT method which has the potential to meet all of the demands necessary to develop predictive physical and mathematical models. However, to maximize utilization of ultrasonics, it is necessary that we have complete understanding of the capabilities and limitations of the method. This paper will review some of the basic aspects of wave propagation in anisotropic materials from the viewpoint as to how these basic physical properties place fundamental constraints upon what we may ultimately expect to learn from ultrasonic interrogation of a composite. Then, a brief discussion is given concerning the characterization of various physical properties of the composite by appropriate quantifiable ultrasonic signal parameters. The physical properties of major interest here are those which influence the mechanical response of the material.

INTRODUCTION

Composite materials are the materials of the future. Just as solid state semiconductor materials have made a revolution in the electronics industry, advanced composite materials will likely one day play a major role in the way we design and use materials for a wide range of engineering structural components. Composites have the ability to be designed from the outset to take advantage of stiffness and strength in the load carrying directions. In addition, they have the advantage of very large strength-to-weight and stiffness-to-weight ratios. Before these materials can be employed with full utilization of their capabilities and advantages, and lead to the revolution predicted, much knowledge must be obtained concerning their mechanical behavior. While a great amount of work has been performed on the study of the mechanical behavior of these materials, there is still missing from the literature one most important piece of information -- a knowledge of the final failure processes which lead to catastrophic rupture of the material. This is of especial importance, of course, for the formulation of failure theories which can be used for design purposes. A failure theory something like fracture mechanics for homogeneous materials has been the subject of many investigations reported in the literature, yet it is obvious that no equivalently useful models have at present been formulated.

To answer the needs of the modelers in formulating a failure theory for composite materials, much experimental information has been gathered and reported in the literature. Most of this information has been gathered by experimental

techniques which, if used by themselves, would be classified as nondestructive. The gathered information has revealed that the failure modes leading up to final rupture of composite laminates is quite complex (ref. 1). Figure 1 is an X-ray radiograph of a graphite epoxy laminate after many cycles of tension-tension fatigue. It is obvious from this radiograph that many different damage modes operate before final rupture, including transverse cracking, longitudinal splitting, and local delamination. Not obvious from the radiograph but known to occur also before final rupture are fiber breakage and fiber-matrix debonding. One thing that is apparent from many such studies is that final failure is not the result of the propagation of a single crack in a self-similar fashion as it is for a homogeneous material. To obtain useful data on such a complex damage state using nondestructive testing methods, and to develop nondestructive evaluation procedures based upon such information, it is necessary that an approach be used different from that which has been followed for homogeneous materials. Rather than developing NDT methods which look for single cracks and attempt to size and orient these, it is necessary to develop NDT methods which can interact with the entire, integrated state of damage in the composite. Several different NDT techniques are capable of doing this; most notably, perhaps, is that of ultrasonics.

Analytic, or quantitative, ultrasonics is also a subject which has received extensive attention in the recent literature. In general, this terminology has been applied to the search for ultrasonic methods which locate and size cracks as mentioned previously. Here we intend it to mean something even more general. We refer to analytic ultrasonics as those ultrasonics techniques which are capable of producing quantitative experimental parameters that are somehow descriptive of the material state, and, in particular, the material damage state. To apply analytic ultrasonics to composite materials, a great deal of care must be expended to understand the capabilities and limitations of the method. This paper reviews some of the basic aspects of wave propagation in anisotropic materials from the viewpoint as to how these basic physical properties place fundamental constraints upon what we may ultimately expect to learn from ultrasonic interrogation of a composite.

WAVE PROPAGATION IN ANISOTROPIC MATERIALS

The propagation of waves in anisotropic, homogeneous materials has been covered well in several texts (see, for example, refs. 2-5). The propagation of ultrasonic waves can be approached by the same techniques covered in those texts as long as the frequency of the waves is below, say, the gigahertz region. (For frequencies in and above this range, the wavelengths begin to approach the size of interatomic spacing and the material can no longer be treated strictly as a continuum.) Composites are, of course, not homogeneous materials, and to treat the propagation of waves in composites by theories established for such materials is not rigorously correct. However, many approaches to the mechanics of composite materials begin with the simplifying assumption that a composite material may be treated as a homogeneous, anisotropic continuum with the underlying symmetry of the composite, usually taken to be orthotropic. Here, we will begin with this assumption also and review the solution to wave propagation in anisotropic, homogeneous materials as if it could be applied to composites. As we shall see, the difficulties encountered in interpreting wave propagation in anisotropic materials are complex enough from this simplified viewpoint. Complete understanding will be required of this solution before we attempt to extend it to heterogeneous materials.

The discussion of wave propagation in homogeneous anisotropic materials begins with the wave equation for a continuum:

$$\sigma_{ij,j} = \rho \ddot{u}_i \quad (1)$$

where σ_{ij} are the stress tensor components, ρ is the material mass density, and u_i are the components of the particle displacement vector. The next step is to consider a constitutive law such as the generalized Hooke's Law for an anisotropic elastic material:

$$\sigma_{ij} = C_{ijkl} \epsilon_{kl} = C_{ijkl} u_{k,l} \quad (2)$$

where ϵ_{kl} are the components of the linear strain tensor. Then, for mathematical convenience, a plane wave solution can be assumed of the form:

$$u_i = A_i \exp i (k_j x_j - \omega t) \quad (3)$$

where A_i are the amplitudes of the particle displacements in the directions of the coordinate axes parallel to the symmetry axes of the anisotropic material, k_j are the components of the wave vector, and ω is the angular frequency of the wave (x_j and t are the independent position and time variables, respectively). For an anisotropic material having orthotropic symmetry, nine independent elastic constants are required to specify the constitutive relation between stress and strain, (eqn. (2)). In so-called reduced notation, these elastic constants are: C_{11} , C_{22} , C_{33} , C_{12} , C_{13} , C_{23} , C_{44} , C_{55} , and C_{66} . Complete wave solutions to the anisotropic wave equation for orthotropic materials have been developed and have appeared in the literature (ref. 6). For our present purposes it will suffice to discuss the general aspects of the solution to the wave equation in anisotropic materials. Particular points applicable to orthotropic materials will be referred to as necessary.

First, as is well known, the plane wave solution to the wave equation is found to describe the possibility of three wave modes, in general. These wave modes travel, generally, with three distinct phase speeds; see, for example, figure 2 for an orthotropic material. These modes do not generally have particle displacements which are purely parallel or perpendicular to the direction of the wave vector (i.e., the direction of propagation of the wave). Thus the modes of propagation in anisotropic materials are generally neither longitudinal nor transverse as the modes in isotropic materials are typically described (fig. 3). Certain particular directions in the material, often coincident with directions of high symmetry but not always restricted to such directions, do allow for the propagation of pure modes, but these are the exception. In other instances, one mode may be purely transverse for all directions (fig. 3). This occurrence is not of no consequence for the experimental application of ultrasonics. All mechanical ultrasonic transducers generate waves by the development of vibrations produced by the piezoelectric effect. These transducers are manufactured to generate either in-plane displacement vibrations (for the production of "transverse waves") or out-of-plane perpendicular displacement vibrations (for the production of "longitudinal waves"). The previous words have been placed in quotes because transducers are generally manufactured for the generation of waves in isotropic materials, in which case the transducers behave as advertised. Figure 4 schematically represents the introduction of longitudinal and transverse waves into an isotropic material. However, for anisotropic materials the directions of particle displacements preferred by the solution to the wave equation (and as ordained by the normal to the

surface of the specimen on which the ultrasonically generated wave is incident, which must, by necessity, be the direction of wave propagation) are not in general either parallel or perpendicular to the surface normal. Thus a mechanical transducer, in general, will generate multiple modes simultaneously in an anisotropic material as the incident particle displacement vibrations will have components in all three directions of particle displacements mandated by the solution to the wave equation.

This phenomenon is of special consequence to the ultrasonic investigation of thin composite laminates since typically the wave propagation time in the material is insufficient to separate the various modes in time. Hence the observed wave may be a combination of multiple modes and not a single mode. This may lead to misinterpretation of travel times or attenuation measurements. It should be noted here, however, that if the incident wave is in the direction normally called the z-direction for the composite (i.e., perpendicular to the lamina plane), then only one wave is established in the laminate, as this is a special direction for the laminate symmetry along which pure modes may propagate. Any deviation from exact normality, however, as may occur in a C-scan tank due to non-normal wave incidence or focused beams, will cause multiple wave generation in the composite.

A second aspect of wave propagation is of importance in anisotropic materials and not at all in isotropic materials. The energy flux vector associated with each wave mode is, by definition, the rate at which energy is propagated across a surface normal to the direction of wave propagation per unit area. Mathematically, this quantity is defined by the contracted product of the stress tensor and the particle velocity:

$$E_i = -\sigma_{ij} \dot{u}_j \quad (4)$$

In general, the energy flux does not coincide with the direction of wave propagation for an anisotropic material (refs. 1-5). This leads to a different set of wave surfaces (fig. 5) often called the group velocity surfaces since these can be shown to be related to the group velocity of the wave. This phenomenon has many consequences for wave propagation in anisotropic materials that are never seen in isotropic materials. For example, if a wave mode is established in a single crystal of finite dimensions, it is possible that the wave flux will cause incidence of the wave upon the lateral surface of the specimen (see fig. 6, for example), thereby leading to mode conversion or longer times of travel in the specimen than anticipated (see also refs. 5 or 8). A second consequence of the phenomenon of energy flux deviation is that, for certain directions in an anisotropic material, one may observe the apparent propagation of more than three wave modes. As many as five distinct modes may be observed in certain directions in the material. The wave normals are not all coincident, the apparent propagation of five modes is due to the deviation of the energy flux vectors associated with mode propagation in other material directions (ref. 4). Again this occurrence in the ultrasonic study of anisotropic materials such as composite laminates may lead to misinterpretation of results unless one is aware of it and is ready to take it into account.

The deviation of the energy flux from the direction of the plane wave normal can be seen easily in a simple experiment that can be performed with a unidirectional composite laminate. If two transducers are mounted on wedge blocks to cause non-normal incidence on the surface of a laminated plate, and the plane containing the normal to the plate surface and the direction of the incident wave is chosen to be at an angle to the fiber direction, then the receiving transducer

cannot be placed in this same plane if a received signal is to be observed. Rather, the receiving transducer must be placed outside of this plane. The angle between this plane and the plane containing the surface normal and the direction of the received wave corresponds to the direction of the energy flux vector for that wave mode. If the two transducers are not set up at precisely the correct angle, the receiver will not detect the maximum signal from the transmitter, or unforeseen constructive or destructive interference patterns may result.

The phenomenon of energy flux deviation also plays an important role when discussing the reflection-refraction problem in an anisotropic material. The reflection-refraction problem for plane waves incident upon a plane boundary has received some attention in the literature for anisotropic materials (ref. 8). Generally, a plane wave incident upon a plane boundary in anisotropic media will reflect as three distinct wave modes. (Figure 7 is an example of the use of slowness surfaces to study the reflection problem in anisotropic media.) Similarly, a wave incident externally upon a plane surface boundary of an anisotropic material will refract in the material as three distinct wave modes. The wave vectors for the incident and reflected (or refracted) modes and the surface normal must all lie in the same plane. The angles of the reflected, refracted, and incident modes relative to the surface normal obey a general statement of Snell's Law. However, the velocities of propagation for each of the reflected waves are dependent on the direction of propagation and hence Snell's Law cannot simply be applied, since there are two unknowns in Snell's relation -- the direction of reflection or refraction, and the velocity of propagation. Hence more involved solution procedures are required (see, for example, refs. 2, 3, and 8). The important point to be made here is that once again the anisotropy of the material leads to complications which are not present in the more familiar problem of reflection in isotropic materials. In the latter case, mode conversion also occurs, but only two waves are reflected or refracted, and the directions can be found immediately from Snell's Law. Furthermore, to belabor the point, in anisotropic materials, the reflected or refracted waves are neither longitudinal nor transverse, in general. Also, the critical angle phenomenon in anisotropic materials is dependent upon the energy flux direction and not the direction of the reflected wave vector as is normally assumed (ref. 9). This fact is of importance to those experimental techniques which utilize measurement of critical angles of reflection of external waves to measure wave velocities in solid materials.

The previous discussion has dealt with plane wave solutions to the wave equation in anisotropic materials. Other types of wave fronts, such as spherical, may always be treated locally as a plane wave. Hence a spherical wave which arises from a point source will display the same propagation characteristics as plane waves propagating in all possible directions simultaneously. Thus for the case of transducers which are focused and thus will have considerable divergence on the far side of the focalpoint, or for the study of ultrasonic waves emanating from acoustic emission sources, very careful consideration must be given to anisotropic wave propagation phenomena, as all of the previously described phenomena, as well as others not yet mentioned, will likely be present.

A number of other interesting phenomena, such as internal and external conical refraction, pure mode axes not coinciding with high symmetry directions, etc., might be discussed. However, for the purposes of this paper, we might close this discussion with a few general observations concerning the experimental application of ultrasonic techniques to composite materials. As long as one is sending an ultrasonic wave in the direction perpendicular to the plane of the laminate, which

indeed is the most frequently used experimental configuration, few of the complexities discussed above need to be considered. However, there will always be some degree of beam divergence and hence even an incident "normal" wave will have some portion of the sound beam which is not strictly perpendicular to the surface and hence will generate some off-axis waves which are of different modes than the purely longitudinal or transverse waves usually expected. Also, other ultrasonic techniques such as the stress wave factor method developed by Vary, et al., (refs. 10-11) establish waves which propagate in the direction of the laminate plane. The laminate plane is, of course, a plane of high anisotropy, and all of the phenomena described previously will occur in this plane. It is unclear at this point (at least to the present authors) how this statement might be modified by a quasi-isotropic laminate such as a $[0,90,+45,-45]_s$ stacking sequence. It seems likely, based upon experimental observation, that some influence of the anisotropy of the individual lamina will influence the propagation of stress waves in the plane of the laminate, and even in this case, some of the phenomena caused by the anisotropy of the material will be evidenced.

Finally, it must be clearly understood that the discussion to this point has dealt with homogeneous, anisotropic materials. Composite materials may be considered as such a material only as a very rough first approximation, although it is true that this is a good approximation in certain wavelength and frequency regimes. When the wavelengths become of the same order of magnitude as laminae thicknesses, fiber diameters, fiber spacings, or other physical size characteristics, then the material must be treated as inhomogeneous. A significant literature has also been developed for such discussions, but will not be referred to further here.

CHARACTERIZATION OF PHYSICAL PROPERTIES BY ULTRASONICS

The characterization of the physical properties of composite materials by various ultrasonic techniques has received a great deal of attention in the literature. For the purposes of this paper, and to illustrate potential utilization of some of the information presented in the previous section, we will discuss some of those works which have directly utilized the phenomena of wave propagation in anisotropic materials for the study of composites. A more complete study would require an extensive review paper and hence is beyond the scope of what we would like to accomplish here.

Perhaps one of the most basic mechanical properties of composite laminates which has been studied by ultrasonics is the elastic constant tensor. Several authors have measured elastic moduli by measuring wave speeds, but perhaps the most complete work in a composite laminate is that done by Kriz and Stinchcomb (ref. 12). Kriz and Stinchcomb determined the complete set of nine elastic constants for a graphite epoxy composite by constructing a 25.4 x 25.4 x 150 mm block of unidirectional material. They then sliced from this block several specimens with orientations appropriate for making nine independent measurements so that all nine constants corresponding to an orthographic material were determined. While one or two of the elastic constants were somewhat in doubt (because the corresponding calculation required taking the difference of two numbers which were nearly the same, and hence small measurement errors were multiplied), the results of this experimental effort were in line with predictions made by the rule of mixtures for composites.

Kriz has suggested that the deviation of the energy flux vector from the direction of wave propagation can be used to determine the moisture content in polymer matrix composites (ref. 13). It is well known that the ingress of water into the matrix of a composite, even in relatively small amounts, can alter the values of the material elastic constants by a few percent. Kriz has performed calculations which show that the deviation of the energy flux vector from the direction of wave propagation changes by measurable amounts when the elastic constants change by the small amounts caused by the presence of moisture (fig. 8). He has verified this by making experimental measurements on graphite epoxy material before and after exposure to moisture in the environment. His results indicate that moisture content can indeed be determined in a laminate if before and after angular deviation measurements are made on the same specimen.

CONCLUSIONS

The phenomena associated with the propagation of elastic waves in anisotropic materials are many and varied, as we have tried to illustrate here. For example, wave modes propagating in general directions relative to the material coordinate system are not purely longitudinal nor transverse. Hence the generation of ultrasonic waves by common piezoelectric transducers will generate multiple modes to some extent. The received signals will likely be a combination of different modes. When using two transducers to send and receive ultrasonic waves, deviation of the energy flux vector may reduce the apparent value of the received signal unless the proper orientation of the two transducers with respect to one another is taken into account. And application of reflection from plane boundaries for the purposes of making certain measurements may lead to misinterpretation of results unless one is aware of the differences in multiple mode generation and critical angle phenomena between isotropic and anisotropic materials. When studies or characterizations of composite materials by ultrasonics are to be performed, these phenomena must be taken into consideration so that proper and correct application and interpretation of the measurements can be made. Finally, attention must be drawn again to the fact that composite materials are heterogeneous by definition. The results discussed here have been determined for homogeneous materials only. While the assumption of homogeneity appears to be valid for certain wavelength ranges in composites, future work must continue to study the phenomena of wave propagation in anisotropic, nonhomogeneous materials.

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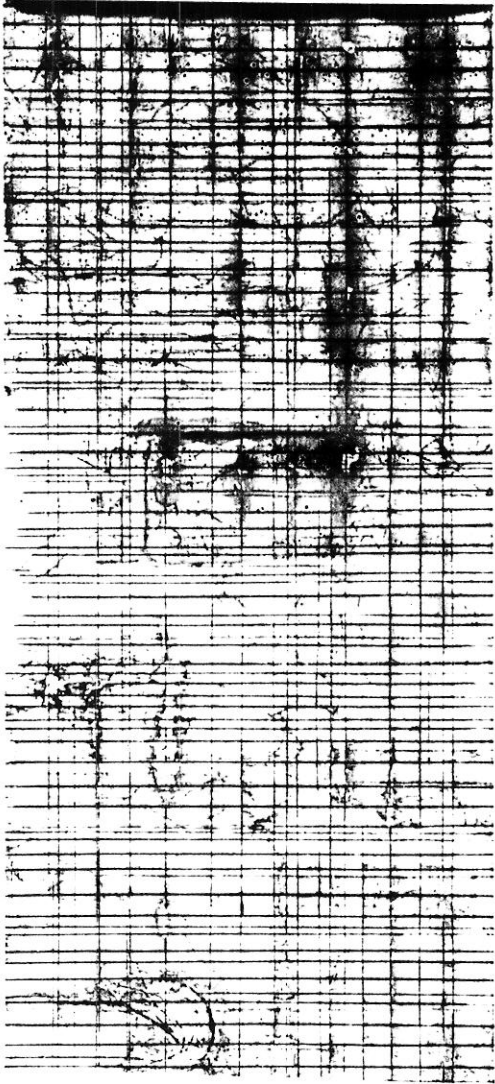


Fig. 1. X-ray radiograph showing advanced state of damage in a fatigued graphite epoxy composite laminate.

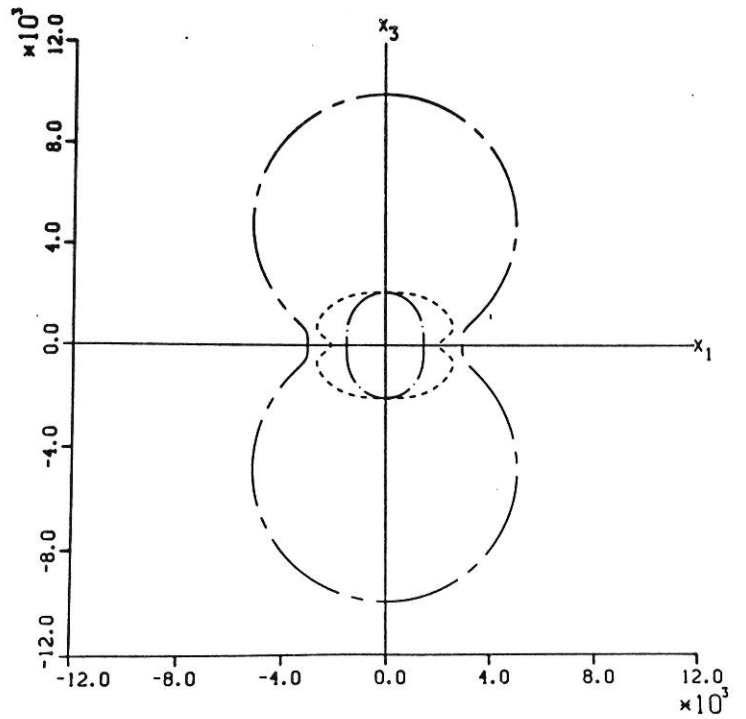


Fig. 2. Phase velocity surface for graphite epoxy composite (after Kriz (ref. 7)).

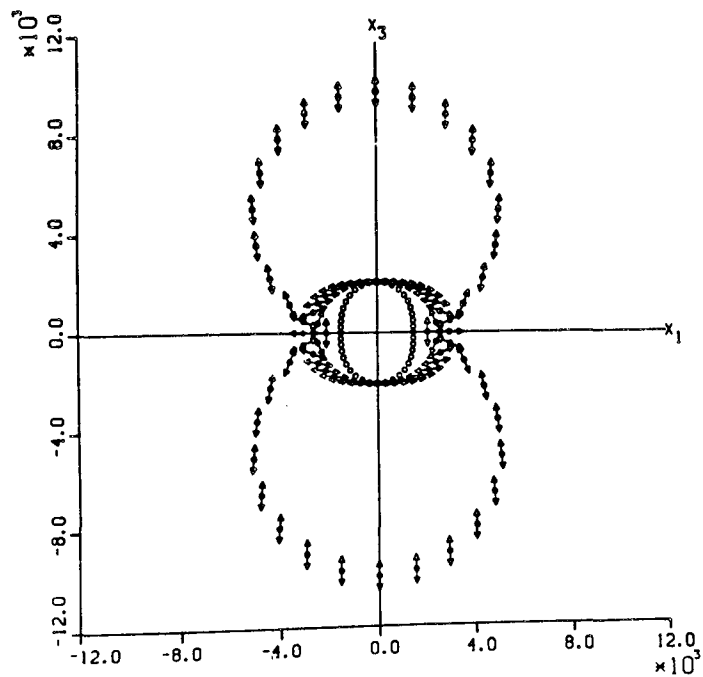


Fig. 3. Arrows indicate relative directions of particle displacements with respect to direction of wave propagation (which is position vector from origin to center of double arrows) (after Kriz (ref. 7)).

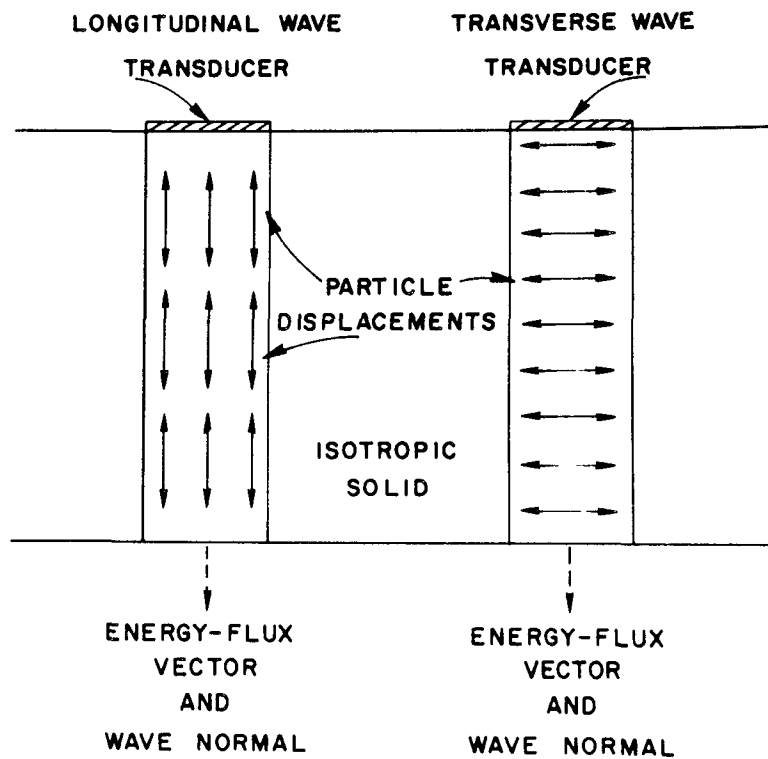


Fig. 4. Schematic representation of longitudinal and transverse waves being generated in an isotropic material (after Green (ref. 5)).

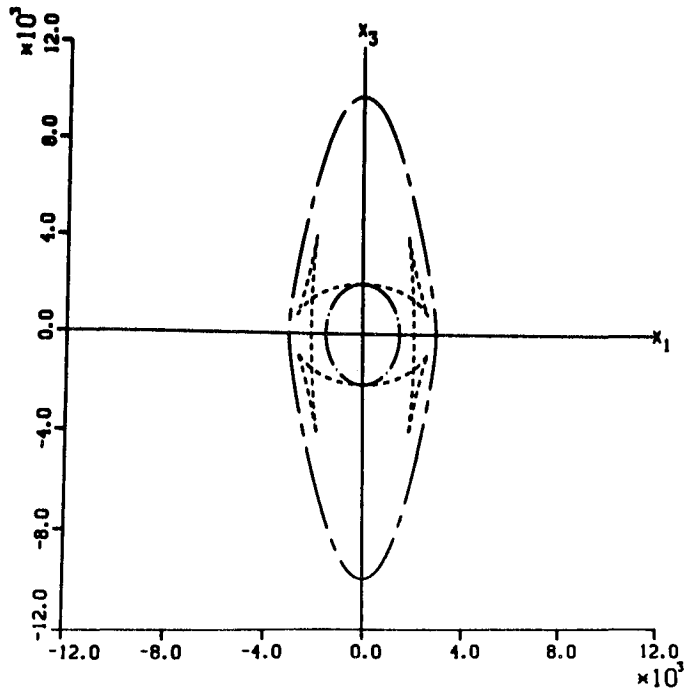


Fig. 5. Group velocity surface for graphite epoxy composite (after Kriz (ref. 7)).

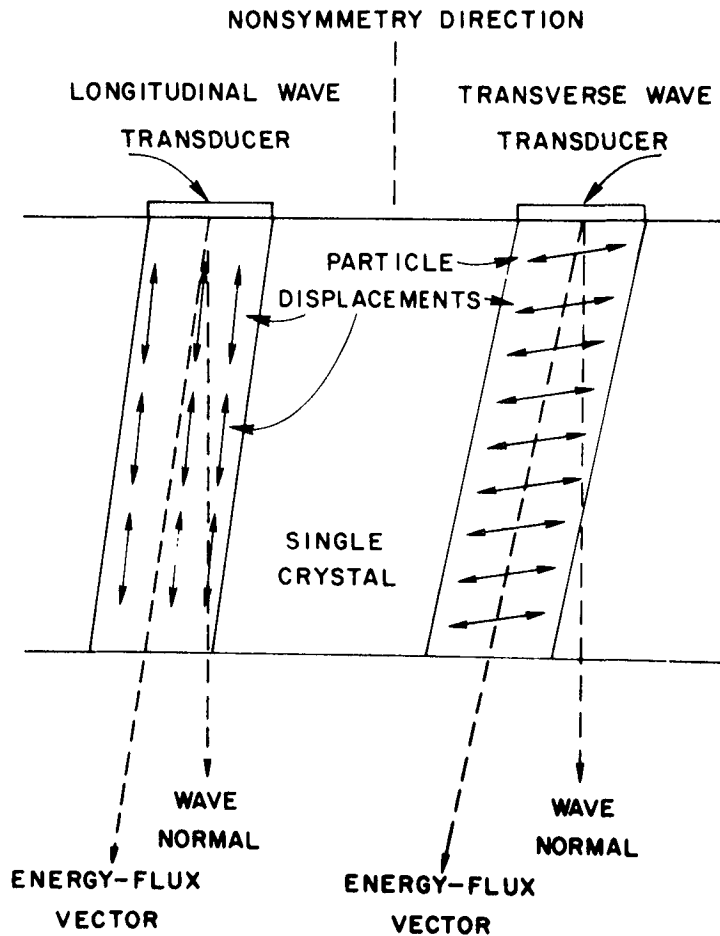


Fig. 6. Schematic representation of waves in an anisotropic material with energy flux deviation occurring for the transverse mode (after Green (ref. 5)).

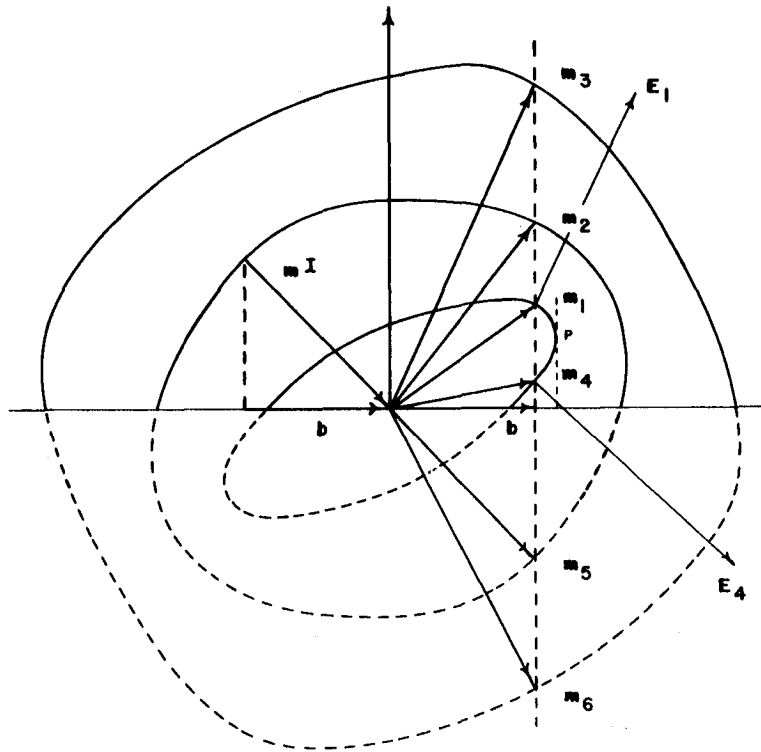


Fig. 7. Reflection of a plane wave at a stress free boundary in an anisotropic material using ray analysis (after Henneke (ref. 8)).

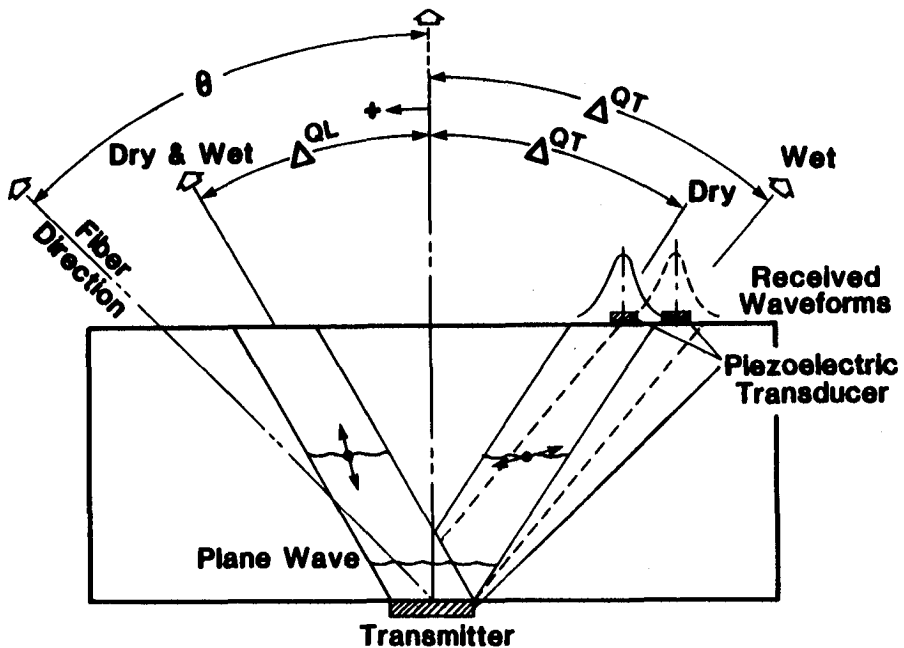


Fig. 8. Schematic representation of changes in energy flux deviation due to moisture in a composite (after Kriz (ref. 14)).