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Separation of Fracture-Induced Anisotropy from Background Anisotropy
ONR Contract # N00014-92-J-1978
Final Research Summary

Description of the Scientific Research Goals

The scientific research goals of this project were to evaluate the effects and determine the amount of oriented, periodic fractures in both heterogeneous, layered isotropic and anisotropic materials by nondestructive evaluation (NDE) methods. The approach was to measure nondestructively the elastic constants of a bulk fractured composite material in order to adequately characterize the material and provide damage assessment. In addition, the effects of the heterogeneous and anisotropic nature of fractured composite materials on plane elastic wave propagation were to be investigated. This work was to involve development of analysis and verification of methods of the quantitative NDE of elastic wave propagation and bulk elastic properties of anisotropic, heterogeneous materials. Work was planned to evaluate wave propagation characteristics in terms of orthorhombic symmetries resulting from fractures embedded in layered composites so as to allow the estimation of fracturing in materials which already possess an inherent anisotropy due to their layering.

Significant Results in the Past Year

Initial work began on a two-component layered composite to evaluate wave propagation characteristic in terms of hexagonal symmetry and to study effects of heterogeneity on wave propagation relative to currently existing thickness-weighted averaging theory and horizontal fracturing models for transversely isotropic homogeneous materials. Vertical fracturing of the hexagonal material which generates orthorhombic symmetry was then examined.

Because of material anisotropy, analytic and experimental work had to consider deviations of the energy vector from the phase vector due to propagation at arbitrary angles with respect to the material symmetry directions. Oblique incidence ultrasonic techniques were used to measure material constants and the effects of fracturing.

This research program entailed experimentally testing the design of Hood and Mignogna [1]. The Schoenberg fracture model [2] was used to analytically incorporate fracturing in the separation techniques offered by Hood and Schoenberg [3], in the experimental design of Hood and Mignogna [1], and was used in this program. The composite was constructed as a heterogeneous mix of isotropic components: glass plates bonded with epoxy. This particular composite exhibited transversely isotropic properties [4,5] and had values comparable to the thickness-weighted predictions of Backus [6] in the long wavelength limit.

Since the time of flight along phase vector or energy vector path is analytically equivalent [7], the time of flight measurements were analyzed using only the phase velocity in the anisotropic material. This greatly simplified analysis and reduced the number of parameters that needed to be measured. Mignogna [8] reported a general analytic closed-form solution for the wave equation which permits all pertinent information to be determined for arbitrary directions of wave propagation in anisotropic materials. An automated experimental system for making the laboratory measurements was used and provided all the necessary parameters for our program.

Accomplishments:

1. The experimental system for making the measurements was automated to assure better precision.

2. The elastic properties of the bulk forms of the homogeneous glass and epoxy were determined.

3. A heterogeneous layered material from the isotropic glass and epoxy was constructed. Models for both heterogeneous layered material and fractured material were considered.

4. Bulk properties and analytic models to predict properties of this composite were used. Predictions to experimental measurements were compared [5,6]. Measurements were made through the layered composite using sufficiently long wavelengths so that long wavelength averaging theory could be used.

5. Further heterogeneity was introduced analytically in the form of fracturing and bulk properties and analytic models were used to predict properties of this fractured composite. The fracturing was simulated by cutting the stack into thin vertical wafers, following Hsu and Schoenberg [9], and rebonding the wafers with the same epoxy. The final specimen displayed orthorhombic symmetry. The introduction of fracturing increased the anisotropy to that of a material with orthorhombic symmetry. This was examined using contact measurements.

6. The orthorhombic material was measured with oblique incidence angles using NRL's automated system. Predictions of the elastic moduli were compared with the values obtained from the experimental measurements.

Publications Resulting from this Research:

Refereed Journal Articles:

Hood, J. A. and R. B. Mignogna, 1995, Determination of elastic moduli in anisotropic media from ultrasonic contact measurements, *Ultrasonics*, **33**, 45–54.

Hood, J. A., R. B. Mignogna, N. K. Batra, K. E. Simmonds, and H. H. Chaskelis, Experimental and analytical determination of elastic moduli in anisotropic physical models: comparison with equivalent media theories, *Geophysics*, submitted Fall 1994.

Conference proceedings:

Hood, J. A., R. B. Mignogna, N. K. Batra, K. E. Simmonds, and H. H. Chaskelis, 1994, Measurement of anisotropic elastic moduli and comparison with equivalent media theories, *Nondestructive Characterization of Materials VI*, Eds. R. E. Green, Jr. *et al.*, Plenum Press, New York, 567–573.

Abstracts:

Hood, J. A., R. B. Mignogna, N. K. Batra, K. E. Simmonds, and H. H. Chaskelis, 1994, Inversion routine to determine all elastic moduli of physical models, *Sixth International Workshop on Seismic Anisotropy*, P1-10.

Hood, J. A., R. B. Mignogna, N. K. Batra, K. E. Simmonds, and H. H. Chaskelis, 1994, Experimental & Analytical Determination of Elastic Moduli in Anisotropic Materials - Comparison with Equivalent Media Theories, *EOS Transactions of the American Geophysical Union*, **75**, 334.

Hood, J. A., R. B. Mignogna, N. K. Batra, K. E. Simmonds, and H. H. Chaskelis, 1993, Measurement of anisotropic elastic moduli and comparison with equivalent media theories, *6th International Symposium on Nondestructive Characterization of Materials*, 111.

References:

1. Hood, J. A. and R. B. Mignogna, 1991, Experimental separation of constituent anisotropies, 61st SEG meeting, Houston, Expanded Abstracts, 1522-1525.

2. Schoenberg, M., 1983, Reflection of elastic waves from periodically stratified media with interfacial slip, Geophysical Prospecting, 31, 265-292.

3. Hood, J. A. and M. Schoenberg, 1992, NDE of fracture-induced anisotropy, Rev. Prog. Quantitative NDE, 11B, Eds. D. O. Thompson and D. E. Chimenti, 2101-2108.

4. Hood, J. A. and R. B. Mignogna, Determination of elastic moduli in anisotropic media from ultrasonic contact measurements, *Ultrasonics*, submitted.

5. Hood, J. A., R. B. Mignogna, N. K. Batra, K. E. Simmonds, and H. H. Chaskelis, Measurement of anisotropic elastic moduli and comparison with equivalent media theories, *Nondestructive Characterization of Materials*, submitted.

6. Backus, G. E., 1962, Long-wave anisotropy produced by horizontal layering, J. Geophys. Res., 66, 4427-4440.

7. Mignogna, R. B., 1990, Ultrasonic determination of elastic constants from oblique angles of incidence in non-symmetry planes, Rev. Prog. Quantitative NDE, 9, Eds. D. O. Thompson and D. E. Chimenti, 1565-1572.

8. Mignogna, R. B., 1991, Determination of elastic constants of anisotropic materials from oblique angle ultrasonic wave measurements I: analysis, Rev. Prog. Quantitative NDE, 10B, Eds. D. O. Thompson and D. E. Chimenti, 1669-1675.

9. Hsu, J. C. and M. Schoenberg, 1990, Characterization of anisotropic elastic wave behavior in media with parallel fractures, 60th SEG meeting, San Francisco, Expanded Abstracts, 1410-1415.

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