ULTRASONIC NDE OF THERMAL DAMAGE IN POLYMER COMPOSITES

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OBJECTIVE

Develop a quantitative NDE method, using stiffness analysis, for the determination of the degradation of composite materials that are exposed to elevated temperatures, prior to the formation of delaminations or other critical defects.

INTRODUCTION:

- Fire damage to composite materials is causing initially material degradation and as the damage become more severe, physical flaws appear.

  Repair of aerospace structures exposed to thermal damage or fire requires removal of all the infected sections.

- Practical NDE methods are unable to indicate thermal infection unless physical damage already occurred (cracking, delaminations, etc.)

EXPERIMENT

SETUP

The specimen is immersed in water and subjected to ultrasounds using pair of broadband transducers in a pitch-catch arrangement.

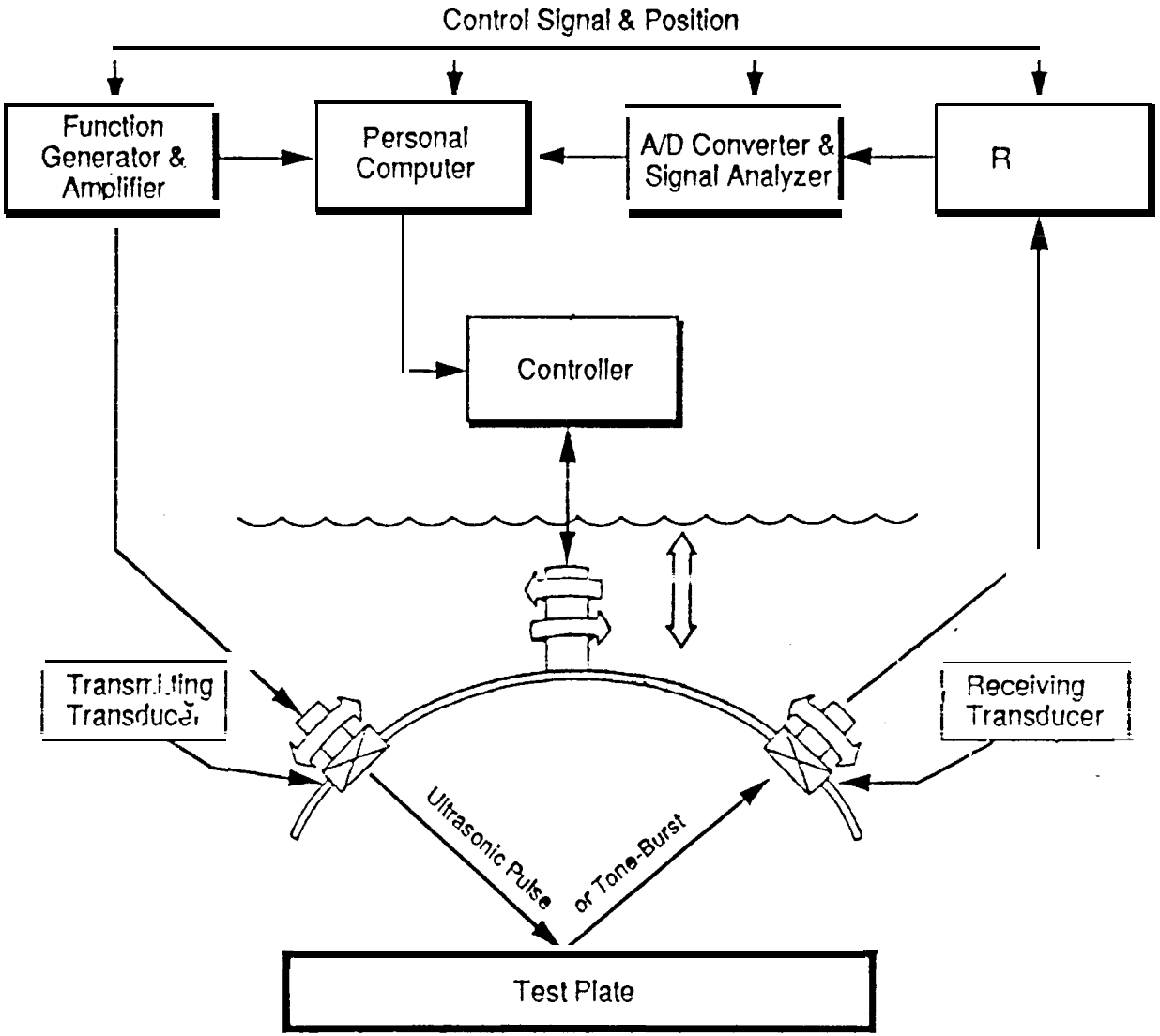
Reflected pulses or tone-bursts [leaky Lamb wave (LLW)] are analyzed to determine the stiffness constants.

TESTS

- Measurements were made before and after heating.

- The dependence of the stiffness degradation on the temperature rise and the duration of heating was investigated.

SCHEMATIC DESCRIPTION OF THE ULTRASONIC SET-UP FOR INVERSION OF ELASTIC PROPERTIES



LEAKY LAMB WAVE (LLW) PHENOMENA

- LLW HAS BEEN STUDIED FOR COMPOSITES SINCE 1983*

- PHENOMENA SENSITIVE TO ELASTIC PROPERTIES, BOUNDARY CONDITIONS, AND DISCONTINUITIES.

- THEORETICAL MODELING OF THE PHENOMENA HIGHLY SUCCESSFUL

- APPLIED TO INVERT COMPOSITES PROPERTIES AND CHARACTERIZE UNBONDS AND DEFECTS

* BAR-COHEN AND CHIMENTI, 1.983.

THEORETICAL BACKGROUND

Method is based on the Leaky Lamb wave (LLW) inversion technique: Mal and Bar-Cohen (1988).

Dispersion Equation

Dispersion curves are calculated from the solution of

$$G(f_i, \rho_o, V_o, V_i, h, \rho, C_{ij}) = 0$$

Where: f_i - Mode frequency
ρ_o - Density of water
V_o - Wave velocity in water
V_i - Phase velocity of the particular mode
h - Thickness of the laminate
ρ - Density of the laminate
C_{ij} - Stiffness constants

Parametric Study

Examine the effect of changing C_{ij} on the characteristic dispersion curves to determine the influence of thermal damage.

Characterization of the material constants from travel times of the reflected rays

Ray theory

The Cauchy's equation:

$$u_{ij,j} - \rho \ddot{u}_i = 0 \tag{1}$$

Plane wave solutions:

$$U_i = U_i e^{i(k_1 x_1 + k_2 x_2 + k_3 x_3) - i\omega t} \tag{2}$$

Eigenvalue problem:

$$\begin{vmatrix} a_2\xi_1^2 + a_5(\xi_2^2+\zeta^2) - 1 & a_3\xi_1\xi_2 & a_3\xi_1\zeta \\ a_3\xi_1\xi_2 & a_5\xi_1^2 + a_1\xi_2^2 + a_4^2\zeta^2 - 1 & (a_1 - a_4)\xi_2\zeta \\ a_3\xi_1\zeta & (a_1 - a_4)\xi_2\zeta & a_5\xi_1^2 + a_4\xi_2^2 + a_1\zeta^2 - 1 \end{vmatrix} \begin{Bmatrix} U_1 \\ U_2 \\ U_3 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix} \tag{3}$$

where

$$\begin{aligned} &a_1 = c_{22}/\rho, \quad a_2 = c_{11}/\rho, \quad a_3 = (c_{12} + c_{55})/\rho \\ &a_4 = (c_{22} - c_{23})/2\rho, \quad a_5 = c_{55}/\rho \\ &\xi_1 = k_1/\omega, \ \xi_2 = k_2/\omega, \ \zeta = k_3/\omega \end{aligned} \tag{4}$$

ξ_1 and ξ_2 are related to the incident angle θ and fiber orientation ϕ:

$$\xi_1 = \frac{\sin\theta\cos\phi}{\alpha_0}, \quad \xi_2 = \frac{\sin\theta\sin\phi}{\alpha_0} \tag{5}$$

where α_0 is the acoustic wave speed in fluid

$$\zeta_k = \sqrt{b_k - \xi_2^2} \quad (k = 1, 2, 3) \tag{6}$$

where

$$b_1 = -(\beta/2\alpha) - \sqrt{(\beta/2\alpha)^2 - \gamma/2\alpha}$$

$$b_2 = -(\beta/2\alpha) + \sqrt{(\beta/2\alpha)^2 - \gamma/2\alpha}$$

$$b_3 = \frac{1 - a_5\xi_1^2}{a_4} \tag{7}$$

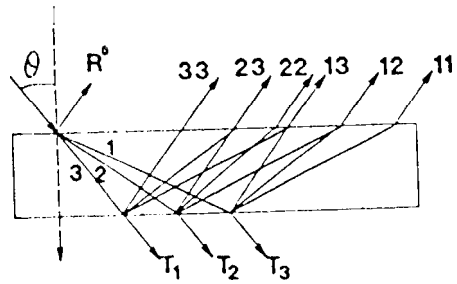
$$\alpha = a_1 a_5, \quad \beta = (a_1 a_2 + a_5^2 - a_3^2)\xi_1^2 - (a_1 + a_5)$$

$$\gamma = (a_2\xi_1^2 - 1)(a_5\xi_1^2 - 1)$$

The ray diagram:

The velocities V', V_l and the angles Ok, θ_l in the diagram are related through

$$\frac{\sin\theta}{\alpha_0} = \frac{\sin\theta_k}{V_k} = \frac{\sin\theta_l}{V_l}$$



(a)

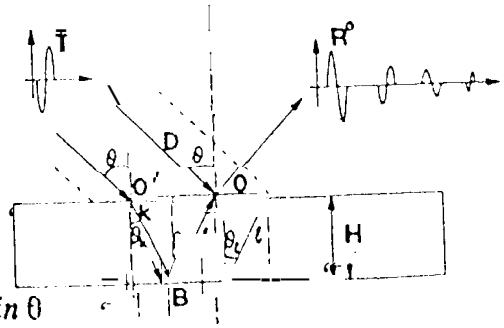
Time of fight t_{kl}

$$t_{kl} = t_k + t_l - t^D$$

where

$$t_k = \frac{H}{V_k \cos\theta_k}, \quad t_l = \frac{H}{V_l \cos\theta},$$

$$t^D = \frac{H(\tan Ok + \tan\theta_l)\sin\theta}{\alpha_0}$$

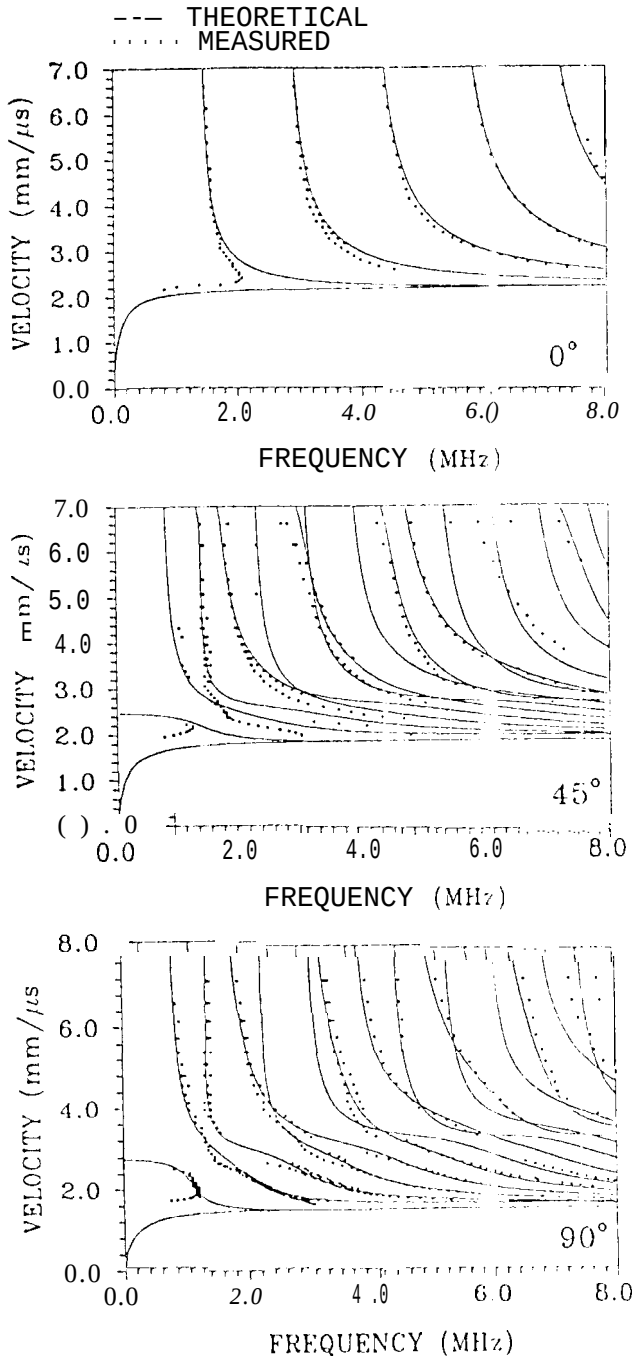


(b)

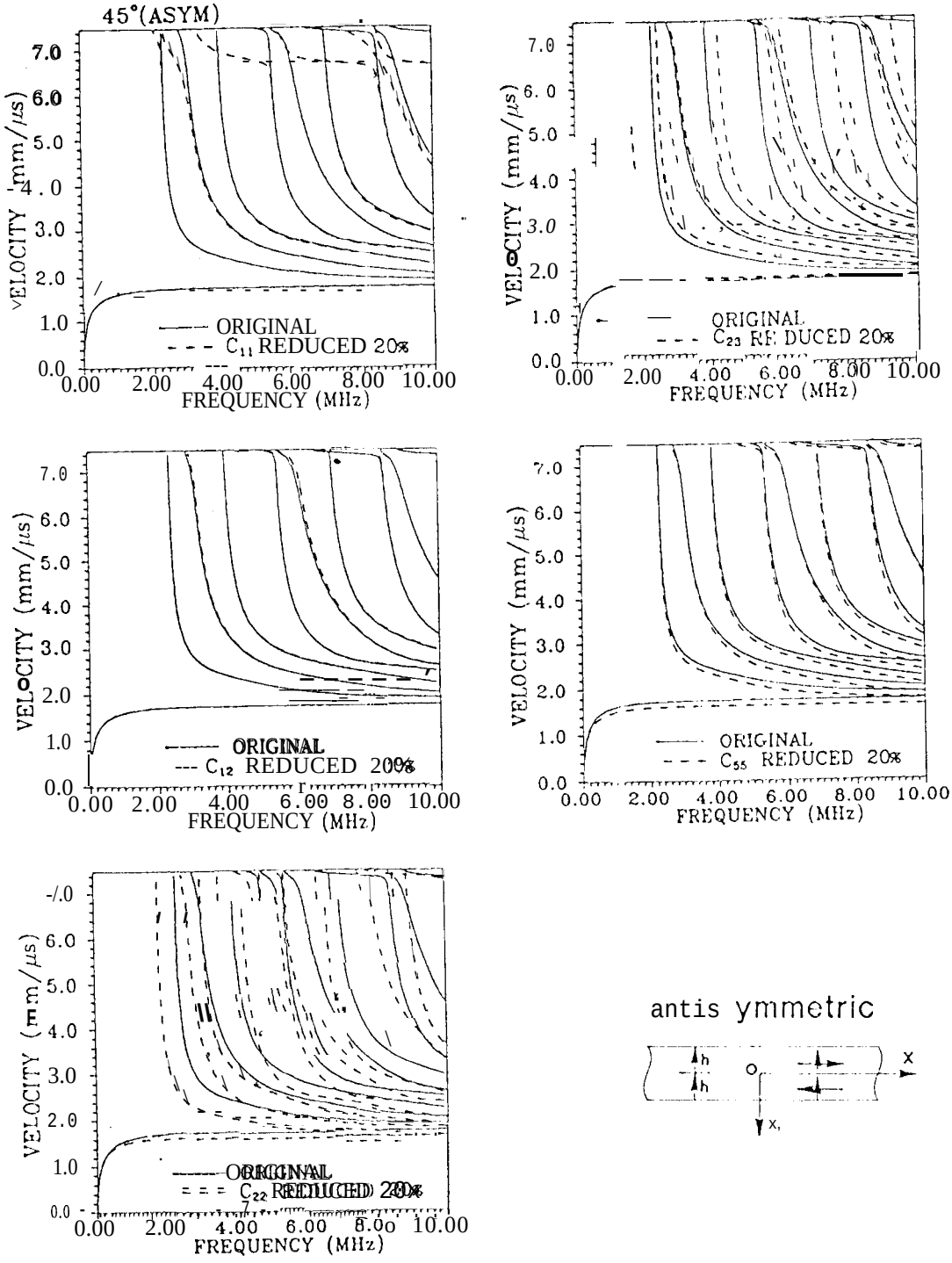
$$t_{kl} = \frac{H}{V_k \cos e_k} + \frac{H}{V, \cos\theta,} - \frac{H(\tan\theta_k + \tan\theta_l)\sin\theta}{\alpha_0}$$

$$\frac{H\cos Ok}{V_k} + \frac{H\cos\theta_l}{V_l} - H(\zeta_k + \zeta_l)$$

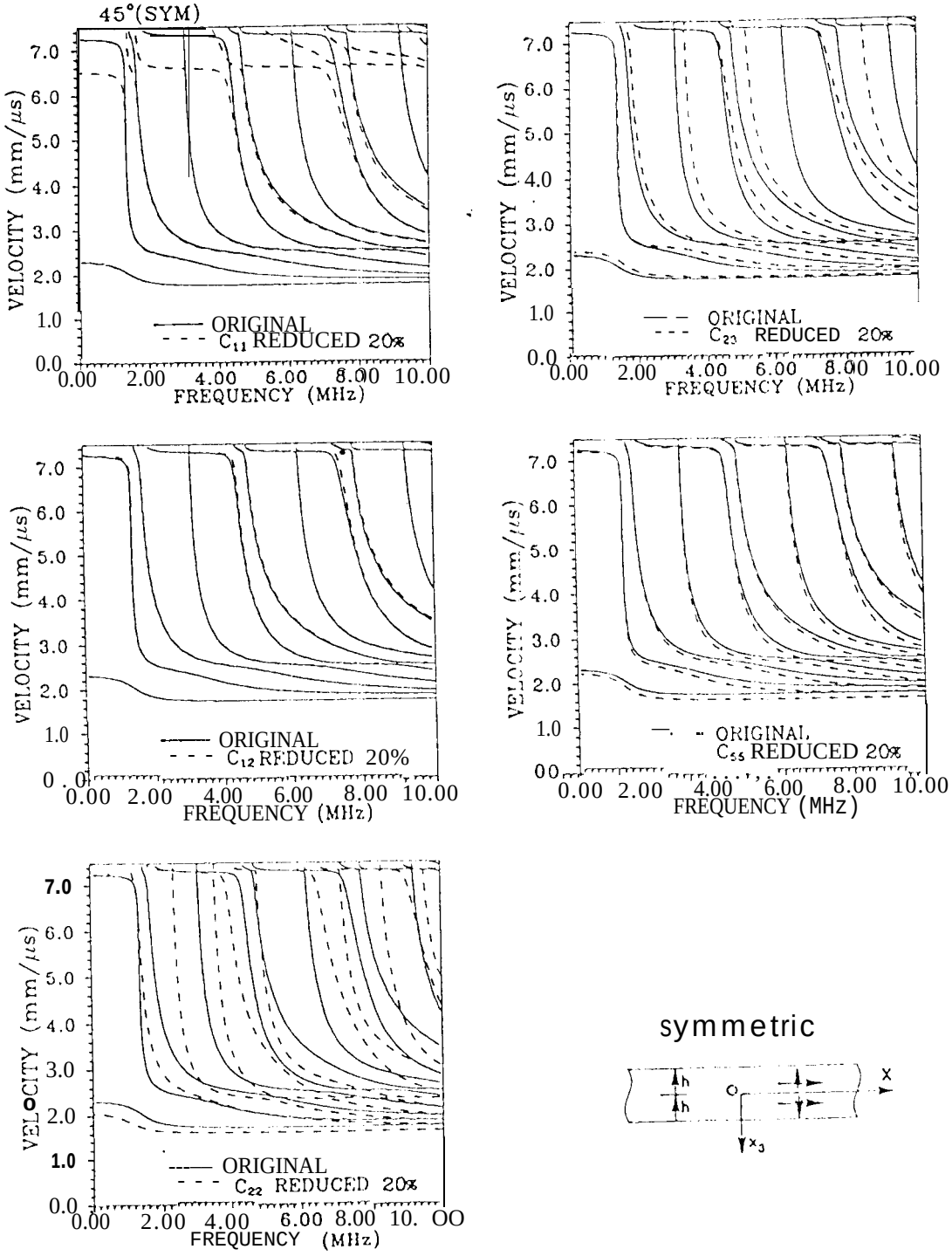
Comparison between measured and theoretical dispersion curves for a 1 mm thick unidirectional graphite/epoxy laminate.



Influence of the stiffness constants c_{ij} on dispersion curves for the antisymmetric mode for wave propagation 45° to the fiber.



Influence of the stiffness constants c_{ij} on dispersion curves for the symmetric mode for wave propagation $4S^0$ to the fiber.



THE INVERSION ALGORITHM

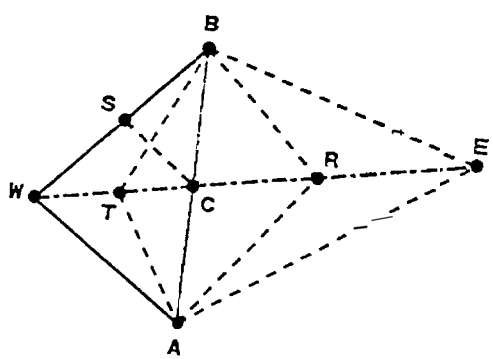
- Least square sum the residuals (LSSR)

  Dispersion Function

  $G(f_i, V_i, h, \rho, C_{ij}) = 0$

  $$LSSR = \sum_{i=1}^{n} W_i G_i^* G_i$$

- Simplex Algorithm (Karim *et al*, 990)



RESULTS

- Unidirectional laminate

  A reduction in the stiffness constants was observed for the $[0]_{24}$ Gr/Ep composite laminate. Inversion of the matrix dominated constants showed a reduction of:

  - 1 1% in C_{22}
  - 1% in C_{23}
  - 40/0 in C_{55}

- **Mutilayered** Laminate

  Experimentally determined dispersion curves have show changes in the LLW modes as a result of the thermal exposure. The inversion of the elastic constants for multi-orientation laminates is currently under development..

INVERSION OF ELASTIC CONSTANTS USING ULTRASONIC MEASUREMENTS

SUMMARY OF PROCEDURE

USING ACCESS FROM ONE-SIDE AND A SINGLE SET-UP ACCURATE INVERSION OF THE ELASTIC PROPERTIES OF COMPOSITE MATERIALS CAN BE CARRIED OUT.

SPECTRAL METHOD

- LEAKY LAMB WAVE ===> C_{22}, C_{23} AND C_{55}

PULSE METHODS

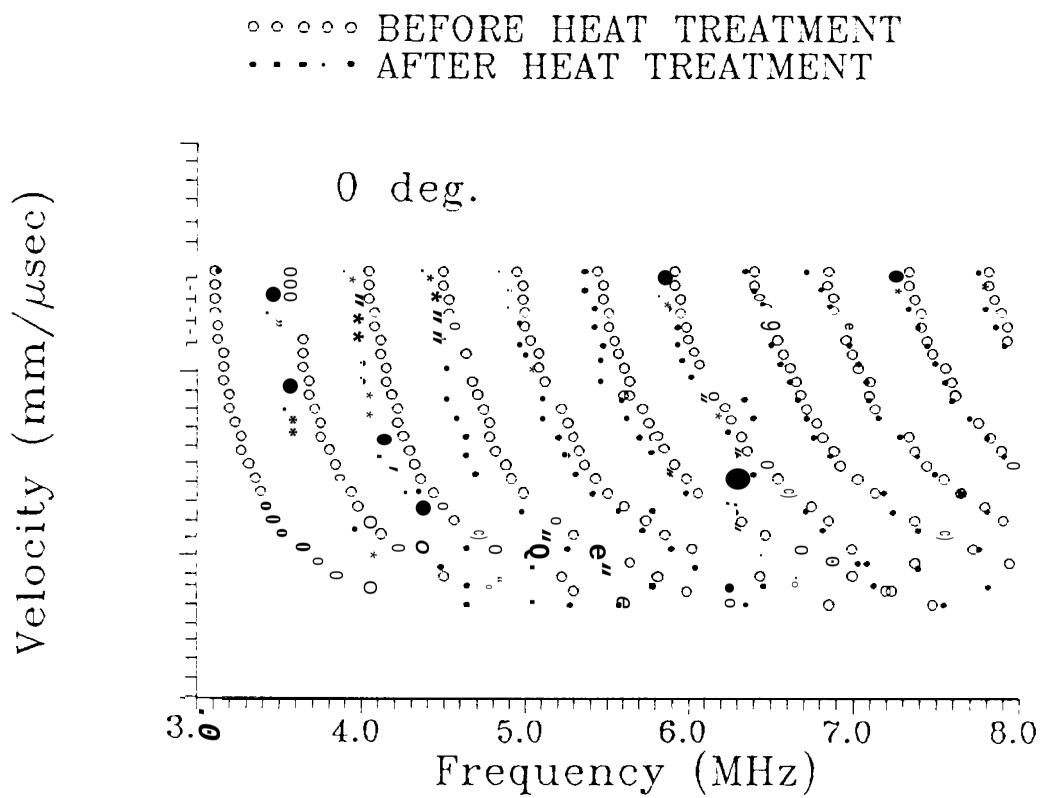
- PULSE-ECHO ===> C_{22}

- OBLIQUE INCIDENCE PULSED TEST
  AT $\phi = 90°$ ===> C_{22} AND C_{23}
  AT $\phi \neq 0°$ & $< \phi_c$ ===> C_{55}

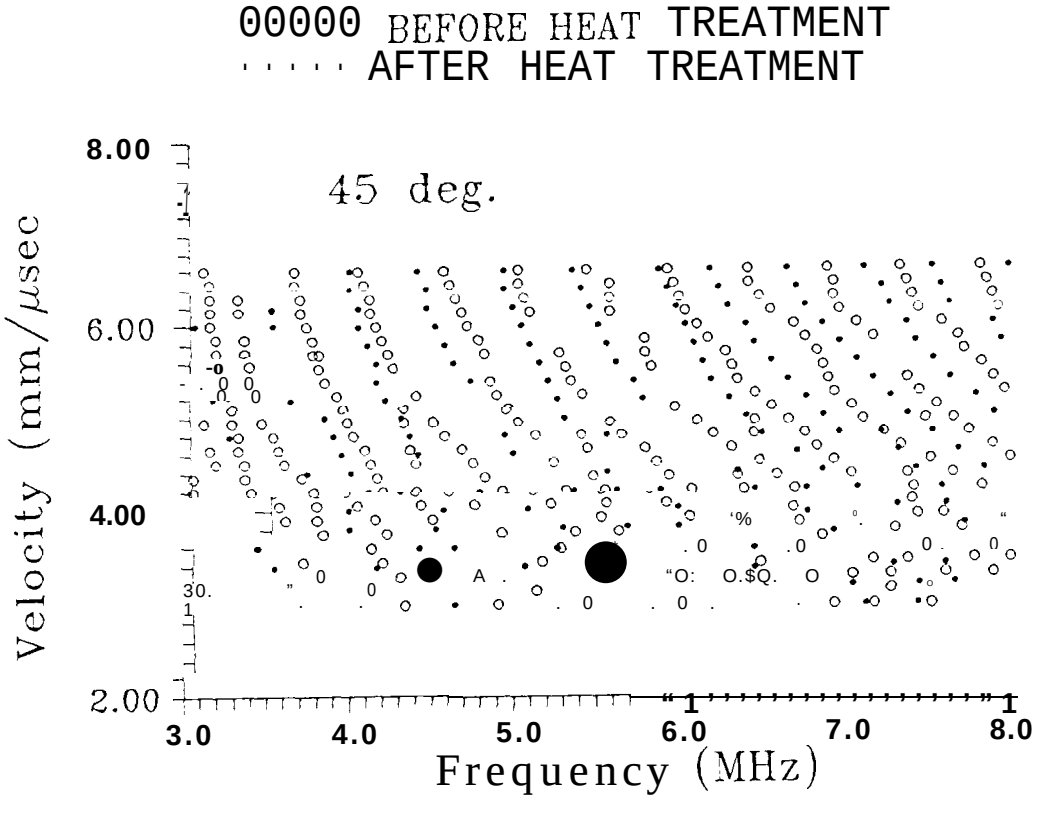
- OBLIQUE INSONIFICATION AT $\phi = 0$, TWO VALUES OF θ
  * INACCURATE ==> C_{11} AND C_{12}

- OBLIQUE INSONIFICATION AT $\phi = \phi_c$, TWO VALUES OF θ
  * ACCURATE ==> C_{11} AND C_{12}

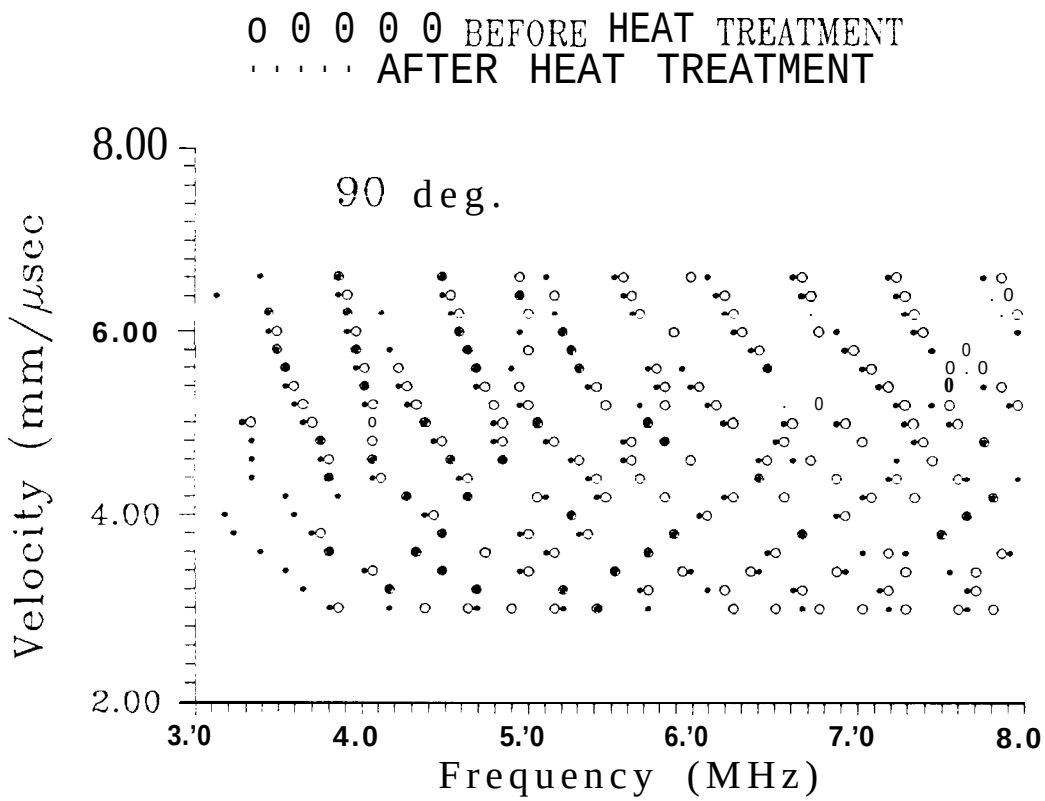
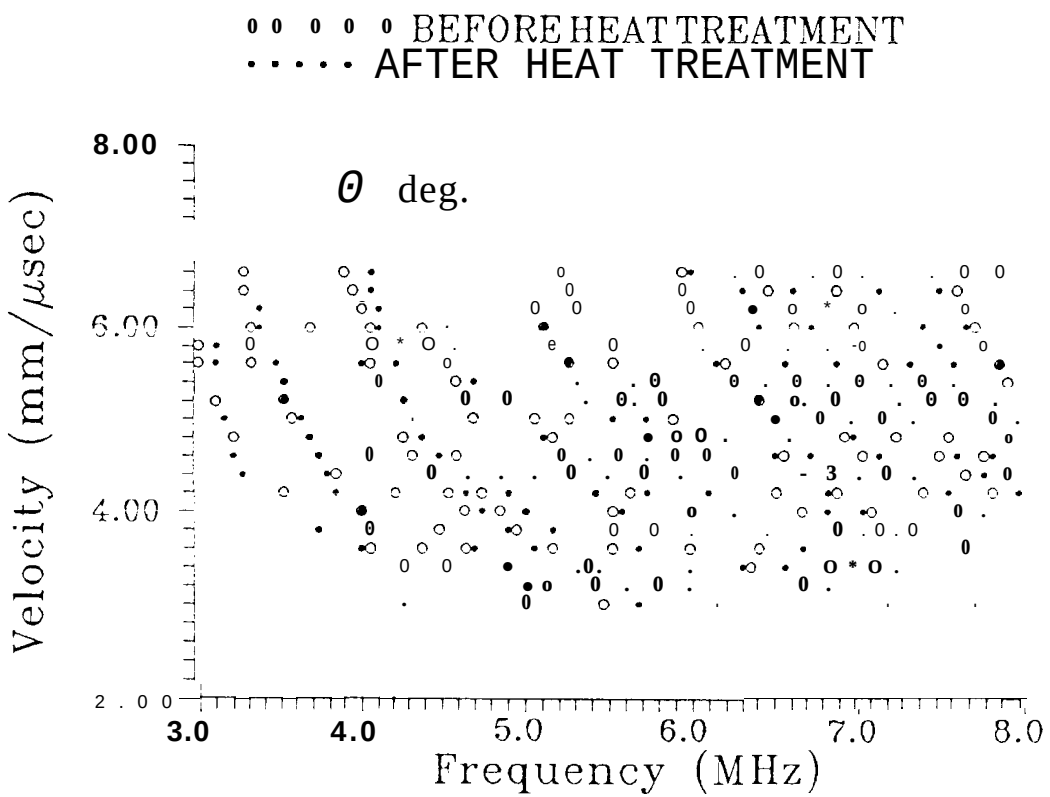
Measured dispersion data for a $[0]_{24}$ Gr/Ep composite before and after heat treatment for wave propagation 0° to the fiber.



Measured dispersion data for a $[0]_{24}$ Gr/Ep composite before and after heat treatment for wave propagation 450 to the fiber.



Measured dispersion data for a $[0]_{24}$ Gr/Ep composite before and after heat treatment for wave propagation 900 to the fiber.



Measured dispersion data for a multilayered Gr/Ep composite before and after heat treatment for wave propagation O ^{0} to the fiber.