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Proceedings of the Second Annual Symposium for Nondestructive Evaluation of Bond Strength

Compiled by
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Proceedings of a symposium sponsored by the
National Aeronautics and Space Administration,
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November 6, 1998

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

May 1999

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PREFACE

Fifteen nondestructive evaluation (NDE) experts met for the Second Annual Review of NASA's NDE of Bond Strength Program at LaRC, NDE Sciences Branch on November 6, 1998. The goal of this research is to nondestructively determine quantitative strength levels in structural bonds. The Symposium was held to review both "in house" NDE research and work performed by sponsored university grantees. The grants reviewed were: "Investigation of Adhesive Bond Cure Conditions using Nonlinear Ultrasonic Methods", The Johns Hopkins University (Dr. Robert Green and Mr. Tobias Berndt); "An Assessement of Adhesive Bond Deterioration by Detection of Nonlinear Effects", Northwestern University (Dr. Jan D. Achenbach and Mr. Zhengeng Tang); "Characterization of Adhesive Bonds Using Nonlinear Ultrasound", The Georgia Institute of Technology (Dr. Jianmin Qu and Mr. Larry Jacobs). Invited presentations were given by Drs. Stan Rokhlin and Lazslo Adler of the Ohio State University & Adler Consultants, and Dr. Donald C. Price of the Computational Industrial Research Organization (CSIRO, Sydney, Australia). Several technologies and approaches were presented including "Microwaves for Bondline NDE" by Dr. Mark Roberts, ARMY-VTC, "Surface Contamination Monitoring using Optical Simulated Electron Emission (OSEE)" by Mr. Daniel Perey, NASA, and "Computational Chemsitry of Bondlines" by Dr. Donald Phillips, NASA. Nonlinear ultrasonics is currently the leading technology for nondestructively detemining bond strength. The Symposium proceedings are published in this NASA Conference Publication.

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Bond Strength Program

Dr. Mark J. Roberts

Friday, 6 November 1998

Schedule

NDE BRANCH WELCOME

8:30-8:45 Dr. Edward Generazio (Head)

NASA BOND STRENGTH

8:45-9:00 Overview and Status of Program: Dr. Mark Roberts

9:00-9:10 Microwaves for Bondline NDE : Dr. Mark Roberts

9:10-9:30 Computational Chemistry of Bonds: Dr. Donald Phillips

9:30-9:50 Surface Contamination Monitoring using OSEE: Mr. Dan Perey

GRANTEE PRESENTATIONS

9:50-10:15 The Johns Hopkins University: Dr. Bob Green & Tobias Berndt

Investigation of Adhesive Bond Cure Conditions using Nonlinear Ultrasonic Methods

10:15-10:30 BREAK

10:30-11:15 Georgia Technology Institute: Dr. Jianmin Qu - Characterization of Adhesive Bonds Using Nonlinear Ultrasound

11:15-11:45 Northwestern University: Dr. Jan Achenbach - An Assessment of Adhesive Bond Deterioration by Detection of Nonlinear Effects

11:45-1:15 LUNCH

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Schedule

EXTERNAL PROGRAMS

1:15-1:45 CSIRO Sydney, Australia : Dr. Donald Price - Progress Towards a Theoretical Model of Nonlinear Guided Wave Propagation in Bonded Joints

1:45-2:45 The Ohio State University & Adler Consultants: Dr. Stan Rokhlin & Dr. Laszlo Adler - Characterization of Adhesive Bond Integrity Using Angle Beam Spectroscopy

2:45-3:00 COFFEE BREAK

3:00-4:00 GENERAL DISCUSSION

4:00 ADJOURN

Sign-IN Sheet

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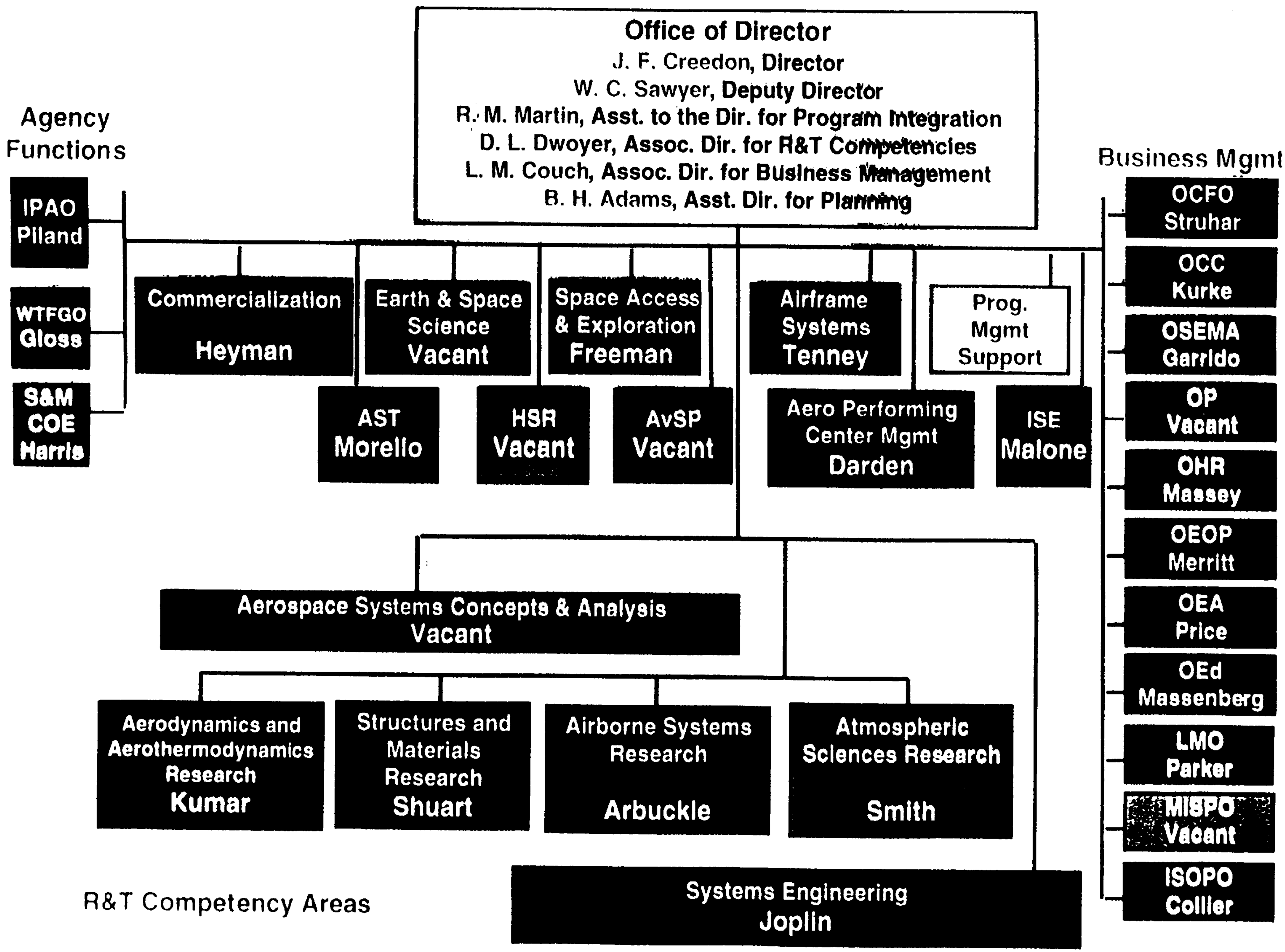
NESB SUPPORT OF PROGRAMS

- OFFICE OF SAFETY AND MISSION ASSURANCE (AGENCY LEAD)
  - SOLID ROCKET COMPOSITE NOZZLE INTEGRITY
  - SSME COMBUSTER LINER INTEGRITY
  - MARS MICROPROBE MICROELECTRONICS PACKAGING INTEGRITY
  - SPACE STATION WINDOW INTEGRITY
- COMPOSITE WING TECHNOLOGY
  - NDE MEASUREMENTS ON WING COMPOSITE COMPONENTS
  - NDE ASSESSMENT OF BONDED STRUCTURES
  - MANUFACTURING PROCESS CONTROL
- HIGH SPEED RESEARCH
  - NDE FOR DURABILITY
  - IN-SITU MEASUREMENTS (DENSITY, STIFFNESS, AND FLAW LOACTION)
- AIRFRAME STRUCTURAL INTEGRITY/ AIRWORTHINESS ASSURANCE
  - NDE FOR DISBOND, CORROSION, AND CRACKS IN AIRFRAME STRUCTURE
  - CRACKS IN THICK METALLIC COMPONENTS, QUANTITATIVE RESIDUAL STRESS, FATIGUE SENSING
- X-33/34 REUSABLE LAUNCH VEHICLE
  - STRUCTURAL HEALTH MONITORING & SHUTTLE UPGRADES
- BASE: QUANTITATIVE NDE OF BOND STRENGTH, MORPHING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Business Mgmt
OCFO Struhar
OCC Kurke
OSEMA Garrido
OP Vacant
OHR Massey
OEOP Merritt
OEA Price
OEd Massenberg
LMO Parker
MISPO Vacant
ISOPO Collier

Program Issues

- Results of Successful Program
  - Could eliminate or reduce rivet / fastening technology
  - Production of higher strength bonds
  - Higher confidence in bonded structures
  - Measurement technique to quantitatively measure strength and assign quality
  - Reduce operational downtime of aircraft significantly
  - Prototype instrument developed would have potential in any industry requiring "on the spot" bond analysis

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Program Issues

- Customer Needs & Requirements
  - Aircraft operational safety
  - General structural integrity (Composite Structures)
  - Cost reduction using bonded structures
- Nondestructive Evaluation Methods
  - Ultrasonics
  - Microwaves
  - OSEE (Q & A)
- Mechanical Testing Methods / Destructive
  - Fatigue test
  - Load tests

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Goals & Approach

- MAIN GOALS
  - Develop and optimize NDE method(s) for measuring bond strength & bond quality levels
  - Develop instrumentation for prototype system capable of measuring bond strength & quality nondestructively

- APPROACH
  - Industry / NASA / University collaboration into third year of work
  - Selected NDE technologies best suited for the bond strength problem solution: Ultrasonics (Overall), Microwaves (Moisture)
  - Perform strength measurements using selected NDE methods
  - Begin system prototype design of bond strength instrument

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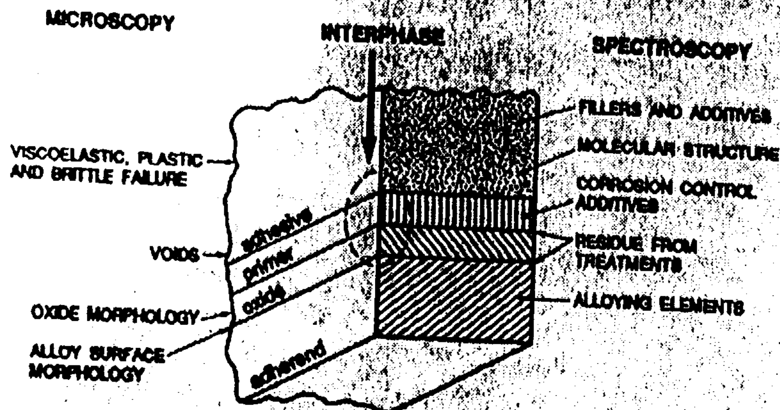
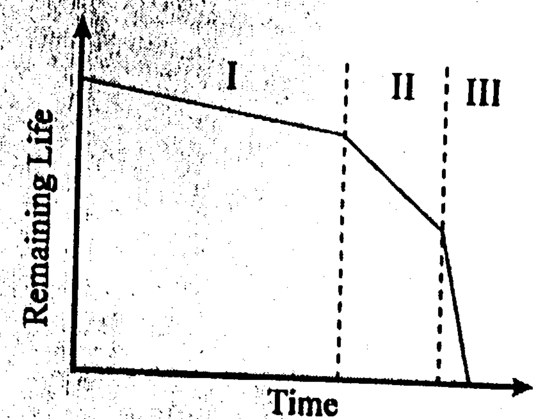
Bond Deterioration Mechanisms

Degradation, Damage and Failure





	Degradation	Damage Accumulation	Failure
Adhesive	*crosslink density* *moisture absorption* *plasticization*	*creep and fatigue* *microvoids* *microcracks*	*fracture* *crazing*
Interphase	*corrosion* *oxidation*	*microvoids* *microcracks*	*debonding* *delamination*
Adherend		*deformation*	*fatigue and fracture*

BONDING KEY ISSUES

- Adhesive bond strength & bond quality effected by
  - Joint type & geometry
  - adherends & adhesives used
  - quality control in bond creation process
  - primer type
  - surface roughness of adherends
  - wettability of adherends
- Modes of failure: Cohesive / Adhesive / Mixed Mode
- Cohesive Properties (Bulk)
  - adhesive chemistry & mechanical properties
  - bondline thickness
  - cure state
- Adhesive Properties (Surface)
  - Interfacial Boundary Properties / mechanical interlocking
  - Existence of weak boundary layers
  - Contamination / Environmental Effects
  - Moisture / water in the bondline

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Collaboration / Resources

- **NASA / VTC Army**
  - 2 NASA CSs & 1 Army - Funding $600 thru FY01
- **University Grantees**
  - Dr. Jianmin Qu - Georgia Institute of Technology
  - Dr. Robert Green - The Johns Hopkins University
  - Dr. J.D. Achenbach - Northwestern University
- **Private Industry**
  - Dr. Wayne Woodmansee - Boeing Airplane Group
Seattle, WA
  - Dr. Donald Price - Computational Sciences Industrial
Research Organization (CSIRO)
Division of Applied Physics
Sydney, Australia
- **ARL Rodman**
  - Dr. Steven McKnight - Adhesive Bonding Microfactory
(Polymers Research Branch)

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Collaborative Work with NASA

- University grantees unanimously conclude that nonlinear ultrasonics best method for bond strength analysis: Johns Hopkins, Northwestern, Georgia Tech
  - ALL Grantees are in their 3rd year of research to conclude 6/30/99

- Industrial partners Boeing & CSIRO Sydney continue work on “weak” bond conditions using peel ply insertion into bonds
  - Report submitted: Static Stress Effects on Guided Waves in Adhesive Bonds (Dr. Don Price of CSIRO)

- Army Research Lab : Rodman Facility Aberdeen (Polymers Research Branch) , *Adhesive Bonding Microfactory*

  Possible Collaboration Opportunity Exists

  Visit to ARL occurred in October ‘98

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In House Research

- Computational Chemistry Approaches to Bondline Analysis (Dr. Donald Phillips)
- Laser ultrasonic methods to analyze adhesively bonded specimens proposed (Madaras / Roberts)
- Microwaves for Moisture Detection in Nonmetallic Bonds (Roberts)
- Optically Stimulated Electron Emission (OSEE) (Perey)

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Accomplishments FY98

- Nonlinear ultrasonic methods was decided as the best way to potentially attain the nondestructive measurement of both bond quality and strength in adhesive bonds
- Nonlinear ultrasonics proved capable of clearer detection of disbond areas in aluminum lap joint
- Nonlinear stress / strain relationship determined to occur before an adhesive bond breaks
- High amplitude ultrasound generates increased harmonics as bonds age at constant temperature suggesting nonlinear material changes
- Bond deterioration caused by increased cyclic fatiguing
- Plate waves used on aluminum and composite stiffener joints showed correlation between good and weakened adhesive joint conditions with peel ply
- Scaled nonlinear parameter shown to be sensitive to 3 known good bonds & 3 bonds containing peel ply material
- Microwaves are feasible for moisture detection in adhesive bonded non-metals

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FY Goals & Milestones : FY99-FY01

NASA

FY99

- Investigate higher order microstructural properties thru harmonic detection
- Examine adhesive & cohesive property effects on an adhesive bond using nonlinear ultrasonics. Begin correlation to strength and quality.
- Conclude university research grant work & utilize conclusions reached for future study
- Fabricate & measure adhesively bonded joints with moisture contamination using microwaves (non-metal adherends)
- Investigate electrical properties of a bondline adhesive
- Test microwave method on good & disjoined bonds (non-metal adherends)

FY00

- Establish database of nonlinear ultrasonics measurements for selected adh. bonds with conditions ranging from initial degradation to accumulated damage to failure
- Determine good, weak and bad quality conditions for selected bonds using database of known stored ultrasonic signals
- Correlate to expected strength and quality level for selected adhesive bonds
- Determine capabilities, if any, for microwaves in general bond analysis

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FY Goals & Milestones : FY99-FY01

FY01

- Start development of prototype system and specifications for bond strength measurement instrumentation.

- Test prototype on adhesively bonded joint

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Future In House Steps

- Continue literature research as more new information becomes available
- Build on existing results provided by university grantees
- Be open to technologies not previously used which could provide scientific insight into bond strength solution
  - Microwave (Moisture contamination)
  - OSEE (Q & A issue)
- Consider numerical modeling techniques to look at effects of changes in cohesive (volume) and adhesive (surface) properties on bondline performance
- Microwave theoretical & experimental work for adhesively bonded nonmetallic joints
  - Joint material changes
  - Moisture / water detection
- Create database of ultrasonic information for various adhesive bonds to quantify strength and characterize quality levels

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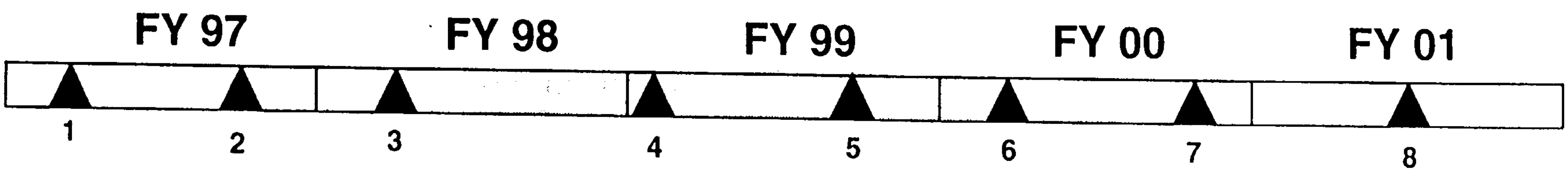
NESB: PROGRAM MILESTONES

- SM.TF.06: Structural Integrity, safety, and health monitoring for reliable aircraft, space transportation vehicles, and space habitat
  - Fundamental Concepts



Milestones

1 Assemble measurement system to test fatigue sensor concept on Al 2024
2 Data on inspection systems for NDE of bond strength
3 Test fatigue/load history probe with Al 2024
4 Down select bond strength approach
5 Optimize sensor for fatigue/integrated history
6 Test and optimize bond strength measurement system
7 Ready fatigue/integrated load history sensor for technology transfer
8 Ready bond strength NDE technique for technology transfer

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Microwaves for Bondline NDE

Dr. Mark J. Roberts

Friday, 6 November 1998

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Microwave NDE Technology

Advantages

- Good penetration of nonconductive media
- Contact or noncontact choice
- Small probe size
- No coupling gels needed on material being measured

Benefits

- Detection of disbond and delamination in stratified structures such as sandwich composites
- Moisture / Water detection capability in nonconductors
- Electrical material characterization
- Possible crack detection in ceramics and composites
- Porosity measurement capability

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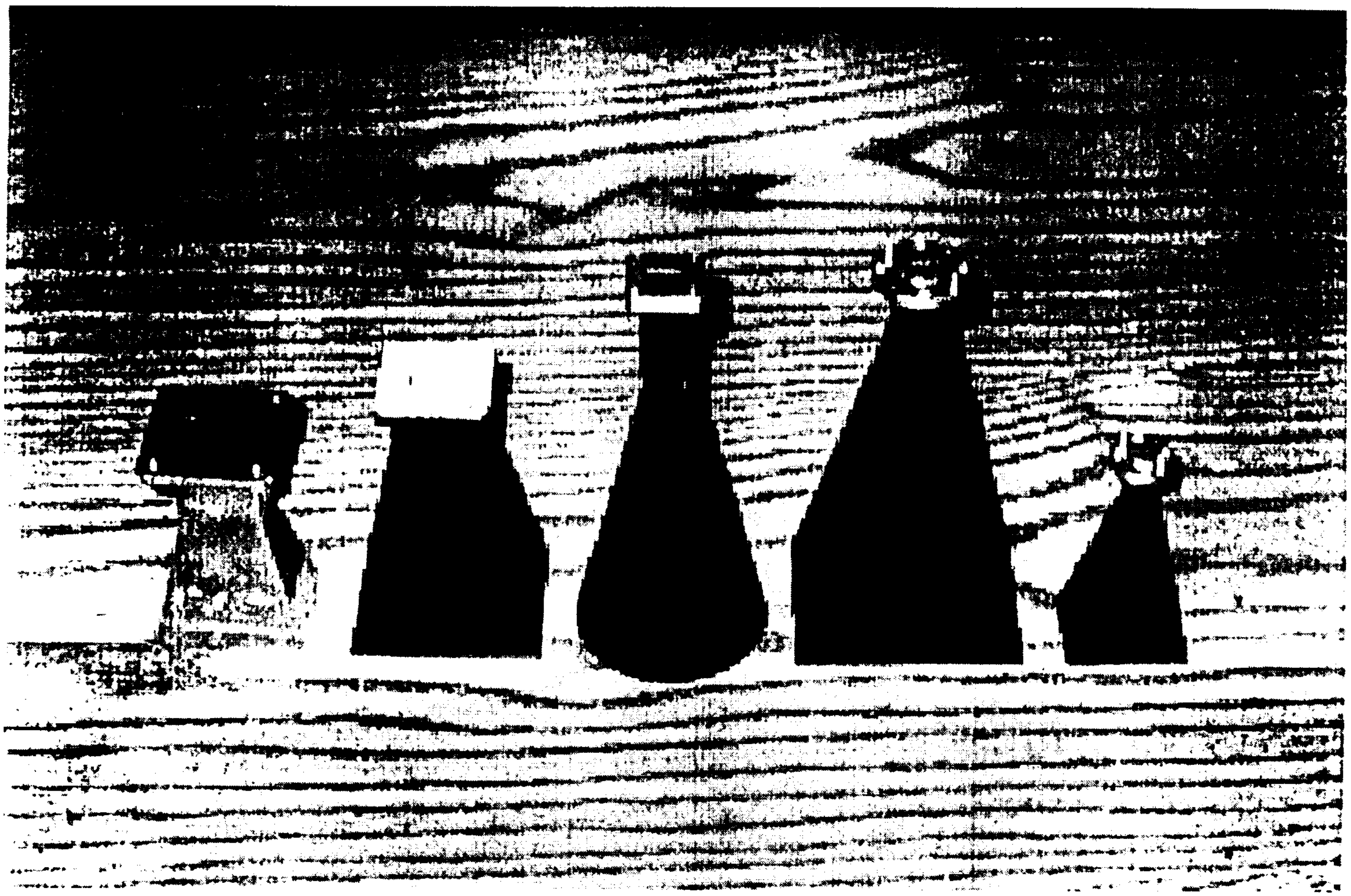
Small Horn Antennas



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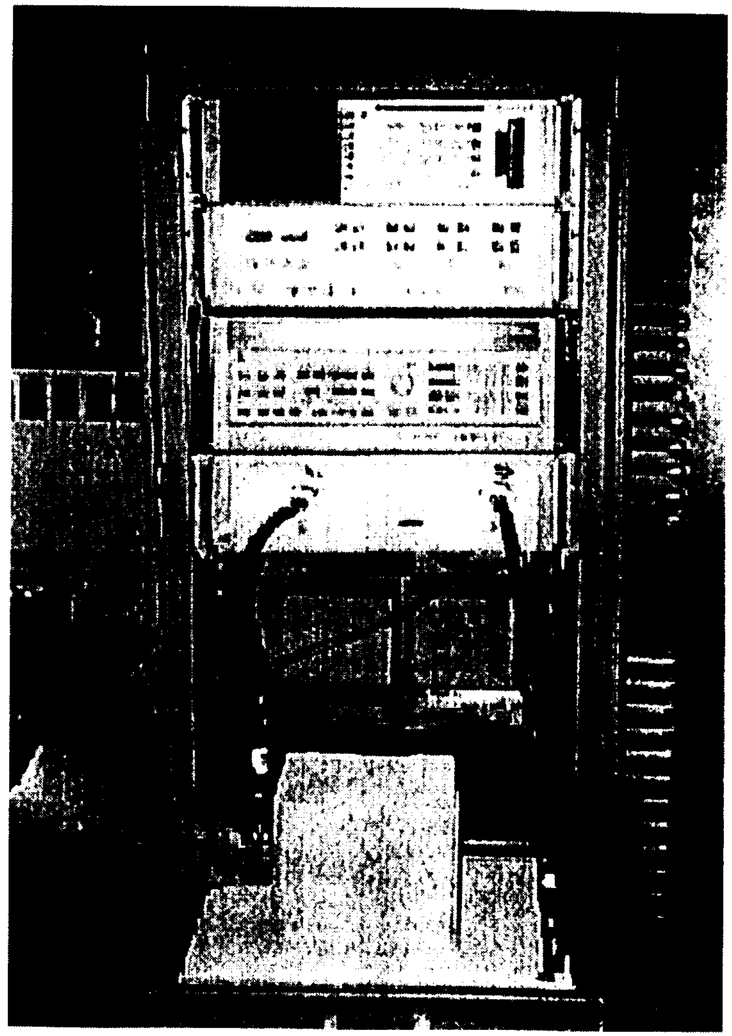
Microwave Spectrum

Band	Frequency (GHz)	Wavelength (cm)
P	0.23 - 1	130 - 30
L	1 - 2	30 - 15
S	2 - 4	15 - 7.5
C	4 - 8.2	7.5 - 3.66
X	8.2 - 12.4	3.66 - 2.42
Ku	12.4 - 18	2.42 - 1.67
K	18 - 26.5	1.67 - 1.13
Ka	26.5 - 40	1.13 - 0.74
mm-Waves	40 - 300	0.75 - 0.1

Apparatus



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MICROWAVE IMAGING

- Arranging microwave detected signal/data (i.e. raster scan) to produce a visual impression of the presence of defects or structural geometry.
- The microwave data may include such information as:
  - Phase of reflection or transmission coefficient
  - Magnitude of reflection or transmission coefficient
  - Combination of both (i.e Synthetic Aperture Imaging)
  - Attenuation information
- This may be accomplished using the far-field (i.e radar imaging) or in the near-field approaches.
- When using near-field microwave imaging, need to understand the information conveyed by the image.
- Probe type, field characteristics everywhere, geometry of the material under test, defect properties, position and geometry must be taken into account.

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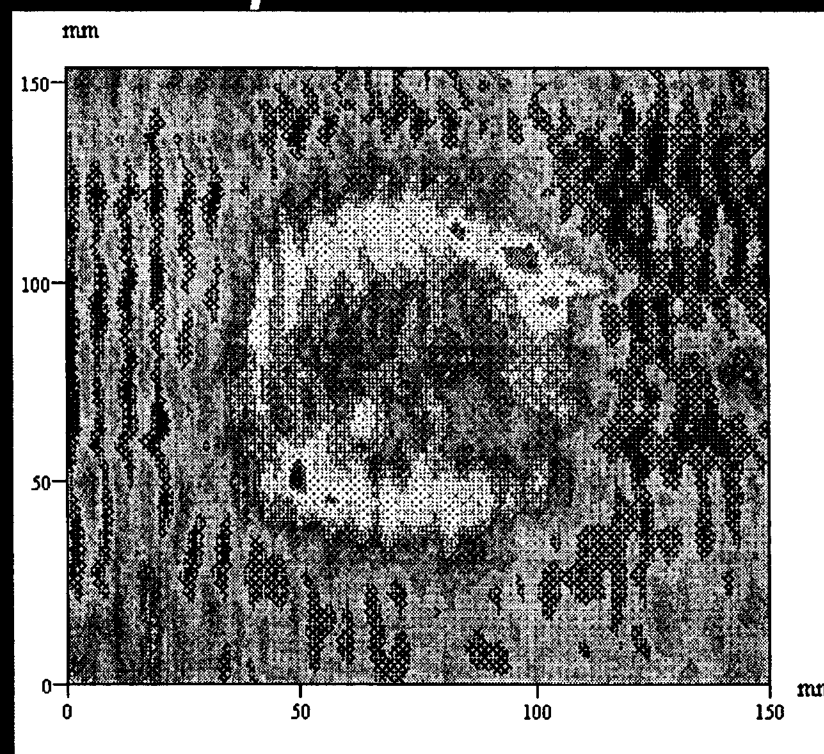
MICROWAVE IMAGING

- Defect characteristics may be determined if all other non-defect influences are taken out
- When using open-ended rectangular waveguides for near-field imaging, one must have an intuitive understanding of its near-field properties.
- Ultimately, one may use inverse models or approaches to obtain defect property information.

DISBOND RESULTS

Skin delamination in Thick Sandwich Composite @ 24 GHz



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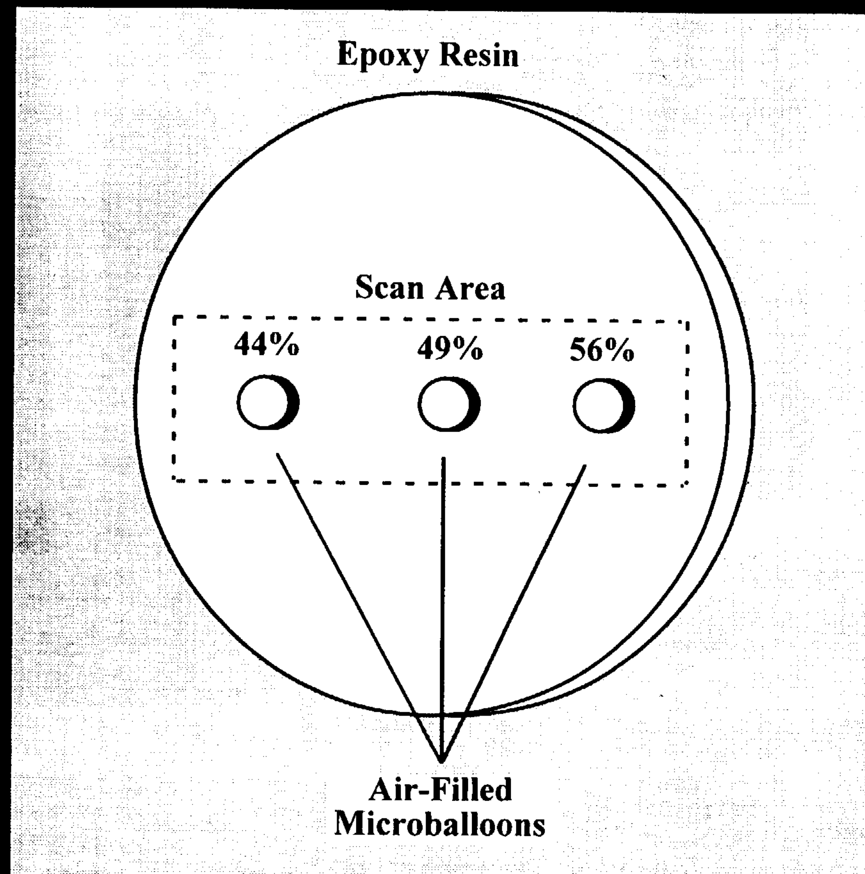
Colorado State University

LOCAL POROSITY



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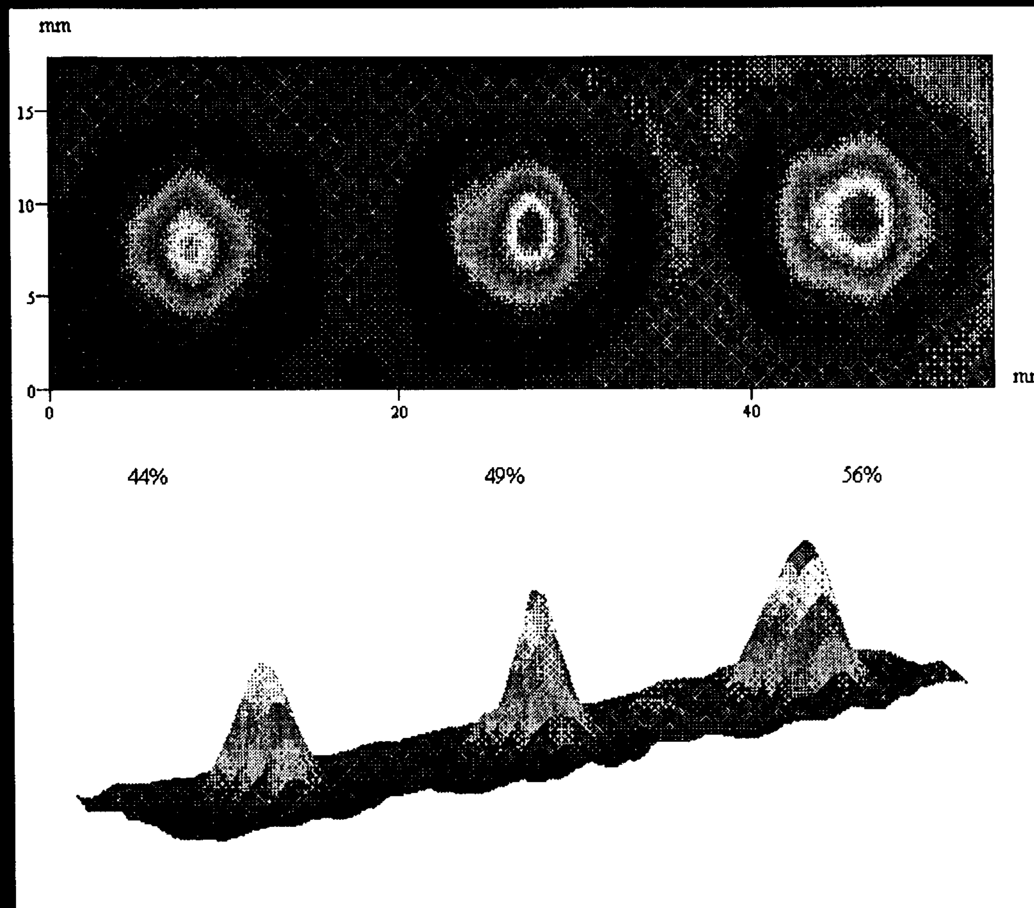
LOCAL POROSITY RESULTS @ 35 GHz



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Microwave NDE: Conclusions & Plans

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Conclusions

- Microwaves are totally reflective to moisture & water
- Both delamination and porosity detection will be much more sensitive when containing moisture
- Cracks / small resolution flaws will have increased probability of detection if containing moisture

Plans for FY99

- Perform measurements to look at moisture between two composite layers which are unjoined
- Determine electrical property of adhesives
- Fabricate and measure composite joints with the following conditions
    - Good joint - no moisture
    - Water spray in or on adhesive before joining
    - Joint containing water voids in adhesive
- Perform analytical and/or numerical approach on above conditions
- Correlate between cohesive & adhesive properties and expected electrical property changes

Computational Chemistry of Adhesive Bonds

Donald H. Phillips

Talk Outline

- Background, Goals
- Model Systems
- Methods
- Comparison of Results for a Simple Model

Background and Goals

- The macroscopic response of a bond layer to external stimulii is determined by the molecular level mechanical and electrical properties of the bond layer. Also, changes in these properties due to degradation stem from chemical changes in the bond layer.
- This investigation is intended to determine the electrical mechanical, and chemical properties of a adhesive bonds at the molecular level. The initial determinations will be followed by investigations of the effects of environmental effects on the chemistry and properties of the bond layer.

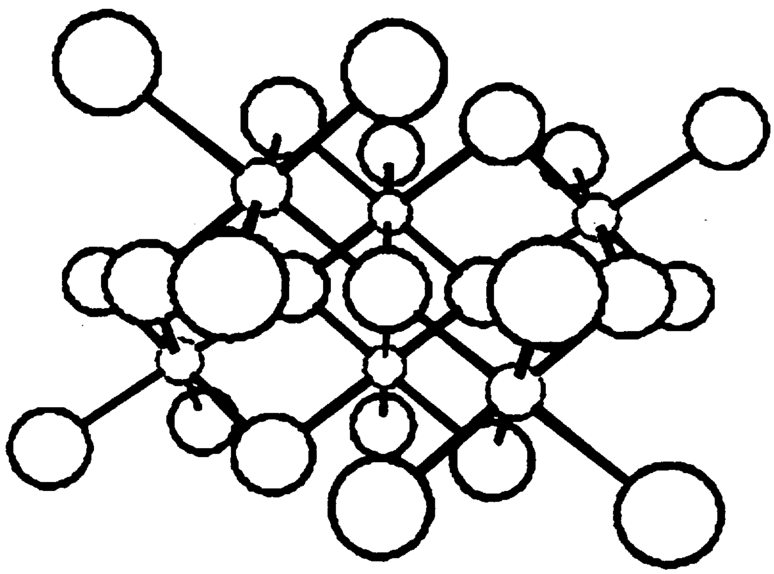
Background and Goals (Continued)

- Possart and Unger (Adhesion **15**, p148 (1991)) found by x-ray photoelectron spectroscopy that the interaction between Aluminum Oxide and Poly(methyl mehtracrylate) (PMMA) ocurred between the oxygen atoms of the oxide and the polymer. They found (1s) orbital energy shifts varying from +0.3 Ev for specific carbon atoms to -1.2 Ev for PMMA oxygen atoms.
- This system was chosen for initial investigation.

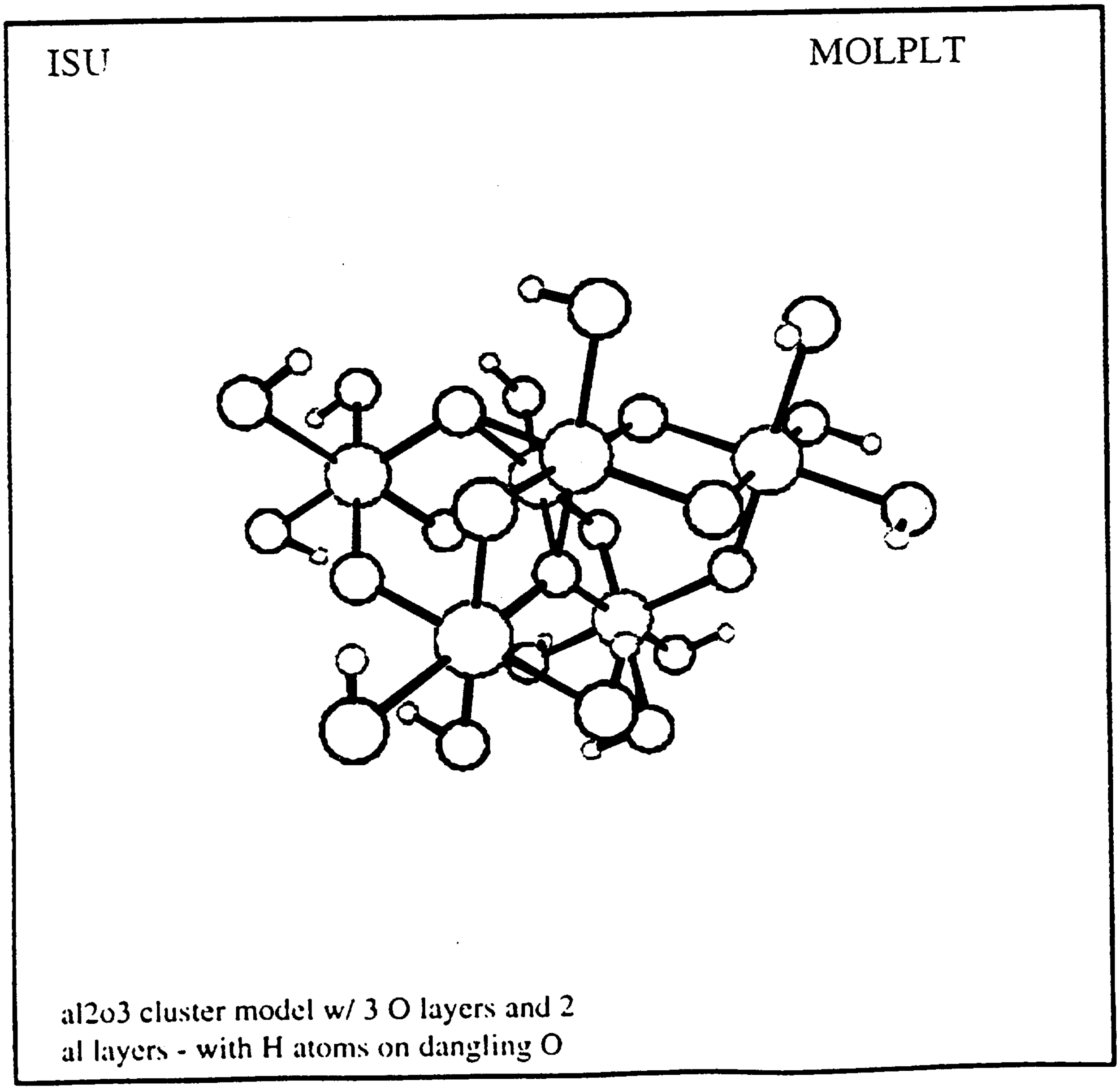
Models

- Cluster Model Issues
  - Surface Structure and Composition
  - Surface to Volume Ratio
  - Dangling Bonds
  - Cluster Size Convergence

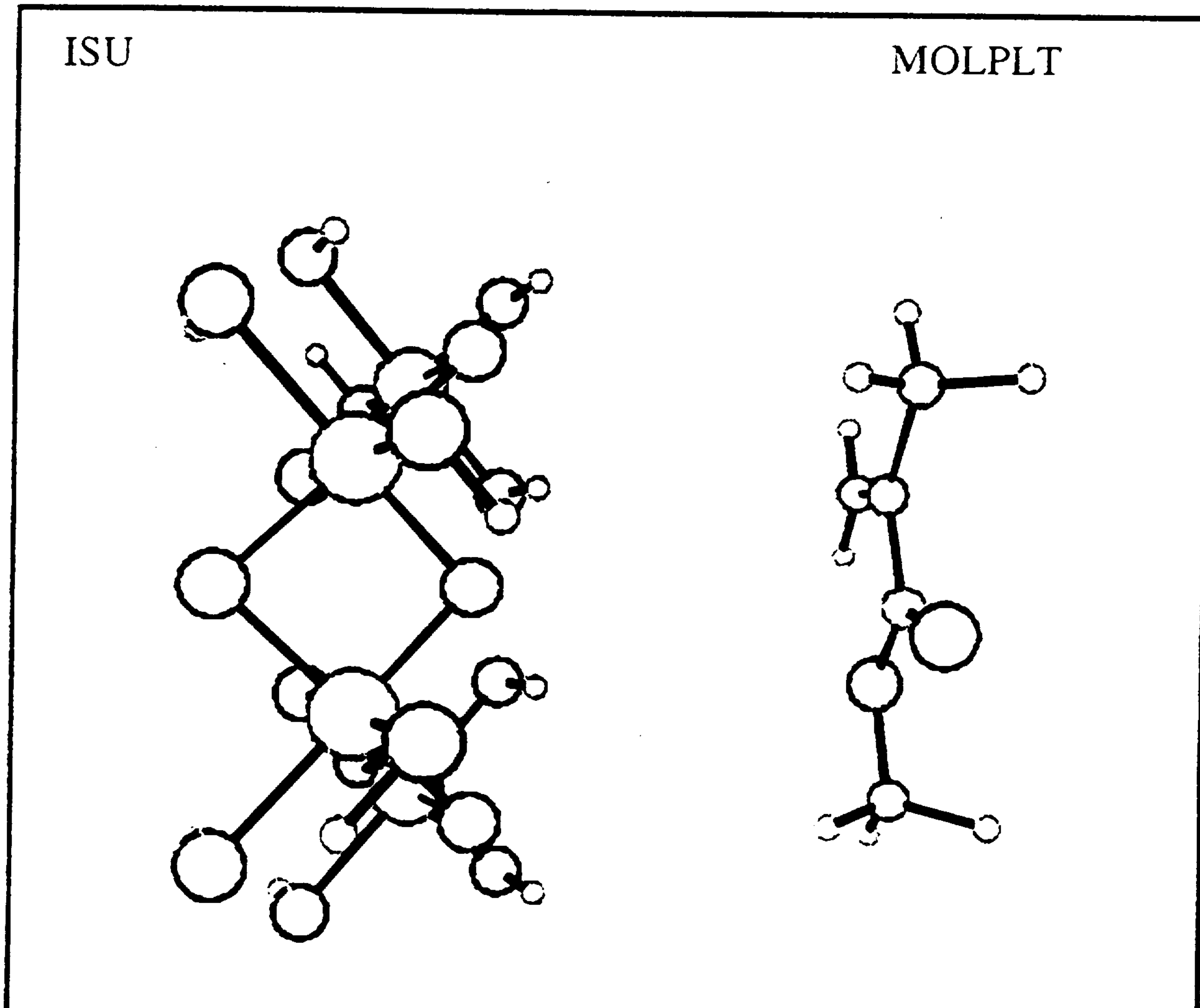
ISU MOLPLT



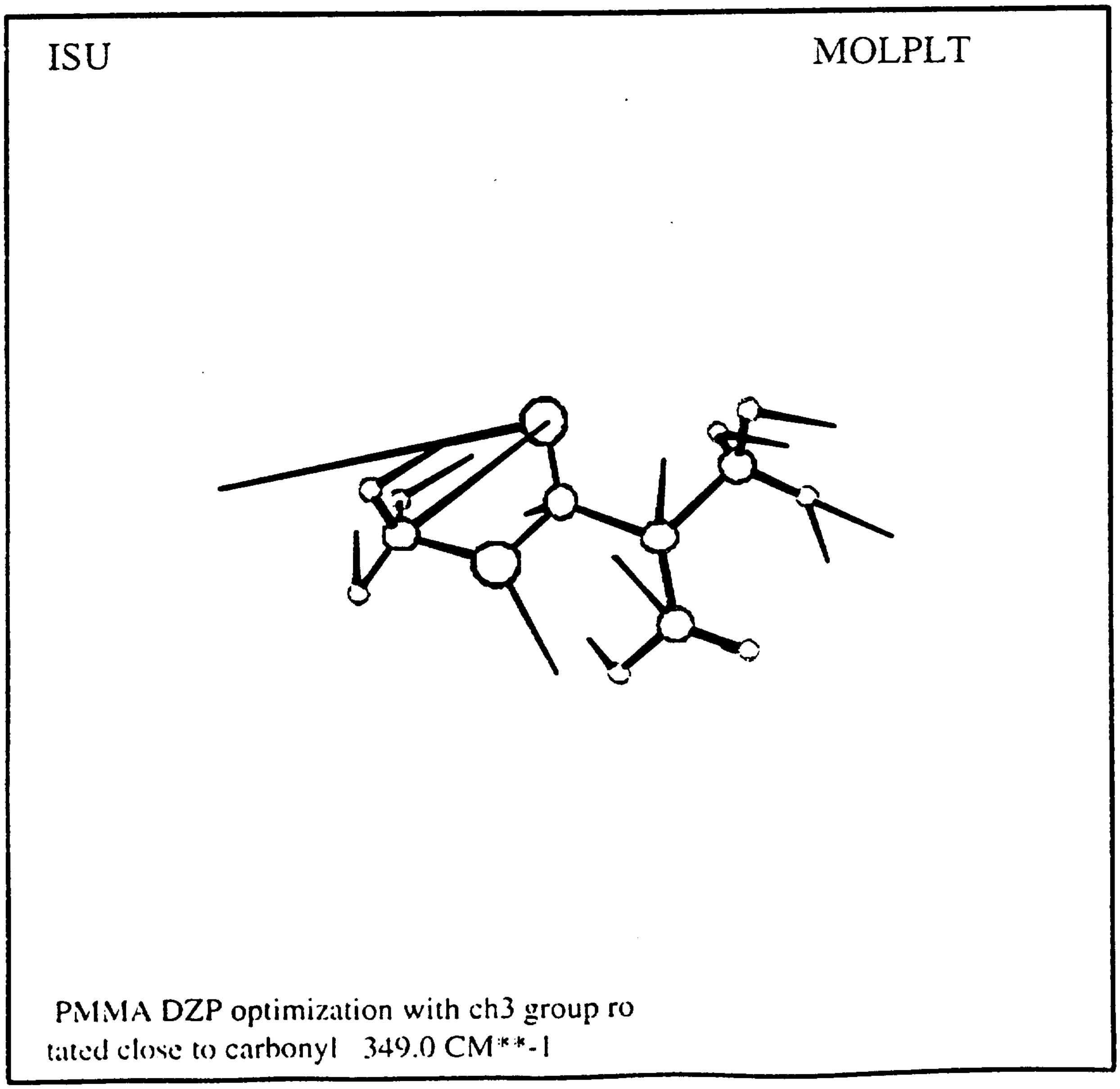
al2o3 cluster model w/ 3 O layers and 2 al layers



al2o3 cluster model w/ 3 O layers and 2 al layers - with H atoms on dangling O



PMMA-AL-Oxide (hydrogenated) Complex
AL-Red, O-Blue, C-Brown, H-Pink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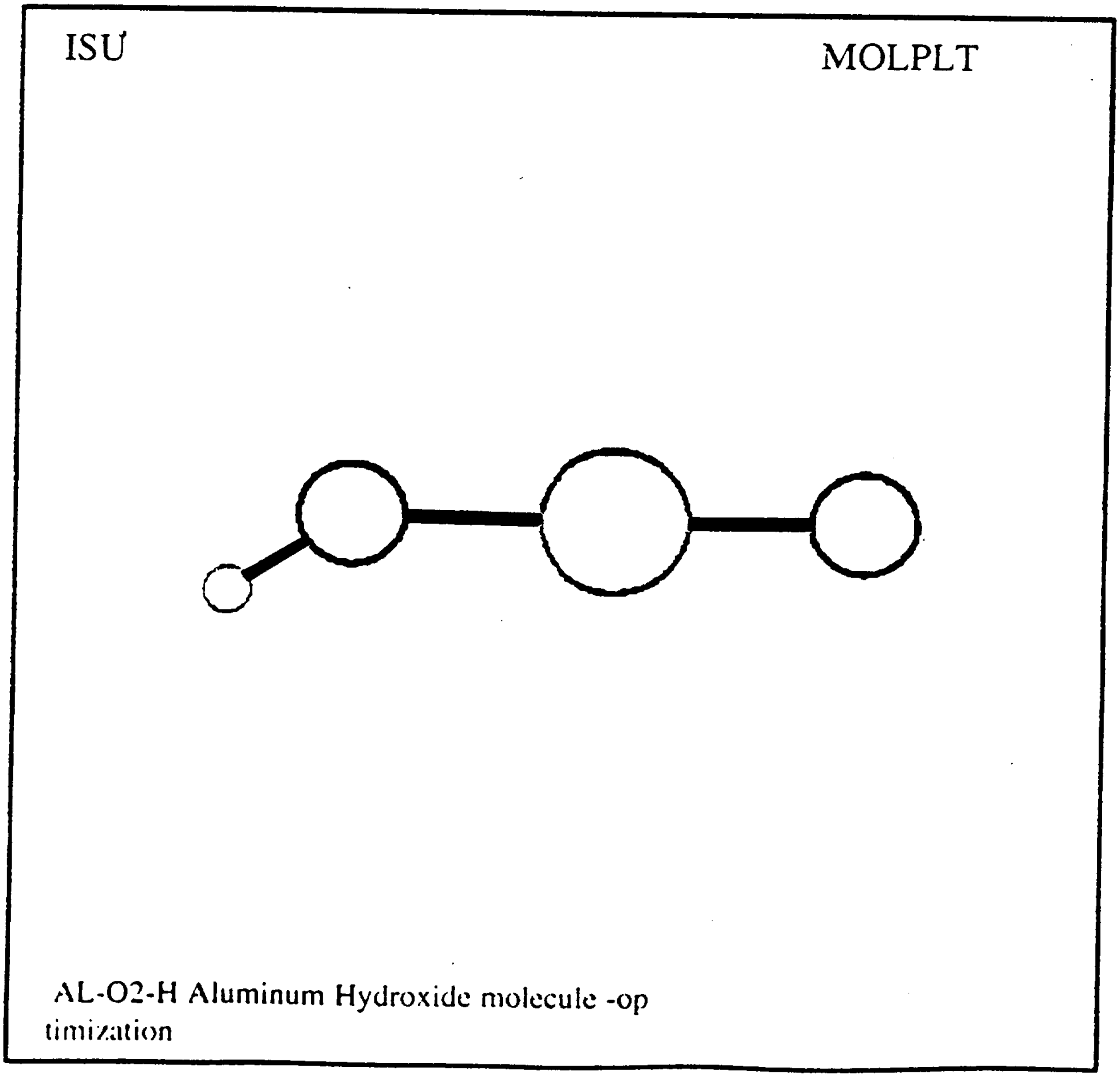


AL-O2-H Aluminum Hydroxide molecule -op timization

Methods

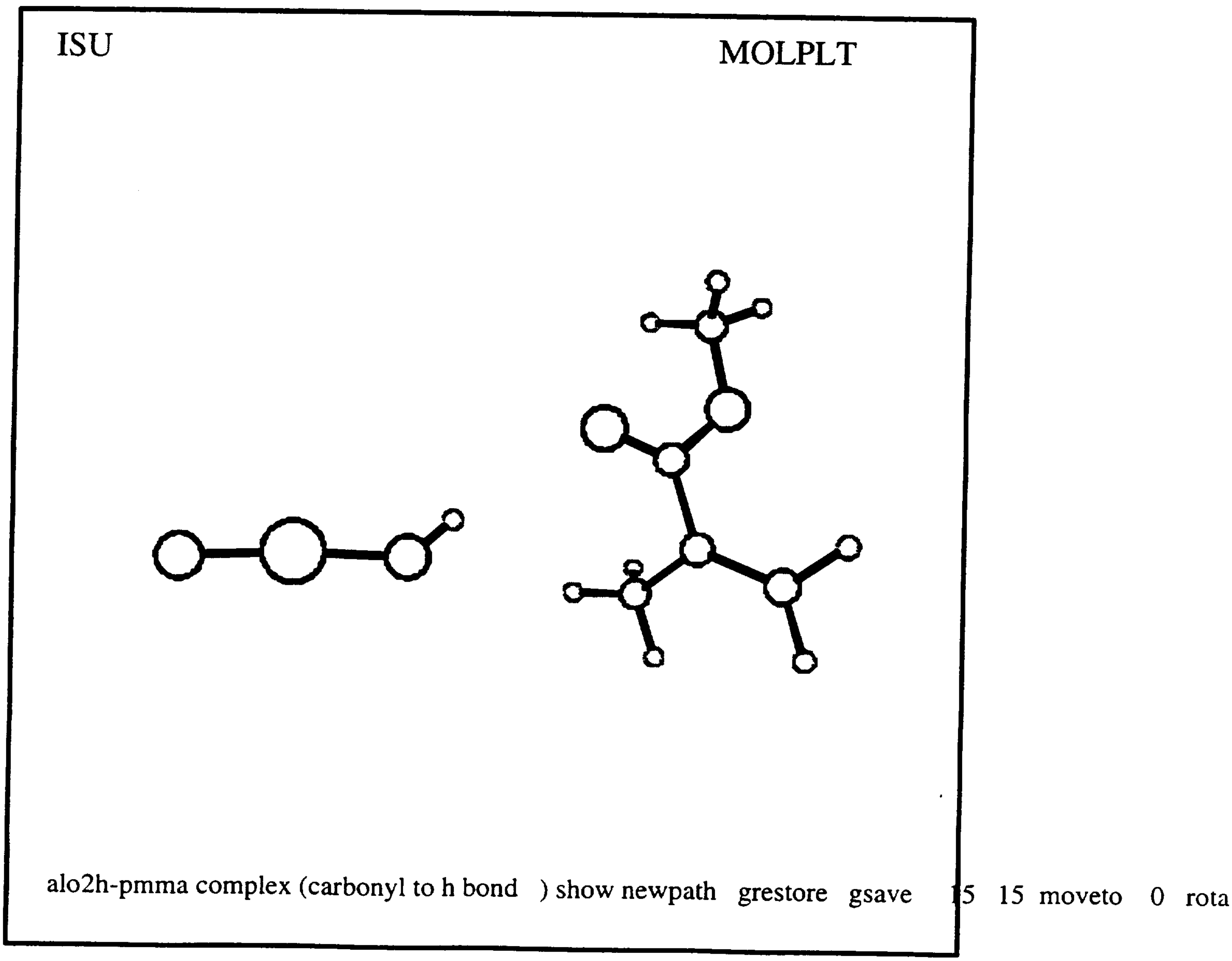
- **First Principles** -all electron-electron interactions
  - Basis Set Quality (Minimum, Good, Accurate)
  - Correlation?
- **Approximate, Semi-Empirical**
  - Parameterization Appropriate for Models?
  - Model Capable of Treating Hydrogen Bonds?
  - Information on Core Energy Levels?
- **Molecular Mechanics**
  - Parameterization Adequate?
  - Electronic, Mechanical Properties?

Results for Monomers

Mol	Method	Struct.	Dipole	Vib
PMMA	scf-dzp	standard	2.04 D	349/cm
	scf-min		1.98	
	PM3		1.89	346 *
	AM1		2.02	345
	MNDO		2.35	363*
AlO2H	scf-dzp		6.19	233
	scf-min			
	PM3		2.62	
	AM1		3.22	
	MNDO		3.39	

Results for PMMA-AlO_2H Complex

Method	D_0^e (KJ/mol)	Dipole M Debye	R =o---h Angstroms
SCF-DZP (uncvgd)	24.7	9.40	1.89
SCF-Min			
AM1	20.5	5.81	2.11
PM3	7.8	4.28	2.93
MNDO	17.5	5.24	3.33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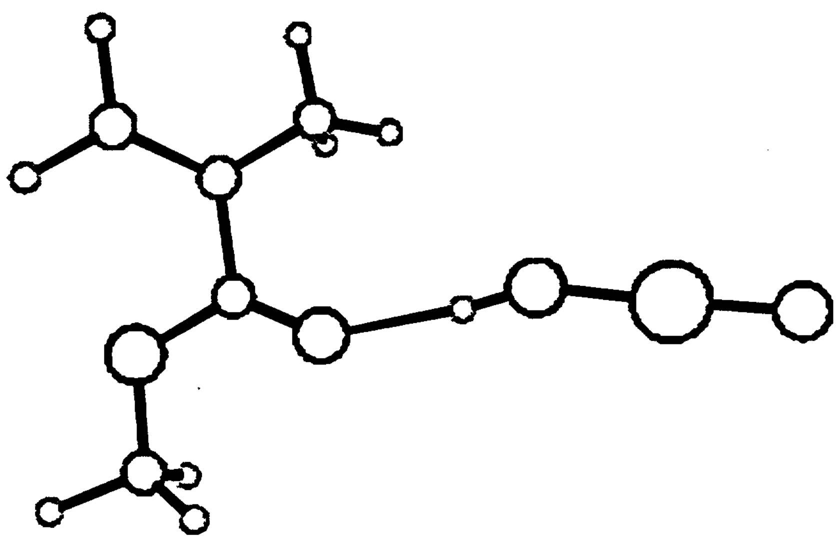
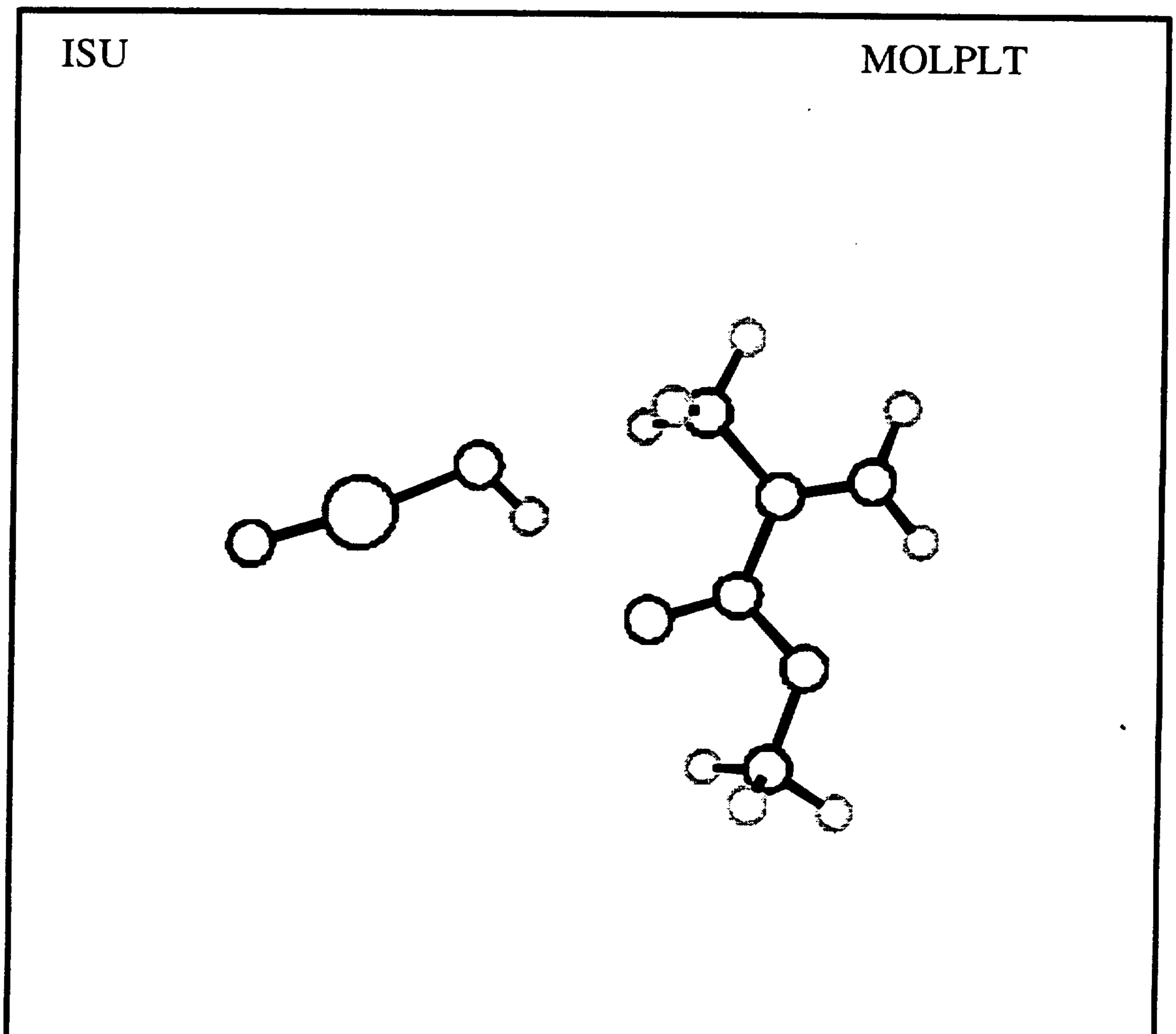
alo2h-pmma complex (carbonyl to h bond) show newpath grestore gsave 15 15 moveto 0 rota



alo2h-pmma complex (carbonyl to h bond c) show newpath grestore gsave 15 15 moveto 0 rota



alo2h-am1 complex (carbonyl to h bond c) show newpath grestore gsave 15 15 moveto 0 rotat

Core Electron Energy Shifts

- For this configuration of the complex, increases of approximately 0.8 eV were computed for both PMMA oxygens and the Carbon 1s attached to the carbonyl O atom.
- This in qualitative agreement with the experiment (ie binding energy increases) but the agreement is not quantitative.

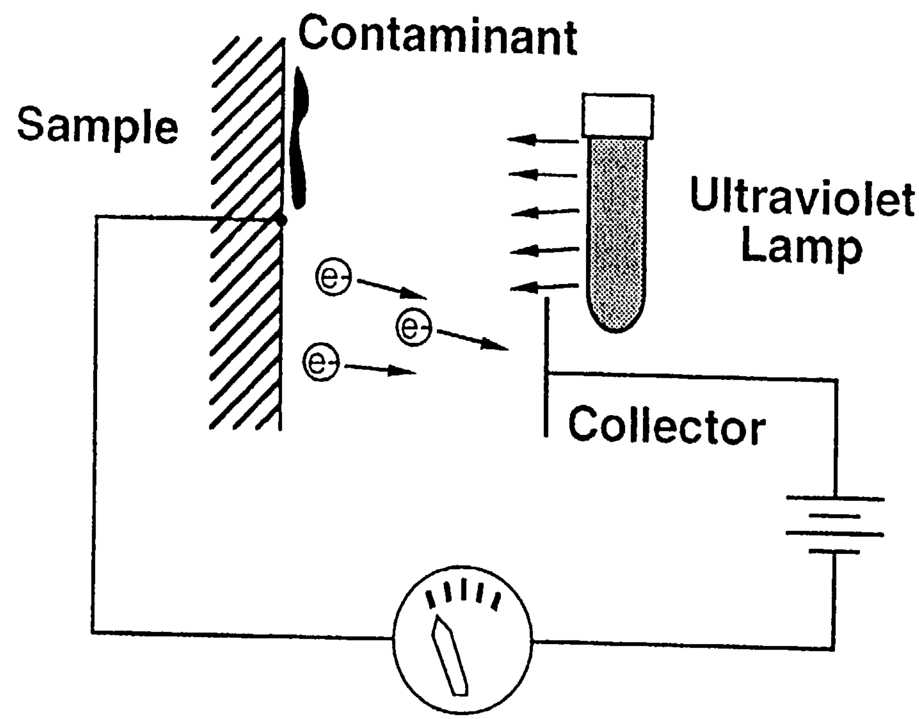
A Portable Surface Contamination Monitor Based on the Principle of Optically Stimulated Electron Emission (OSEE)

Daniel F. Perey

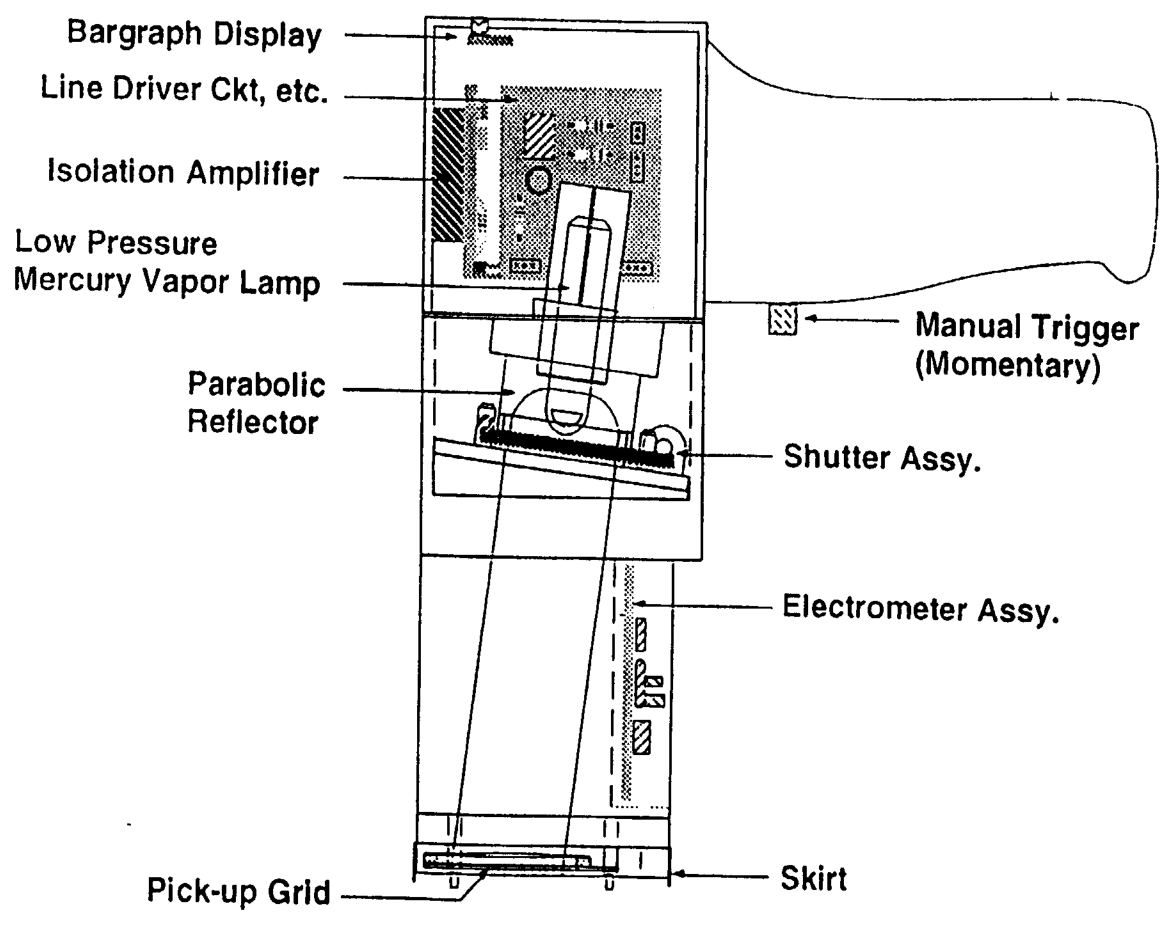
NESB Group Leader for
Instrumentation Development

NASA Langley Research Center
Hampton, VA

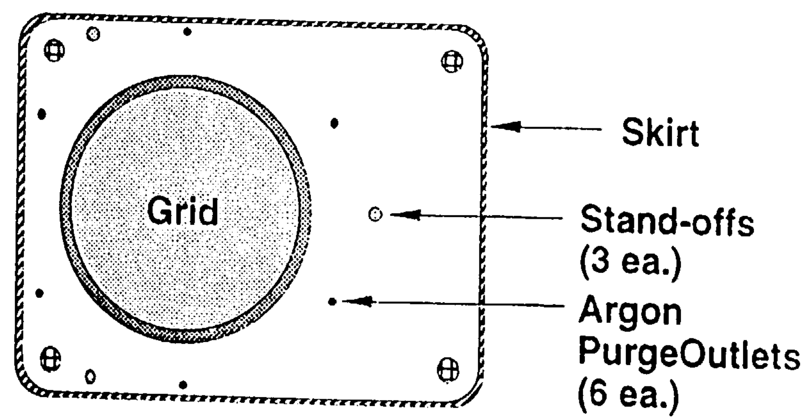
OSEE - How It Works



Probe Cross Section



Bottom View of Probe



Ultrasonic Nondestructive Characterization of Adhesive Bonds

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Atlanta, GA 30332

Objectives

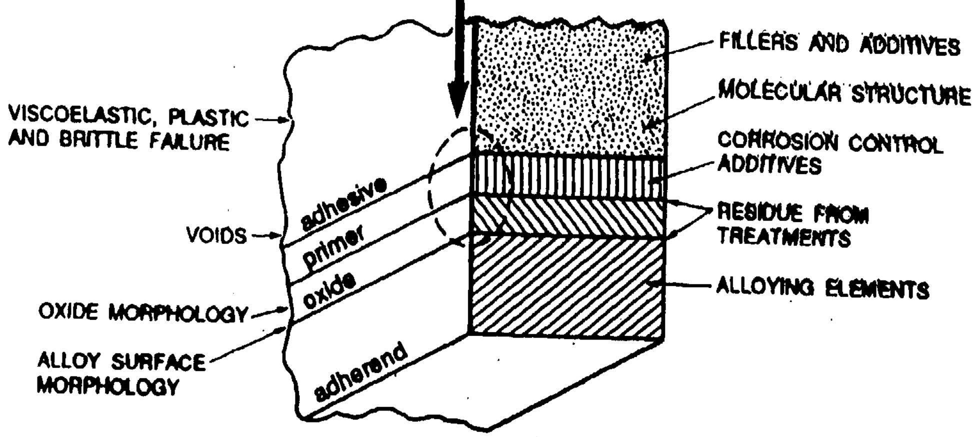
This project is concerned with the qualification of reliability and integrity of metal/polymer bond joints. The objectives are

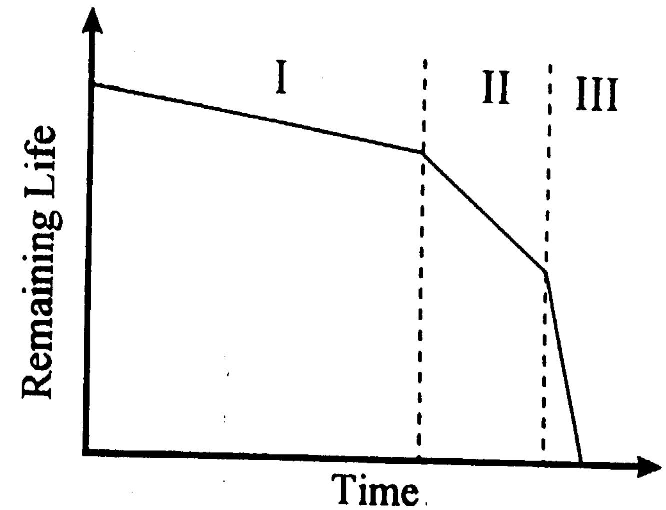
* To establish the correlation between the microstructural changes and ultrasound propagation characteristics.

* To develop ultrasonic nondestructive methods to measure the microstructural changes caused by the degradation of bond strength.

* To predict remaining bond strength from ultrasonic measurement based on the fundamental structure-property-performance relationships of the constituents and their interfaces.

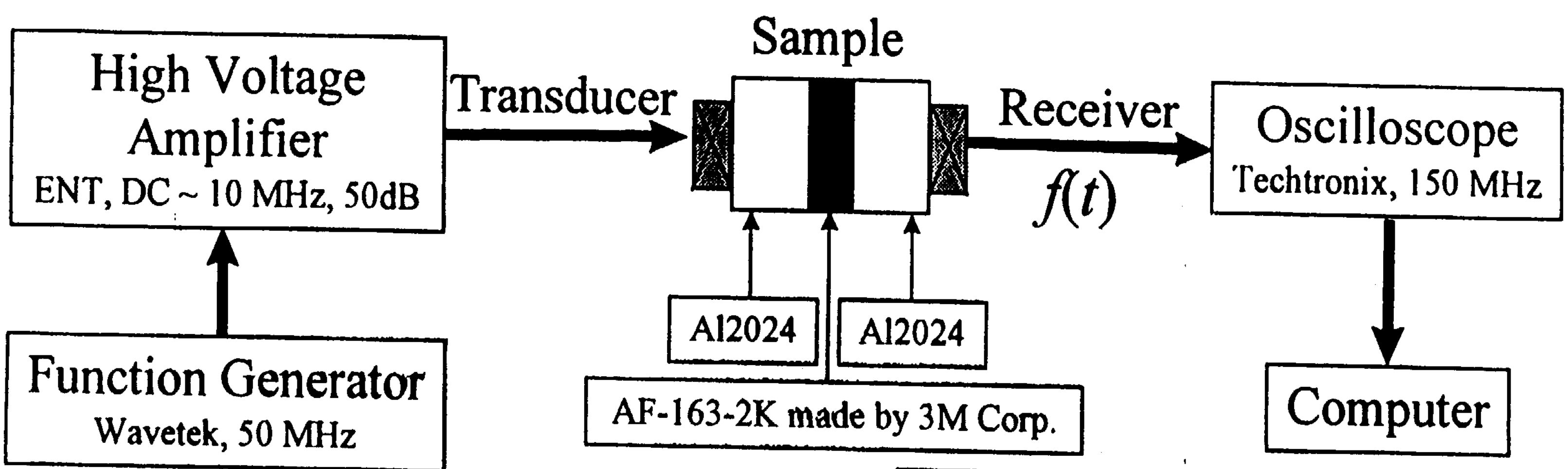
Degradation, Damage and Failure
(durability)

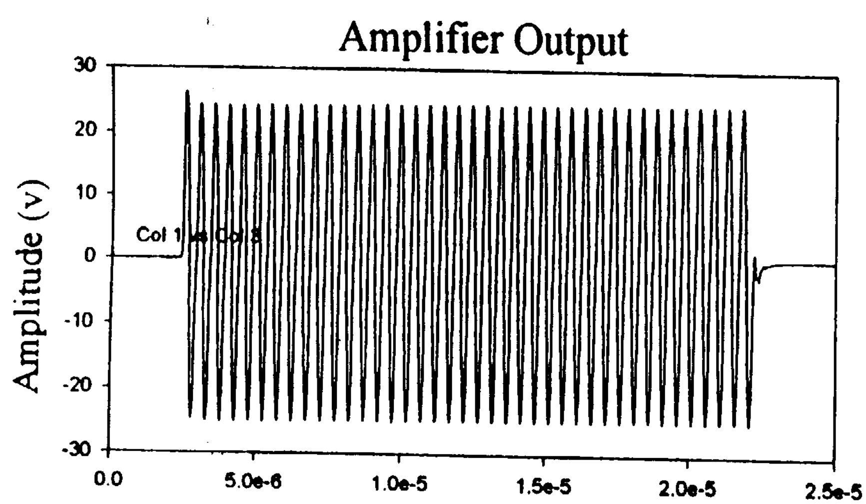




	Degradation	Damage Accumulation	Failure
Adhesive	*crosslink density* *moisture absorption* *plasticization*	*creep and fatigue* *microvoids* *microcracks*	*fracture* *crazing*
Interphase	*corrosion* *oxidation*	*microvoids* *microcracks*	*debonding* *delamination*
Adherend		*deformation*	*fatigue and fracture*

Through Transmission Test





Generation Transducer

* PZT (2.5 MHz, Narrow-band)
  (Ultra, KC50 -2, 1.25MHz at -6dB)
* PZT (5.5 MHz, Narrow-band)
  (Ultra, KC50 -5, 3.5MHz at -6dB
* Single Crystals
  (Quartz, lithium niobium)

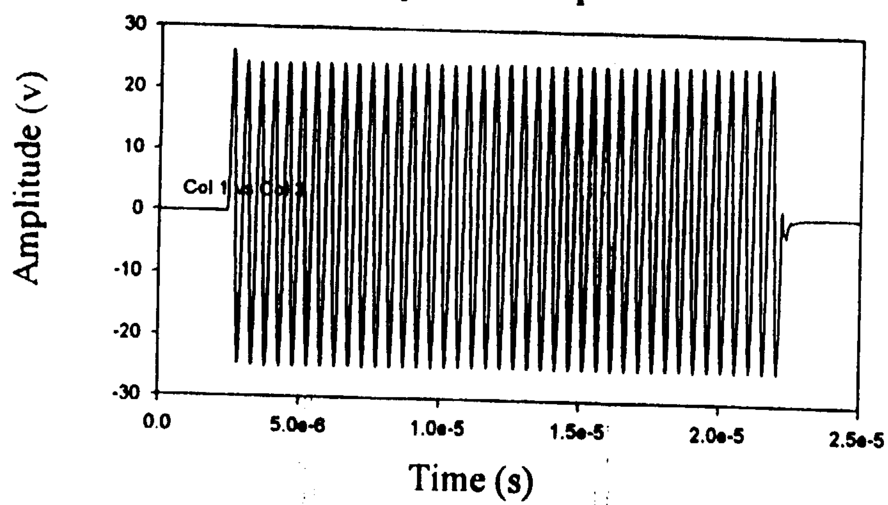
Detection Receiver

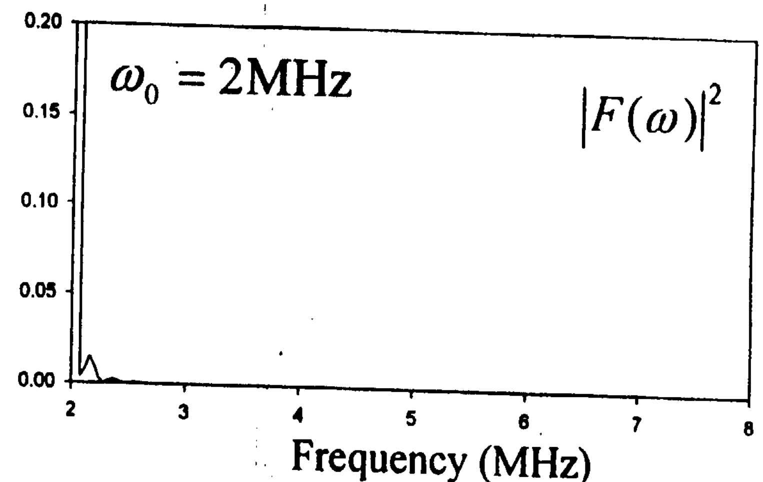
* PZT (5.5 MHz, Narrow-band)
  (Ultra, KC50 -5, 3.5MHz at -6dB)
* PZT (7.5 MHz, Narrow-band)
  (Ultra, KC50 -10, 8.5MHz at -6dB)
* Laser Interferometer

Fourier Transforms

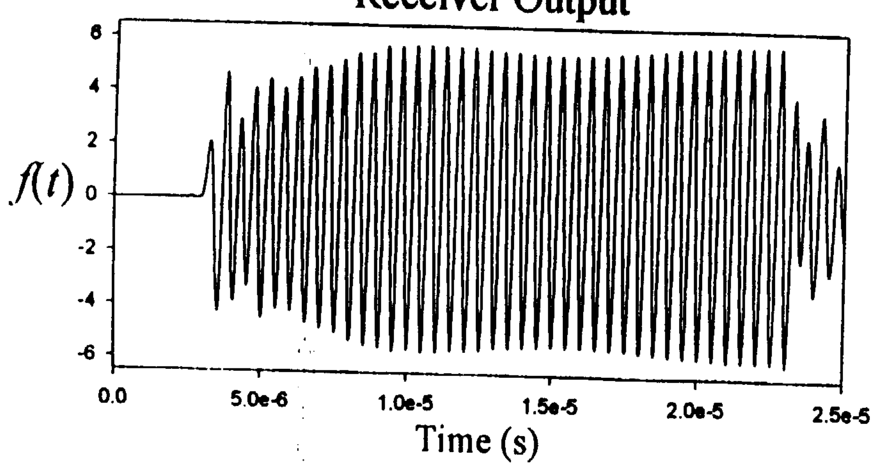
$$F(\omega) = \int_0^\infty f(t)\exp(i\omega t)dt \qquad A_n = |F(n\omega_0)| \qquad n = 1, 2, 3\cdots$$

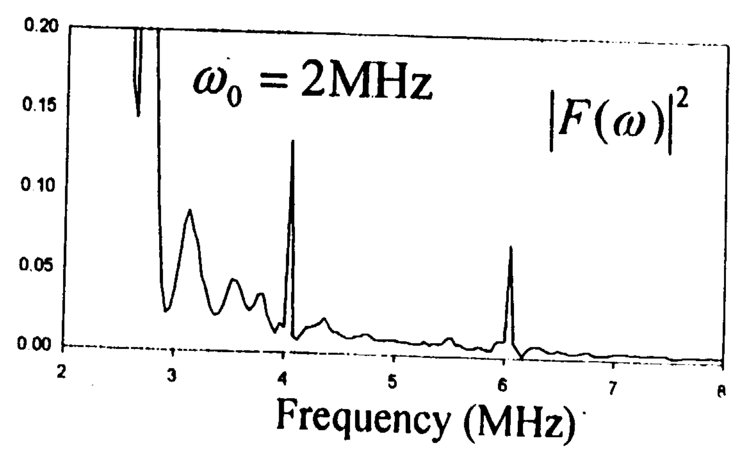
Amplifier Output

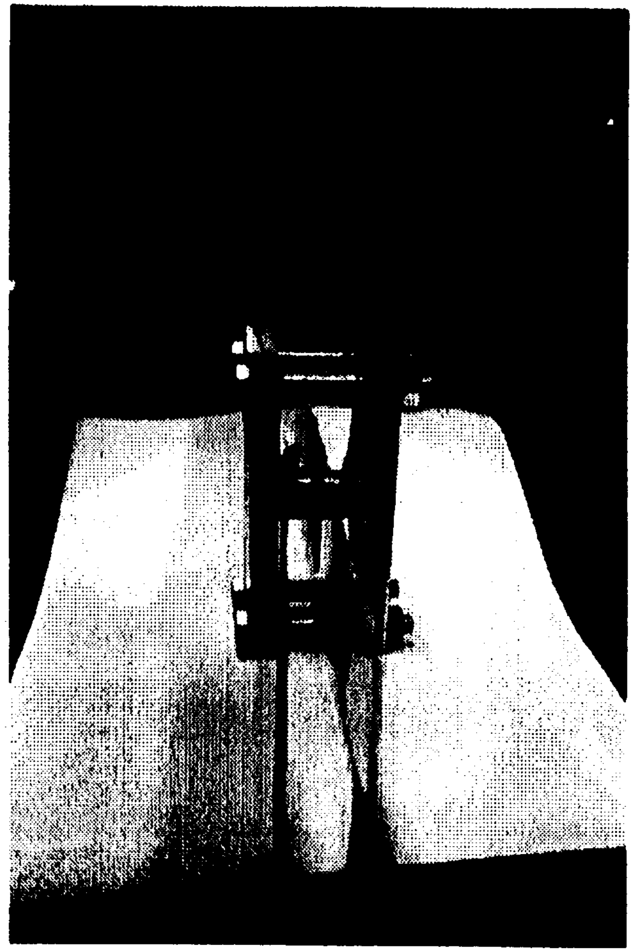




Receiver Output

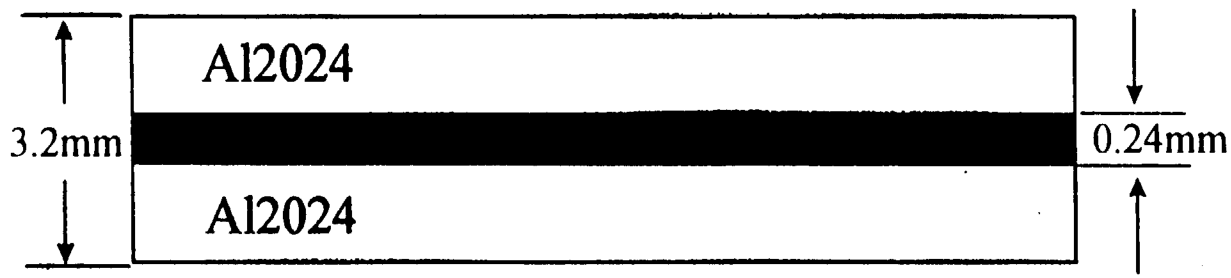






PZT/PZT

Samples with Different Curing States



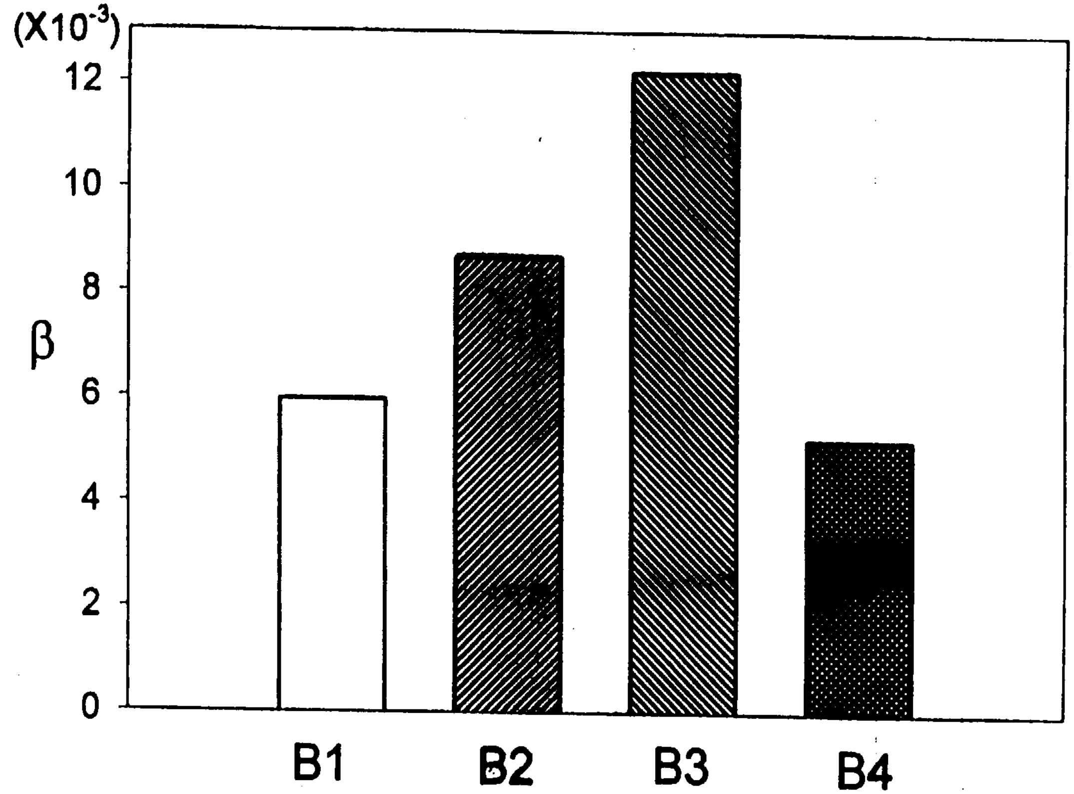
The Material Properties

Material	$\rho(kg/cm^3)$	E(GPa)	ν
Al2024	2.78	73.0	0.35
AF-163-2K	1.21	1.11	0.34

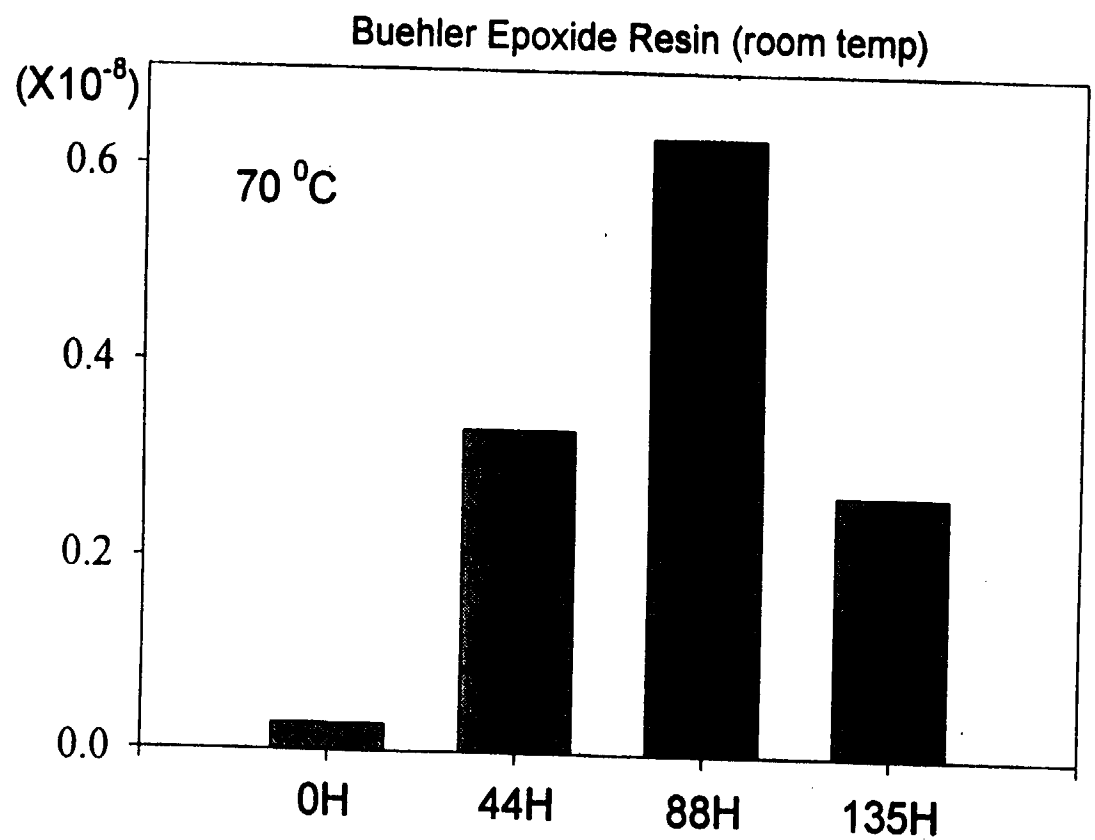
Differenct Curing Conditions

Sample Number	B1	B2	B3	B4
Curing Temperature (°C)	121	82	82	90
Curing Time (min.)	90	60	120	60
Curing Pressure (MPa)	0.34	0.34	0.34	0.34
Total Thickness (mm)	3.54	3.51	3.55	3.55
Shear Strength (MPa)	35	4.0	3.3	4.1

Nonlinear Parameter of Different Samples



Sample Number	B1	B2	B3	B4
Curing Temp. (°C)	121	90	82	82
Curing Time (min.)	90	60	60	120
Bond Strength (MPa)	35	4.1	4.0	3.3


Buehler Epoxide Resin (room temp)
(X10-8)
0.6
0.4
0.2
0.0
70 0C
0H
44H
88H
135H

Generation of Higher Order Harmonics

Wave Equation

$$\frac{1}{\rho}\frac{\partial \sigma}{\partial \varepsilon} = \frac{\partial^2 u}{\partial t^2}$$

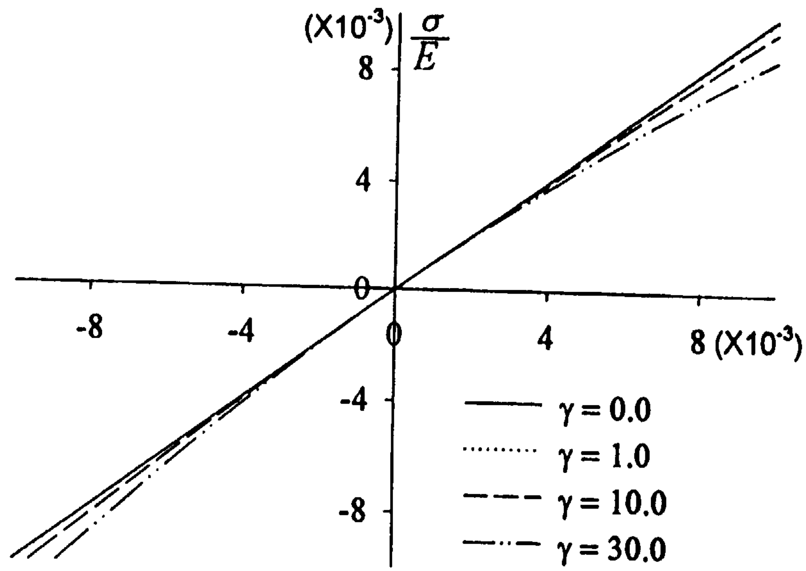
Stress-Strain Relation
(material nonlinearity)

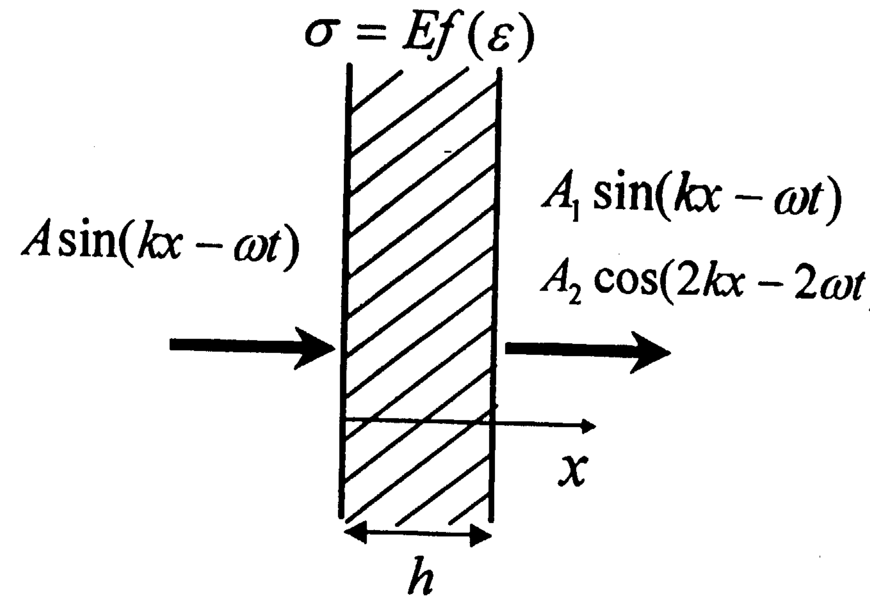
$$\sigma = Ef(\varepsilon) \qquad \varepsilon = \frac{\partial u}{\partial x}$$

$$\boxed{\frac{1}{c^2}\frac{\partial^2 u}{\partial t^2} - \frac{\partial^2 u}{\partial x^2} = [f'(\varepsilon) - 1]\frac{\partial^2 u}{\partial x^2}}$$

Example

$$f(\varepsilon) = \varepsilon(1 - 0.5\gamma\varepsilon)$$





$$A_2 = \frac{\gamma}{8} k^2 x A_1^2 = \frac{\gamma}{8c^2} \omega^2 x A_1^2$$

$$\beta = \frac{8A_2}{k^2 h A_1^2} = \gamma$$ Nonlinear parameter

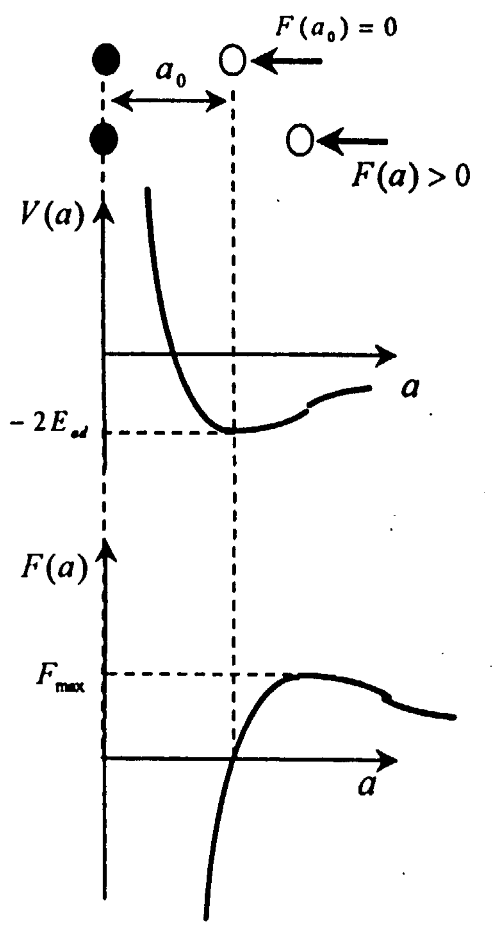
For

$h = 320\mu m$ $c = 6410\, m/s$ $\omega = 2\pi \times 2\text{Hz}$

$$\frac{A_2}{A_1} \approx 1.5 \times 10^{-4} \gamma \frac{A_1}{\mu m}$$

Generation of Harmonics in Metals

Lattice Anharmonicity



Dislocation Motion

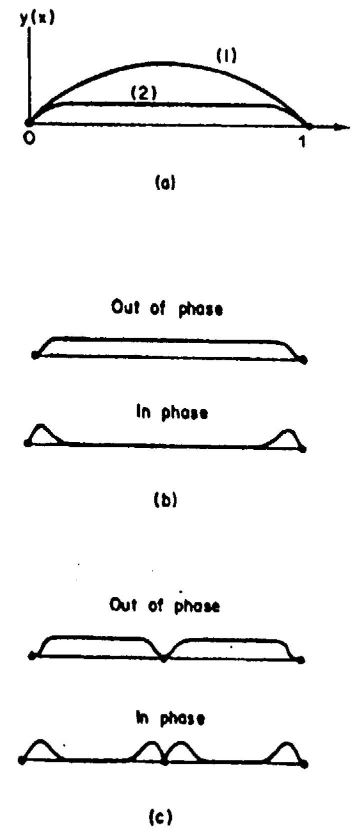
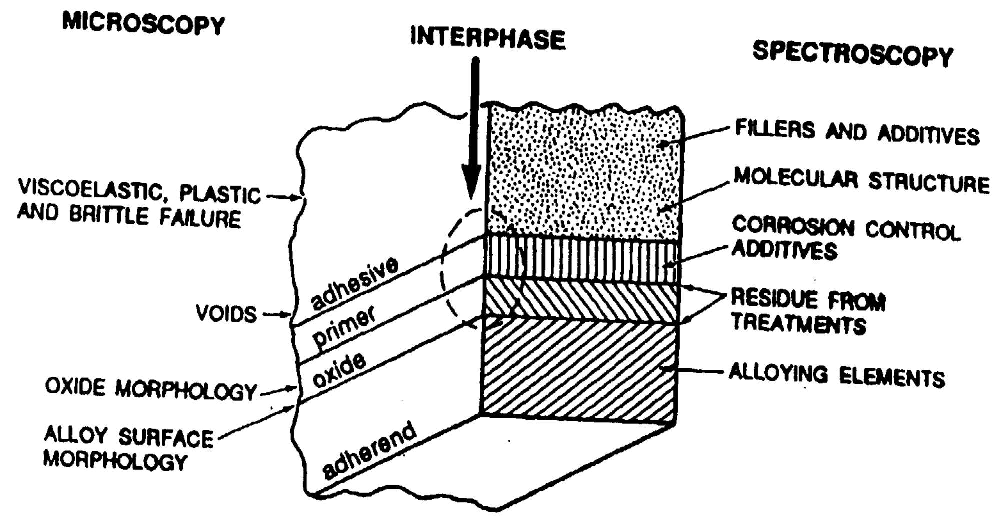
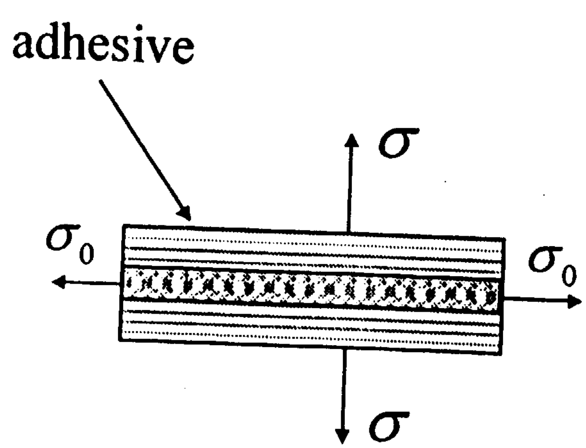
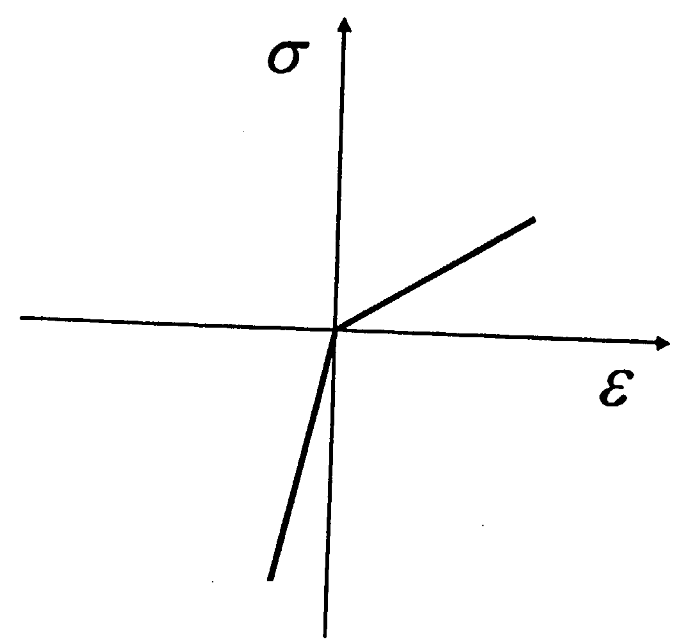


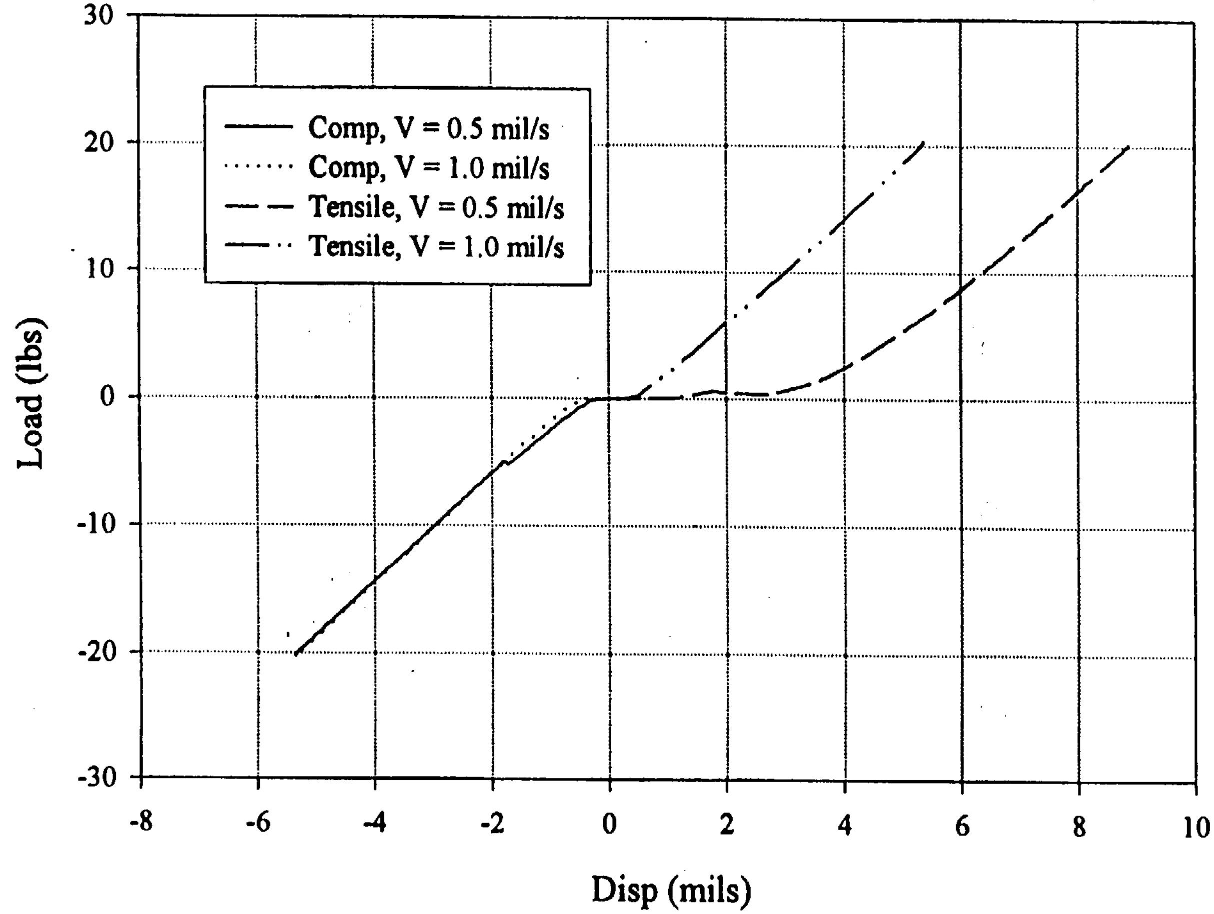
Fig. 8-10. Displacement of a dislocation under stress (schematic). (a) Curve 1: dislocation displacemont amplitude at low damping (small phonon density); curve 2: dislocation displacement amplitude for high damping. (b) Out-of-phase and in-phase component of dislocation displacement for high damping. (c) Change in Fig. 3-10b when pinning point is added at center of dislocation loop. (Pinning increases area of in-phase component, thereby decreasing elastic modulus and decreasing velocity of ultrasonic wave) (after Truell and Granato [168]).

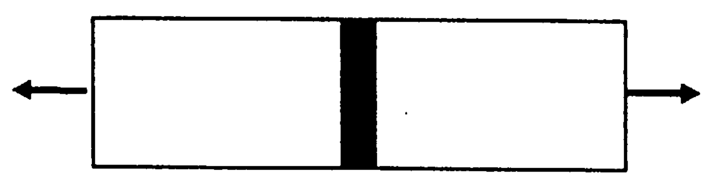

MICROSCOPY
INTERPHASE
SPECTROSCOPY
VISCOELASTIC, PLASTIC AND BRITTLE FAILURE
VOIDS
OXIDE MORPHOLOGY
ALLOY SURFACE MORPHOLOGY
adhesive
primer
oxide
adherend
FILLERS AND ADDITIVES
MOLECULAR STRUCTURE
CORROSION CONTROL ADDITIVES
RESIDUE FROM TREATMENTS
ALLOYING ELEMENTS


adhesive
σ
σ₀
σ₀
σ

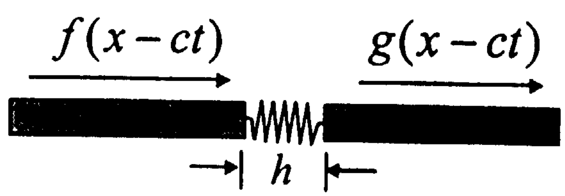

σ
ε

Tensile *vs* Compressive Response of Epoxy Thin Layer





A Simplistic Model



Interface Conditions

$$\sigma(t)=\sigma(0^+,t)=\sigma(0^-,t)$$

$$u(0^+,t)-u(0^-,t)=\frac{h}{E_s}\sigma(t)$$

$$E_s=\begin{cases}E_s^t & \text{when } \sigma(t)>0\\ E_s^c & \text{when } \sigma(t)<0\end{cases}$$

$$\eta_t=\frac{E_s^t}{E} \qquad \eta_c=\frac{E_s^c}{E}$$

E_s = Adhesive stiffness

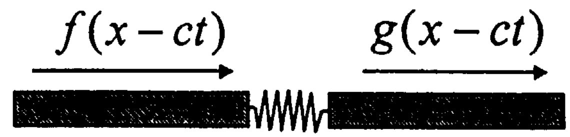
E = Adherend stiffness

Solution

$$g(x-ct)=f(x-ct)+\frac{1}{2}V(t-\frac{x}{c})$$

$$V(t)=u(0^+,t)-u(0^-,t)$$

Example



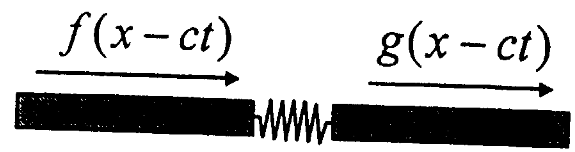
$$f(x-ct) = A\cos[k(x-ct)] \qquad g(x-ct) = f(x-ct) + \frac{1}{2}V(t-\frac{x}{c})$$

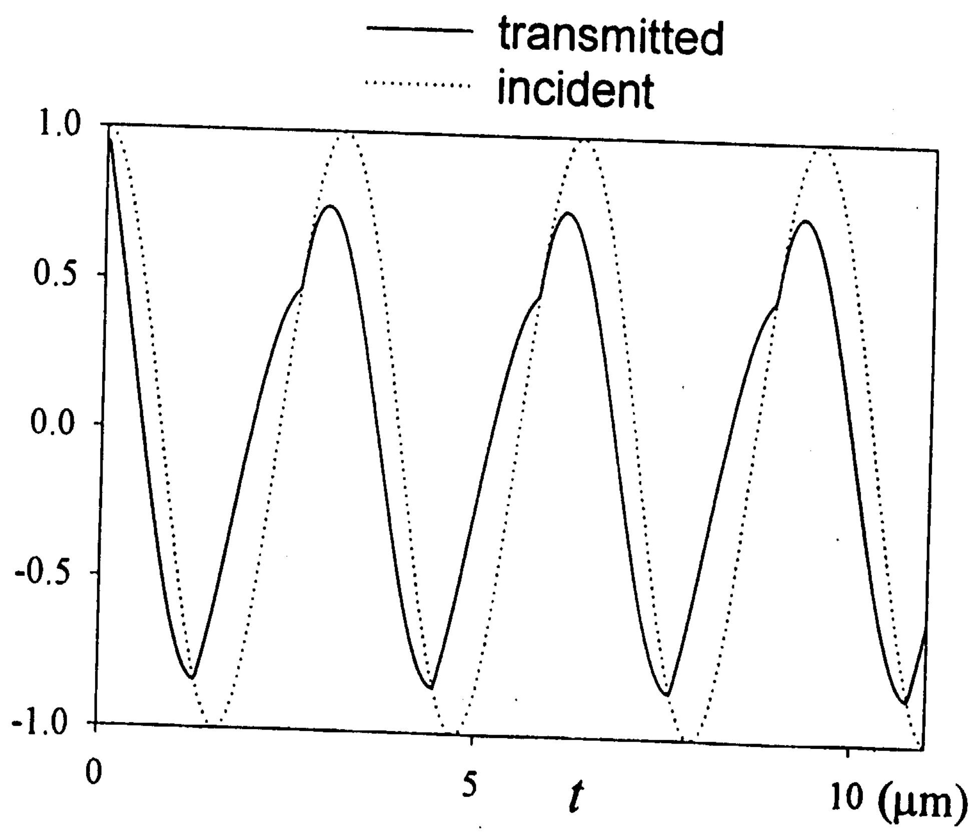
where

$$V(t) = \begin{cases} 2A\sin\varphi_c[\sin(\omega t_n + \varphi_c)e^{-\xi_c(t-t_n)} - \sin(\omega t + \varphi_c)], & n = 0,2,4\cdots \\ 2A\sin\varphi_t[\sin(\omega t_n + \varphi_t)e^{-\xi_t(t-t_n)} - \sin(\omega t + \varphi_t)], & n = 1,3,5\cdots \end{cases}$$

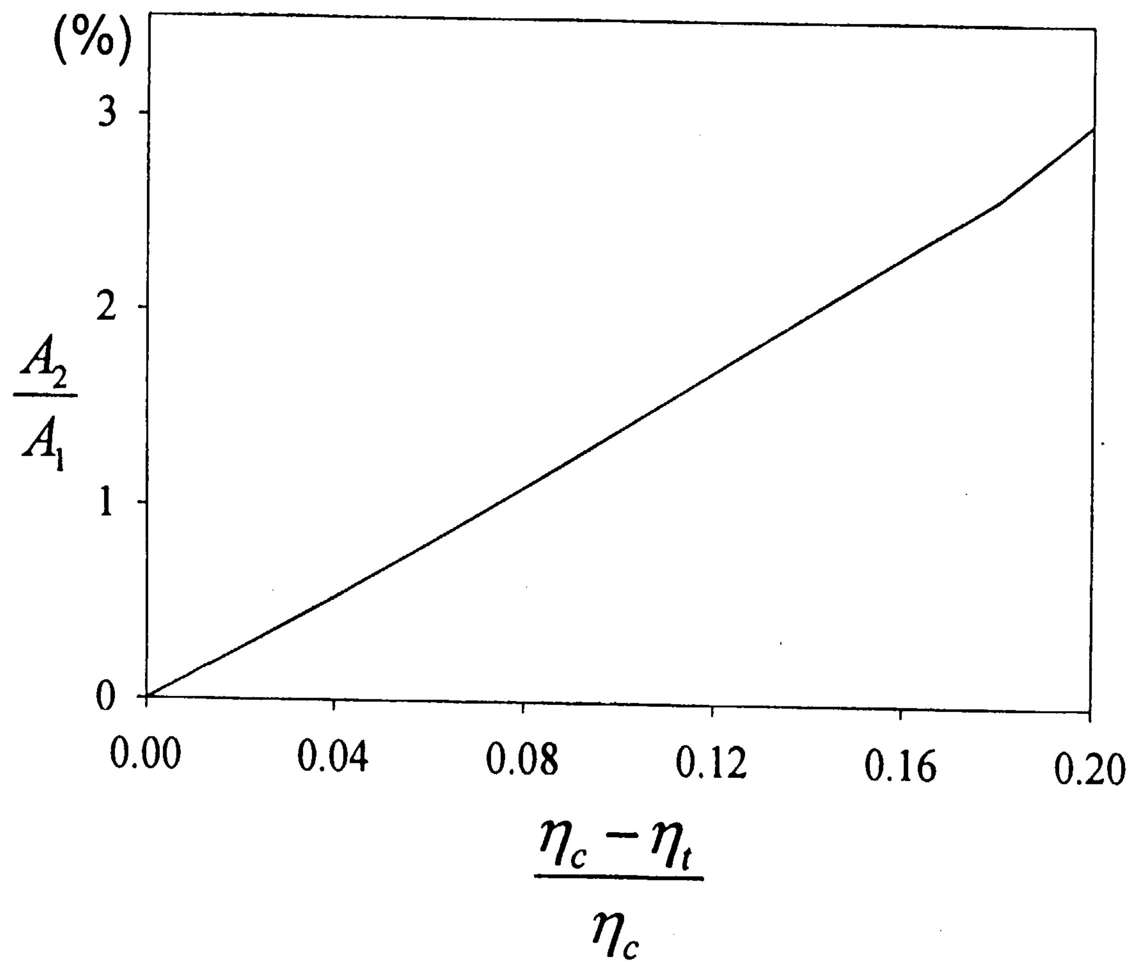
$$\xi = \eta\frac{c}{h} \qquad \varphi = \sin^{-1}\left(\frac{\omega}{\sqrt{\xi^2+\omega^2}}\right) \qquad V(t_n) = 0 \qquad t_0 = 0$$

$h = 100\mu\text{m} \quad c = 6410\, m/s \qquad \omega = 2\text{Hz}$

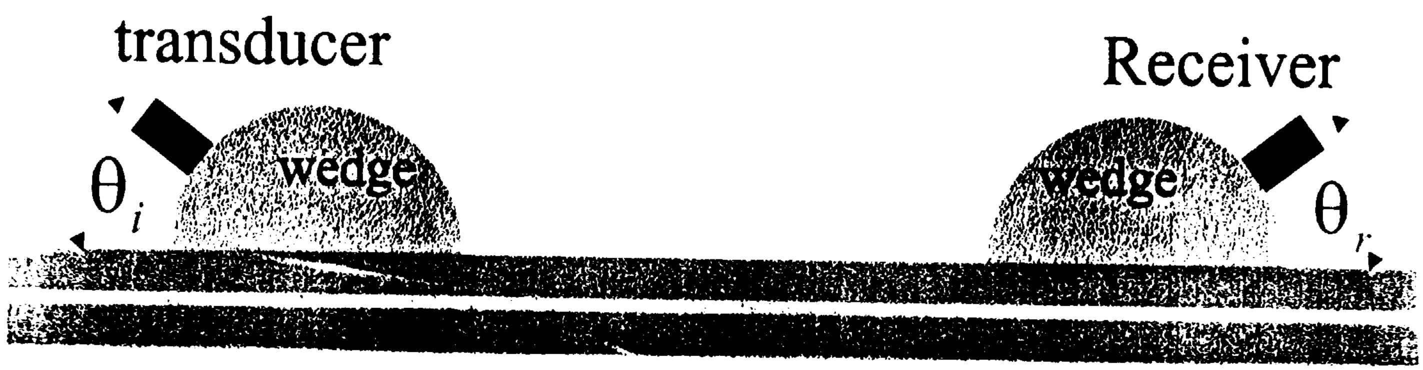


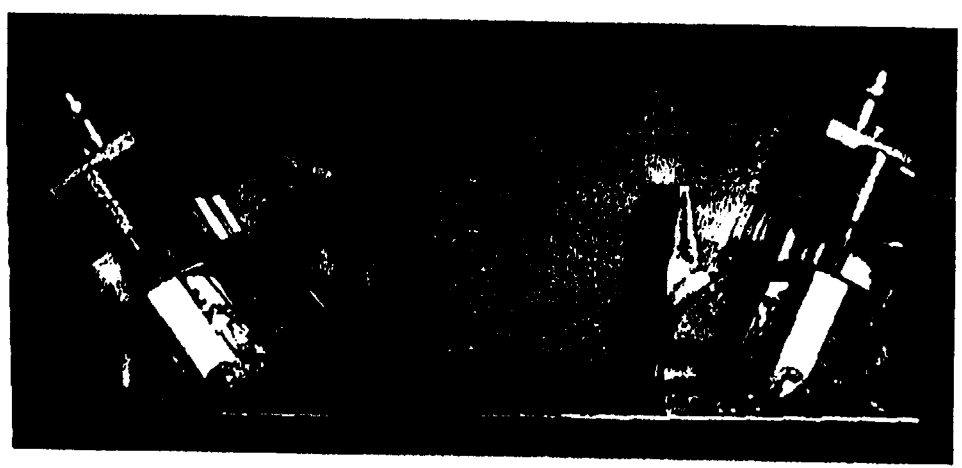


$h = 100\mu m \quad c = 6410\, m/s \qquad \omega = 2\text{Hz} \qquad \eta_c = 0.05$



Setup for Guided Wave Measurement





ASSESSMENT OF ADHESIVE BOND DETERIORATION BY DETECTION OF NONLINEAR EFFECTS

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GENERAL OBJECTIVE

To develop an ultrasonic nondestructive technique to assess deterioration of adhesive bonds by the detection of nonlinear effects. The work on this project is both analytical and experimental in nature.

The adhesive bond behavior can be represented by a relation between tractions, τ, and gross displacements, Δ, across the adhesive layer. Figure 1 shows four typical τ-Δ curves with their associated failure points. Figure 1a represents a brittle bond with a linear relation between τ and Δ. When τ reaches a critical value τ_{cr} the bond breaks in a brittle fashion. Deterioration of the bond gives rise to a lower value of τ_{cr}. Figure 1b shows a bond with nonlinear elastic behavior typical of rubbery adhesives. The failure point is reached for $d\tau/d\Delta=0$. Deterioration of this bond may be described by the curves shown in Fig. 1c or Fig. 1d. Note that in Fig. 1c the slope remains the same at $\tau=0$, while in Fig. 1d this slope changes. For the case of 1d the slope at $\tau=0$, which can be determined by ultrasonic methods, can be correlated with residual strength. This has been done by many investigators. Here we will address the more difficult case represented by Fig. 1c.

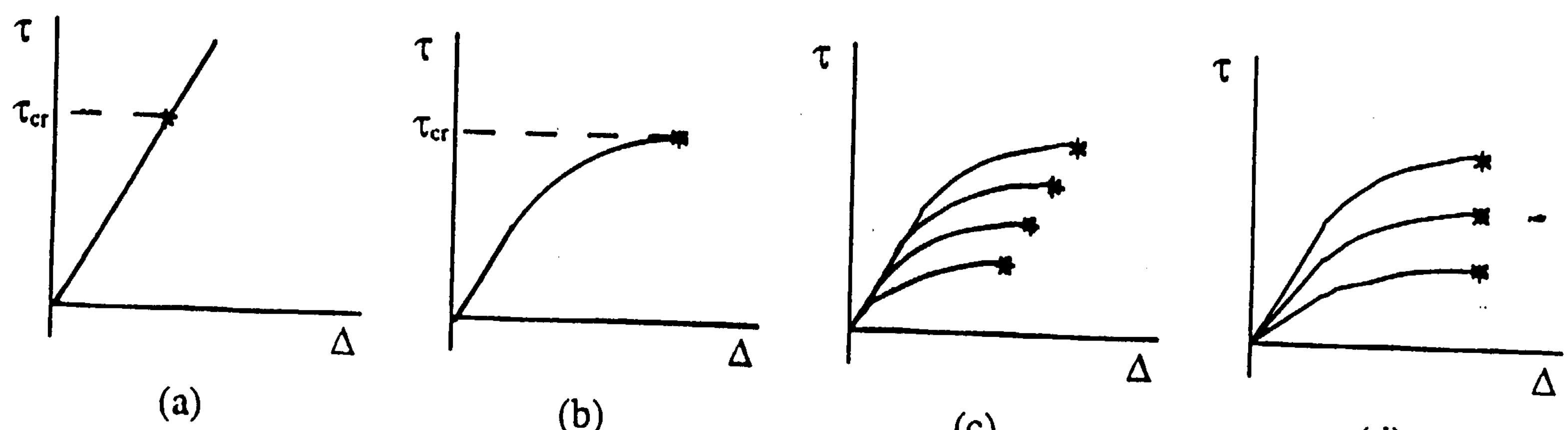
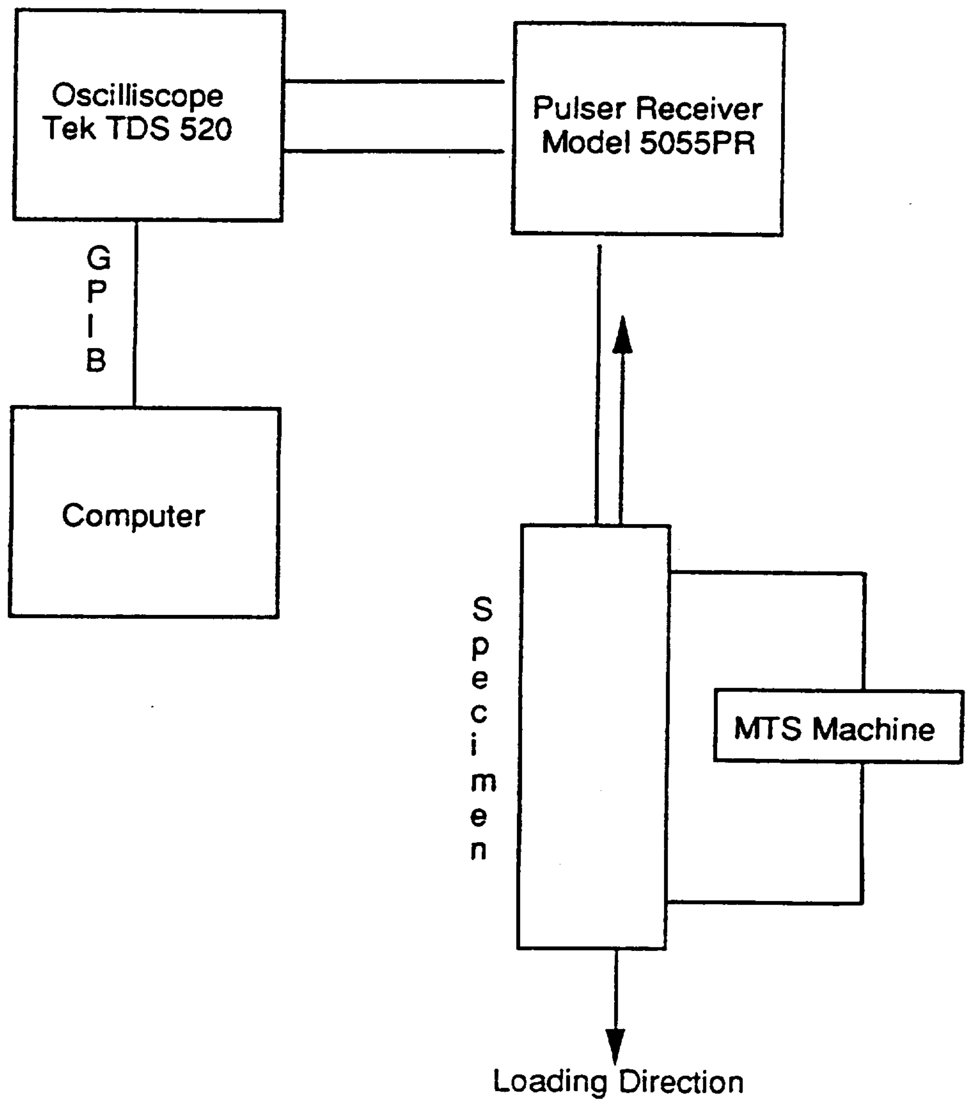


Figure 1. Traction-displacement curves and associated failure points.

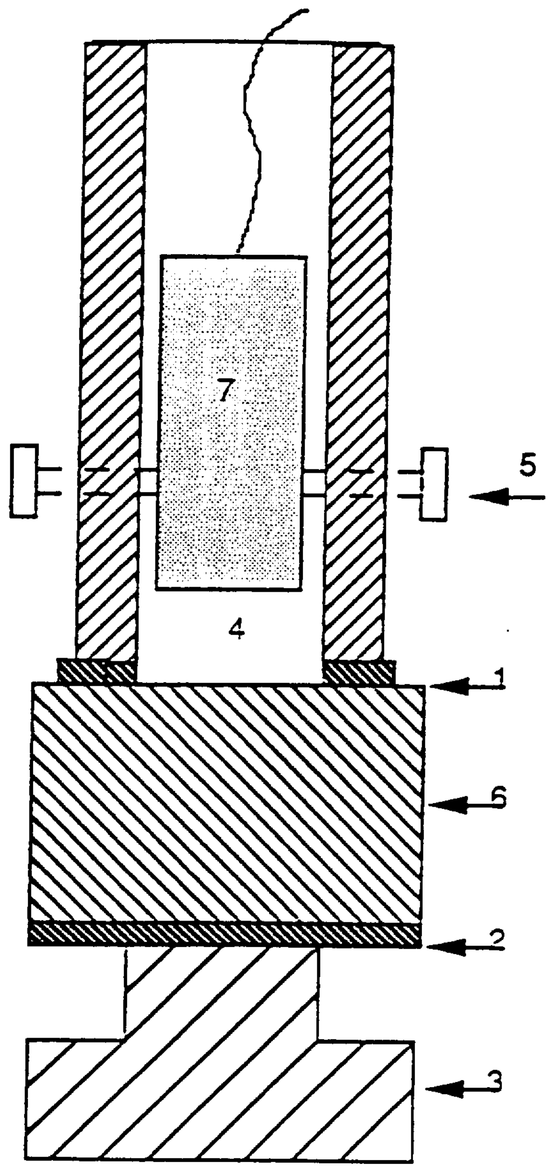
Outline

- Ultrasonic Evaluation of Adhesive Bond Degradation By Detection of the Onset of Nonlinear Behavior Induced by Static Load
  - ⋆ Superimposed longitudinal wave
  - ⋆ Superimposed shear wave
- Summary
- New Approach —— A Strain-Temperature Correspondence Principle
- Digitized Waveform Decomposition Technique
- Preliminary Results
- Conclusions and Future Work

EXPERIMENT SETUP



SPECIMEN



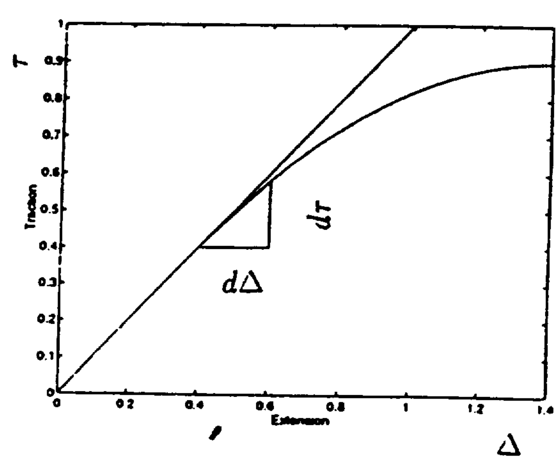
1. Adhesive (connection)
2. adhesive (testing layer)
3. Al block (adherend 2)
4. Al Tube (water tank)
5. Screw
6. Al block (adherend 1)
7. Transducer

Methodology of Nonlinear Behavior Study

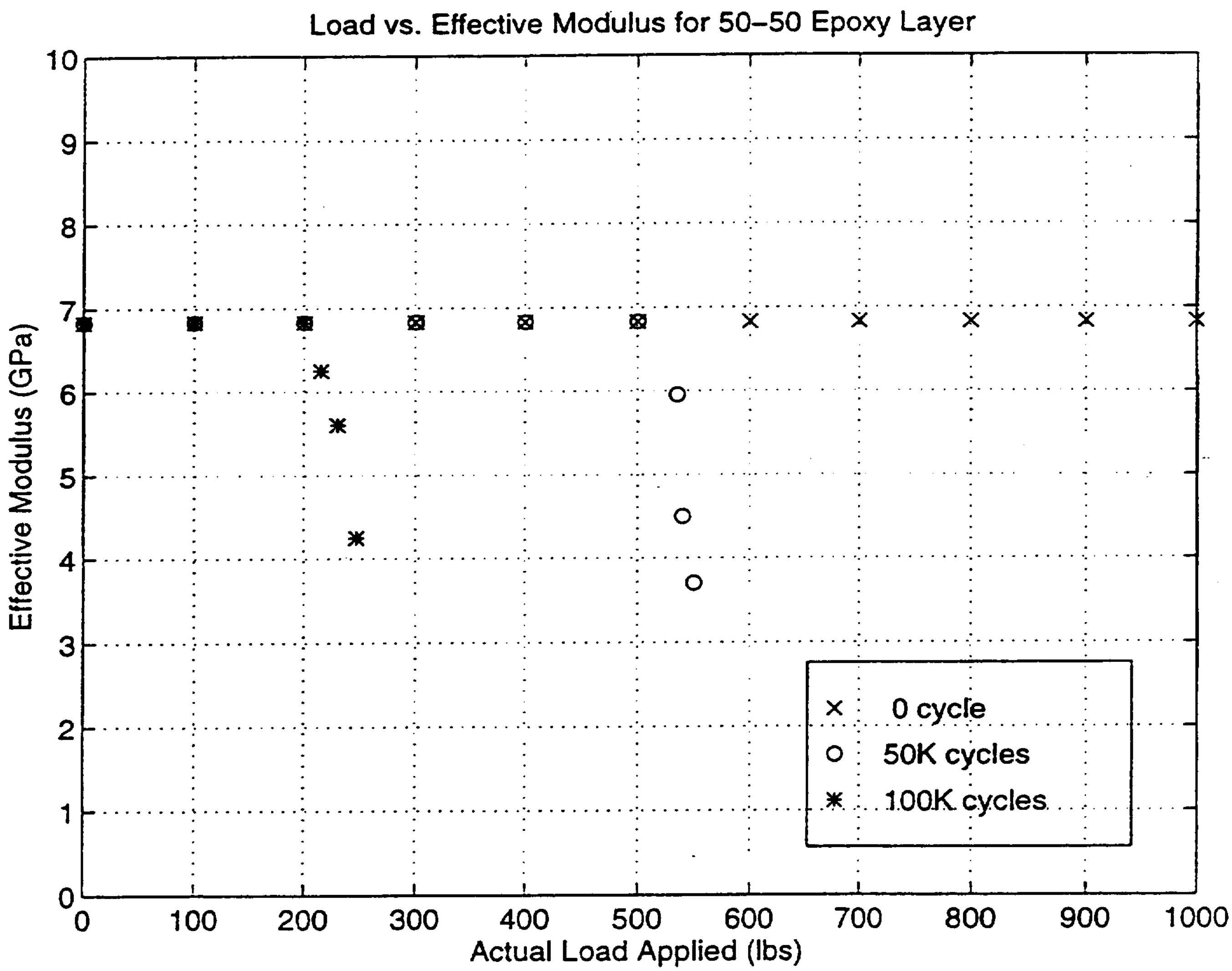
Use different fatigue cycles to generate different severities of degradation.

By varying the static load, ultrasonic measurements allow us to get the slope of the $\tau - \Delta$ curve at several points.

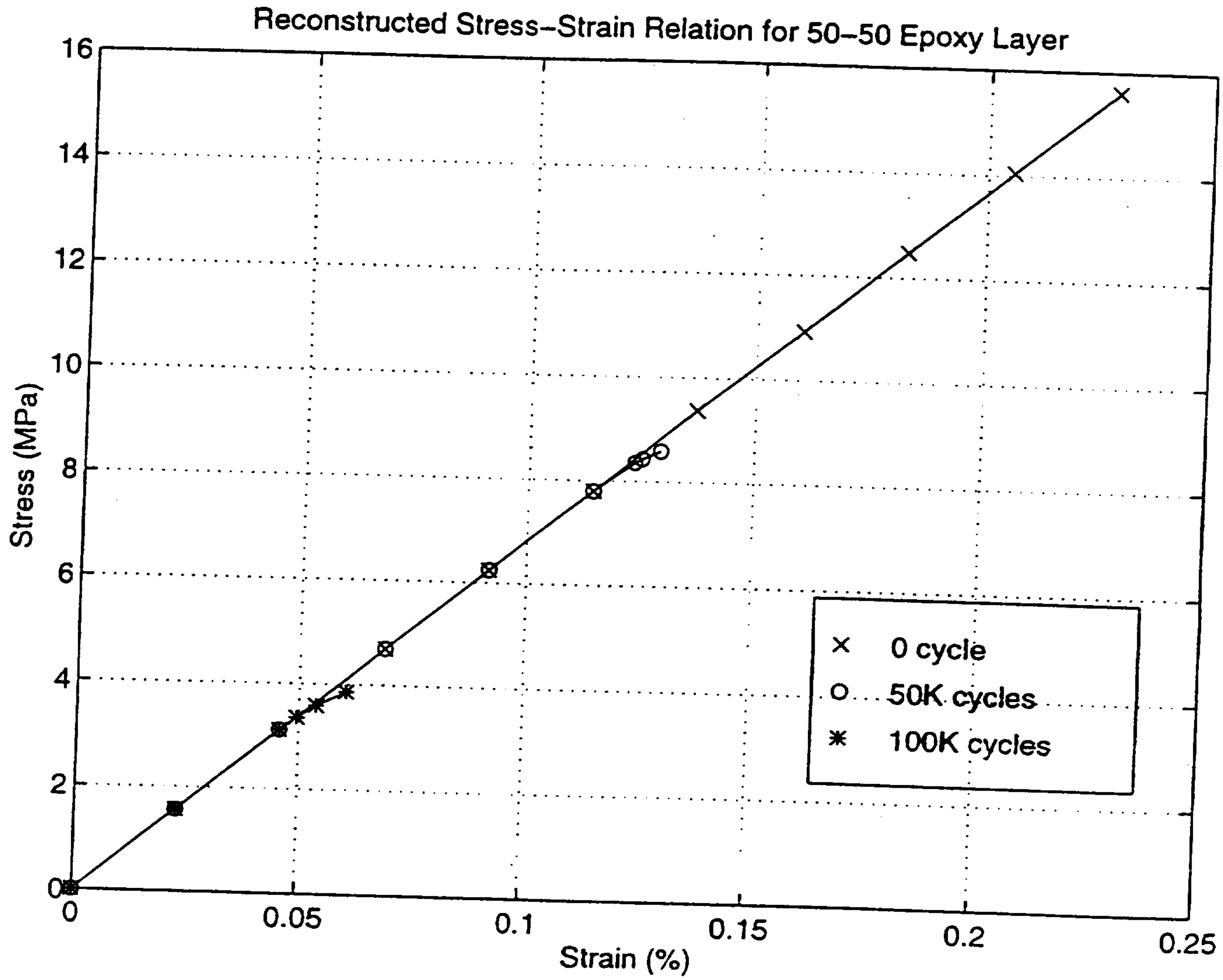
$$\frac{d\tau}{d\Delta} \approx \frac{\sigma}{\delta} = \beta$$



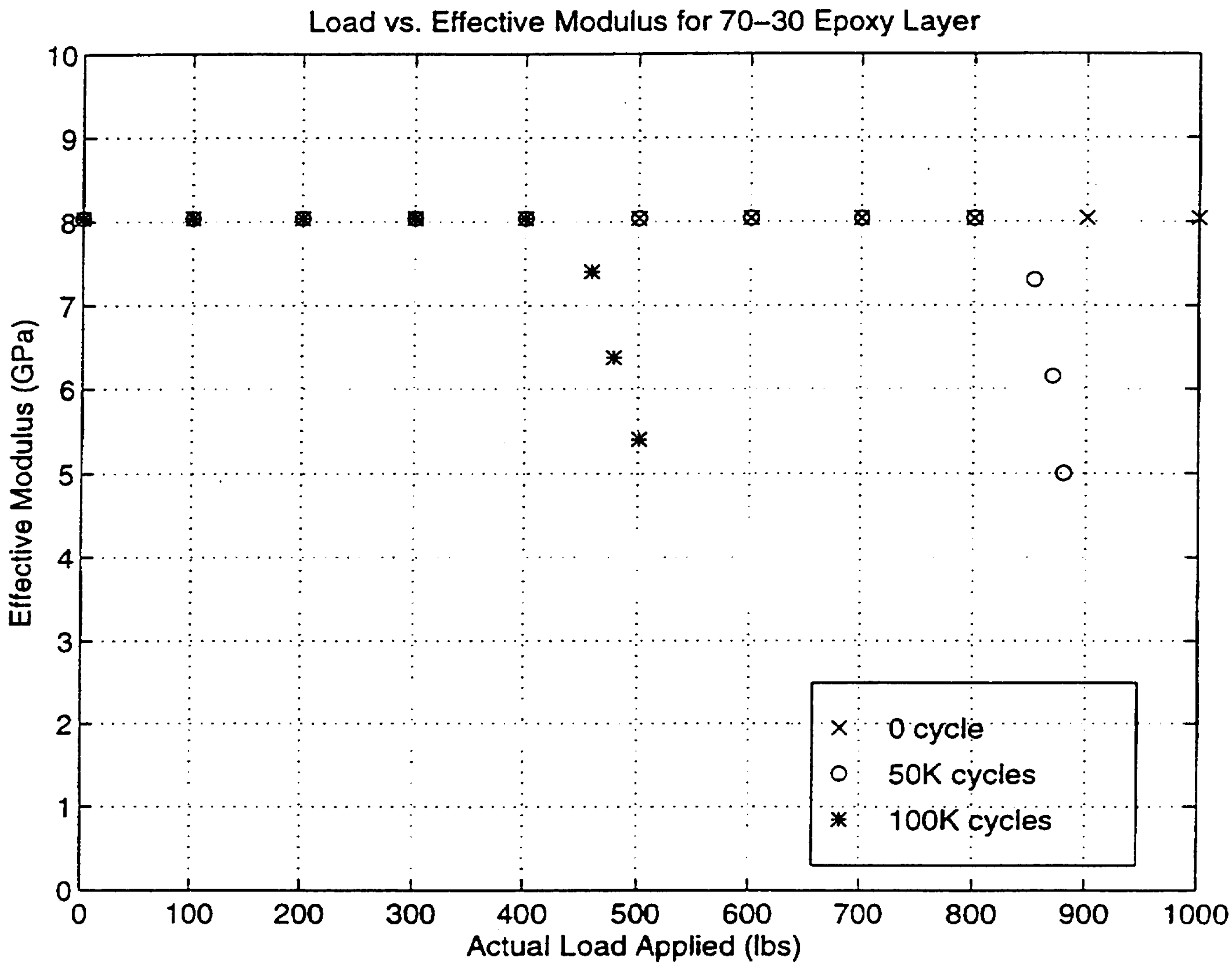
Load vs. Effective Modulus for 50-50 Epoxy Layer



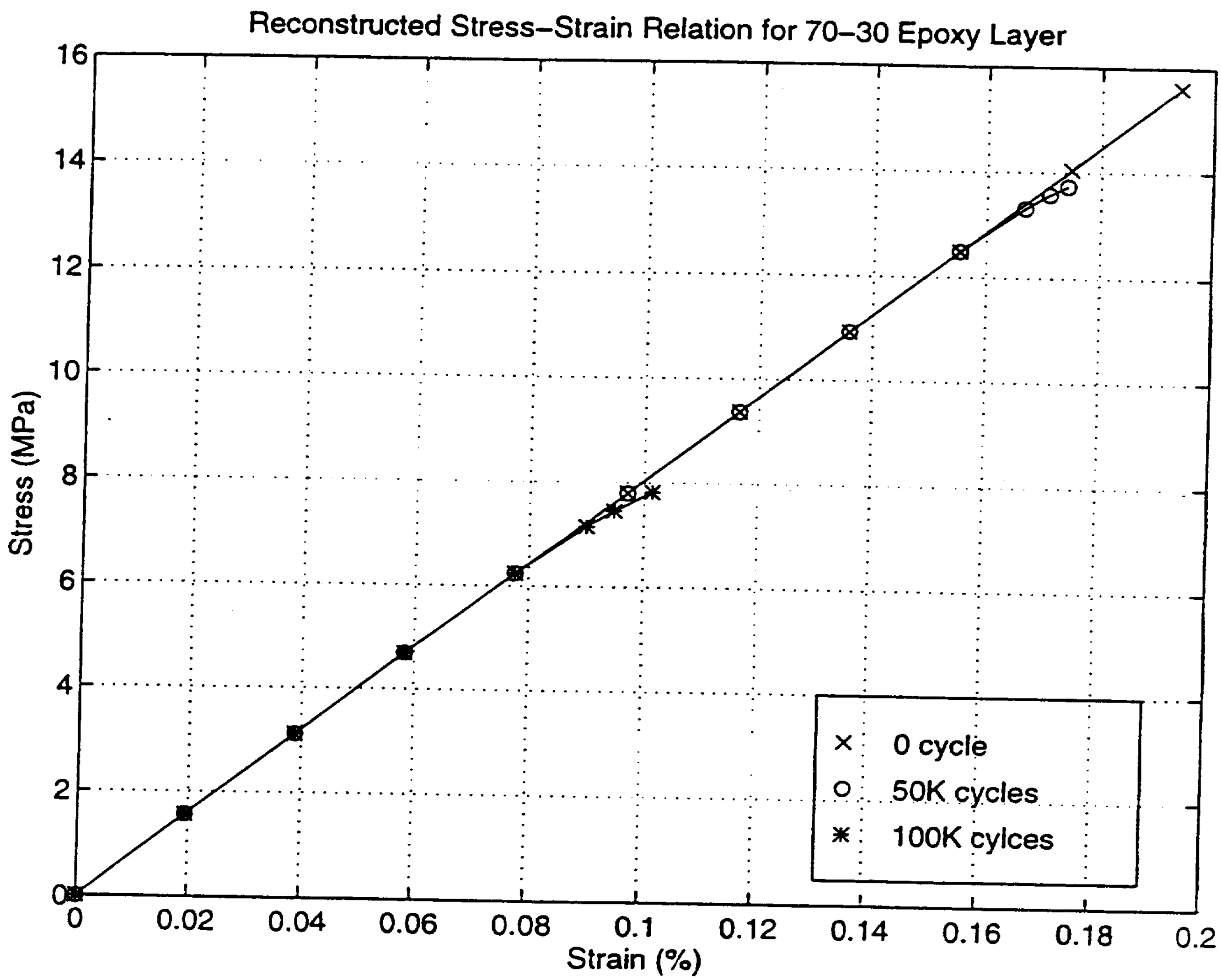
Reconstructed Stress-Strain Relation (50-50)



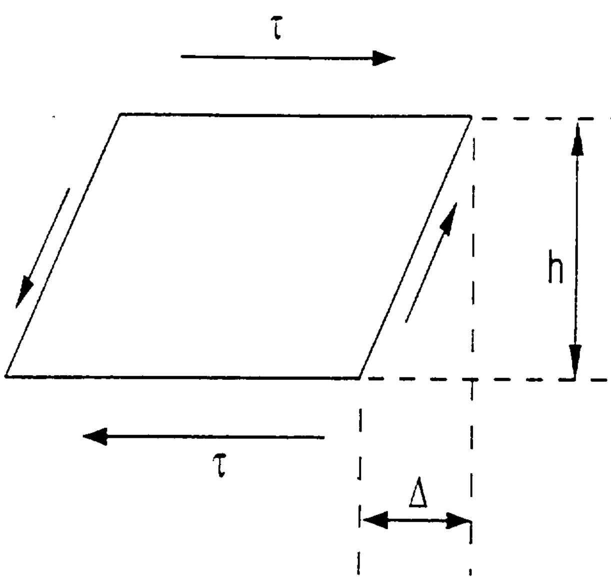
Load vs. Effective Modulus for 70-30 Epoxy Layer

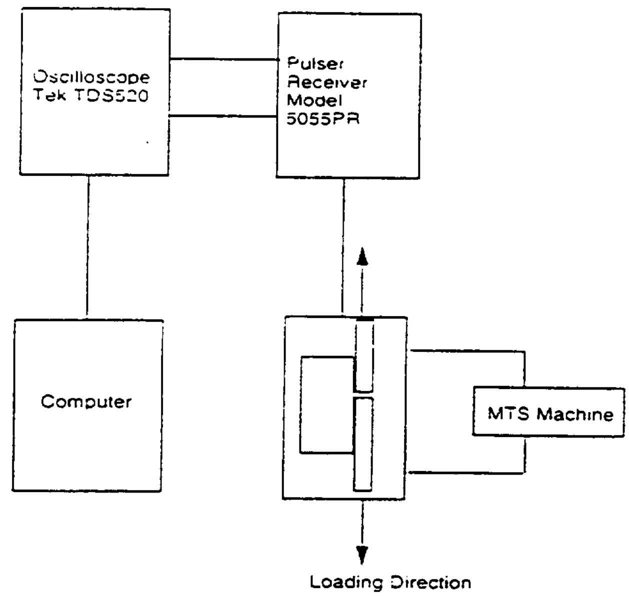


Reconstructed Stress-Strain Relation (70-30)



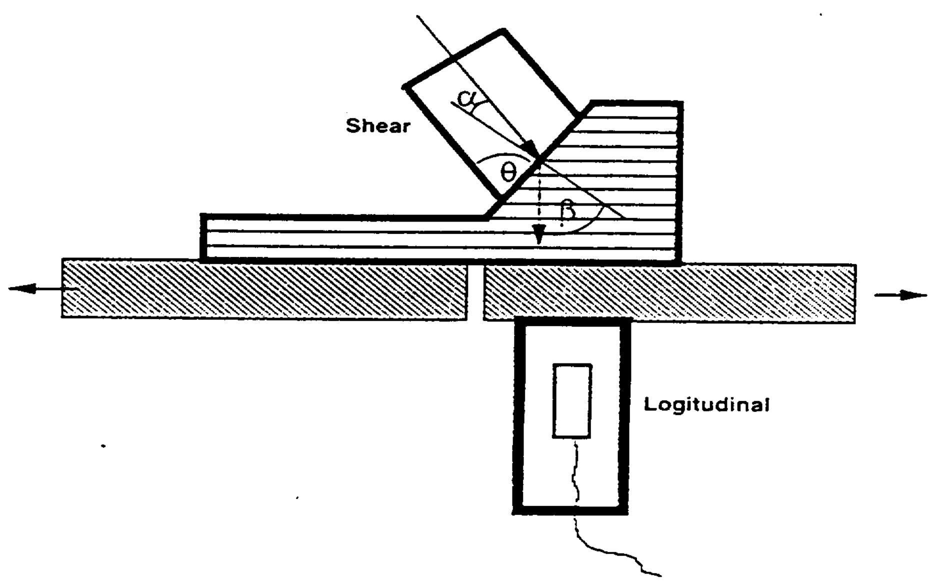
A Superimposed Shear Wave





Shear deformation illustration

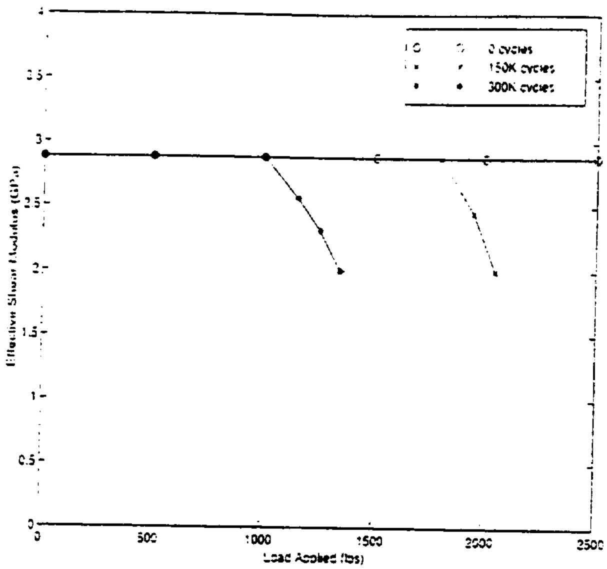
Experiment set-up



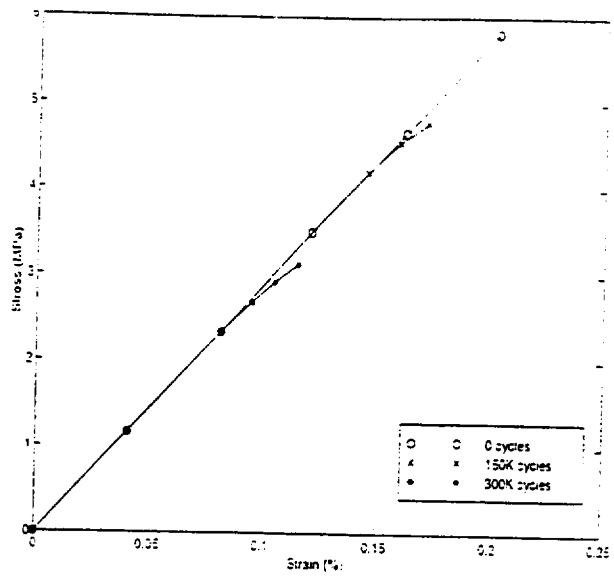
$$\alpha = sin^{-1}[(C_w/C_t)sin\beta] \quad (5)$$

$$\theta = \frac{\pi}{2} - \alpha \quad (6)$$

Superimposed Shear Wave—Results

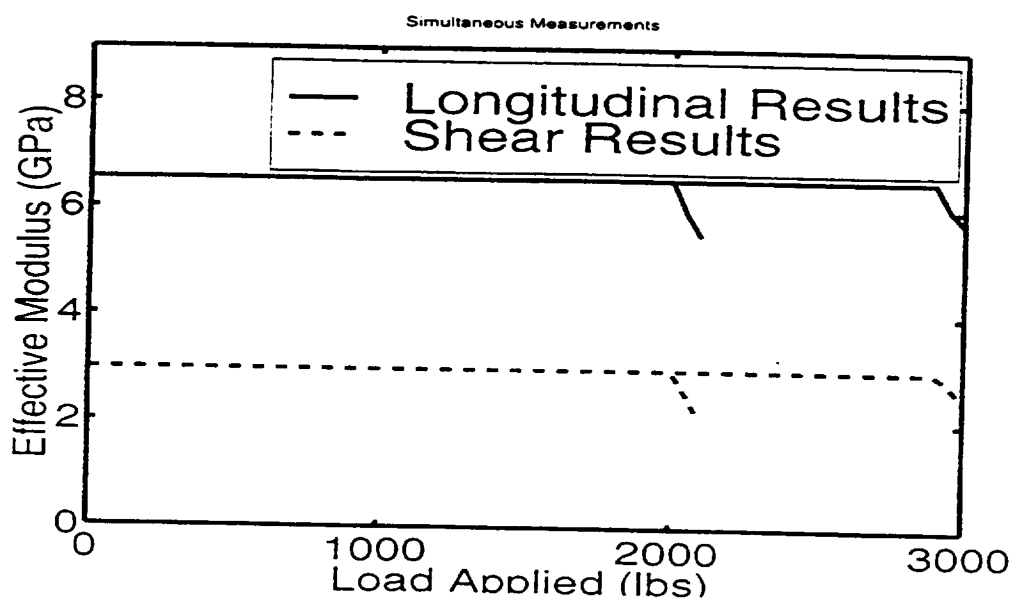


Load vs. Shear Modulus



Stress-Strain Curve

Simultaneous Measurements



Load vs. Modulus

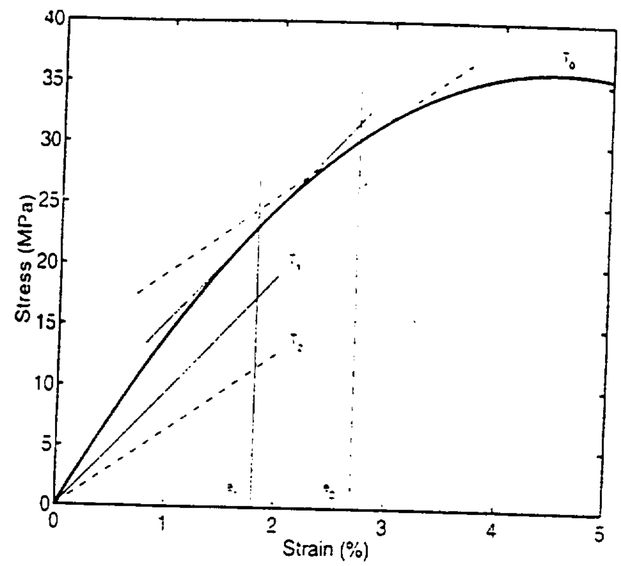
Summary

The onset of nonlinear behavior of adhesive bonds can be detected ultrasonically. The results show that the degradation due to cyclic fatigue can be detected by the reduction of the linear portion of the stress-strain curve without any change of slope in the linear range.

Shear waves can be used to detect the onset of nonlinear behavior of adhesive bond degradation generated by cyclic fatigue while the specimen is under shear loading. Longitudinal waves can also be used for this purpose.

The nonlinear behavior of a cyclically fatigued specimen is initiated at a lower stress level of the shear loading than the tensile loading. For practical reasons, it is preferable to subject the specimen to shear loading while the detection uses longitudinal waves.

A New Approach — A Strain-Temperature Correspondence Principle



The initial slopes at temperature T_1 and T_2 and slopes at strain ϵ_1 and ϵ_2 are the same.

$$\sigma = C_0\left[\epsilon + f(\epsilon)\right]; \qquad \frac{d\sigma}{d\epsilon} = C_0\left[1 + f'(\epsilon)\right] \tag{7}$$

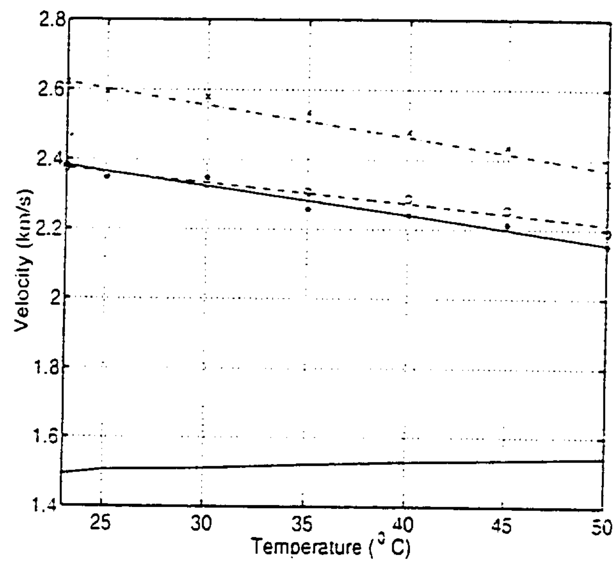
$$C(T) = C_0\left[1 + h(T)\right] \tag{8}$$

Strain-Temperature Correspondence Relation

$$h(T) = f'(\epsilon) \tag{9}$$

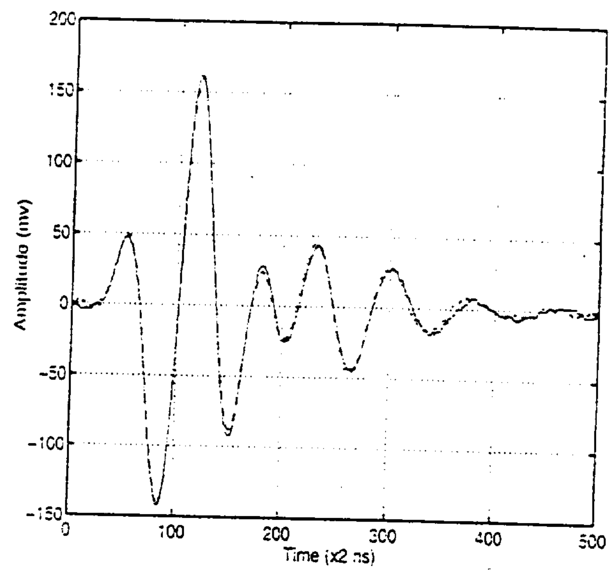
Preliminary Results

Temperature Dependence of velocity for several materials



Temperature dependence of velocity for various materials. Water (solid), FM73 (dashed), DER Epoxy (dashdot), AB Epoxy(solid)

Complete Recovery of Ultrasonic Signal



Complete recovery of ultrasonic signal after one cycle of heating of sample #3. 22^0C before heating (solid line), 22^0C after cooling (dashed line)

A Simple Model

Quadratic Nonlinear Term

$$\sigma = C_0 \left[\epsilon - \frac{\epsilon^2}{2\epsilon_0} \right] \quad (11)$$

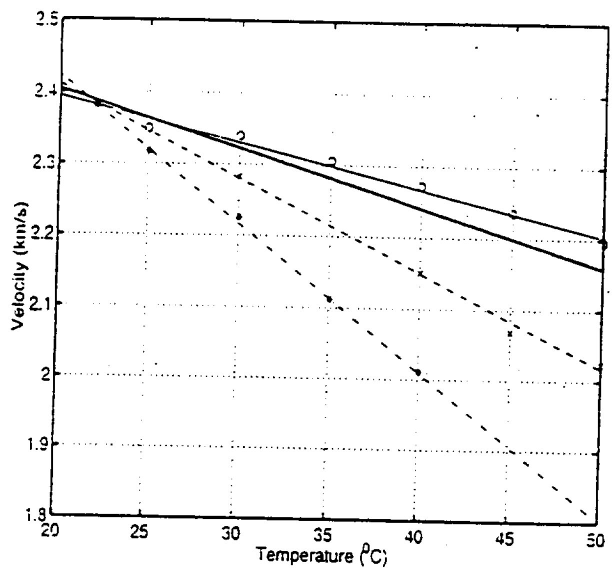
Definition of Temperature-Velocity Coefficient α_c

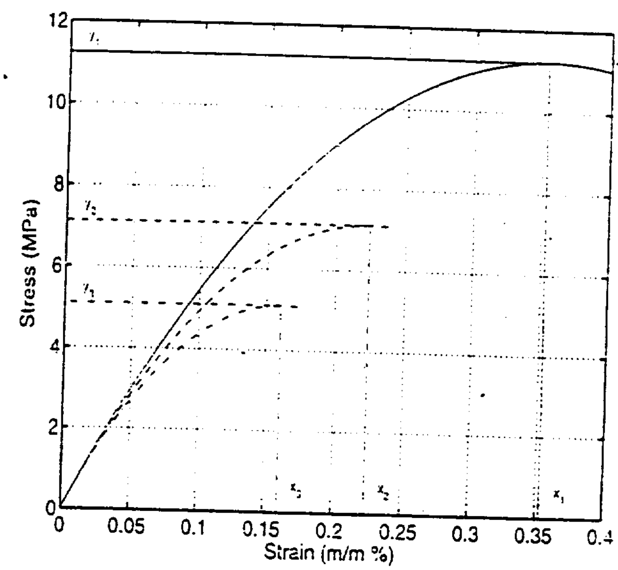
$$\frac{dc(T)}{c_0 dT} = -\alpha_c \quad (12)$$

Strain-Temperature Correspondence Relation

$$\frac{\epsilon}{\epsilon_0} = 2\alpha_c \Delta T - (\alpha_c^2 + 6\alpha_c\beta)\Delta T^2 + 3\alpha_c^2 \beta \Delta T^3 \quad (13)$$

Reconstructed Results





(a) (b)

(a)Temperature dependence of velocity in three samples and the bulk sample. bulk sample (solid line), sample $\#1$ (solid line, 'o'), sample $\#2$ (dashed, 'x'), sample $\#3$ (dash-dot, $'*'$).

(b)Theoretical prediction of ultimate strain and ultimate stress for AB Epoxy specimens. Solid (sample $\#1$), Dashed (sample $\#2$), Dash-dot (sample $\#3$)

Conclusions and Future Work

Conclusions

It has been shown that the new approach has potential. The application of the strain-temperature correspondence nondestructively yields nonlinear parameters which can only be obtained destructively otherwise. These nonlinear parameters can define the residual strength of an adhesive bond.

Future Work

(1) Improve the temperature controlling system.

(2) Measure the correspondence function.

(3) Apply this principle to study adhesive bond degradation.

35-38

Investigation of Adhesive Bond Cure Conditions using Nonlinear Ultrasonic Methods

Tobias P. Berndt and Robert E. Green, Jr.

CNDE
Center for Nondestructive Evaluation
The Johns Hopkins University

Department of Materials Science and Engineering

Acknowledgments:

Funding by NASA Langley and CNDE

Samples by BOEING

November 6, 1998

Objective

Investigate various Cure Conditions of Adhesive Bonds
using Nonlinear Ultrasonic Methods
with Water Coupling

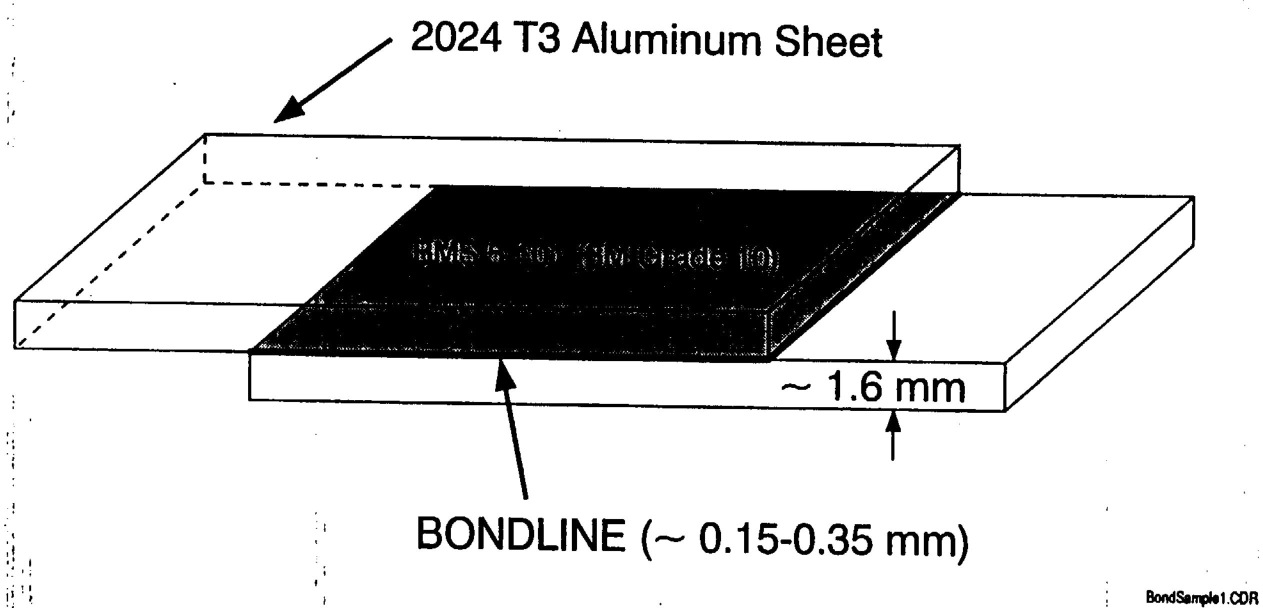
- **Normal Incidence**
- **Oblique Incidence**
- **Wave Mixing**

Samples

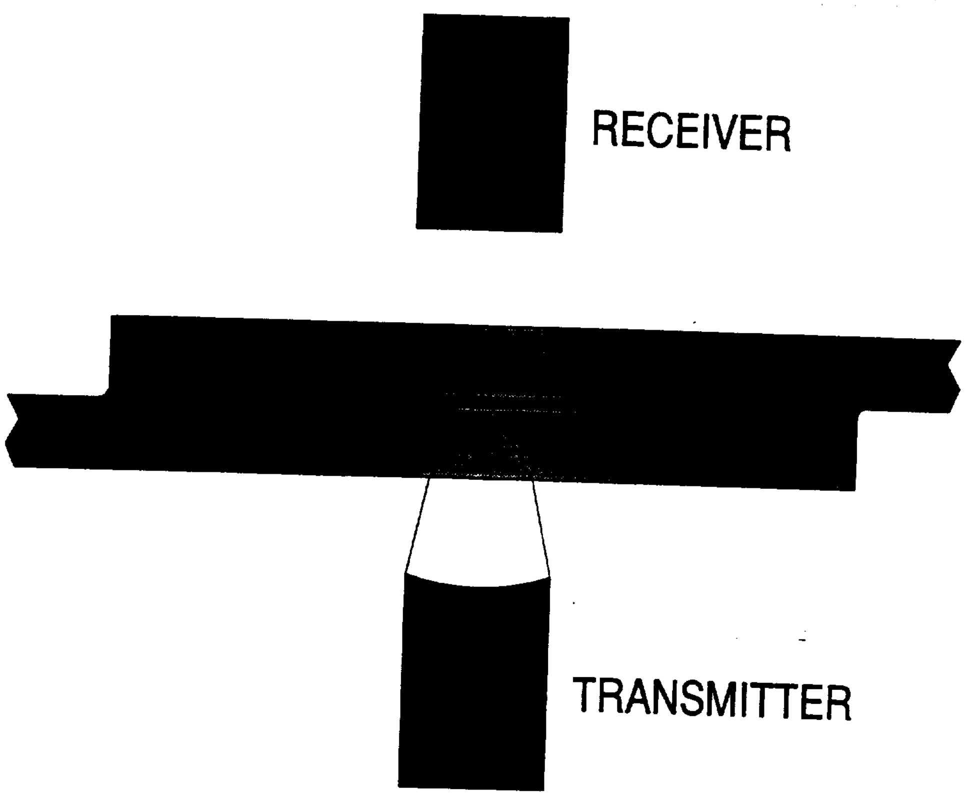
- 250 °F for 90 min at 50 psi (*Normal*)
- 180 °F for 60 min at 50 psi
- 180 °F for 120 min at 50 psi
- 195 °F for 60 min at 50 psi

- No significant differences in Bond Thickness across Samples
- Thicknesses: ~360μm (center) to ~150μm (edge)
- Longitudinal Velocity through Normal Bond (~2.33 mm/μs) up to 7% lower than in all other cases
- Shear Velocity through Normal Bond (~0.96 mm/μs) up to 6% lower than in all other cases

Adhesive Bond Sample

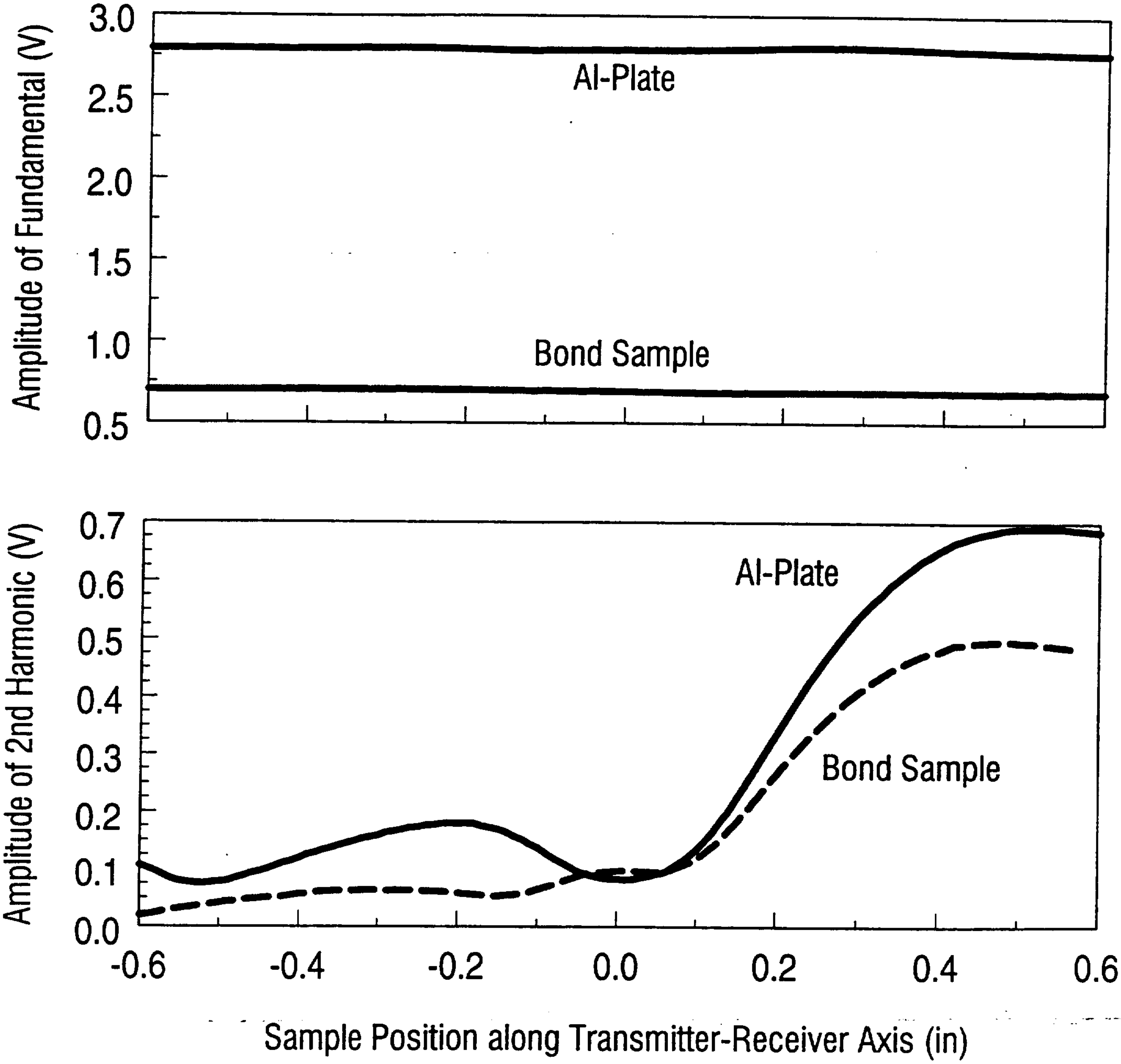


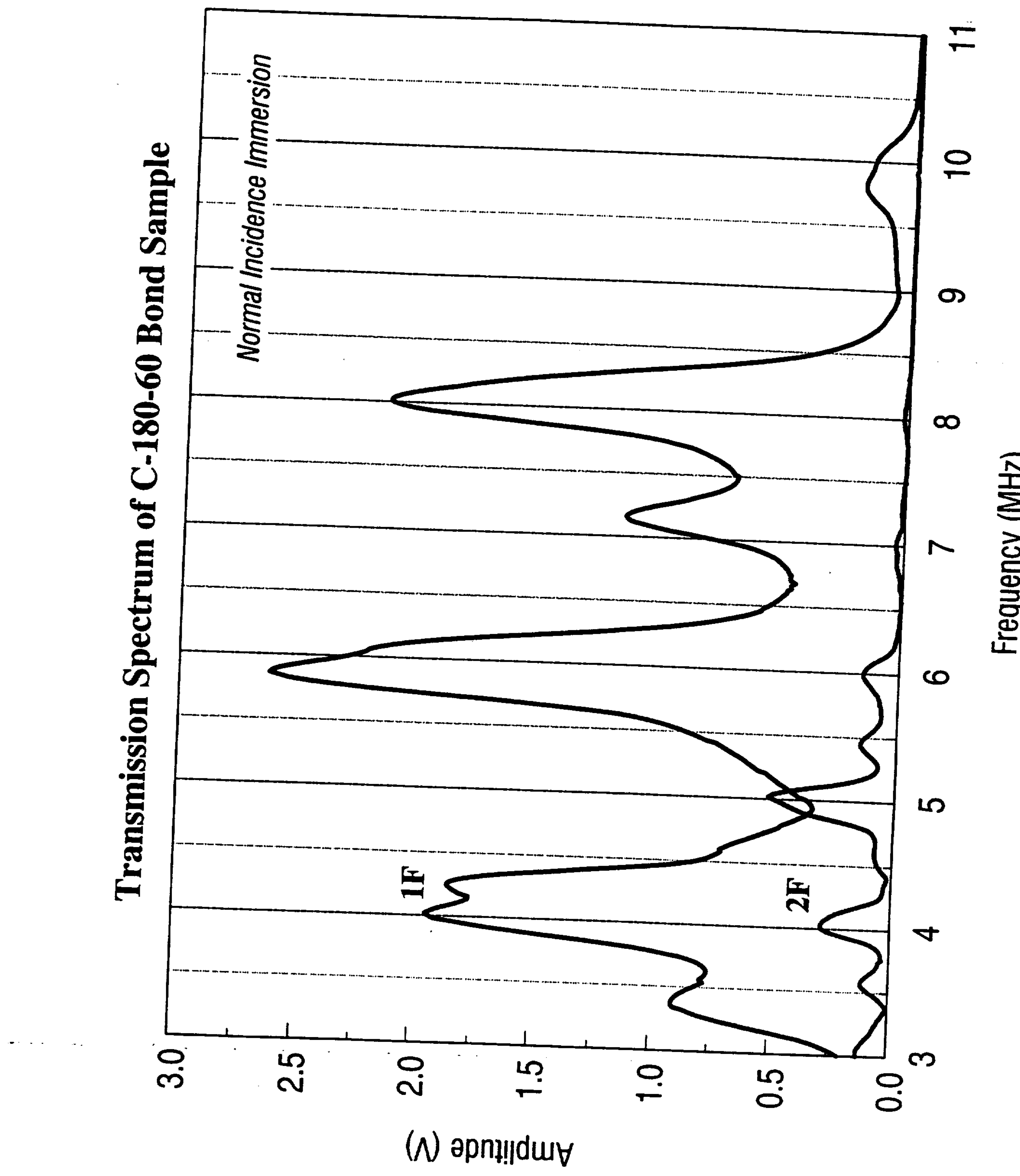
Normal Incidence
(Longitudinal Transmission)

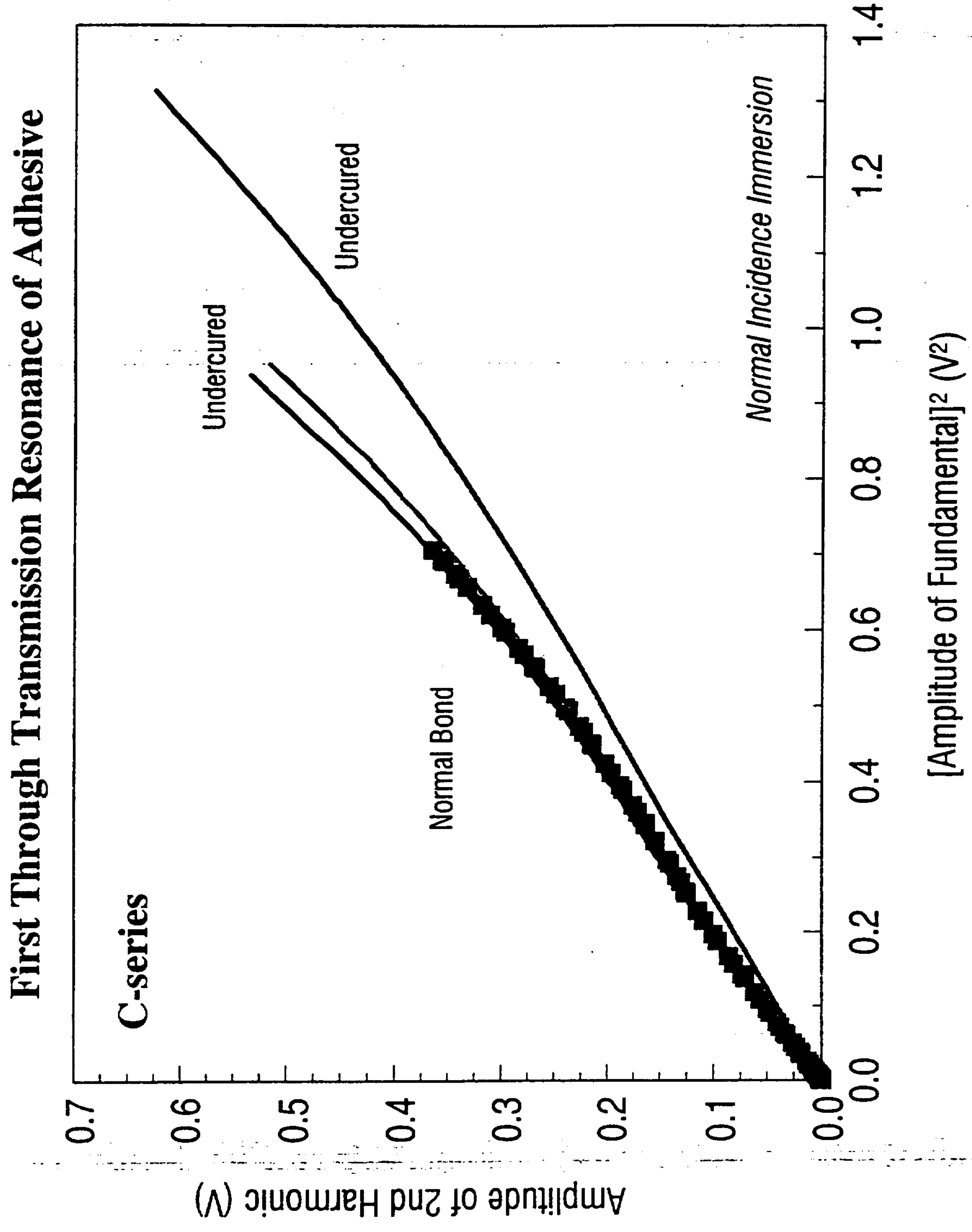


SFLTT_5.CDR

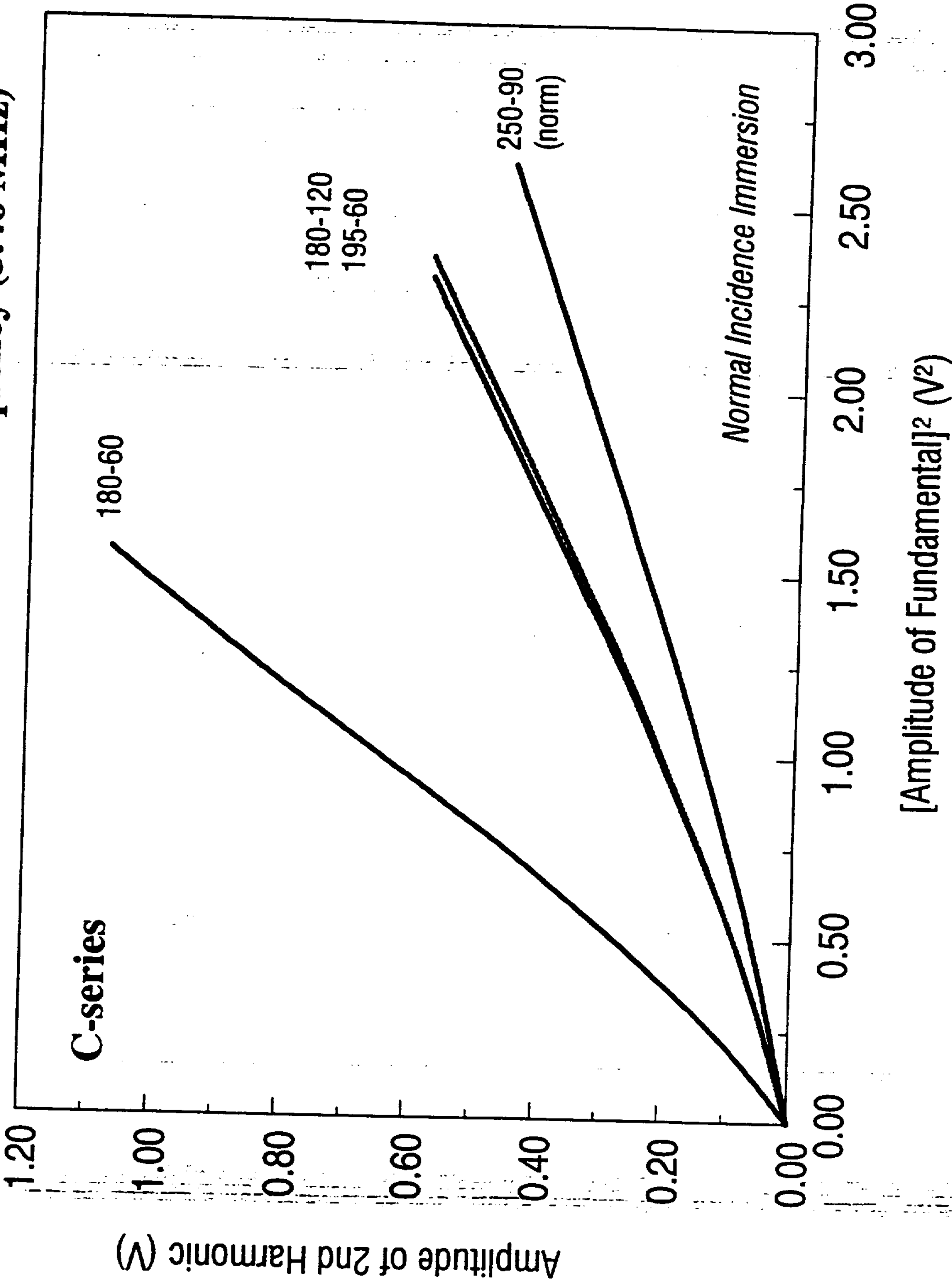
Bond Sample versus Single Aluminum Plate

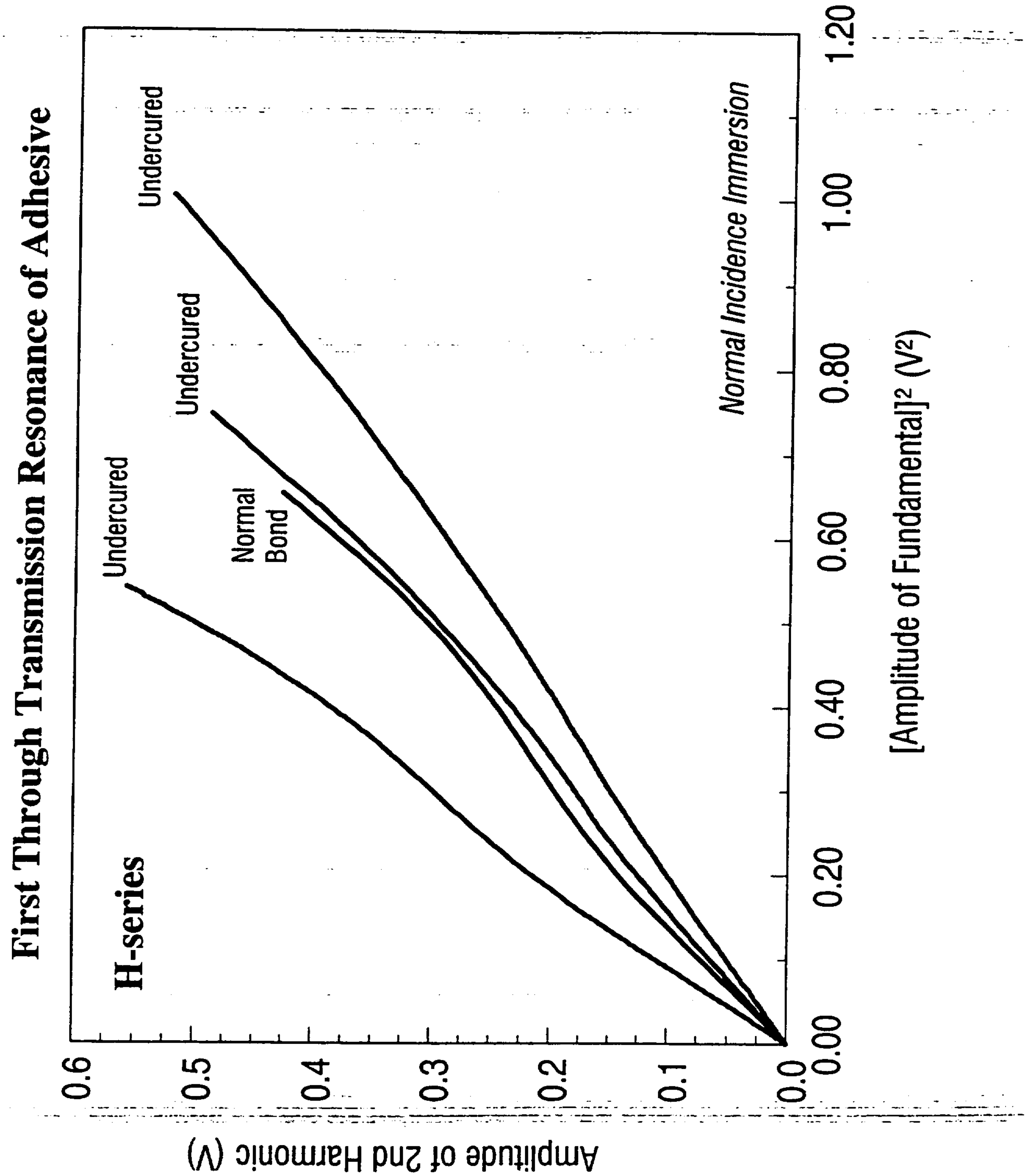


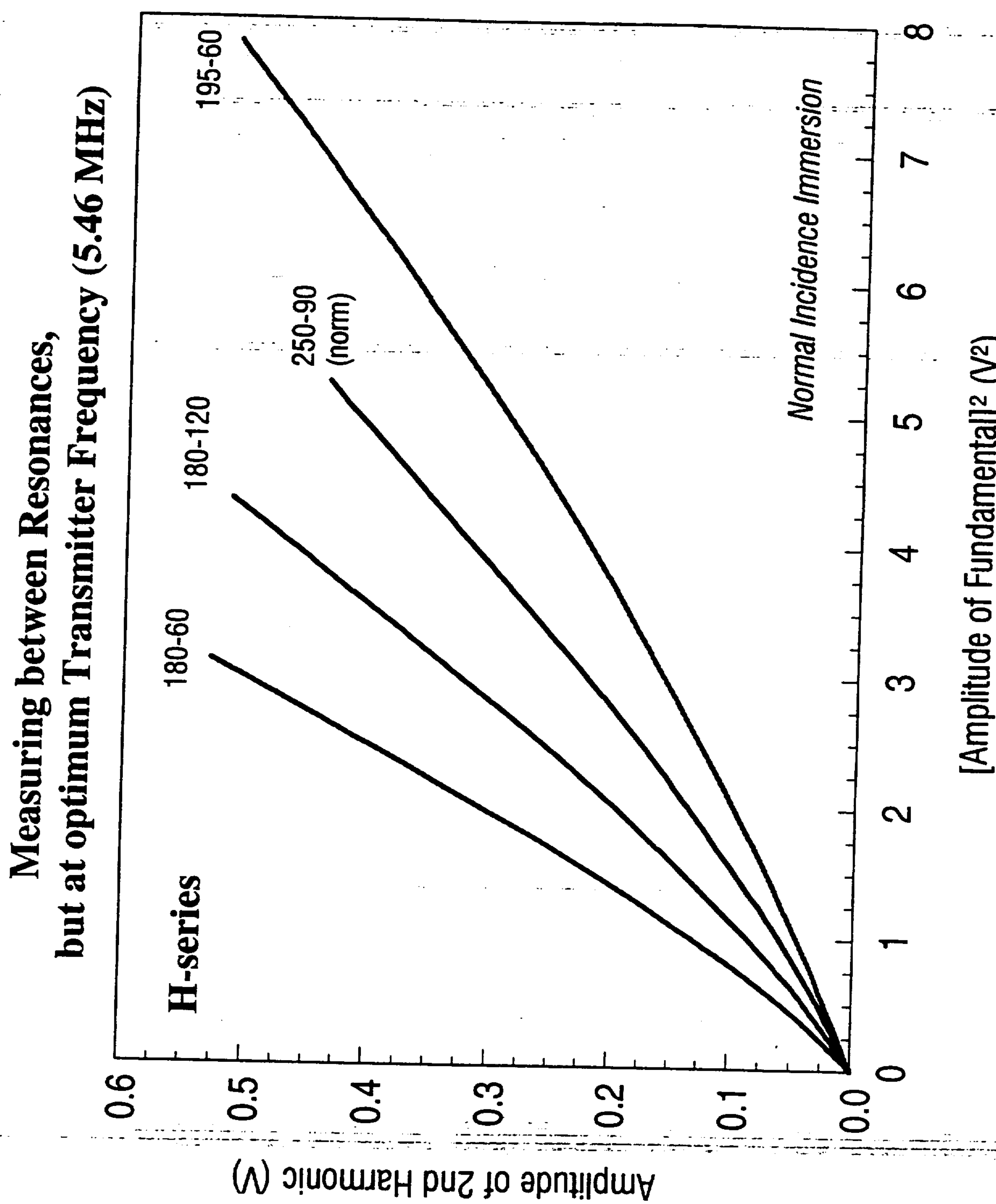

Transmission Spectrum of C-180-60 Bond Sample
Normal Incidence Immersion
1F
2F
Amplitude (V)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Frequency (MHz)
3
4
5
6
7
8
9
10
11


First Through Transmission Resonance of Adhesive
C-series
Undercured
Undercured
Normal Bond
Normal Incidence Immersion
Amplitude of 2nd Harmonic (V)
[Amplitude of Fundamental]² (V²)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Measuring between Resonances, but at optimum Transmitter Frequency (5.46 MHz)



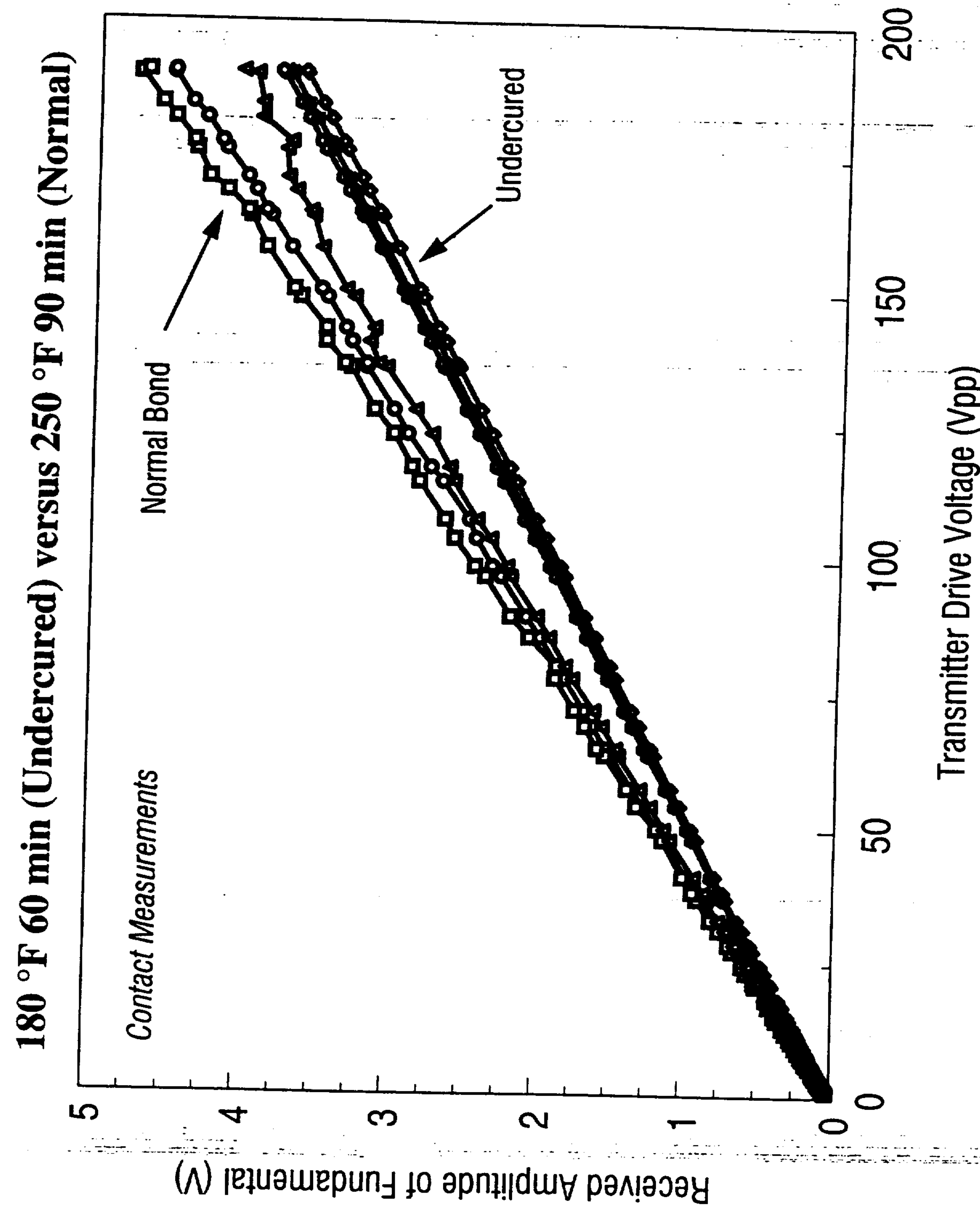

First Through Transmission Resonance of Adhesive
H-series
Undercured
Undercured
Undercured
Normal
Bond
Undercured
Normal Incidence Immersion
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Amplitude of 2nd Harmonic (V)
0.00
0.20
0.40
0.60
0.80
1.00
1.20
[Amplitude of Fundamental]² (V²)



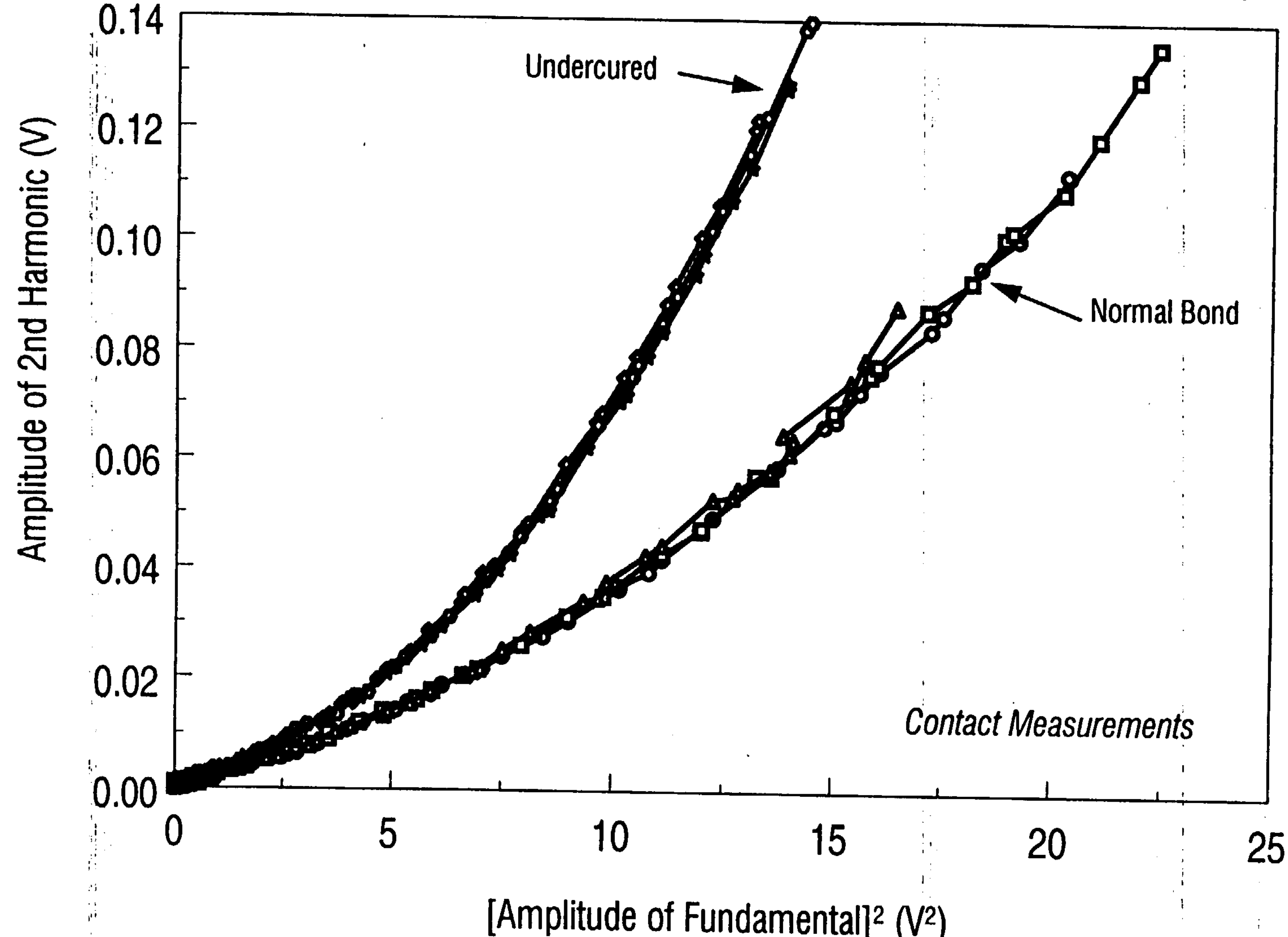
Measuring between Resonances,
but at optimum Transmitter Frequency (5.46 MHz)
H-series
180-60
180-120
250-90
(norm)
195-60
Normal Incidence Immersion
Amplitude of 2nd Harmonic (V)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
[Amplitude of Fundamental]² (V²)
0
1
2
3
4
5
6
7
8

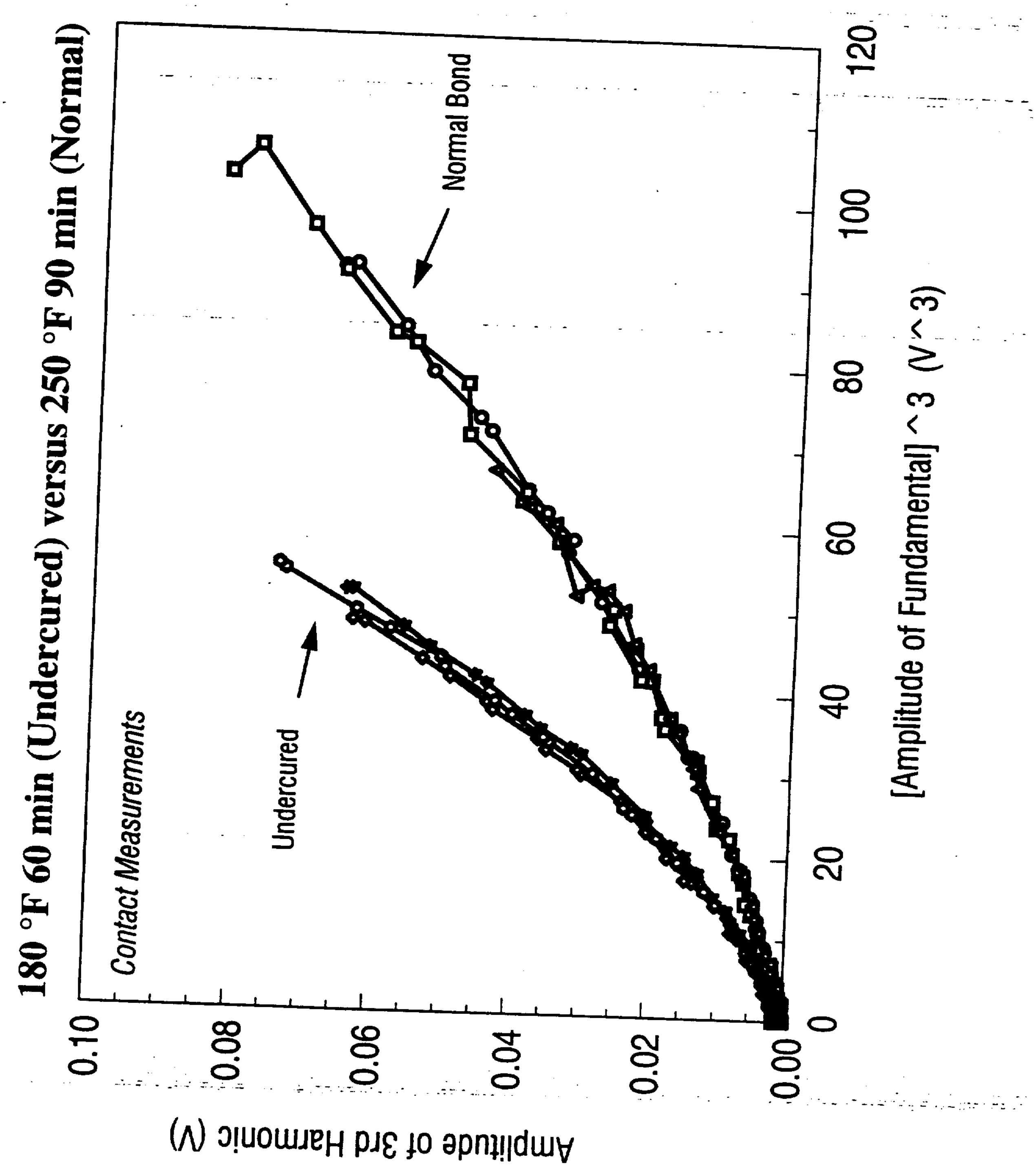
Contact Measurements

- To verify existence of and differences in both 2nd and 3rd Harmonics in given Bond system
- Transmitter: 5 MHz $LiNbO_3$ bonded with SALOL
- Receiver: 10 MHz broadband (commercial contact)
- Samples: 0.25" Aluminum Substrates

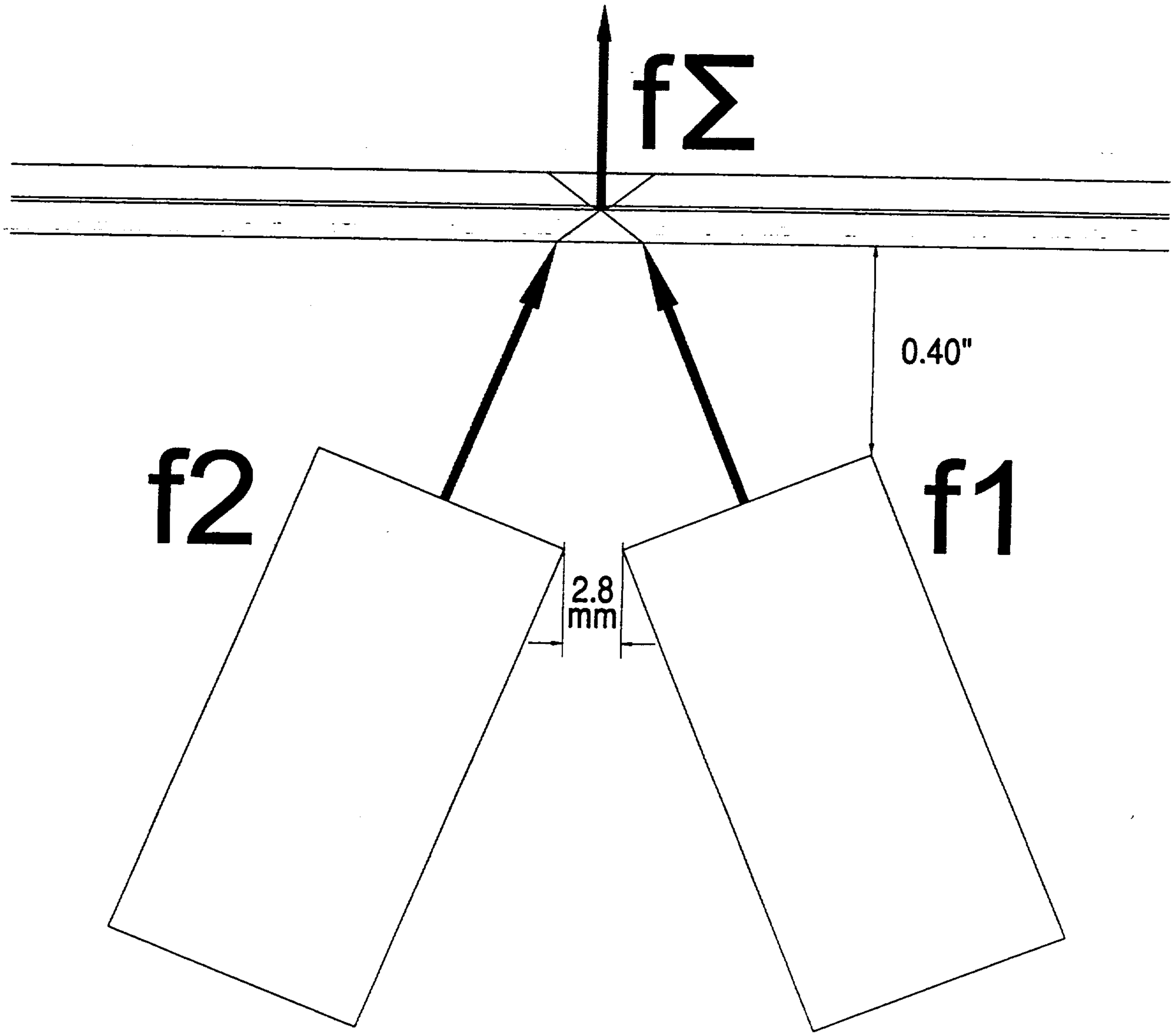

180 °F 60 min (Undercured) versus 250 °F 90 min (Normal)
Contact Measurements
Normal Bond
Undercured
Received Amplitude of Fundamental (V)
Transmitter Drive Voltage (Vpp)
0
1
2
3
4
5
0
50
100
150
200

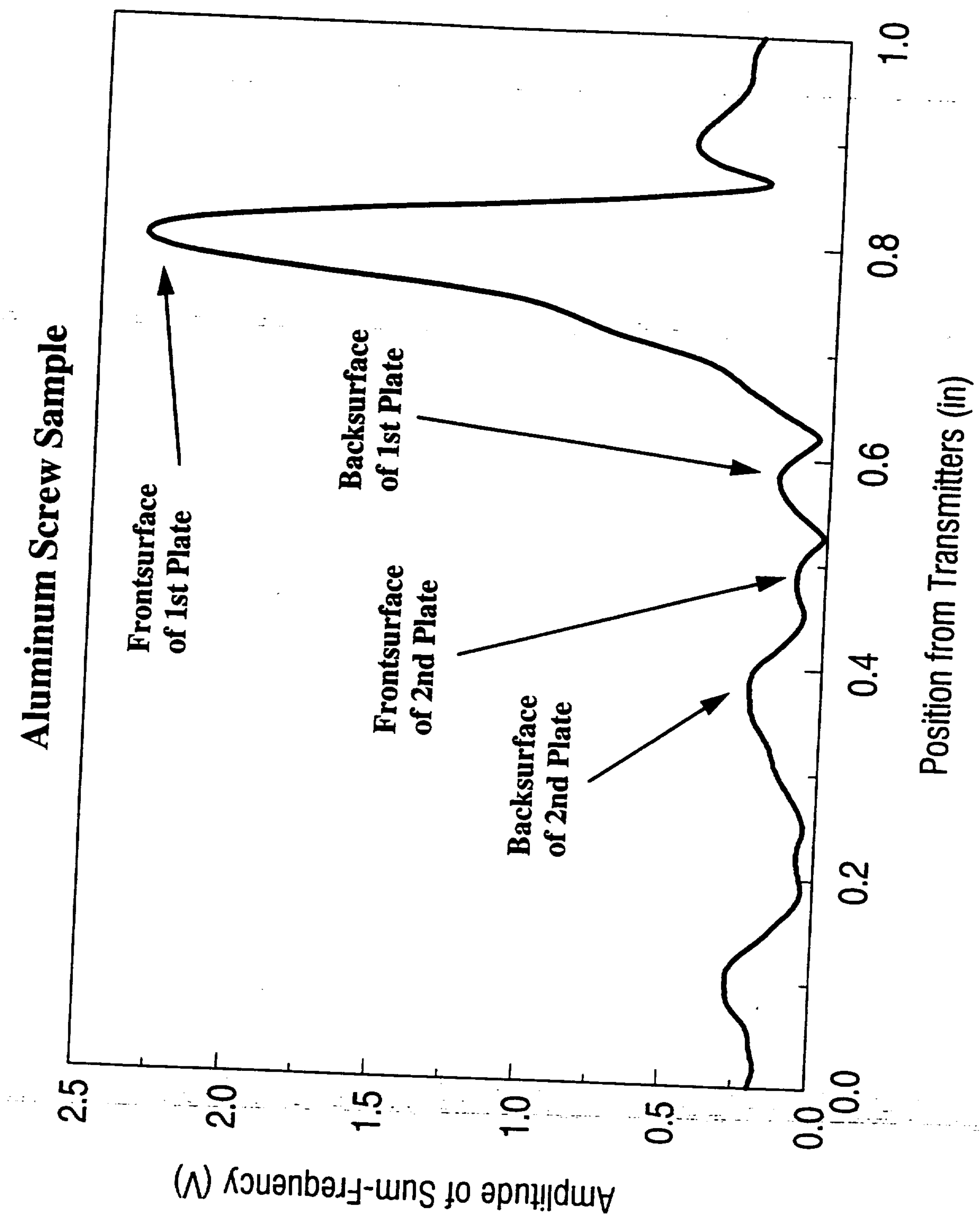
180 °F 60 min (Undercured) versus 250 °F 90 min (Normal)



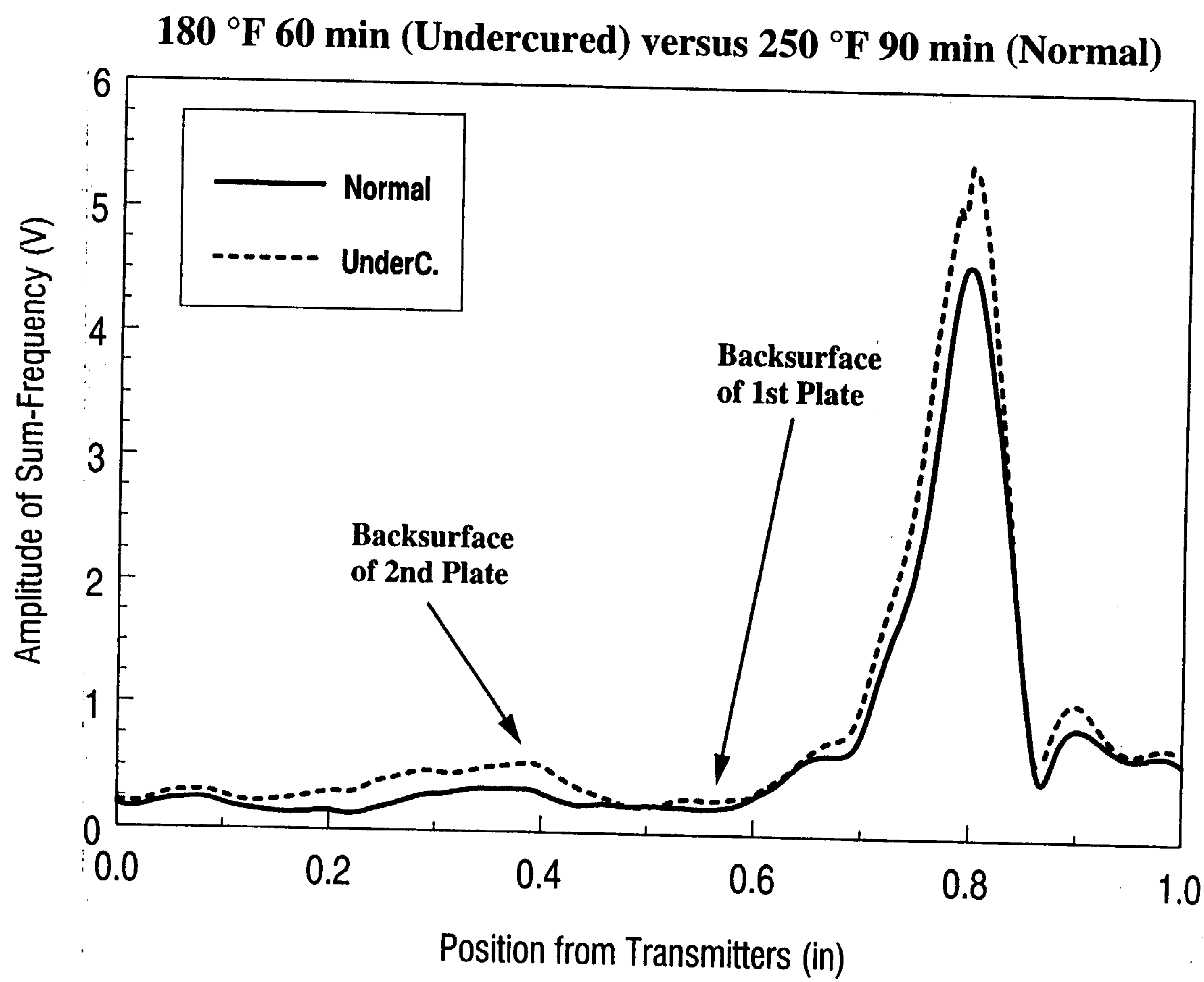


180 °F 60 min (Undercured) versus 250 °F 90 min (Normal)
Contact Measurements
Undercured
Normal Bond
Amplitude of 3rd Harmonic (V)
[Amplitude of Fundamental] ^3 (V^3)
0.00
0.02
0.04
0.06
0.08
0.10
0
20
40
60
80
100
120

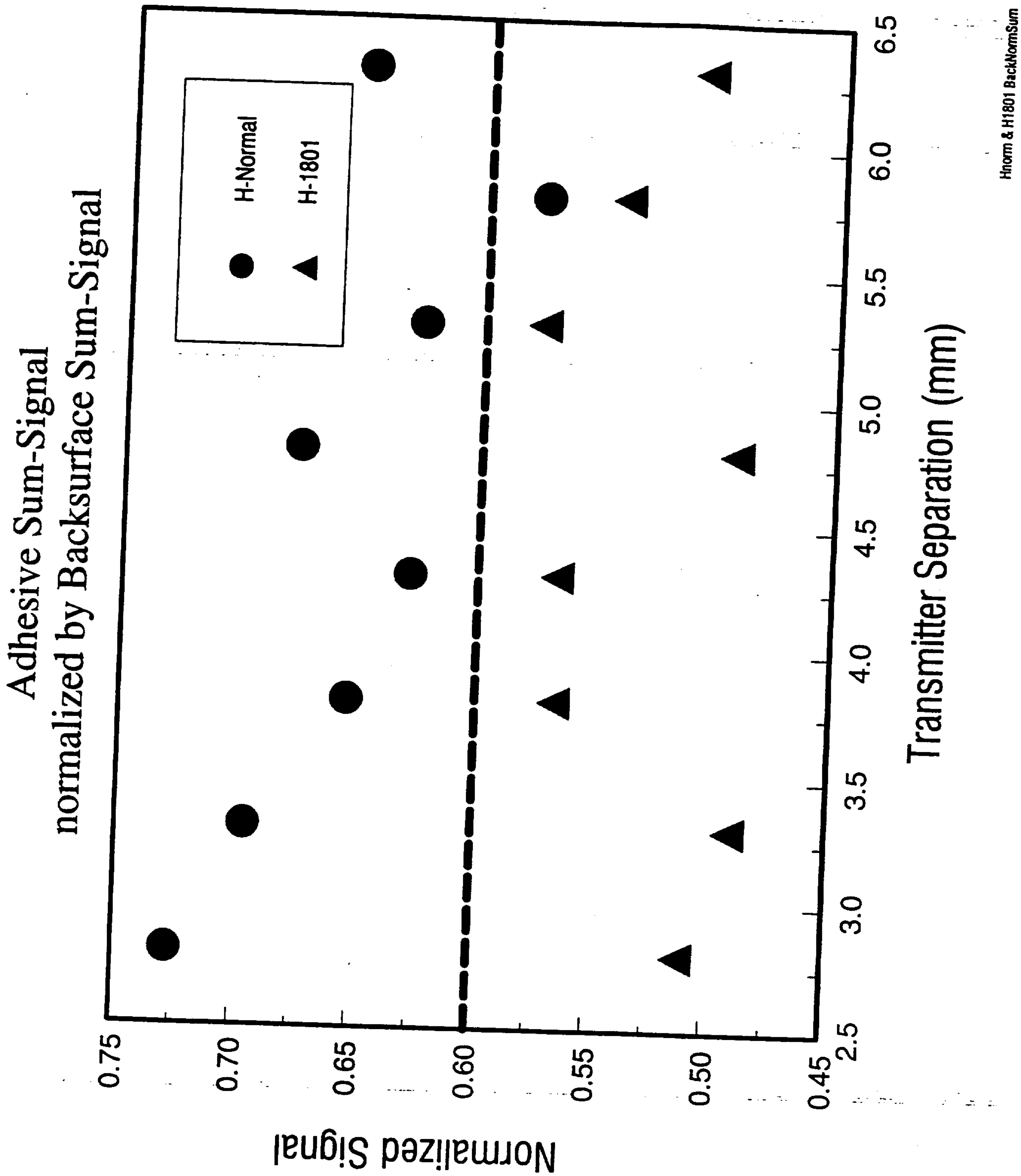

fΣ
0.40"
f2
f1
2.8
mm



Aluminum Screw Sample
Frontsurface of 1st Plate
Backsurface of 1st Plate
Frontsurface of 2nd Plate
Backsurface of 2nd Plate
Amplitude of Sum-Frequency (V)
Position from Transmitters (in)
0.0
0.5
1.0
1.5
2.0
2.5
0.0
0.2
0.4
0.6
0.8
1.0



180 °F 60 min (Undercured) versus 250 °F 90 min (Normal)
Normal
UnderC.
Backsurface of 1st Plate
Backsurface of 2nd Plate
Amplitude of Sum-Frequency (V)
Position from Transmitters (in)
0
1
2
3
4
5
6
0.0
0.2
0.4
0.6
0.8
1.0


Adhesive Sum-Signal
normalized by Backsurface Sum-Signal
H-Normal
H-1801
Normalized Signal
0.75
0.70
0.65
0.60
0.55
0.50
0.45
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
Transmitter Separation (mm)
Hnorm & H1801 BackNormSum

ABUS System for Quantitative Inspection of Adhesive Bonds

Laszlo Adler, Stanislav I. Rokhlin
Christophe Mattei, Gabor Blaho

Adler Consultants, Inc.
Columbus, Ohio.

Supported by S.B.I.R. Program, Contract #N68335-97-C-0328

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Outlines

- **Our Approach to Quantitative Bond Inspection**
  - Statement of the problem
  - Ultrasonic Spectroscopy
  - Bond Quality Scanning
- **The ABUS Scanning Inspection System**
  - System Hardware description
  - System Software Description
- **Validation results**
  - Inspection results
  - ABUS Data Correlation to Strength

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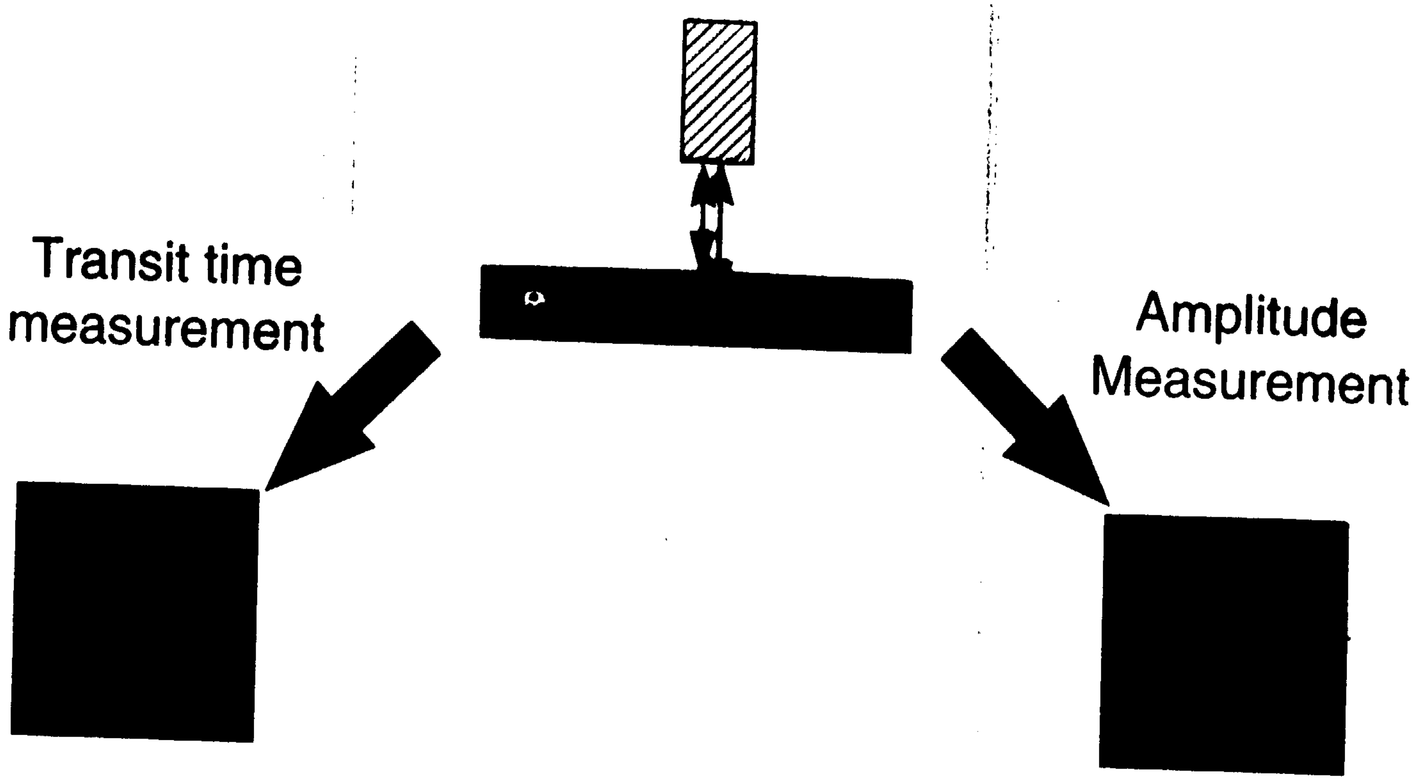
Problem Statement

- Adhesive bond integrity depends on:
  - Adhesive bulk properties
  - Adhesion between adhesive and the substrates
- Usually, weak bonds are associated with poor adhesion or effect of kissing bonds.
- Weak bonds remain hidden from conventional inspection methods

Conventional Ultrasonic Inspection



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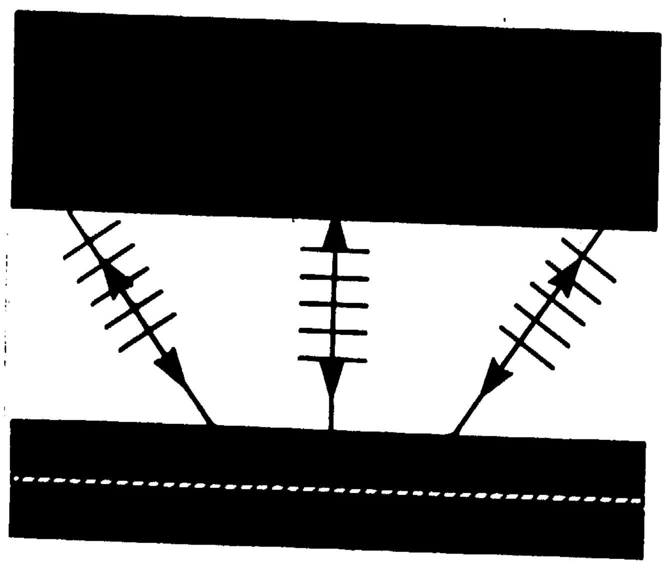
Angle Beam Ultrasonic Spectroscopy for Adhesive Joint Inspection: Approach

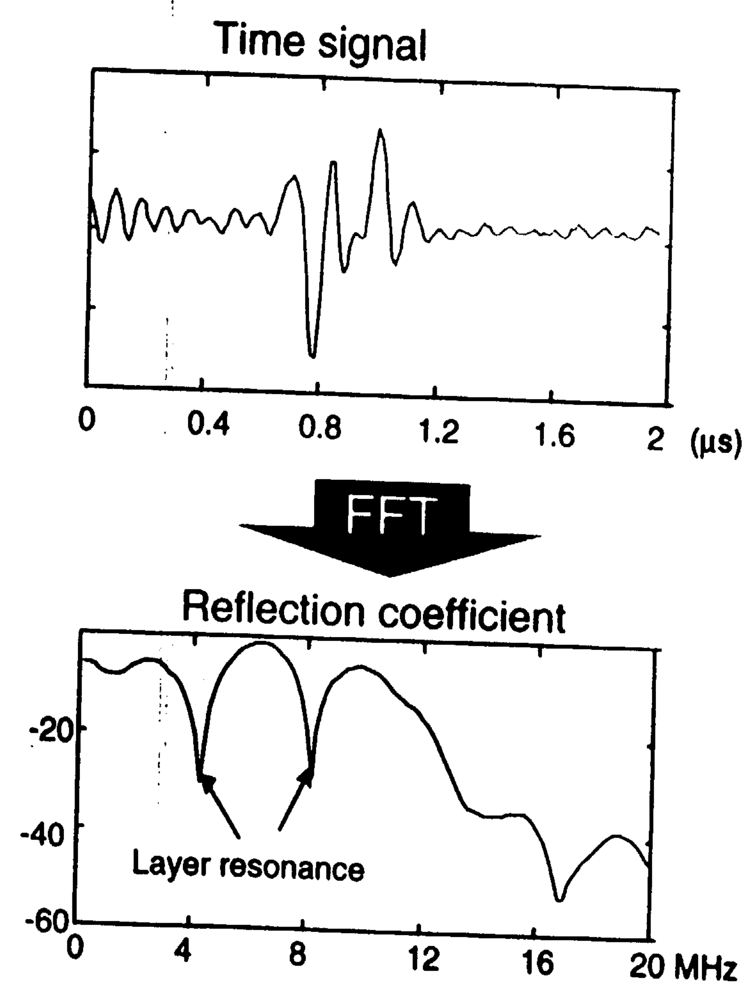
The novelty of this approach is:

- It combines the application of obliquely and normally incident ultrasonic beam on the bond line
- It measures the frequency response of the bond line
- The oblique wave introduces shear stress on the bond line, allowing discrimination of kissing or poor bond from good bonds
- The normally incident wave is used to decouple the effect of the bond line thickness

Angle Beam Ultrasonic Spectroscopy



Simultaneous Normal and Oblique Incidence Reflection Coefficient



7

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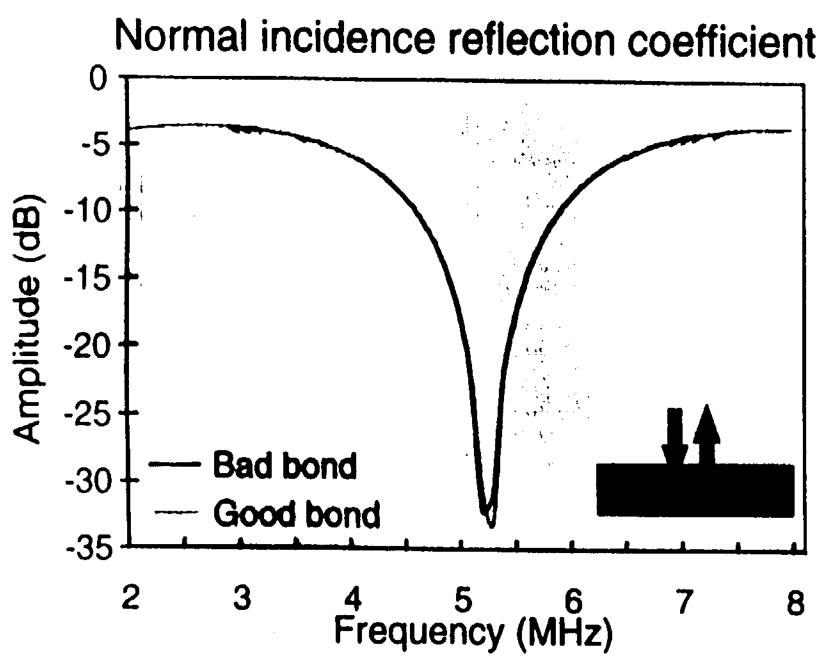
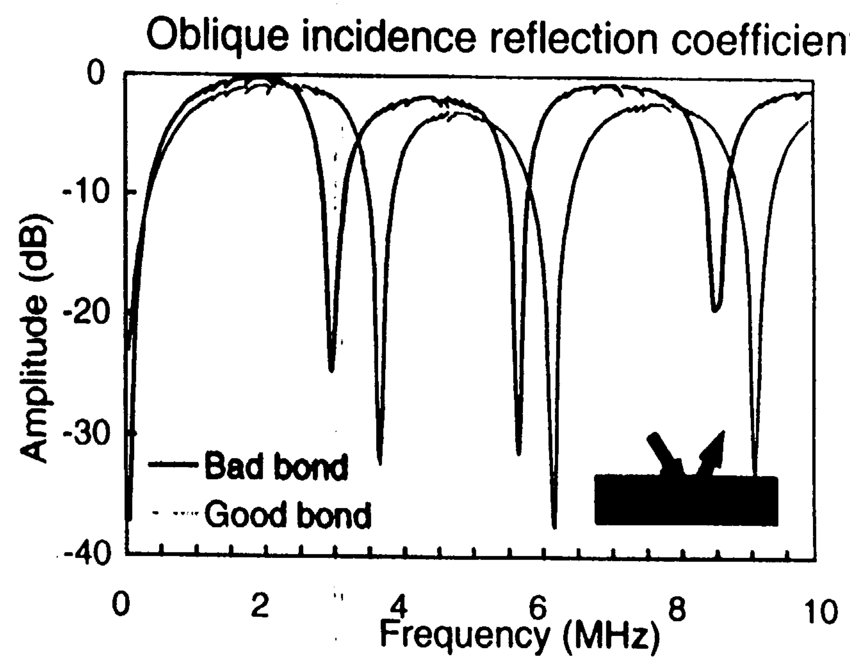
Reflection Coefficients Calculation



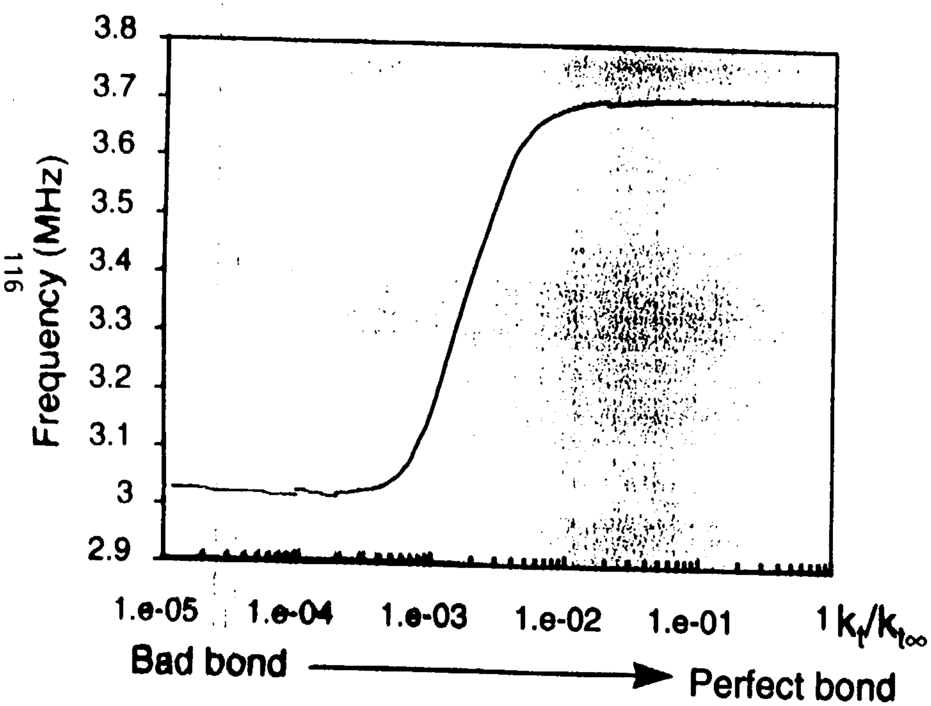


Conclusion:

Adhesive joint degradation effect:

- Little effect on the normal incidence reflection spectrum
- Oblique incidence reflection spectrum exhibits strong shift of the spectrum minima

Effect of Imperfect Layer/Substrate Interface on Ultrasonic Signature

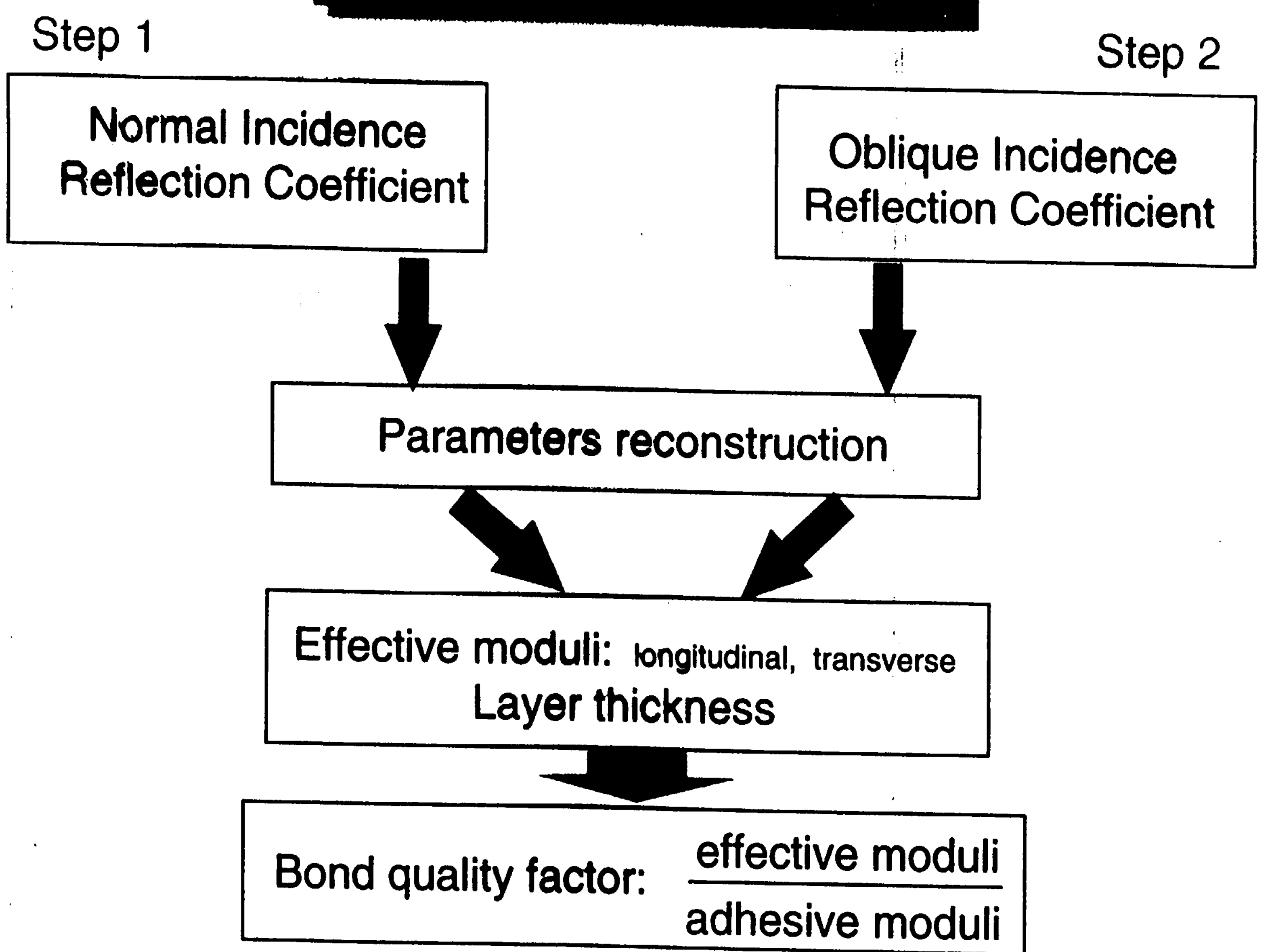


Simulation of frequency shift as function of interface spring constant for an oblique incident angle on composite

- Oblique incident ultrasonic waves are sensitive to adhesive / adherent interface quality

- Interface modeling allows us to select incidence angle which is sensitive to interface quality

The ABUS concept:
Layer Properties Reconstruction



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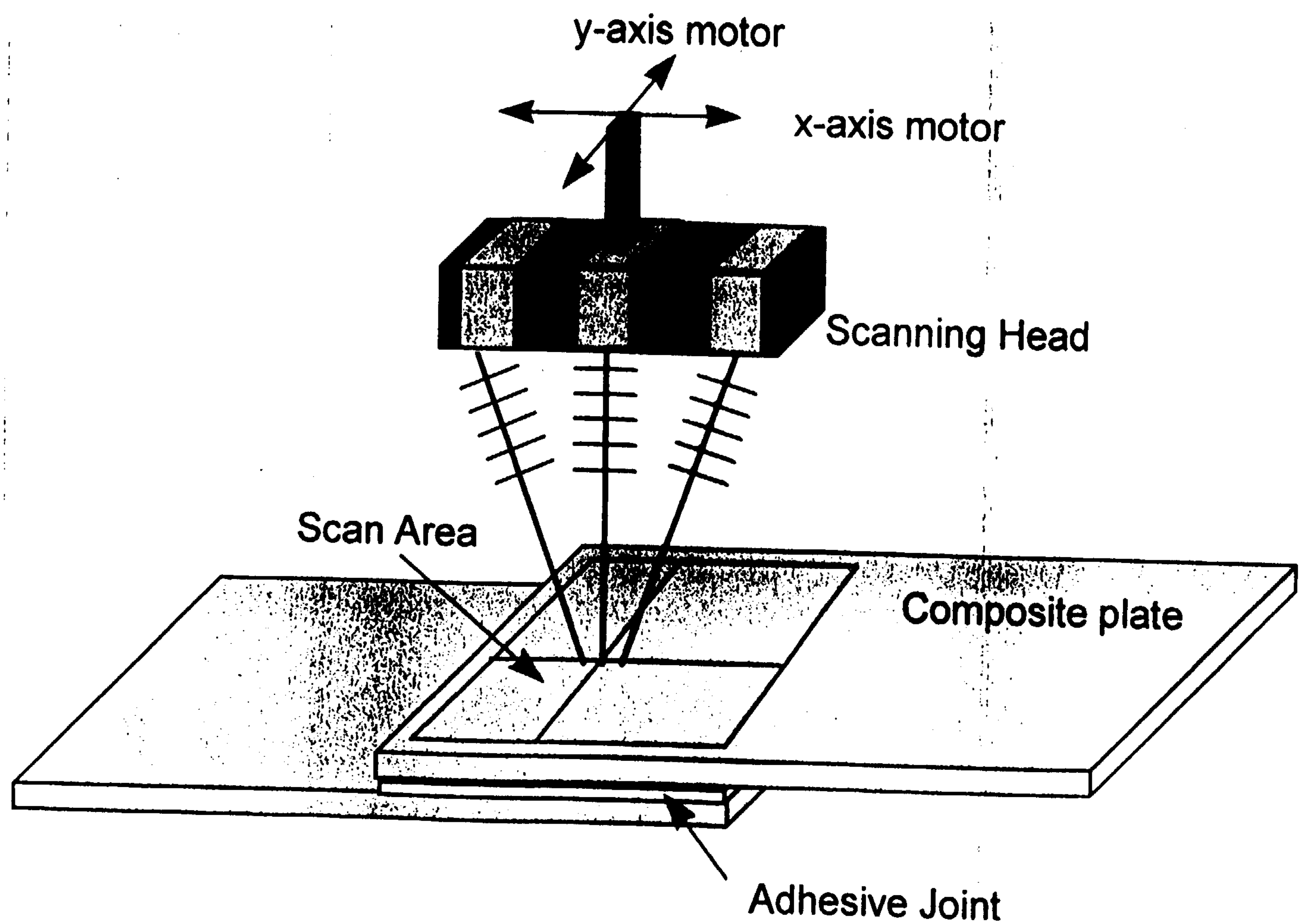
The Angle Beam Ultrasonic Spectroscopy (ABUS) Scanner Concept



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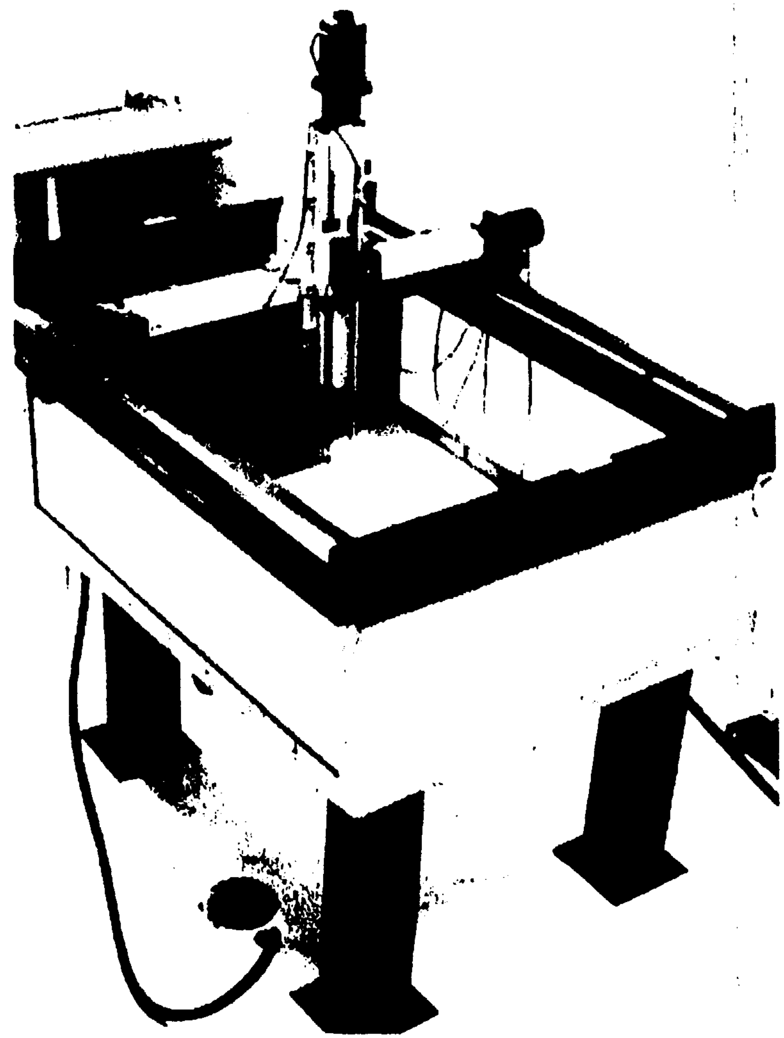
The ABUS System



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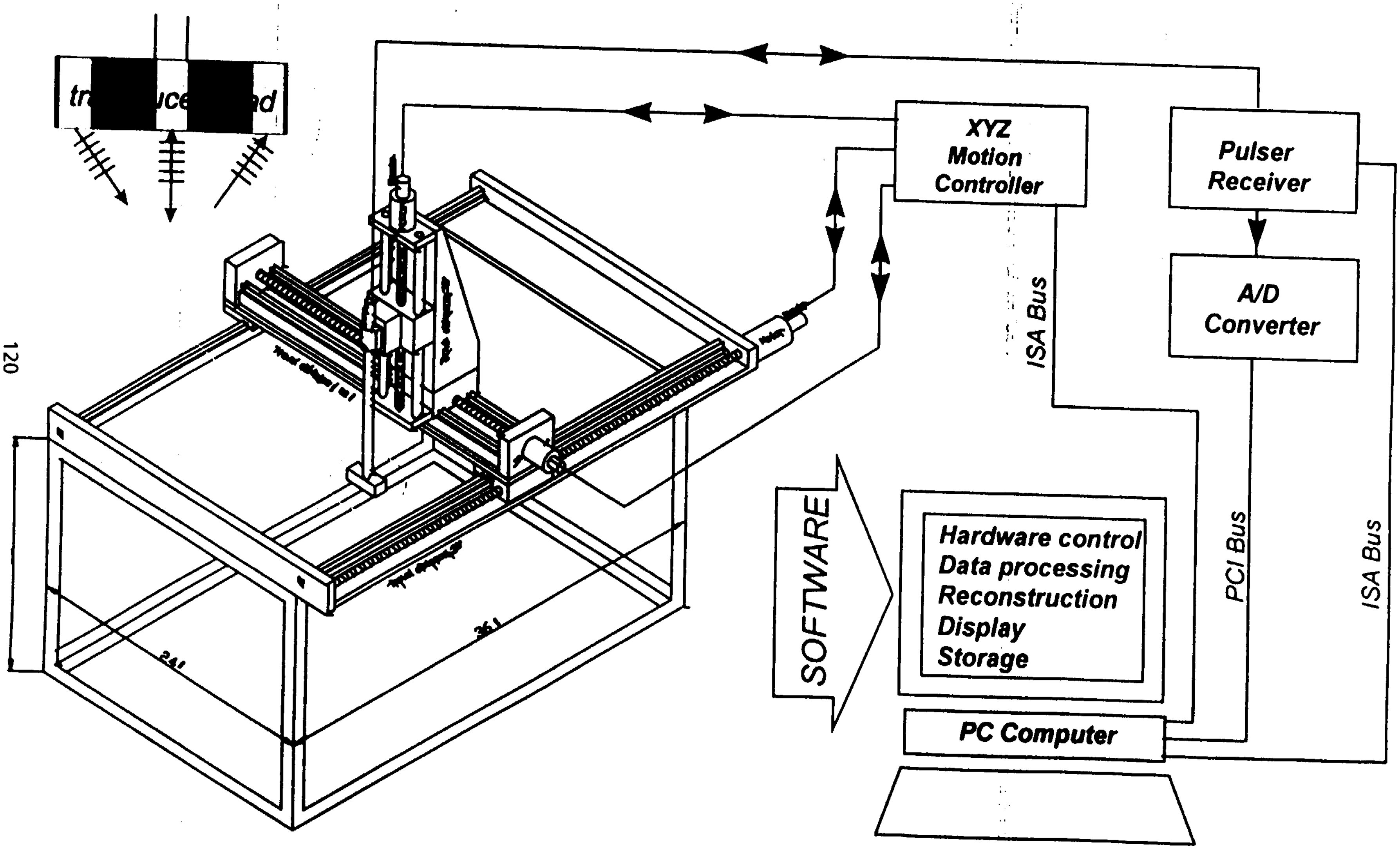
The ABUS System



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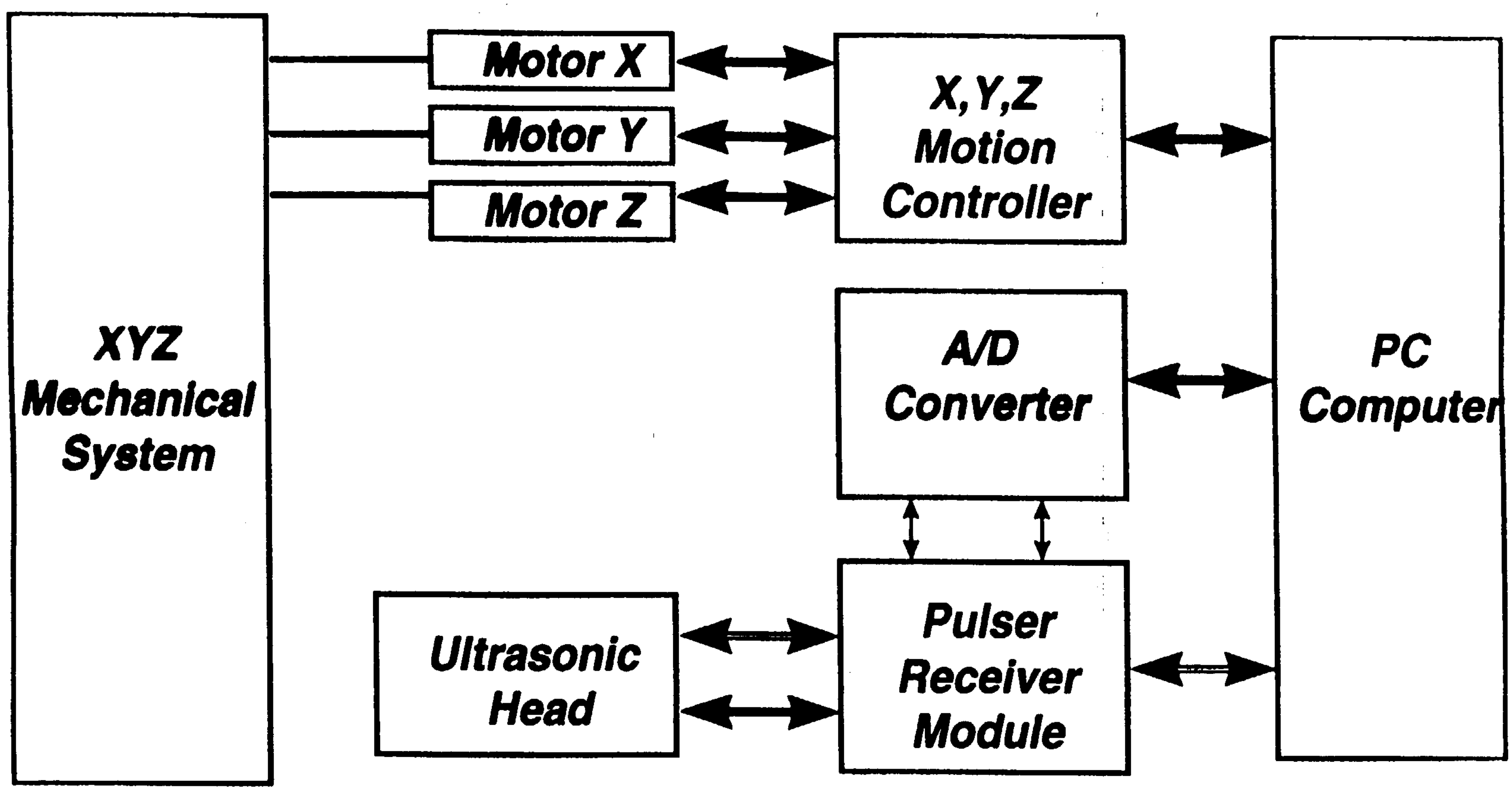
ABUS System Hardware Overall Design



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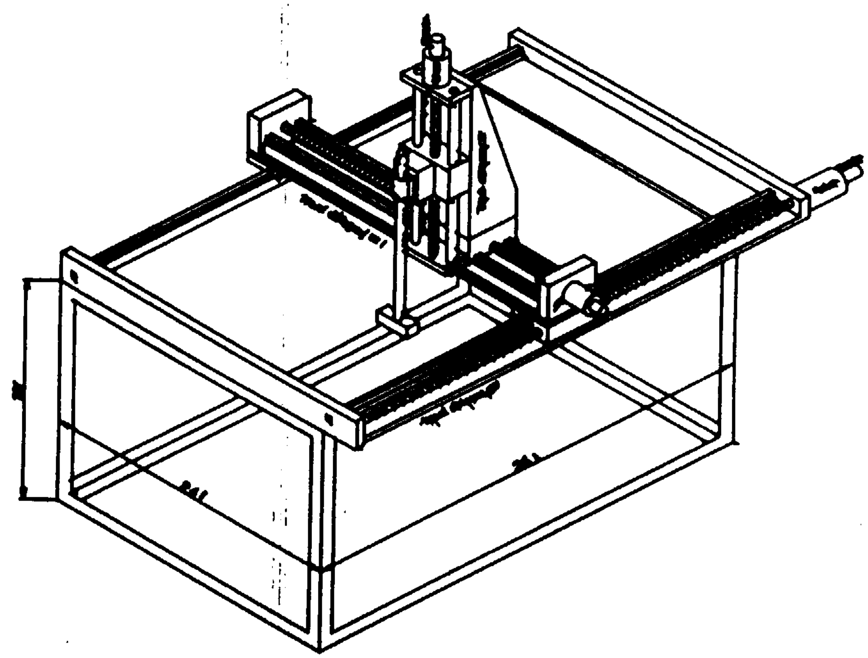
ABUS System Hardware Mechanics

- ***Three axis Parker Deadal mechanical system***

X axis: Open Frame Square Rail Positioning Table
38"x24" opening in base plate
40" travel, Max. travel speed: 1'/s
Precision Ground Ball Screw
Optical home and end of travel

Y axis: Square Rail Positioning Table
23.6" travel, Max. travel speed: 1'/s
Precision Ground Ball Screw
Optical home and end of travel

Z axis: Square Rail Positioning Table
11.8" travel, Max. travel speed: 1'/s
Standard Ball Screw
Optical home and end of travel



- *American Precision Industries* ***Microstep Motors****:* 300 oz-in torque, 45000 step per revolution
- *American Precision Industries Low EMI* ***microstepping drive and power supply***
- *Parker Compumotor PC Based* ***Step Motor Controller***

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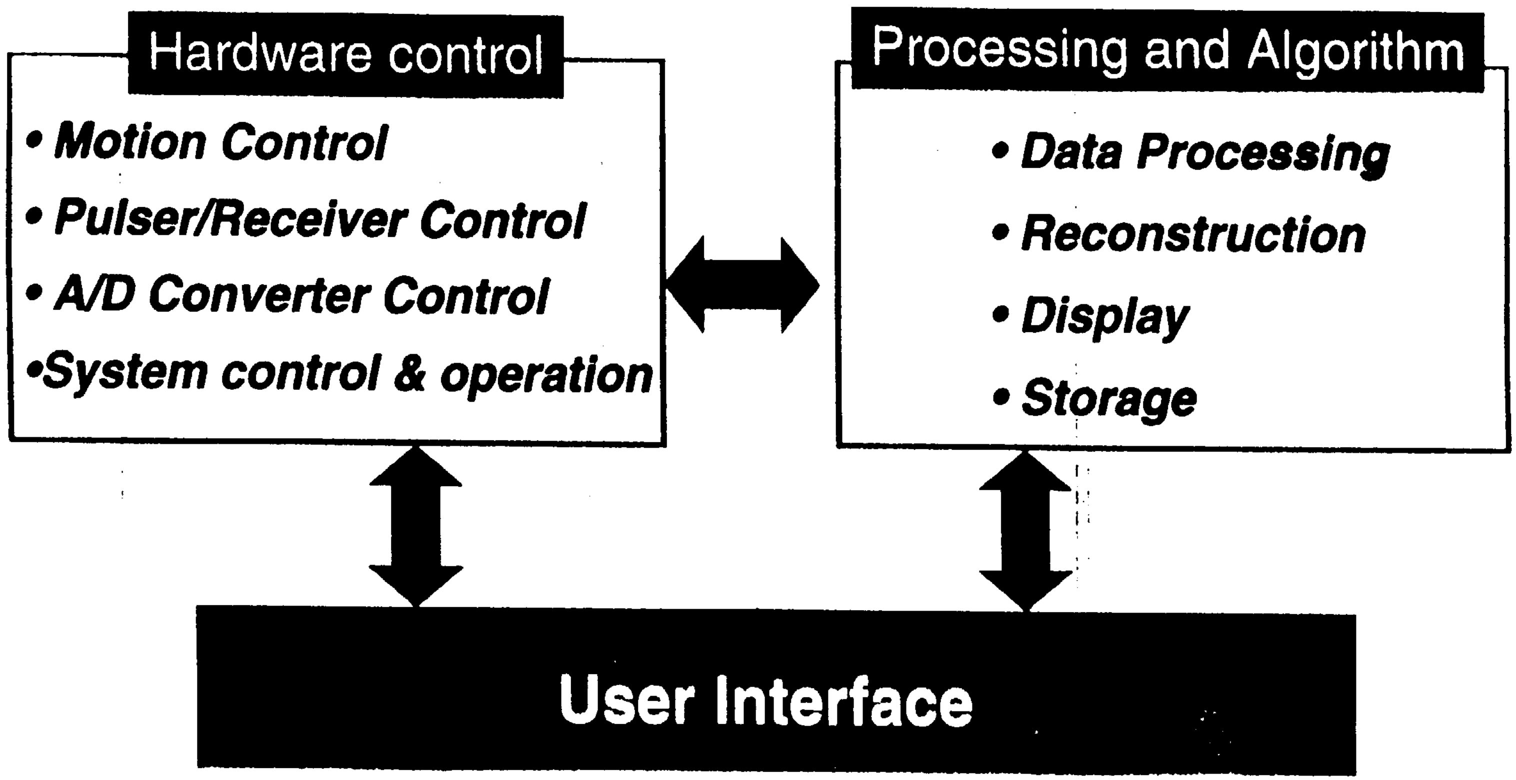
ABUS System: Software
Overall Design



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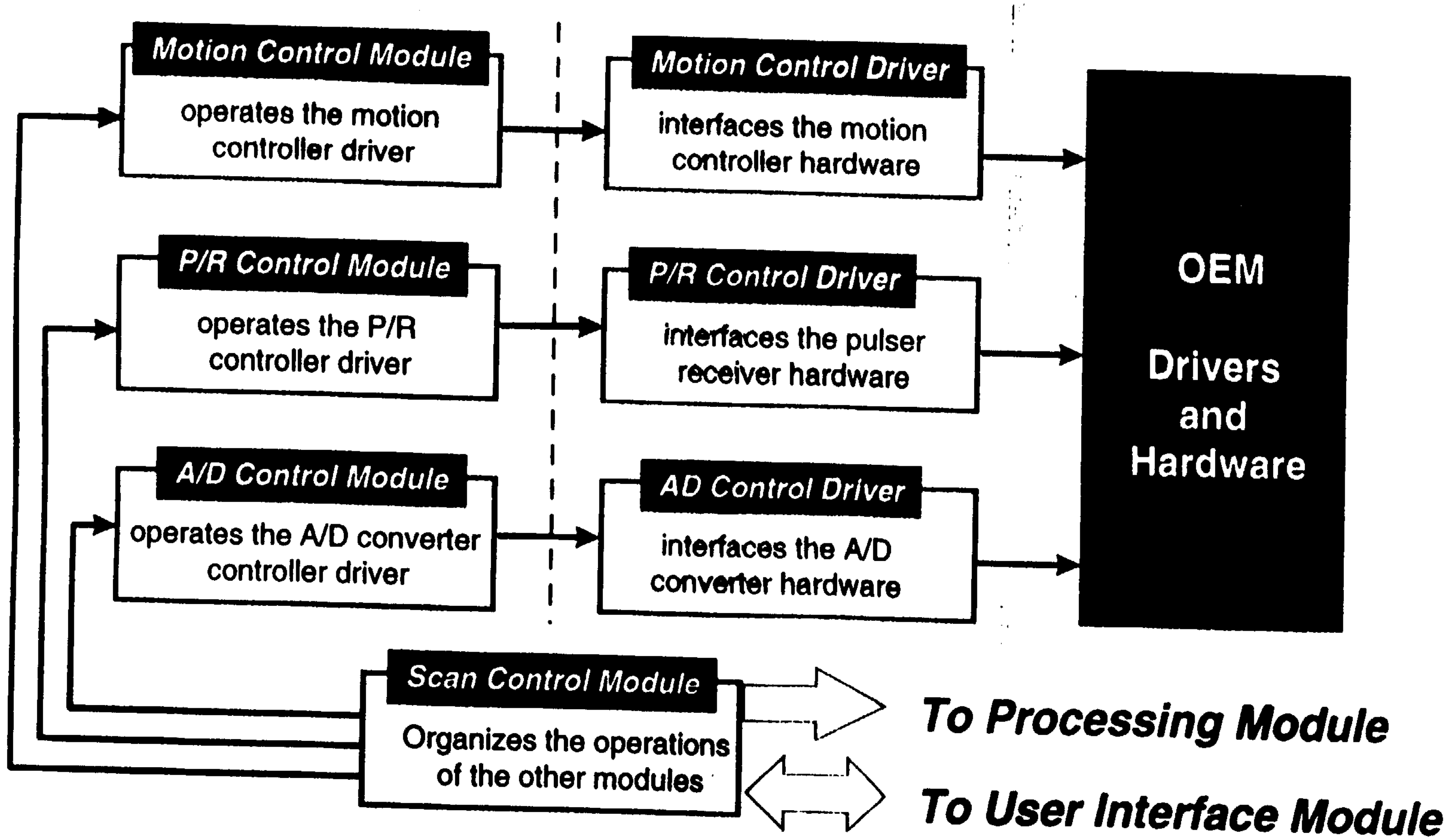
ABUS System: Software Hardware Control



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ABUS System: Software User Interface Design

System operation control

A/D Control

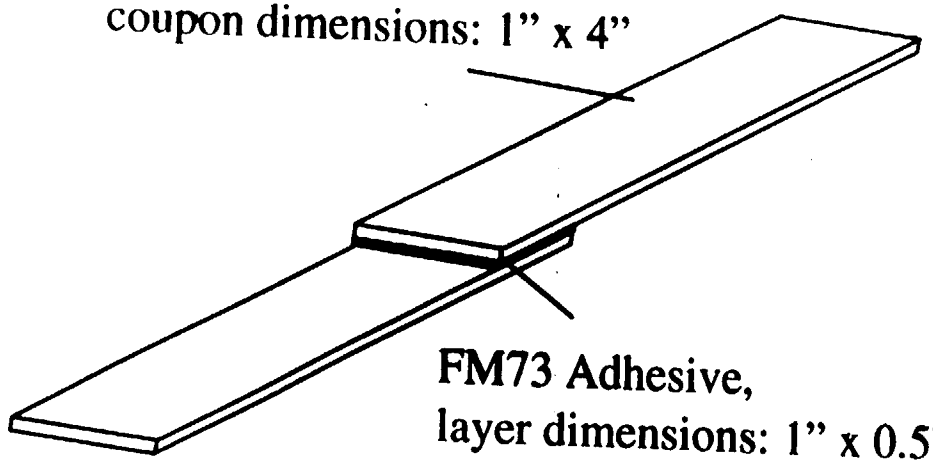
2 Channels (Normal and Oblique)
- Sampling rate
- Trigger control
- Time domain signal display

3 gates per channel:
- Gates position control (start and width)
- Gates display

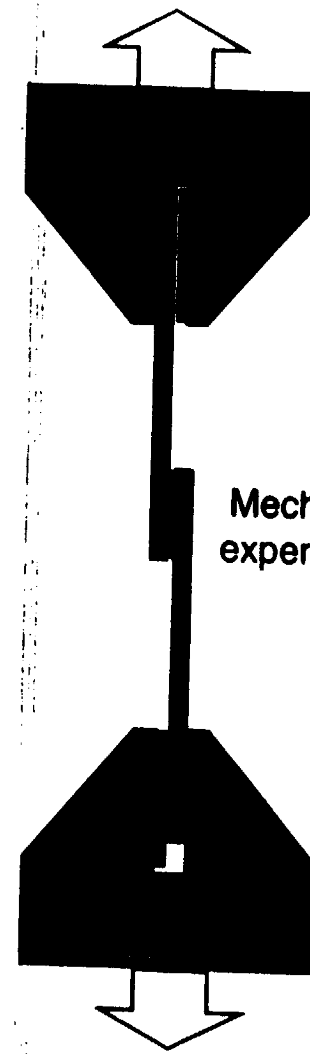
Scan Control

- Scanning size
- Scanning step
- Scanning speed
- Reference points control

Sample Preparation and Mechanical Testing



	Average failure load
Treated samples	800 lb
Reference samples	1400 lb



Mechanical testing experimental set-up

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ABUS System: Software User Interface

Data processing and display

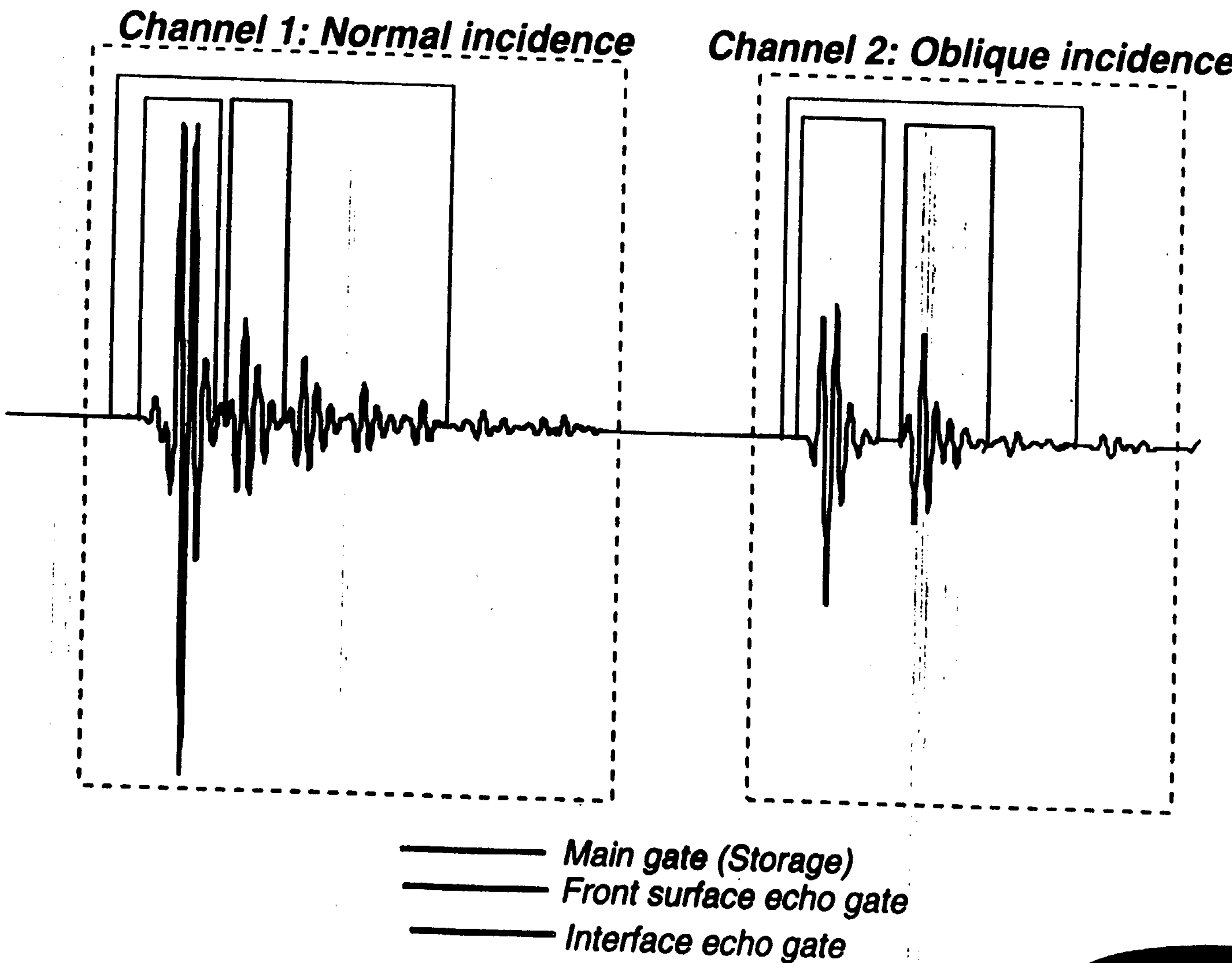
Processing control

- *FFT control parameters*
- *Frequency domain gate control*
- *Reconstruction*
- *Storage*

Result display

- *Bond quality display*
- *C-scan display*
- *Gray and/or color levels*
- *Storage*

ABUS System: Software User Interface



ABUS System Software Algorithms

Data processing and properties reconstruction

Signal processing → **Properties reconstruction**

Algorithm

Scattering reduction

Fast Fourier Transform

↔

Algorithm

Propagation in multi-layered composites

↕

Reconstruction

↕

Separation of adhesive/adherent properties

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ABUS System: Validation

Sample Matrix

- ***Preparation of Graphite/Epoxy and Al Joints***

Samples Testing

- ***Testing of Graphite/Epoxy and Al/Al Joints***

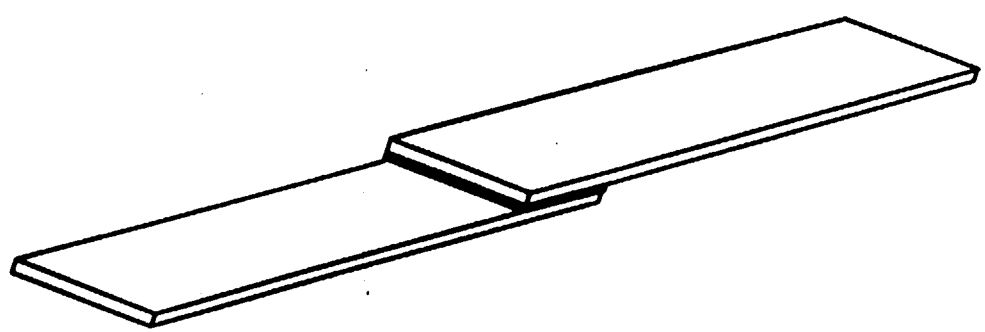
Boeing Sample Testing

- ***Testing of Al/Al and GrE/GrE Boeing Samples***

ABUS System: Validation Sample Matrix

Sample Matrix Description

Type of Sample	Number of treated samples	Number of non-treated samples
Al/FM73/ Al	20	5
GrE/FM73/GrE (quasi-isotropic multilayered)	20	5



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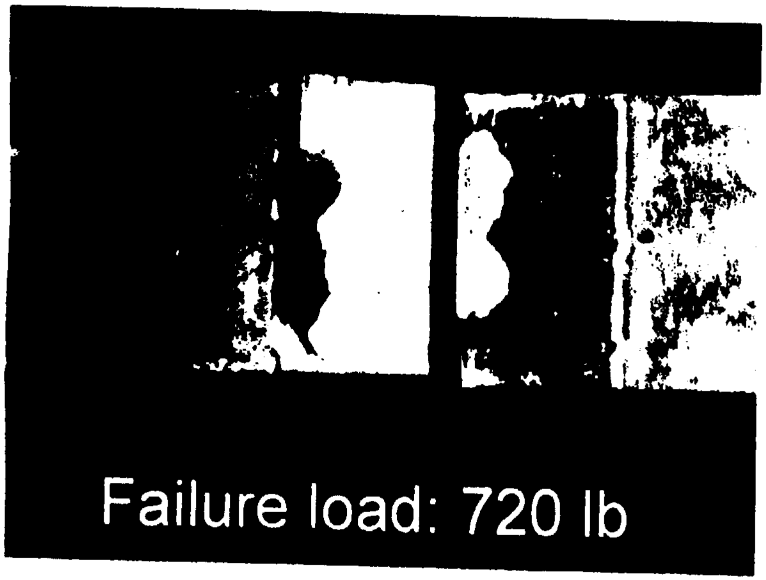
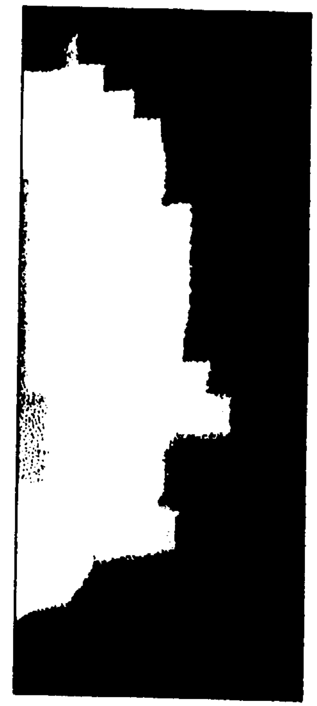
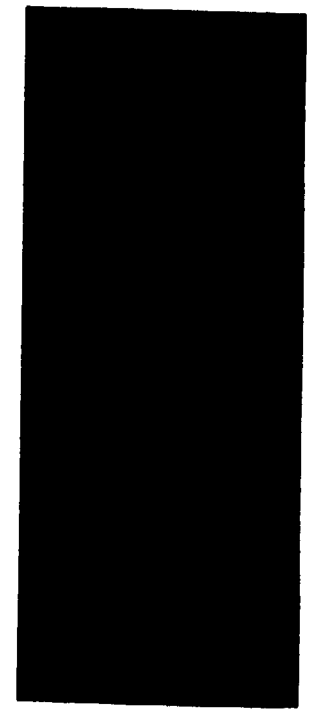
Weak (treated) Lap-shear Joint

Mechanical Testing:




Abus Scan


C- Scan

- Low average value of the effective stiffness
- Inhomogeneous pattern over the bond area

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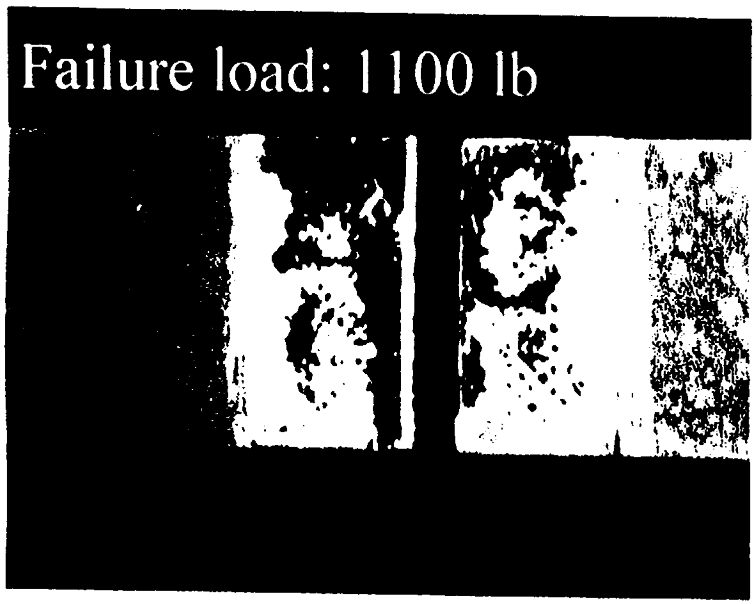
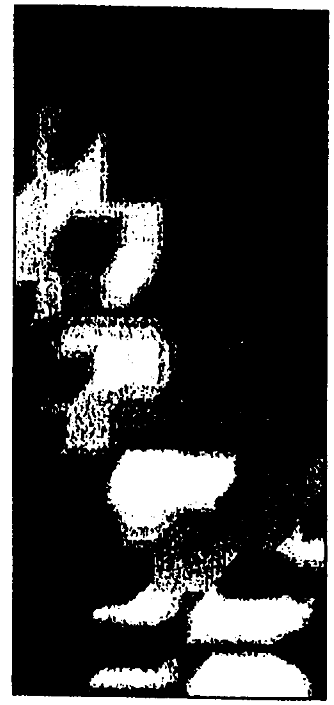
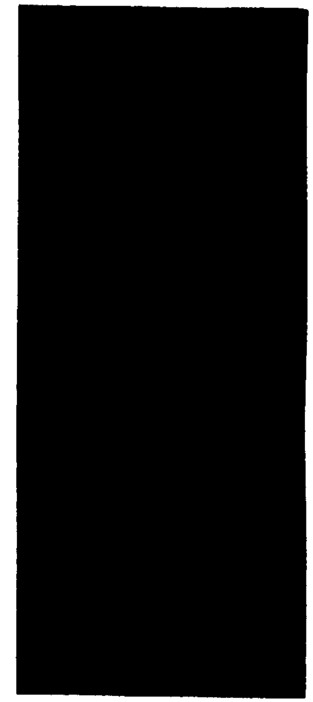
Results: Reference Lap-shear Joint

Mechanical Testing:





Abus Scan



C- Scan

- High average value of the effective stiffness
- Homogeneous pattern over the bond area

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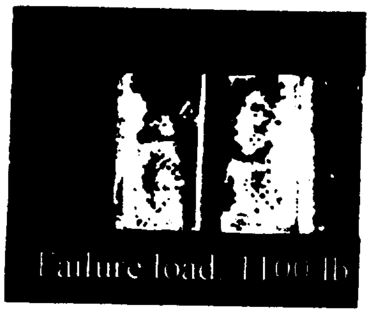
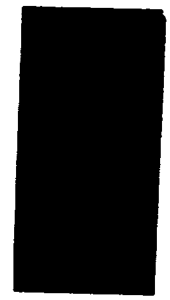
INSPECTION RESULTS

Reference bond: mixed mode failure

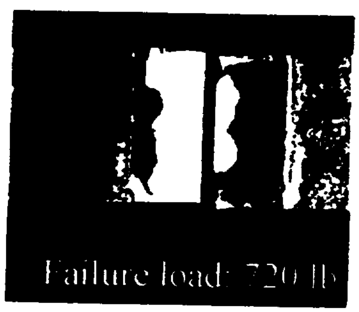


Abus Scan

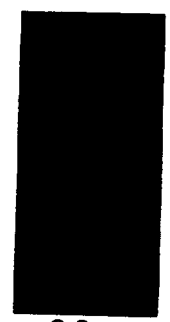


C-Scan

Poor bond: Interfacial mode failure

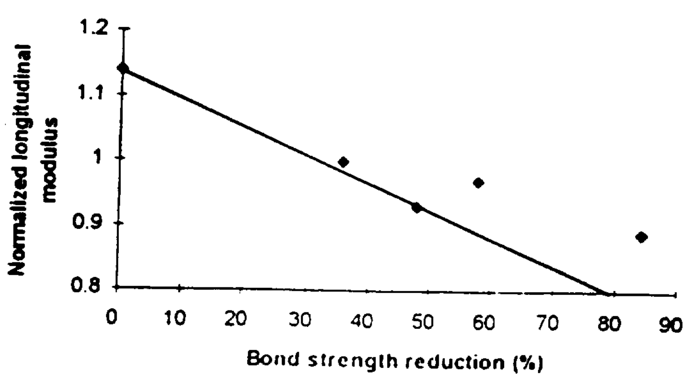


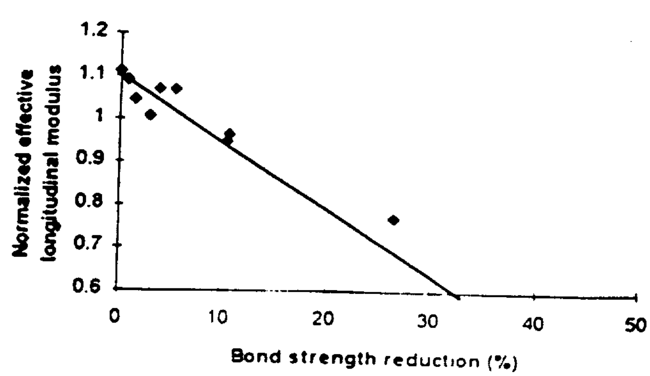
Abus Scan



C-Scan

ABUS Data Correlation to Strength

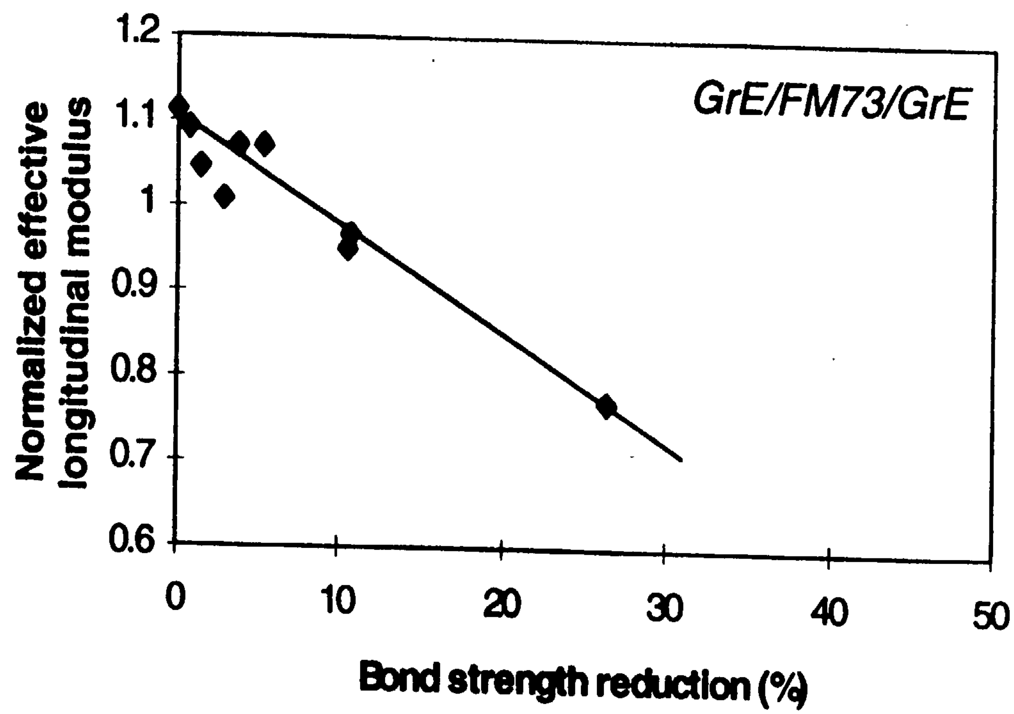




ABUS System Validation
System Testing: Composites samples

Testing of GrE/GrE

- ***Testing of samples from the Samples Matrix***
- ***Correlation with mechanical tests***



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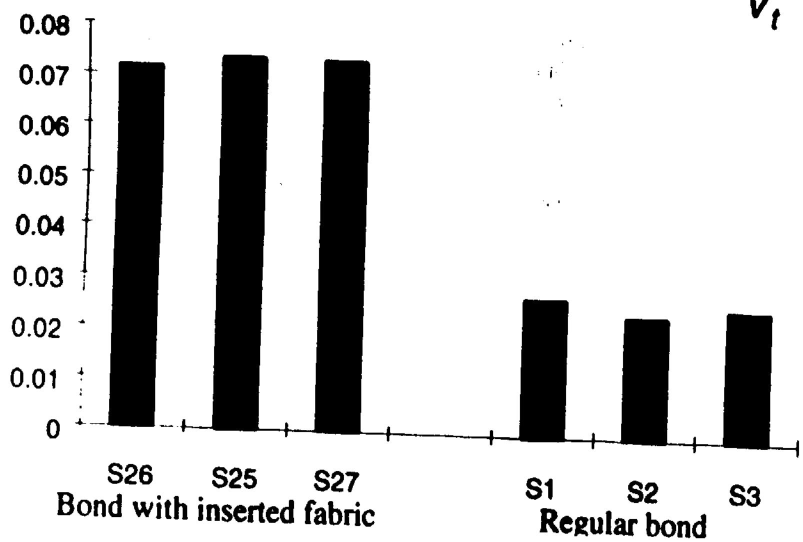
ABUS System: Validation
Boeing Sample Testing

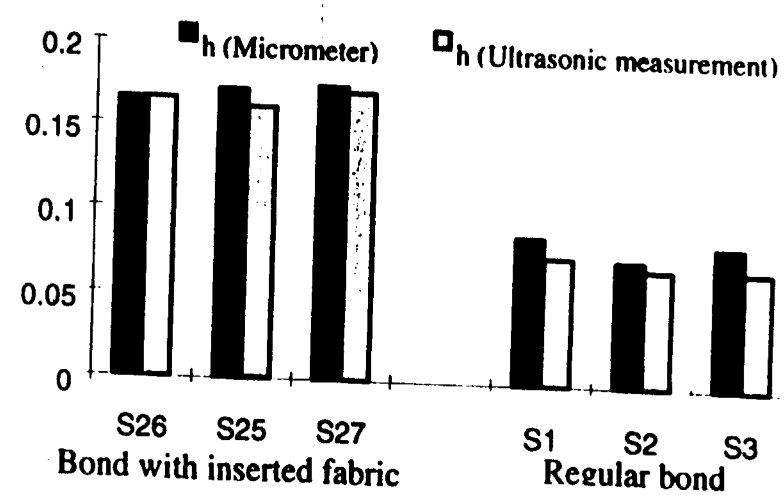
Boeing Sample Testing

- ***A series of six Al/Al joint have been sent by Boeing. Two process were used to joint the bonds (standard and with additional fabric).***
- ***The Abus system has been able to discriminate the two process***

Non-dimensional parameter $\frac{\omega . h}{V_t}$



Reconstructed thickness



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Conclusion

The Angle Beam Ultrasonic Spectroscopy (ABUS) Scanning System for evaluation of adhesive bond integrity has been developed.

Features:

- Separation of thickness effect from bond quality effect.
- Ability to give a bond line quality factor.
- Ability to scan bond line quality over the bond area

Correlation between ultrasonic signatures measured with the ABUS method and the strength of the adhesive bond was obtained.

The ABUS System is capable of detecting weak bonds which are not detectable by C-Scan.

Adler Consultants Inc.

Characterization of Adhesive Bonds Integrity Using Angle Beam Ultrasonic Spectroscopy

S. I. Rokhlin[1,2], L. Adler[2]

1) The Ohio State University

2) Adler Consultants, Inc.

97-39

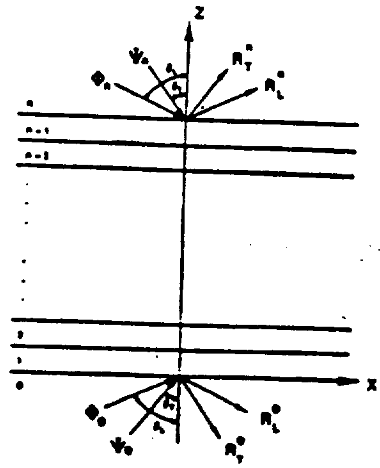
Outline

- Angle beam ultrasonic spectroscopy
- Assessment of environmental degradation of adhesive bonds
- Manufacturing of adhesive bonds with weak interfaces
- Characterization of adhesive bond integrity after manufacturing

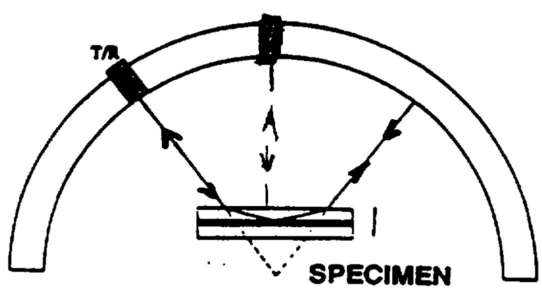
APPROACH:

Theoretical model:

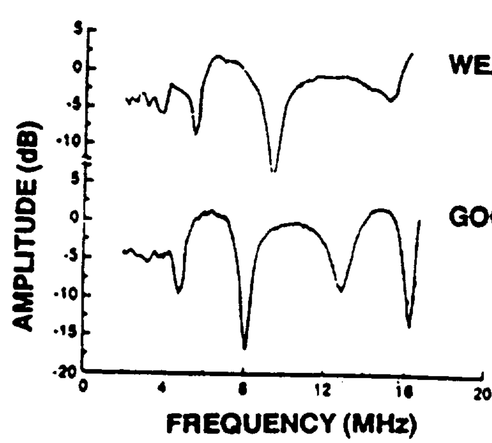
- An adhesive joint is considered having multilayered interphases including anisotropic porous aluminum oxide and weak boundary layers.



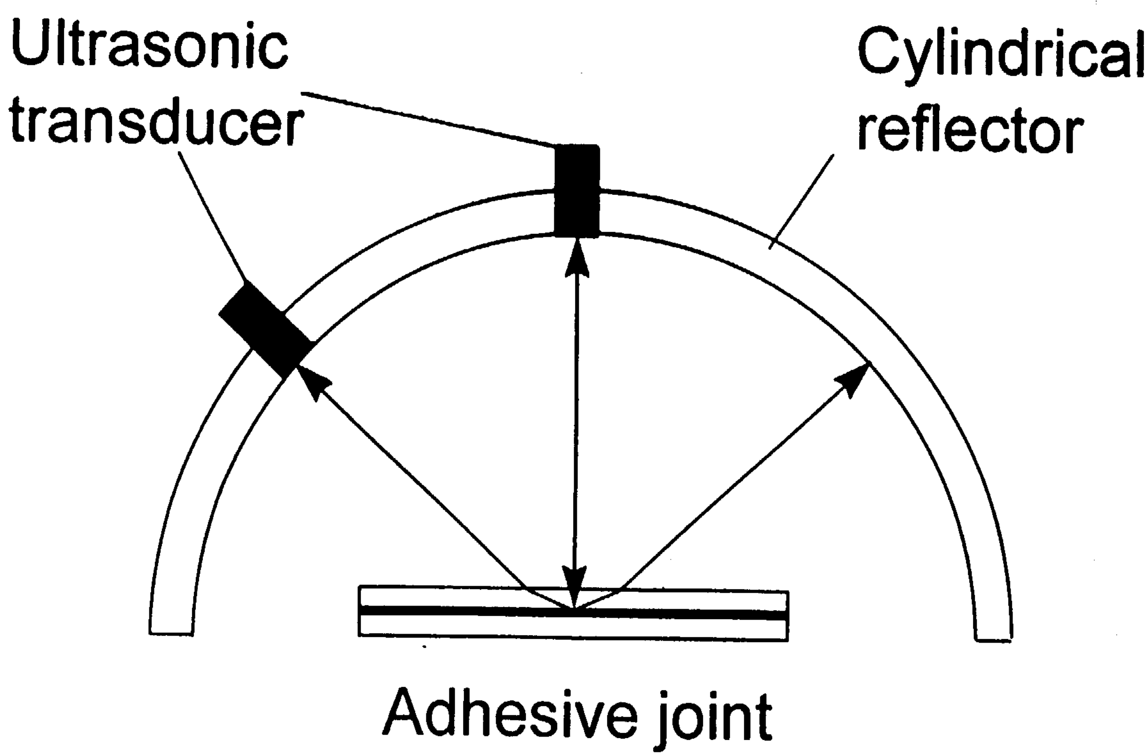
- A special ultrasonic goniometer is developed for experimental investigation.

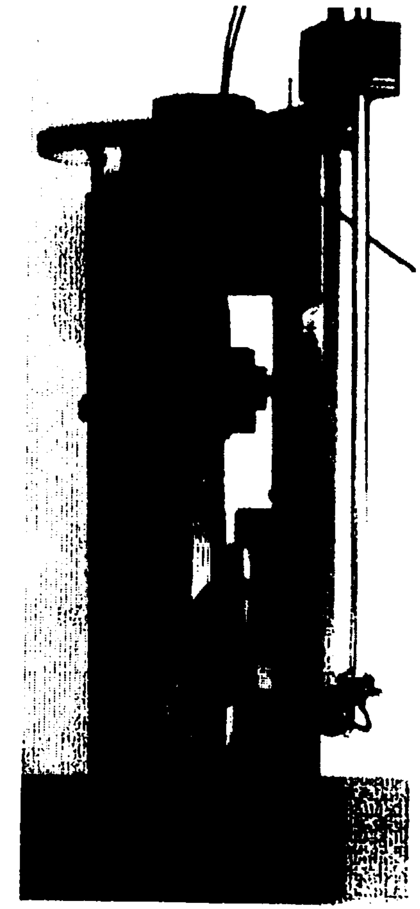


- Spectrum of the obliquely reflected ultrasonic signals is basis for interphase property reconstruction.

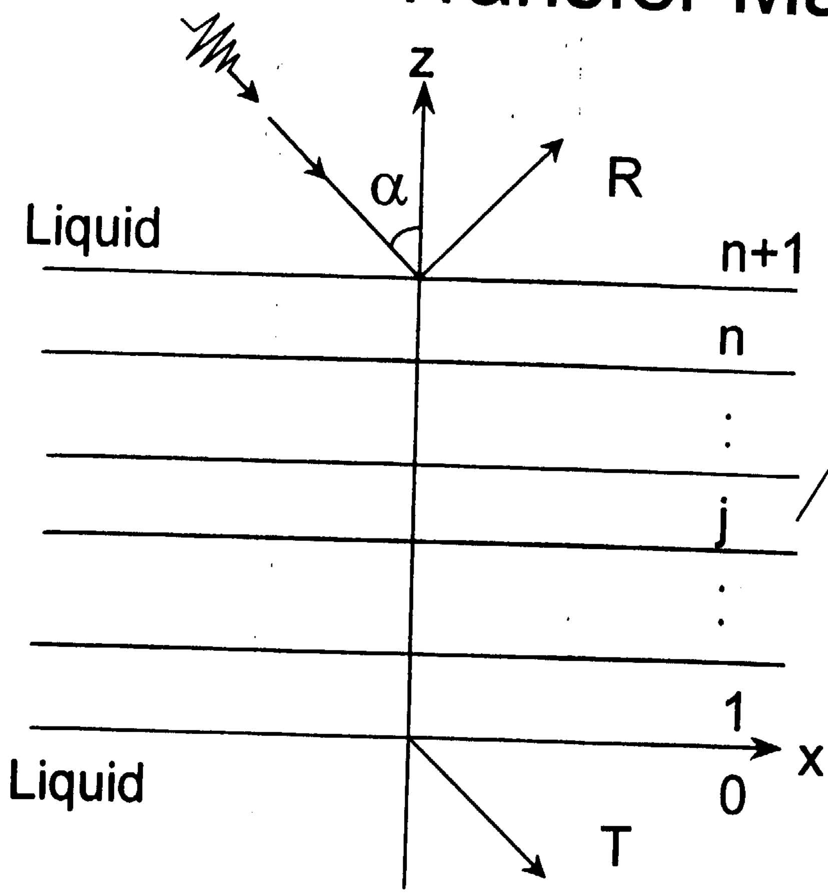


Ultrasonic technique for evaluation of adhesive joints





Transfer Matrix Algorithm



Unknown transfer matrix B_j
(Layer properties)

$Z_N, h_l, h_{\theta l}, h_{\theta t}, \alpha_l, \alpha_t$

six nondimensional parameters

↓

$(\lambda+2\mu), \mu, \rho, h, \alpha_l, \alpha_t$

six dimensional parameters

$R,T(\prod_{i=1}^{n} B_i)$ is function of the product of transfer matrices

B_i (i=1 to n) is [6×6] transfer matrix for off plane orthotropic layer

Nondimensional Parameters

$$Z_N = \frac{\rho V_\ell}{Z_1}$$

$$\bar{h}_\ell = \omega_0 \frac{h}{V_\ell}$$

$$\bar{h}_{\theta\ell} = \omega_0 \frac{h\cos\theta_\ell}{V_\ell}$$

$$\bar{h}_{\theta t} = \omega_0 \frac{h\cos\theta_t}{V_t}$$

$$\alpha_\ell$$

$$\alpha_t$$

where:

$$V_\ell = \sqrt{\frac{\lambda + 2\mu}{\rho}},$$

$$V_t = \sqrt{\frac{\mu}{\rho}},$$

$$\theta_\ell = \arcsin\left[\frac{V_0}{V_\ell}\sin\theta_0\right],$$

$$\theta_t = \arcsin\left[\frac{V_0}{V_t}\sin\theta_0\right]$$

Objective

- Determine six parameters of the layer:

$$(\lambda+2\mu),\ \mu,\ h,\ \rho,\ \alpha_l \text{ and } \alpha_t$$

using normal and oblique incident ultrasonic wave

Relation between Parameters

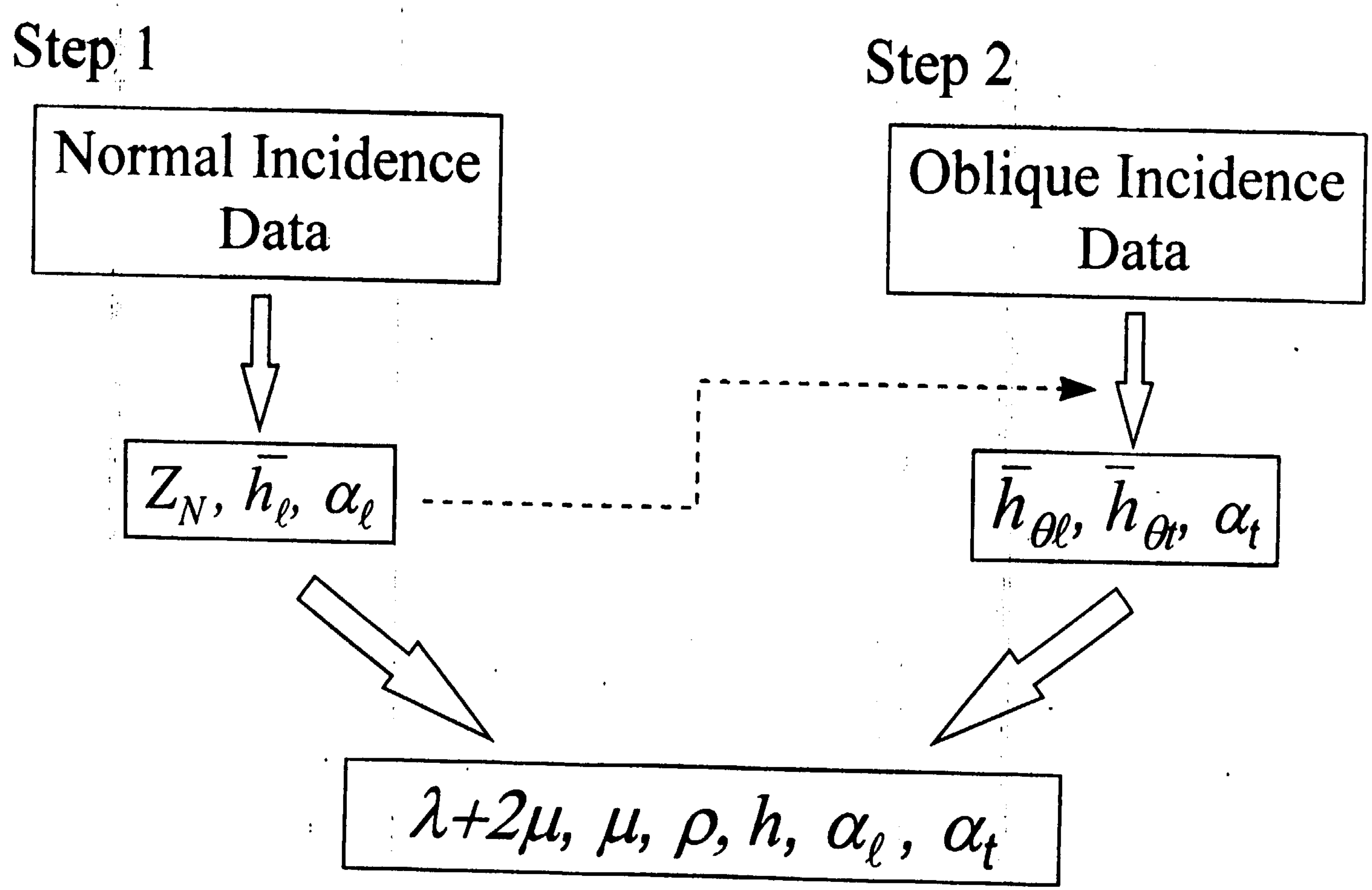
$$(\lambda+2\mu)=\frac{Z_N Z_1}{\xi_0}\frac{\sqrt{\bar{h}_\ell^2-\bar{h}_{\theta\ell}^2}}{\bar{h}_\ell^2},$$

$$\mu=\frac{Z_N Z_1}{\xi_0}\frac{\sqrt{\bar{h}_\ell^2-\bar{h}_{\theta\ell}^2}}{\bar{h}_\ell^2+\bar{h}_{\theta t}^2-\bar{h}_{\theta\ell}^2},$$

$$\rho=\frac{Z_N Z_1}{\sqrt{\bar{h}_\ell^2-\bar{h}_{\theta\ell}^2}}\xi_0,$$

$$h=\frac{\sqrt{\bar{h}_\ell^2-\bar{h}_{\theta\ell}^2}}{\xi_0\omega_0}, \quad \text{where } \xi_0=\frac{\sin\theta_0}{V_0}$$

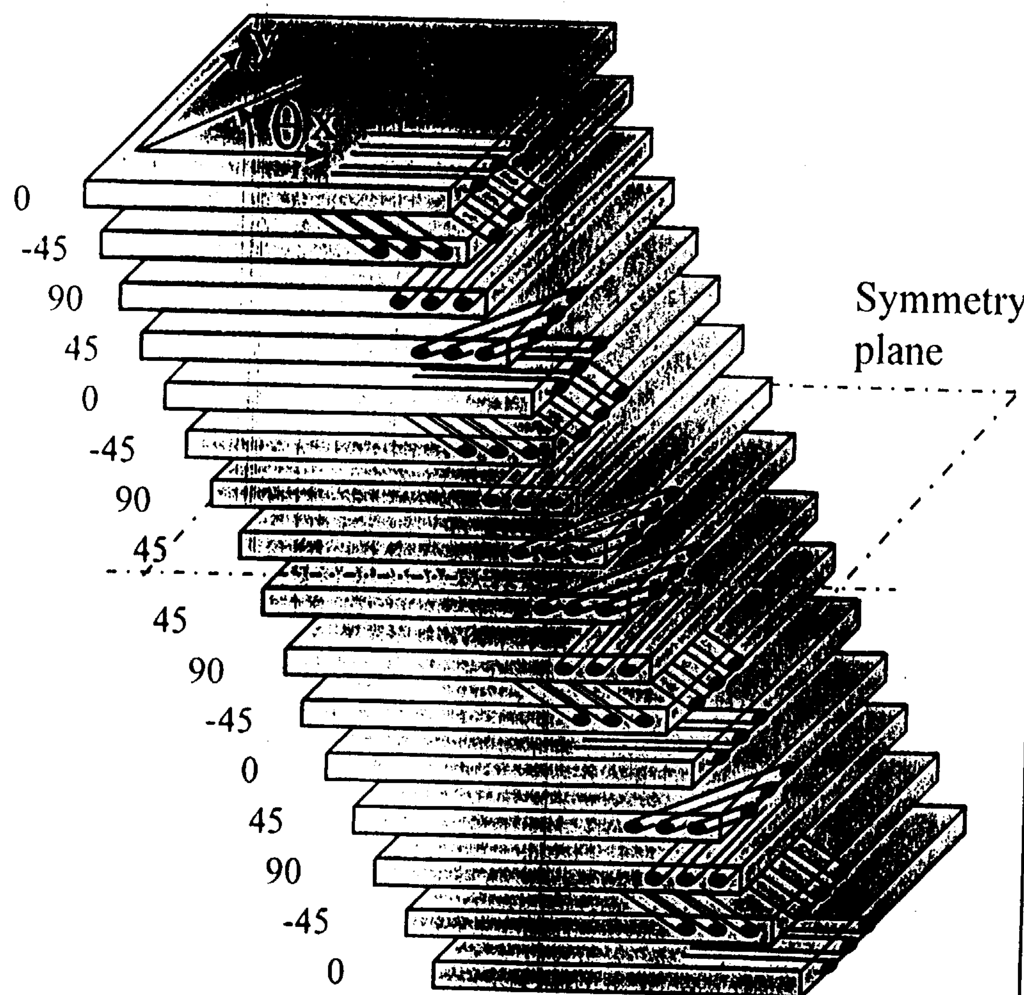
Strategy for Reconstruction



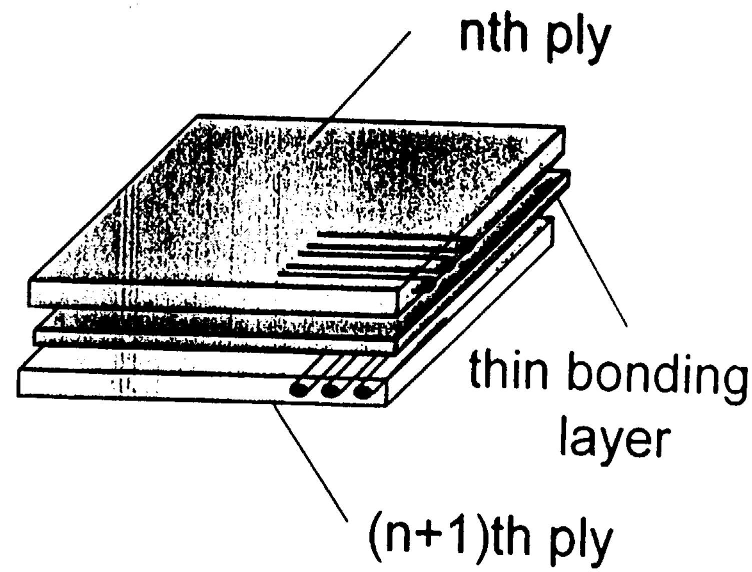
Results of Inversion

	$\lambda+2\mu$, GPa	μ, GPa	ρ, g/cc	h, mm
Polystyrene film inside joint	4.46	0.844	1.07	0.141
Polystyrene film extracted	4.48		1.072	0.144
Heat treated polystyrene	4.69	0.828	1.072	

Multi-ply Laminated Composite Sample



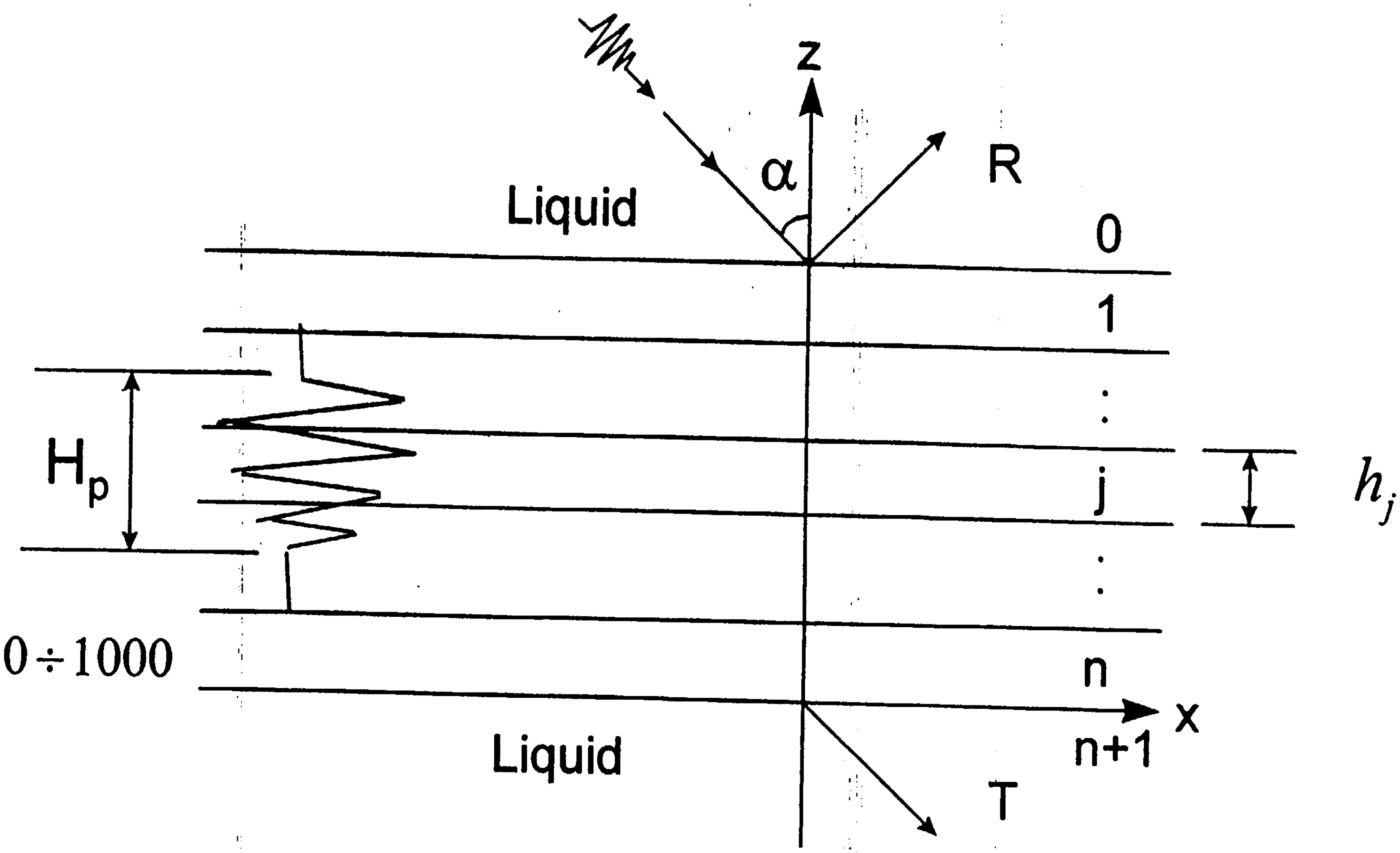
$[0/-45/90/45/0/-45/90/45]_s$
laminate lay-up



There is an excess of epoxy forming a thin bonding layer between the plies

Ply thickness:	app. 0.2 mm
Number of plies:	16
Plate thickness:	3.1mm

Transfer Matrix Algorithm

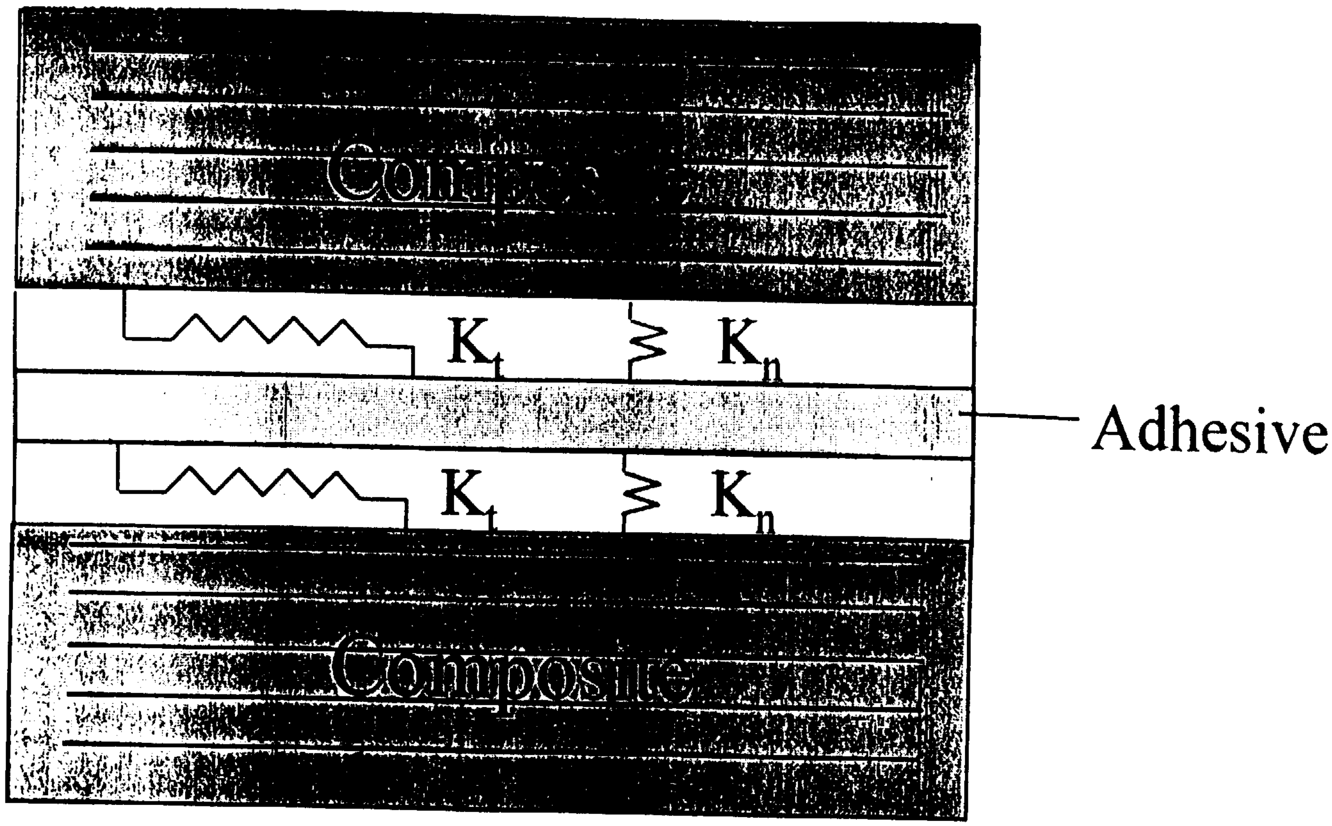


$$H_p = \sum_{i=1}^{n} k_t^i h_i \sim 0 \div 1000$$

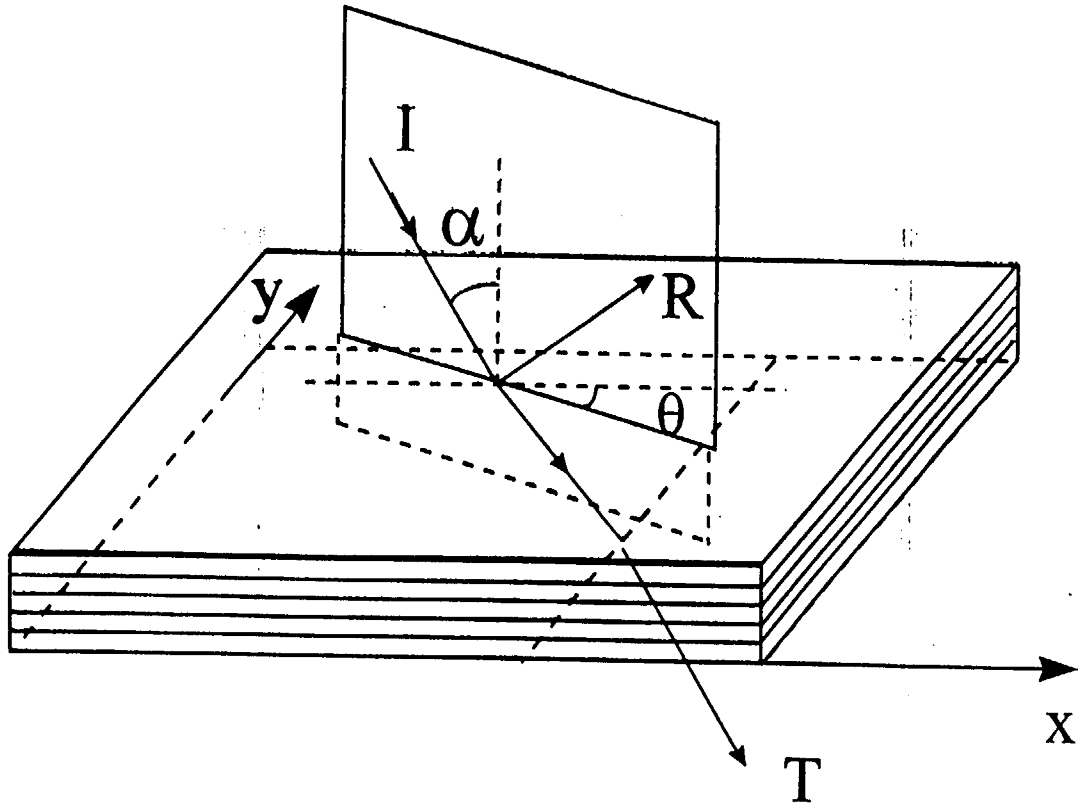
$R,T(\prod_{i=1}^{n} B_i)$ is function of the product of transfer matrices

B_i (i=1 to n) is [6×6] transfer matrix for off plane orthotropic layer

Model for the composite joints



Multi-ply Composites Ultrasonic Measurements



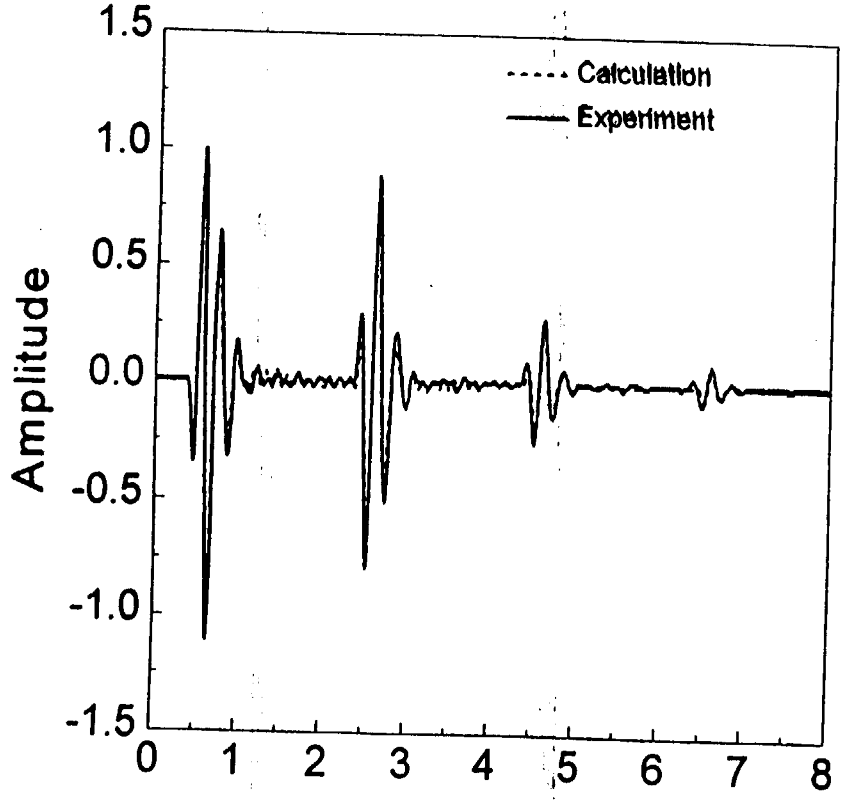
α: Incident angle

θ: Orientation angle (Angle between incident plane and plate axis)

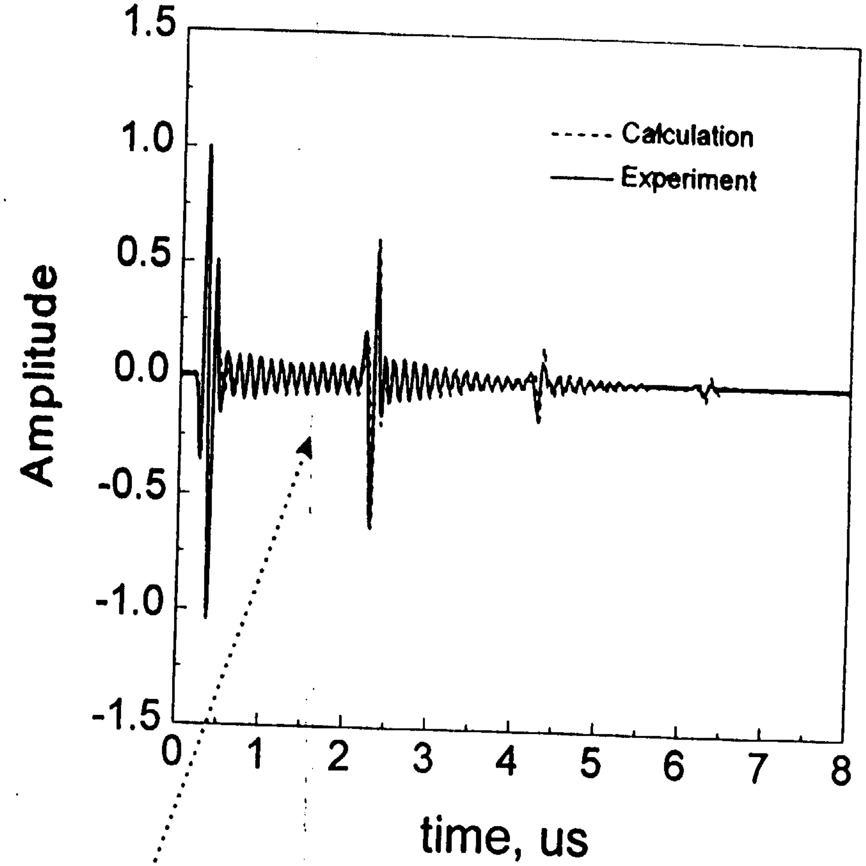
Investigate reflection and transmission characteristics vs. incident angle α and orientation angle θ

Normal Reflection Time Domain Signal from the Laminate

5 MHz

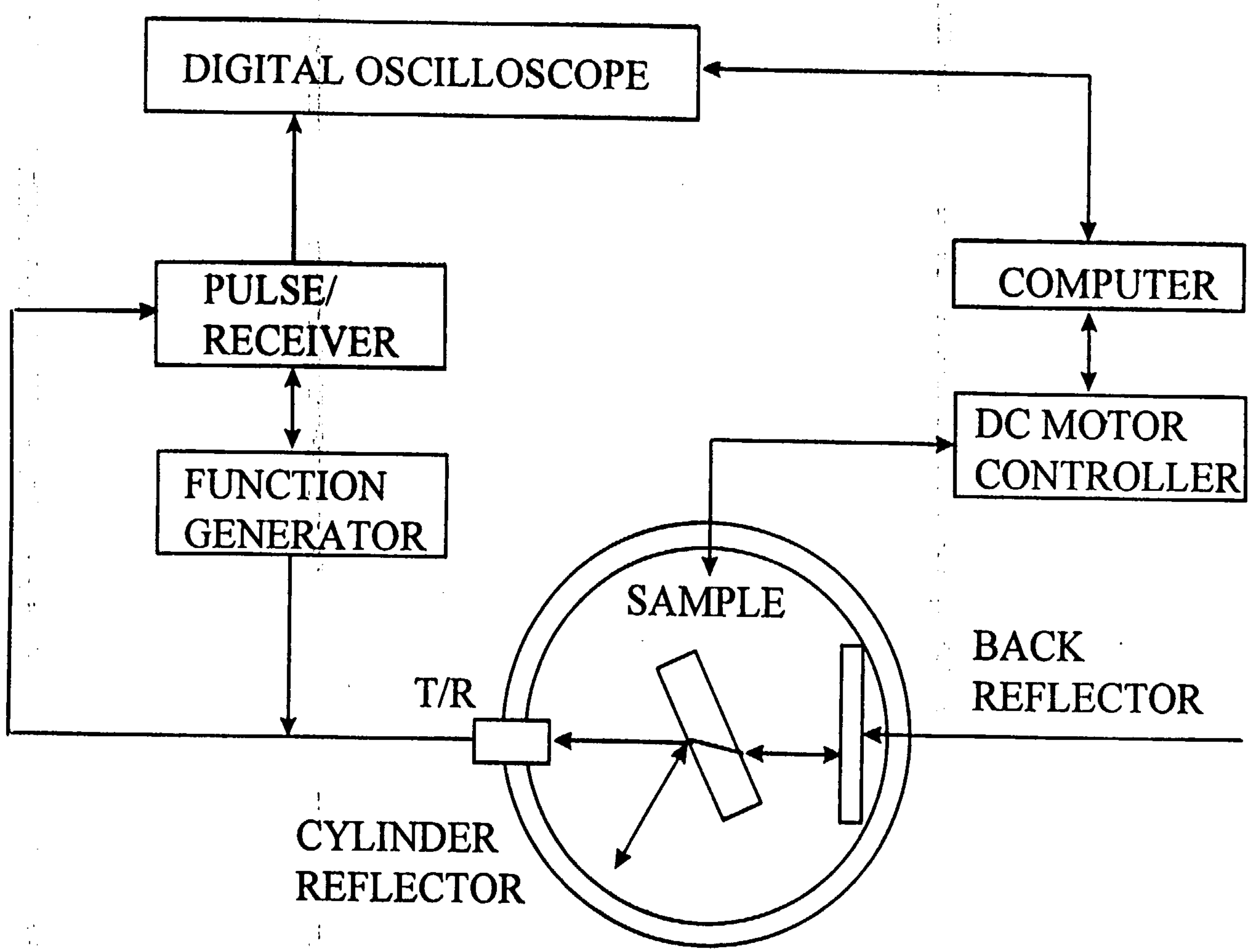


10 MHz



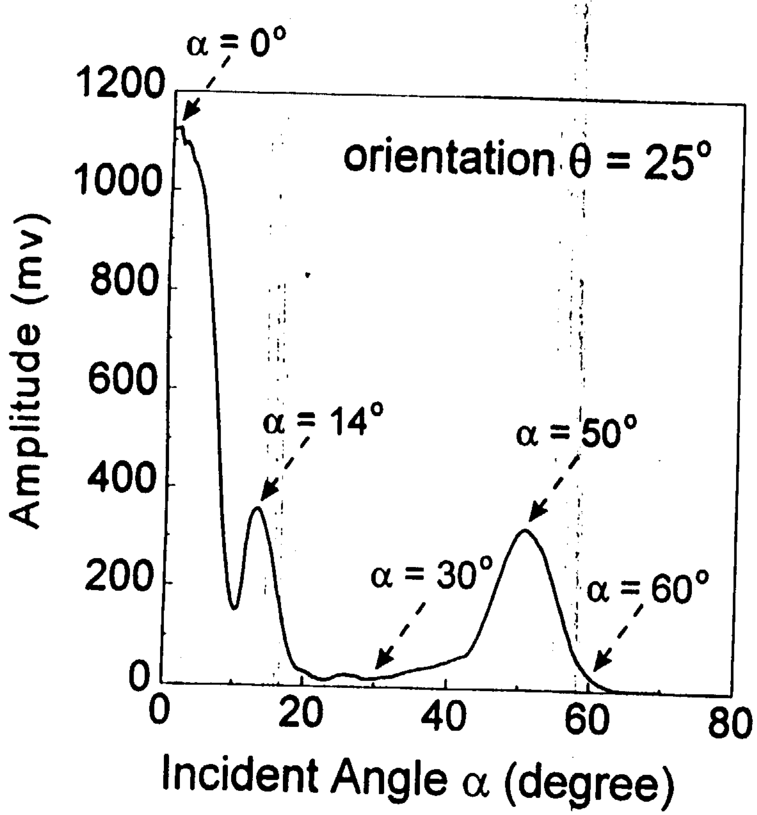
Reverberation signal can be used to find parameters of thin bonding layer between different plies

Experimental Apparatus for Double Transmission Amplitude Measurement

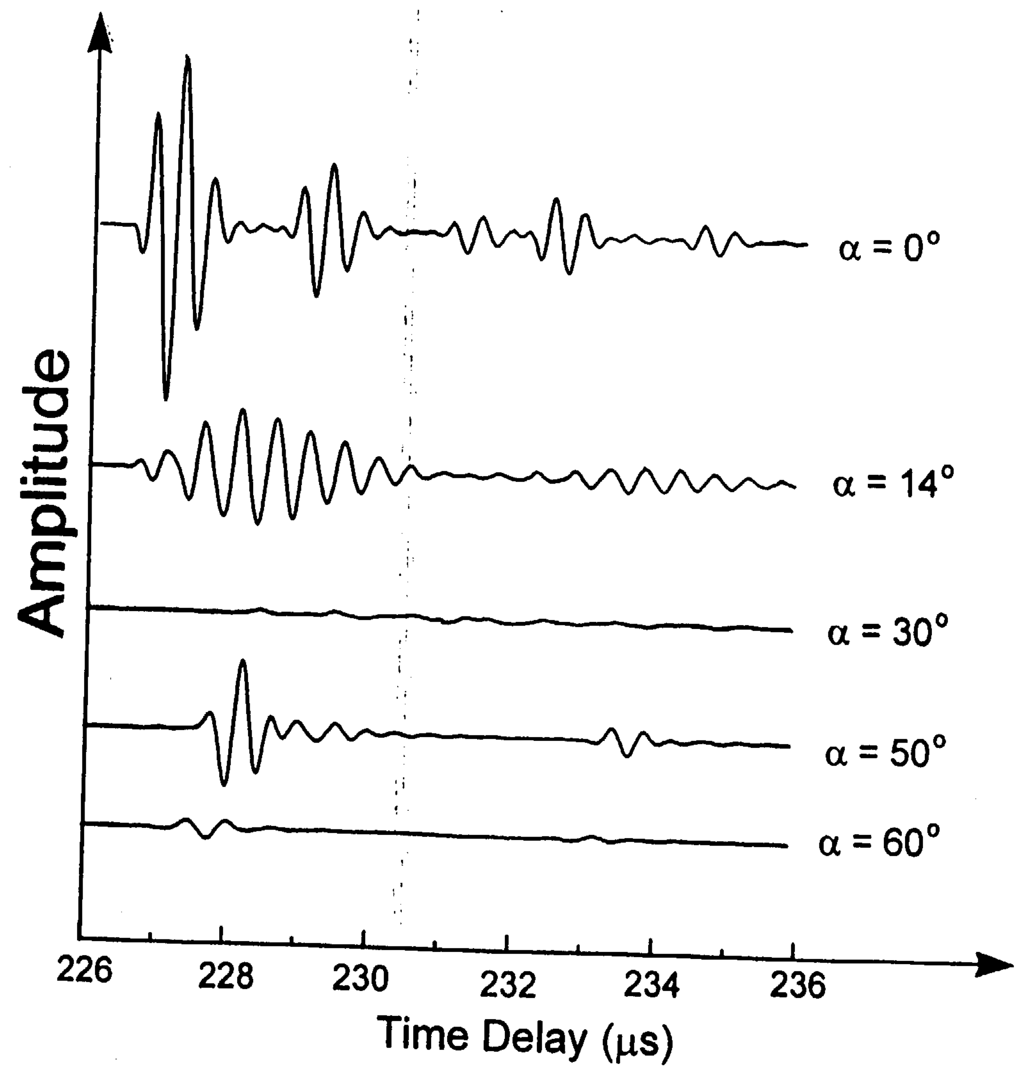


Double Through Transmission Characteristics at Orientation Angle $\theta = 25^o$ (Experiment)

2.25 MHz center frequency

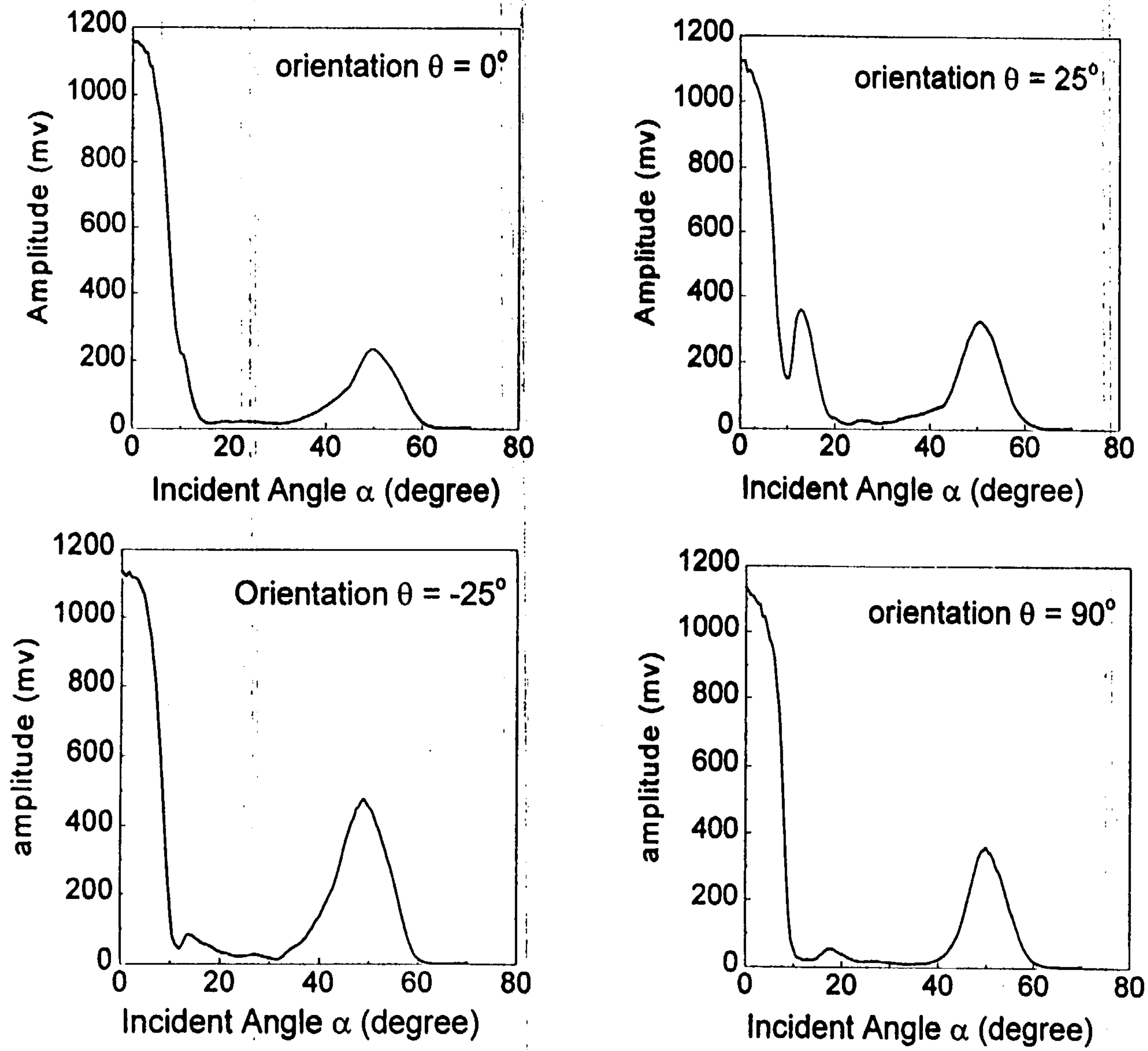


Amplitude

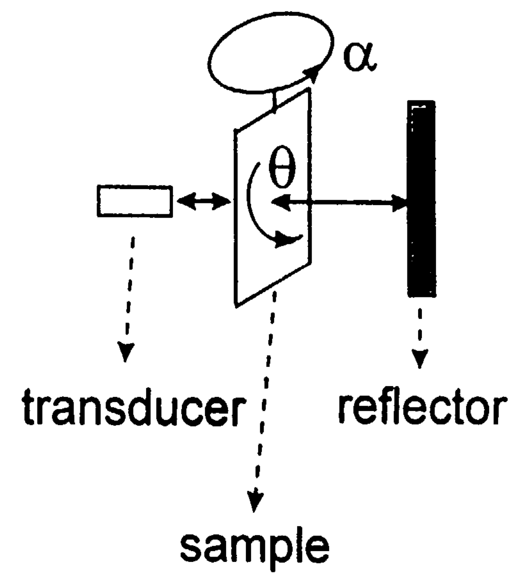


Waveform at different incident angle

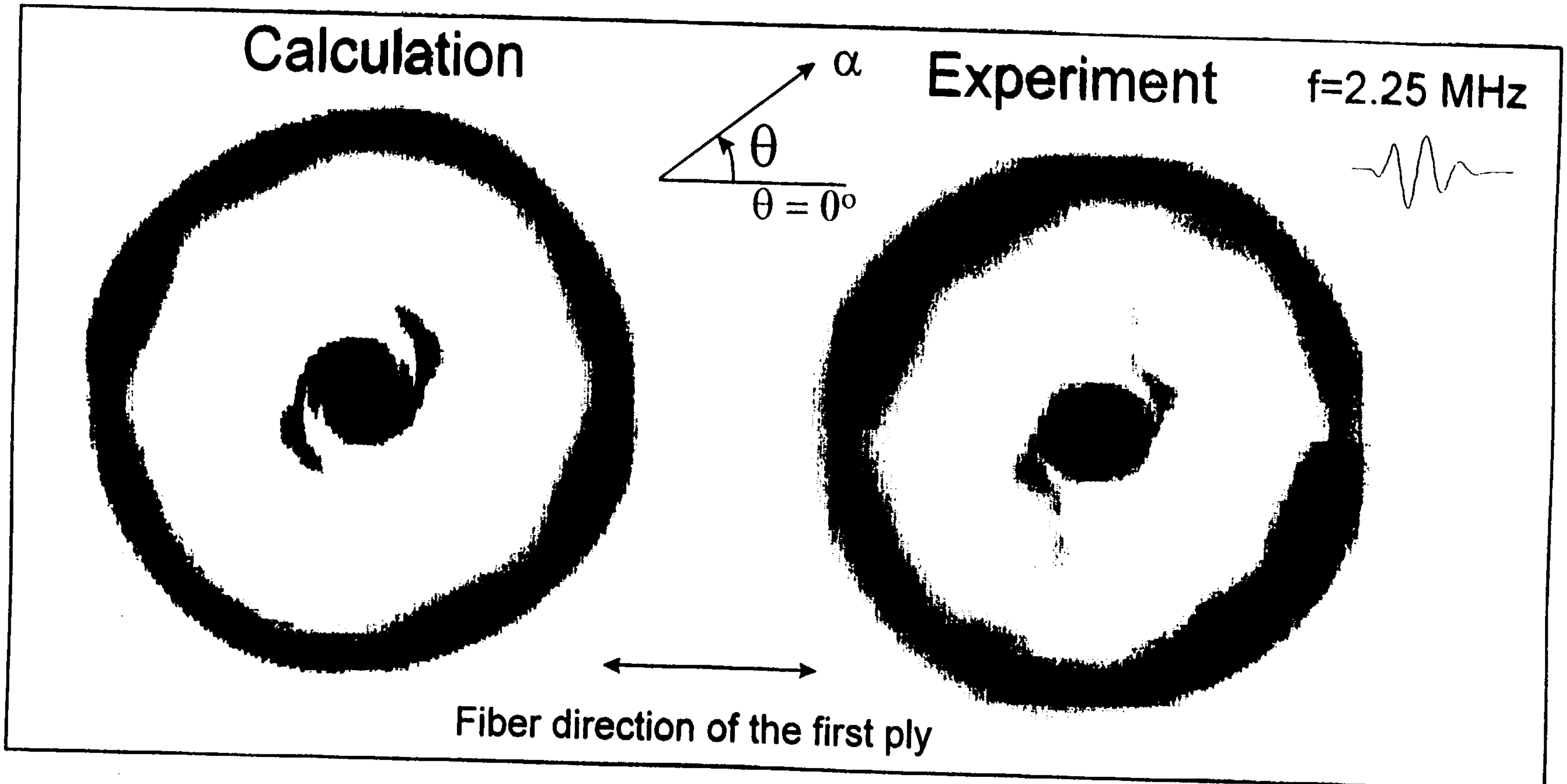
Amplitude of Double Transmission vs. Incidence Angle α Experiment



2.25 MHz center frequency pulse:



Amplitude of Double Through Transmission Signals at Different Incidence and Orientation Angles

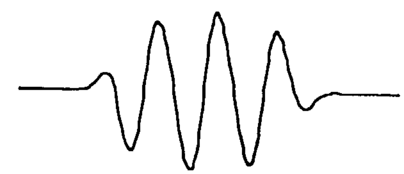


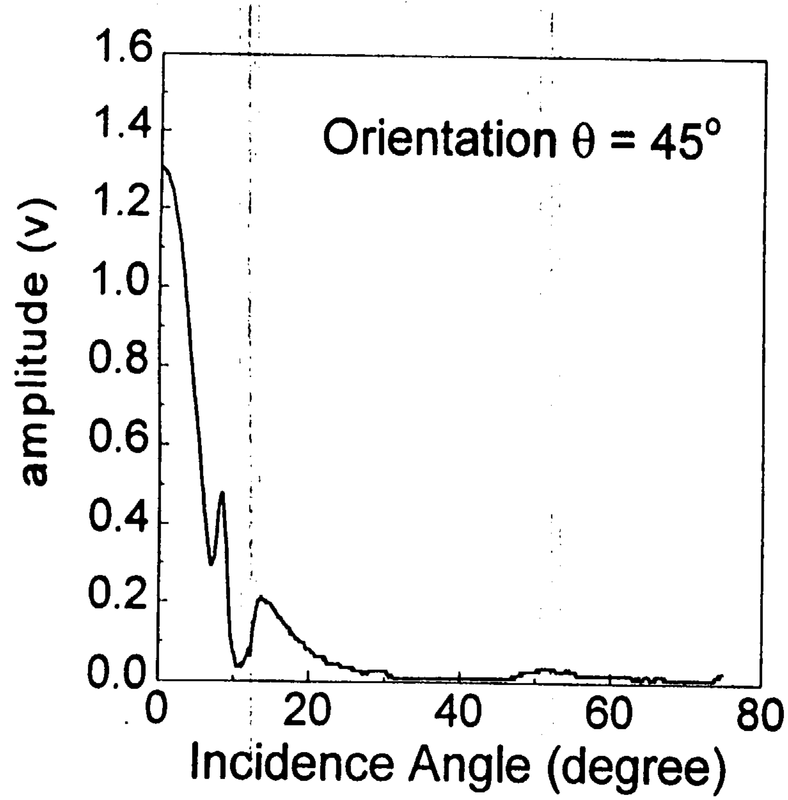
Double through transmission amplitude

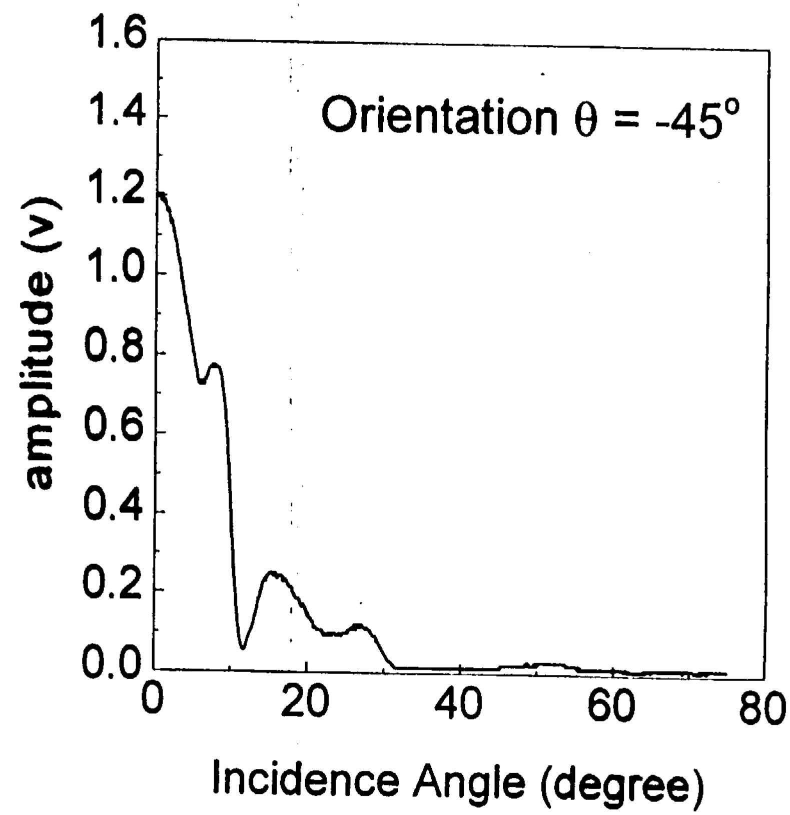
- has 180° rotation symmetry
- has no reflection symmetry (θ and – θ)

Amplitude of Double Transmission vs. Incidence Angle α

Experiment (5 MHz tone-burst)







Transmission amplitude depends strongly on frequency

OUTLINE

- STATEMENT OF THE PROBLEM

- SUMMARY OF THE EXPERIMENTAL RESULTS

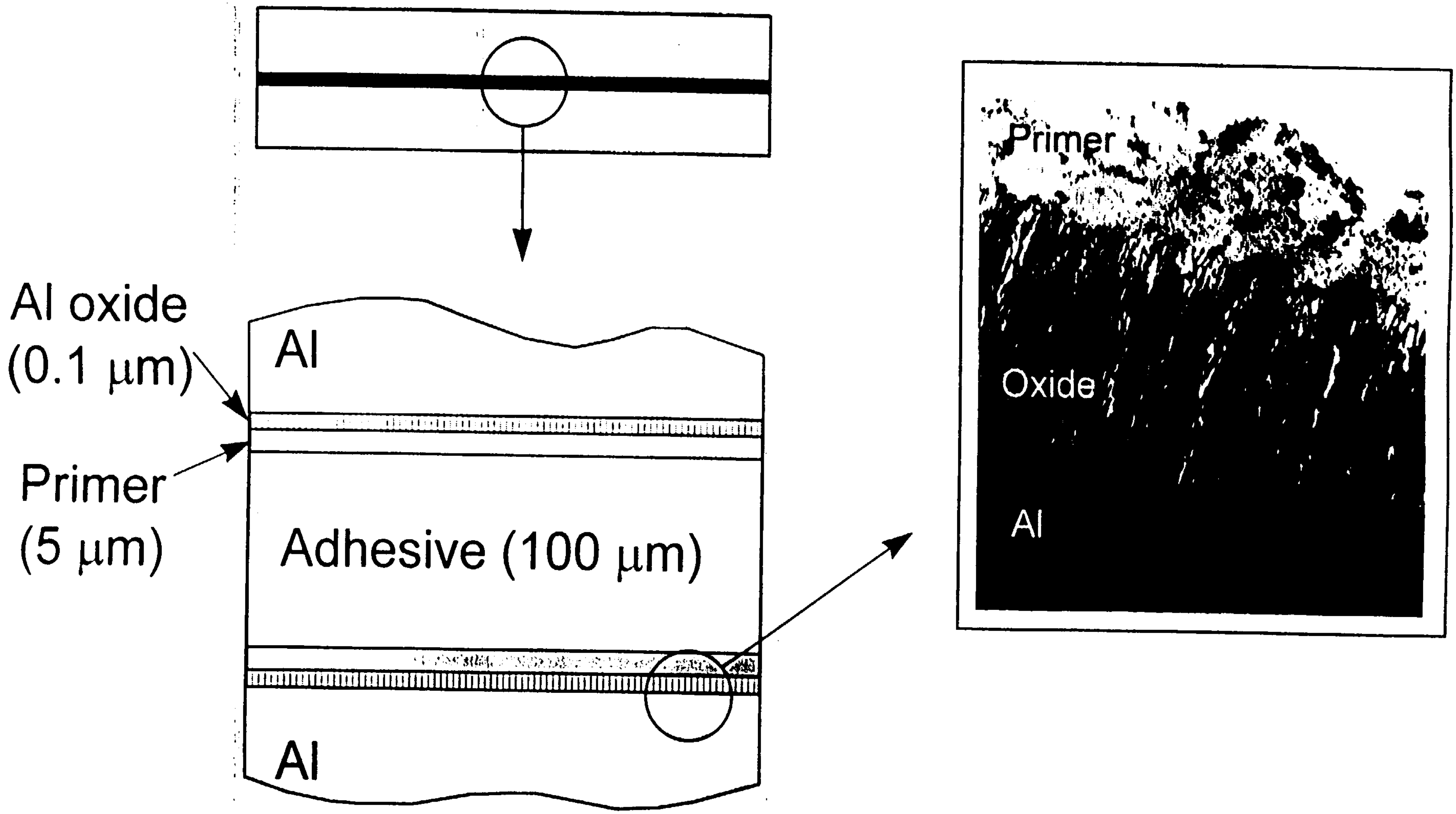
- MODELS OF INTERFACE IN ADHESIVE JOINT:

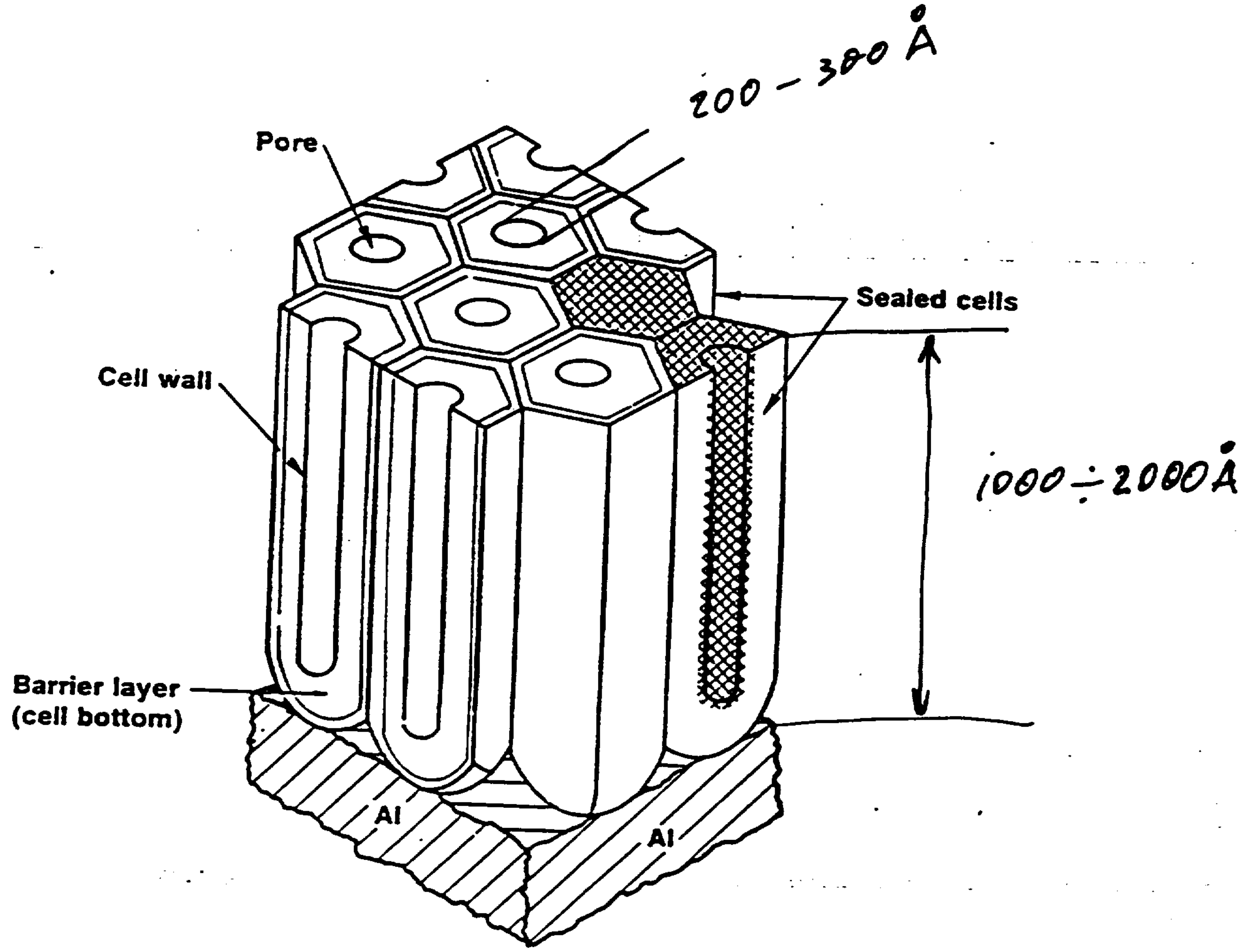
  - "COMPOSITE" WEAK BOUNDARY LAYER

  - INTERFACIAL SPRINGS

- CONCLUSIONS

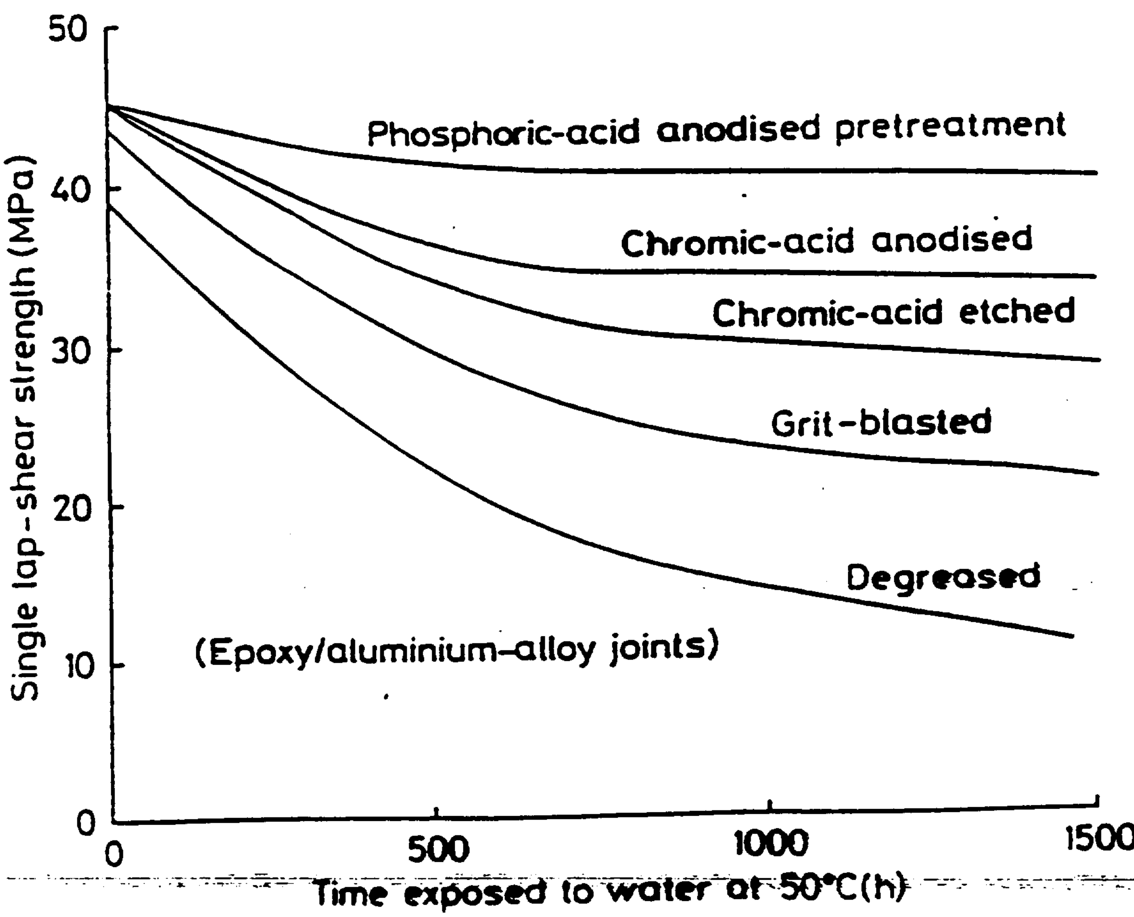
Layered structure of adhesive joints





Texture of Porous Anodic Oxide

EFFECT OF SURFACE PRETREATMENT ON THE PERFORMANCE OF ALUMINUM-ALLOY EPOXY JOINTS SUBJECTED TO ACCELERATED AGING IN WATER AT 50°C



PROCEDURE FOR JOINT PREPARATION

- Surface cleaning in Alconox detergent solution

- Surface deoxidation
  (sodium dichromate + sulfuric acid + distilled water)

- Phosphoric acid anodization

- Priming of surface by BR-127 primer

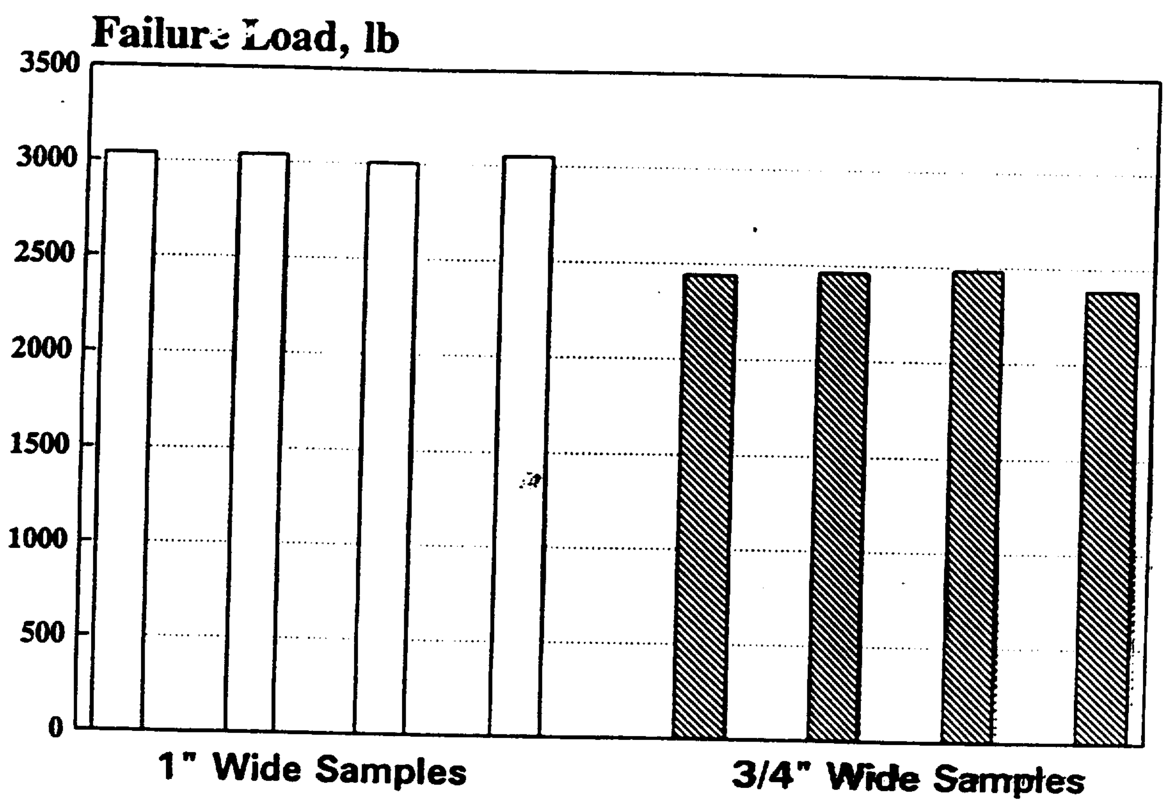
- Bonding by FM-73 adhesive film

CONDITIONS FOR ACCELERATED AGING

- EXPOSURE MEDIUM:
  saturated solution of NaCl at 68°C
- LOAD: 800 or 1000 lb

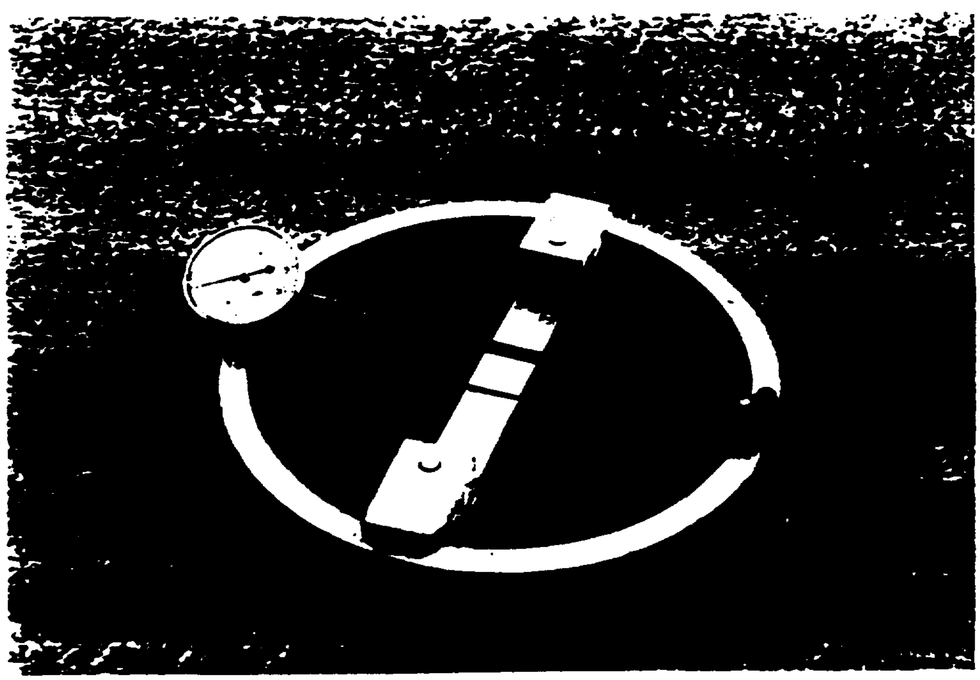
Under these conditions the joints broke in 1-3 weeks

INITIAL FAILURE LOADS OF ALUMINUM SINGLE LAP ADHESIVE JOINT SAMPLES BONDED WITH FM-73 FILM ADHESIVE AND BR-127 PRIMER

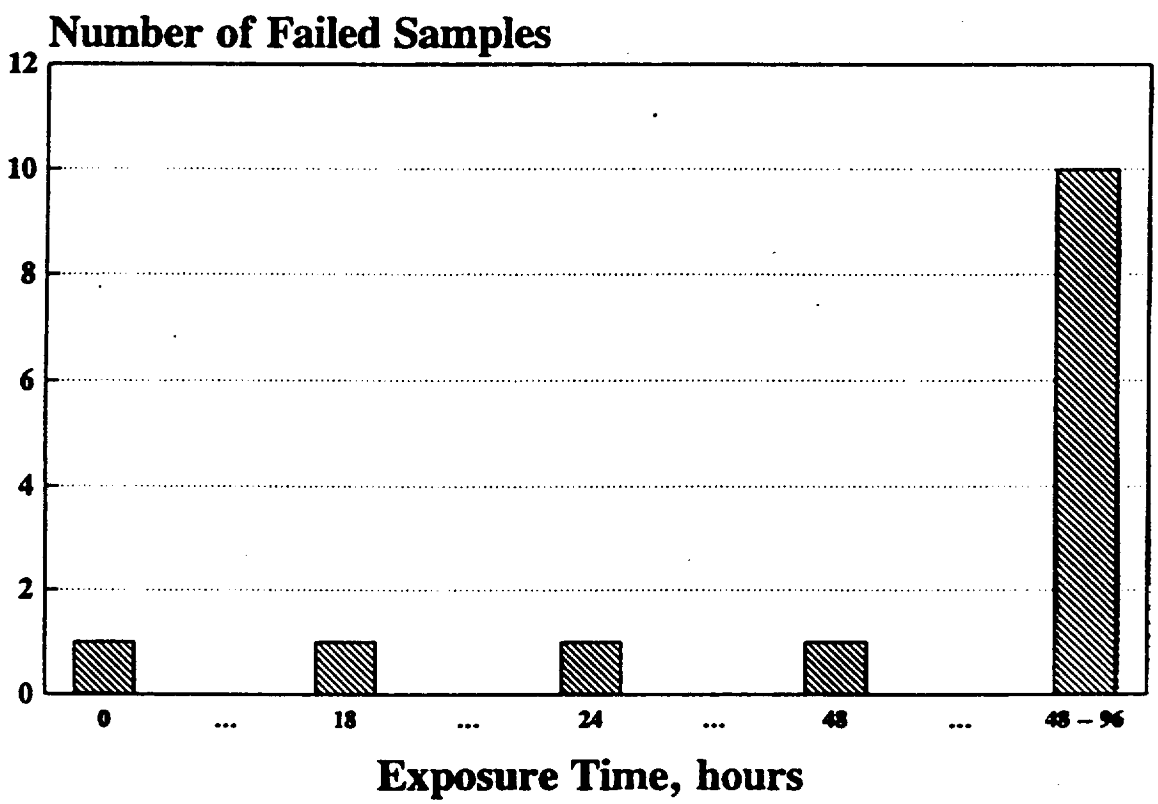


LOADING ARRANGEMENT FOR A SINGLE LAP ADHESIVE JOINT SAMPLE USING STRESS FIXTURE

APPLIED LOAD IS MEASURED AS DEFLECTION OF THE FIXTURE BY DIAL INDICATOR



LIFETIME OF SINGLE LAP SHEAR ADHESIVE JOINTS AGED IN SATURATED NaCl SOLUTION UNDER 1000 lb LOAD AT 70°C



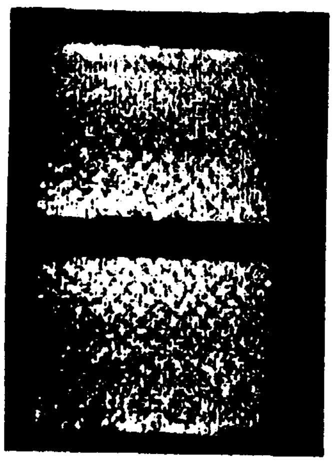
Problem Statement:

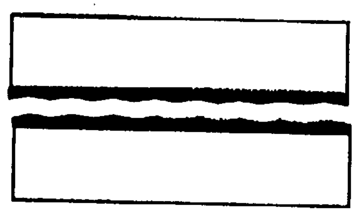
- Adhesive joints can fail catastrophically in severe environments
- Residual strength and lifetime of joints is independent of initial joint strength

This shows the necessity of nondestructive evaluation of adhesive joints in service

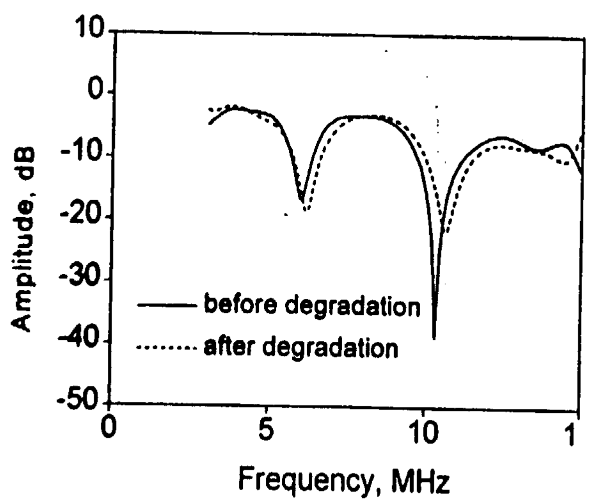
Modes of failure in adhesive joints

Before degradation

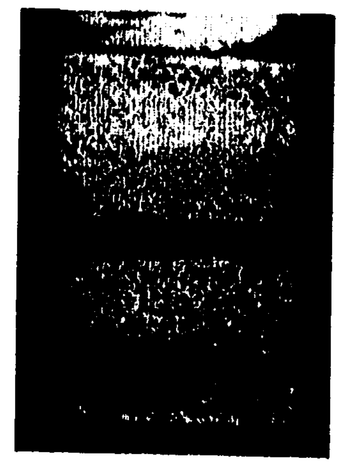


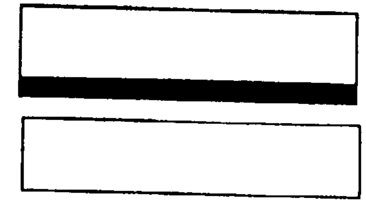


Cohesive mode of failure

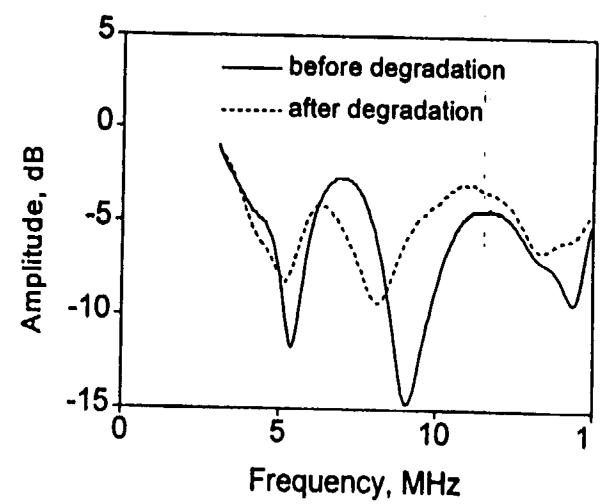


After degradation



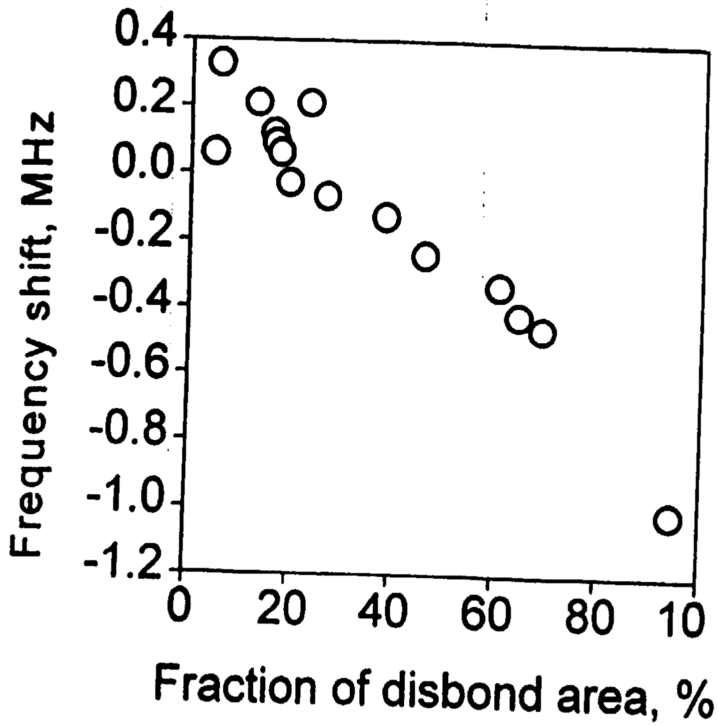


Interfacial mode of failure

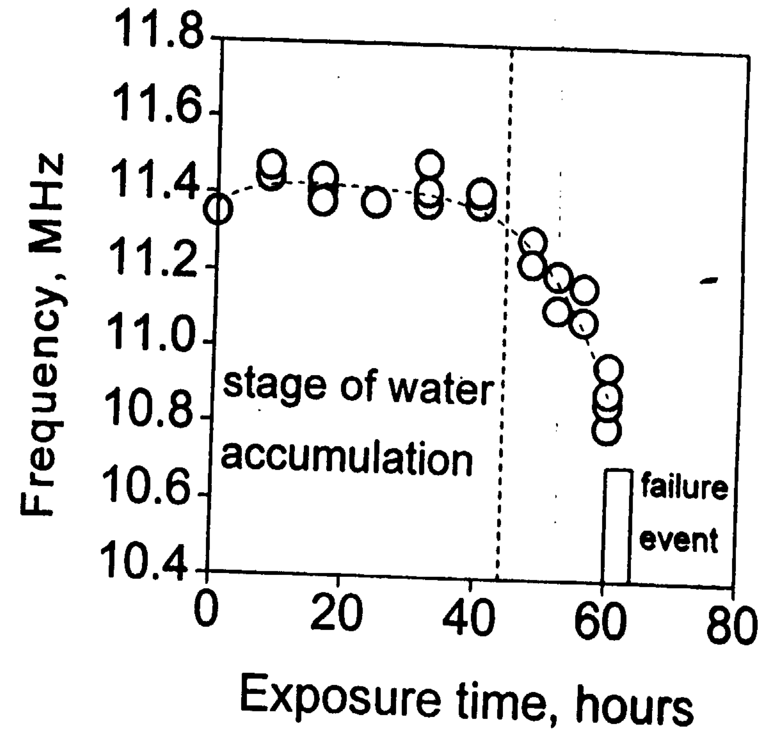


Two types of experiments:

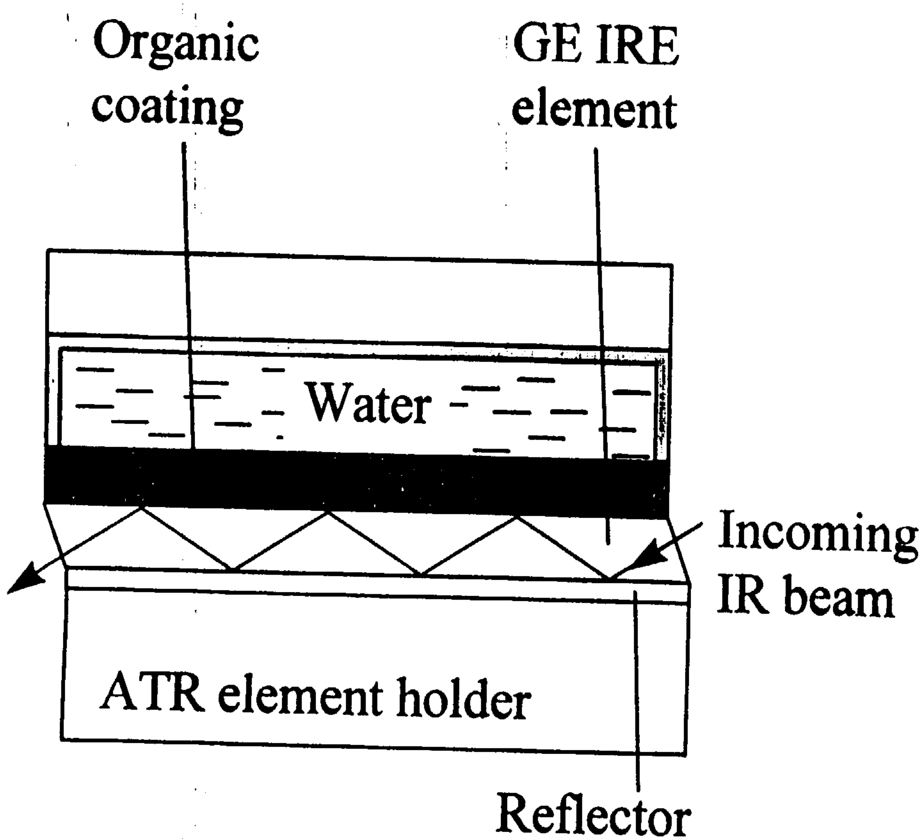
Reflection minima shift
vs. interfacial failure area

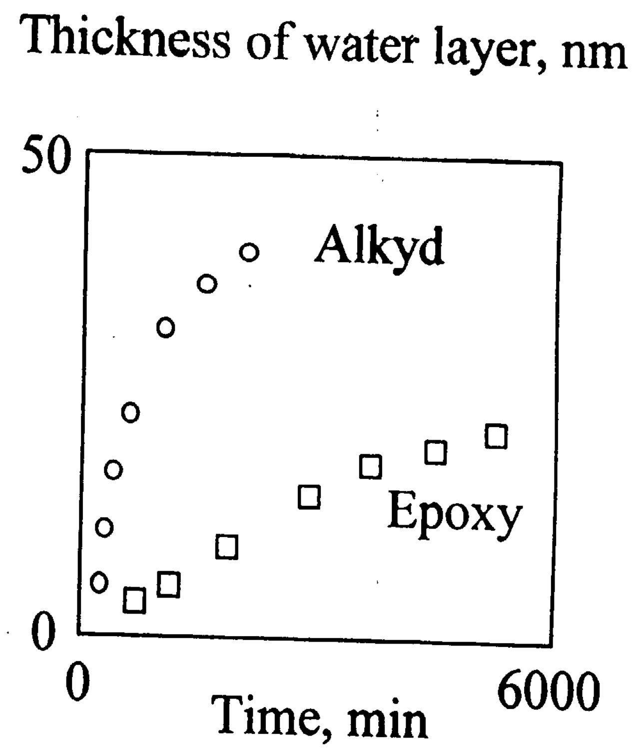


Reflection minima shift
vs. time of degradation

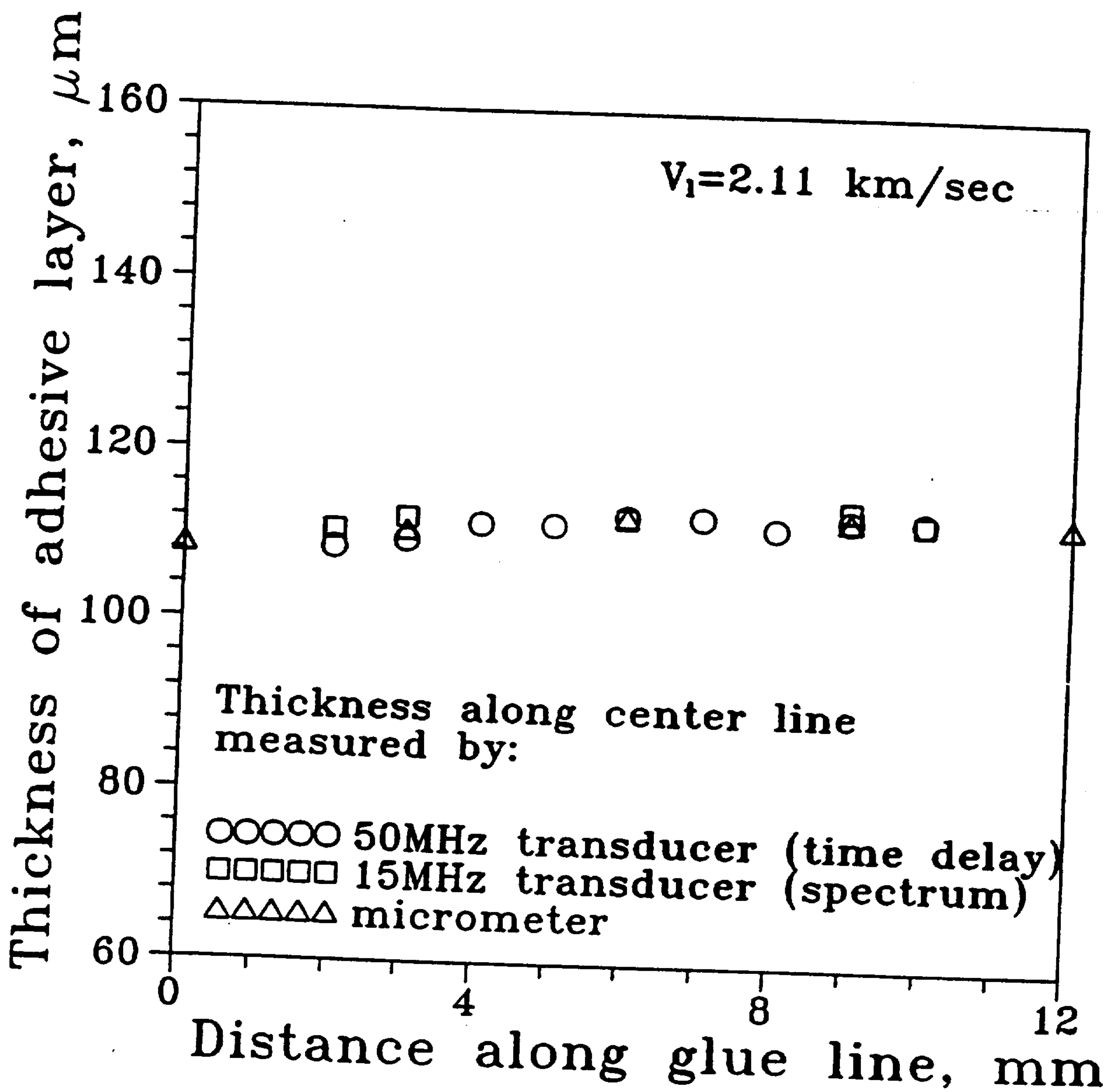


Measurement of water layer thickness at the coating/Ge interface

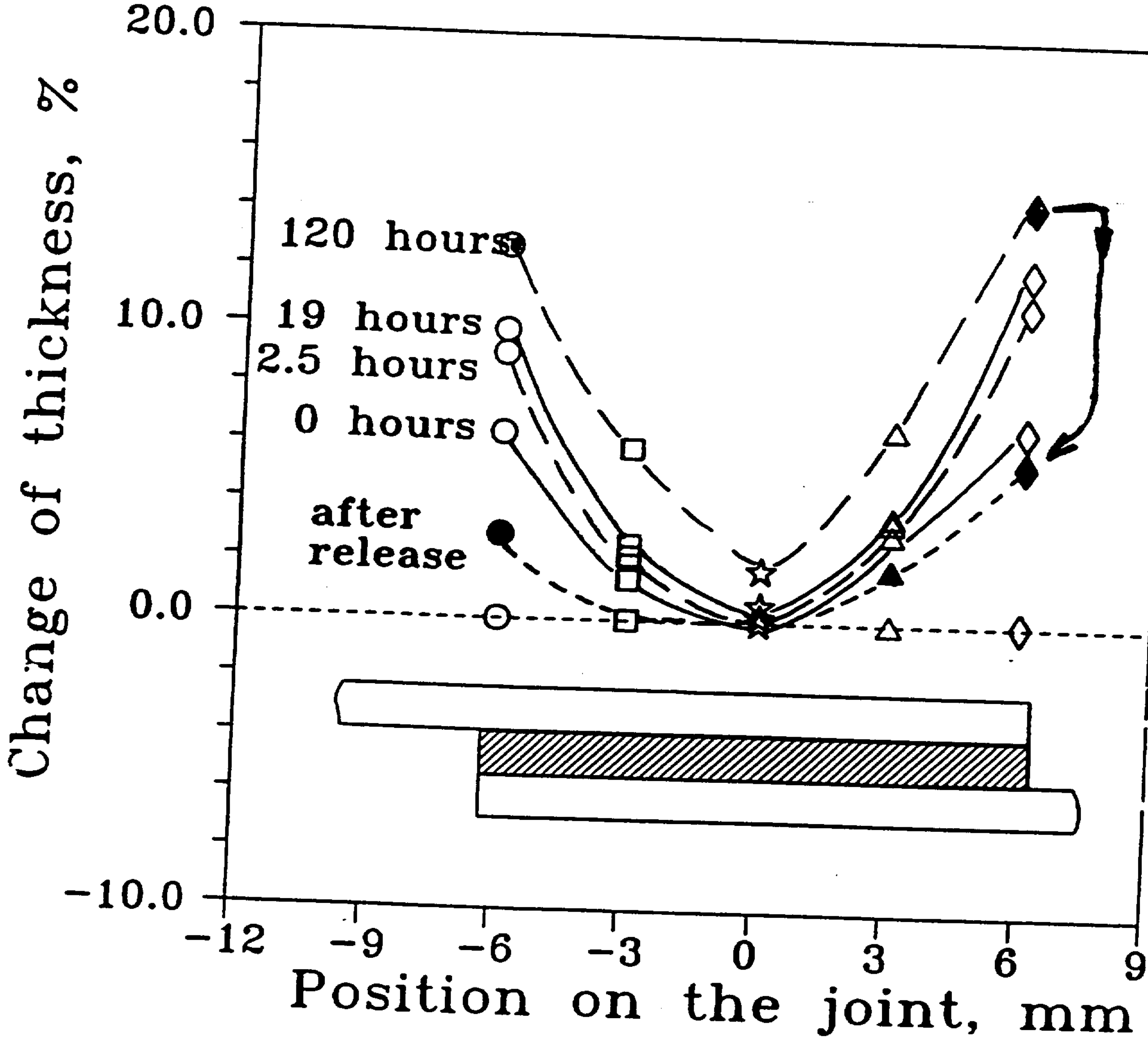




EXAMPLE OF THICKNESS MEASUREMENT FOR THE SAMPLE BEFORE DEGRADATION



RELATIVE THICKNESS CHANGE OF ADHESIVE LAYER DUE TO EXPOSURE IN NaCl SATURATED SOLUTION AT 68°C UNDER 800 LB LOAD



CONCLUSIONS:

i) Three factors were found to affect position of frequency minimum for obliquely reflected signal:

- adhesive layer thickness increase (including creep)
- bulk adhesive properties change
- interface degradation

ii) Measurements at normal incidence on the joint are sensitive only to thickness and bulk property changes

- this is a basis for separation of interfacial degradation effects from thickness and bulk property change effects

iii) Frequency-minimum shift at the edges of the joint is larger than predicted from the adhesive thickness change.
The excess is due to interface degradation

iv) Frequency-minimum shift at the center of the joint is less than predicted from the adhesive thickness change.
This may be attributed to stress redistribution and stress change at the joint center

BOEING / CSIRO JOINT RESEARCH PROJECT

NDT OF BONDED STRUCTURES

Report No. 16

NON-LINEAR PROPAGATION OF GUIDED ELASTIC WAVES

I. THEORETICAL ASPECTS

D C Price

CSIRO Telecommunications & Industrial Physics

November 1998

Non-linear wave equation:

$$\rho_0 \ddot{u}_i = \sum C_{ijkm} \frac{\partial^2 u_k}{\partial x_j \partial x_m}$$

$$+ \sum M_{ijkmpq} \frac{\partial^2 u_k}{\partial x_j \partial x_m} \cdot \frac{\partial u_p}{\partial x_q}$$

$$+ \;\ldots\ldots\ldots$$

$$M_{ijkmpq} = C_{ijkmpq} + C_{ijmq}\delta_{kp} + C_{jmpq}\delta_{ik} + C_{jkmq}\delta_{ip}$$

OR

$$\rho_0 \ddot{u}_i - C_{ijkm} \frac{\partial^2 u_k}{\partial x_j \partial x_m} = F_i(\underline{u})$$

$F_i(\underline{u})$ is non-linear driving force

Successive approx. approach

Put

$$\underline{U} = \alpha \underline{U}^{(1)} + \alpha^2 \underline{U}^{(2)} + \cdots\cdots$$

$$\underline{U}^{(1)} \gg \underline{U}^{(2)} \gg \cdots\cdot$$

α an arbitrary expansion parameter

Equating terms of equal powers in α

$\longrightarrow$

$$\rho_0 \ddot{U}_i^{(1)} - C_{ijkm} \frac{\partial^2 U_k^{(1)}}{\partial x_k \partial x_m} = 0 \qquad (1)$$

$$\rho_0 \ddot{U}_i^{(2)} - C_{ijkm} \frac{\partial^2 U_k^{(2)}}{\partial x_k \partial x_m} = F_i(\underline{U}^{(1)}) \qquad (2)$$

$$F_i(\underline{U}^{(1)}) = M_{ijkmpq} \frac{\partial^2 U_k^{(1)}}{\partial x_j \partial x_m} \cdot \frac{\partial U_p^{(1)}}{\partial x_q}$$

$\underline{F}$ is driving force that depends only on linear waves $U^{(1)}$

Boundary conditions

- must be satisfied at all points at all times

∴ continuity conditions must be true at f and 2f separately.

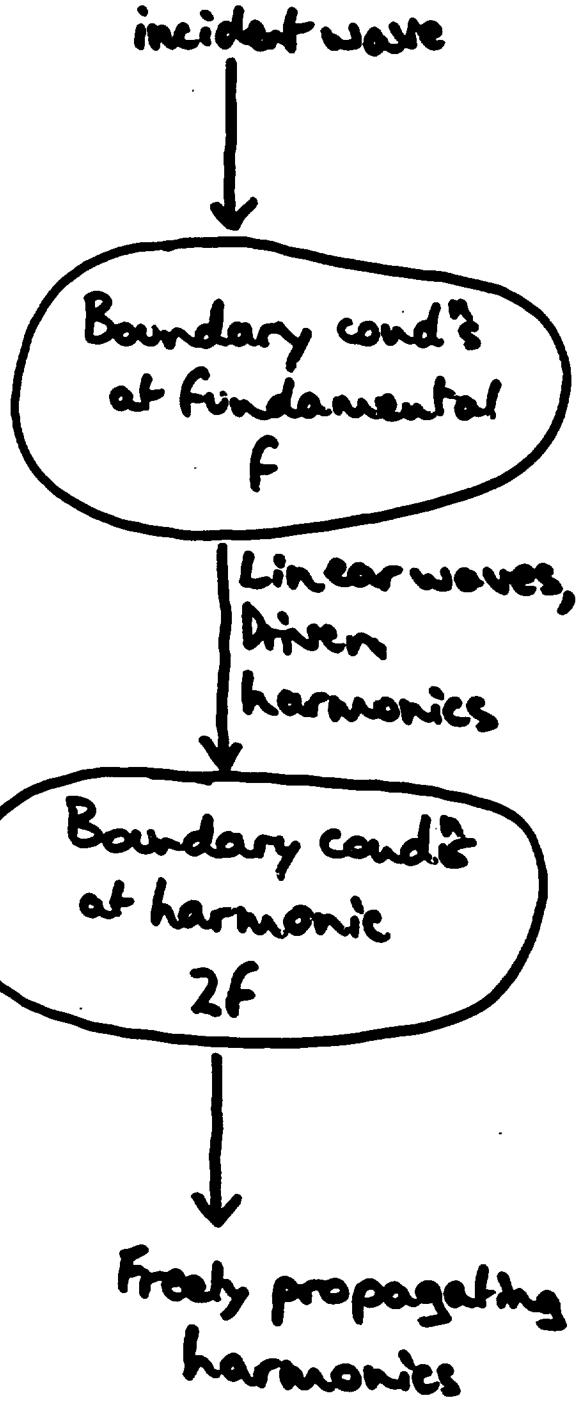
At 2f, stress at boundary includes:

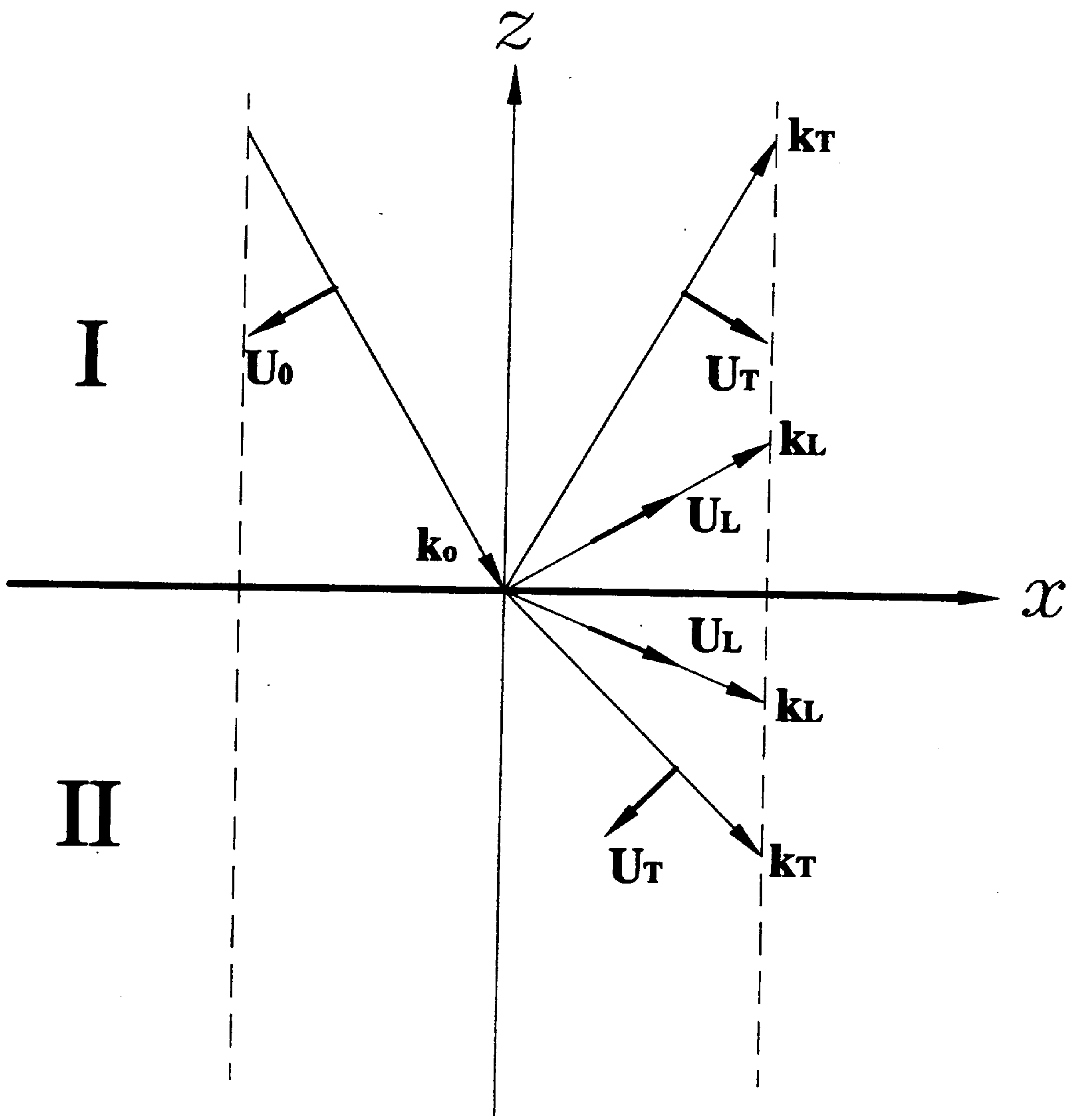
- stress due to free harmonics (to be determined)
- stress due to driven harmonics
- second-order stress terms from linear waves

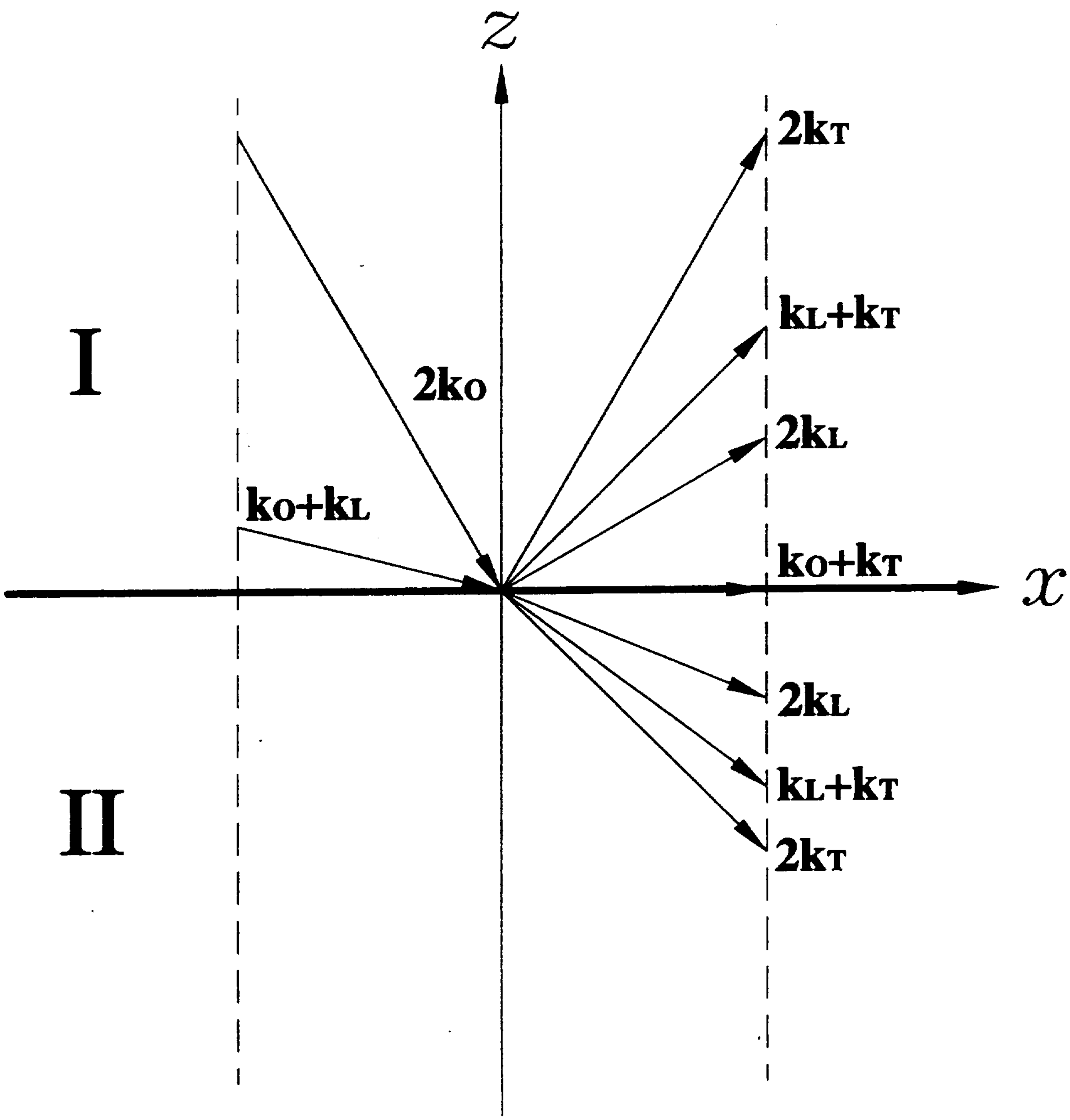
$$T_{ij} = C_{ijkm} \frac{\partial U_k}{\partial x_m} + B_{ijkmpq} \frac{\partial U_k}{\partial x_m} \cdot \frac{\partial U_p}{\partial x_q} + \cdots$$

Summary

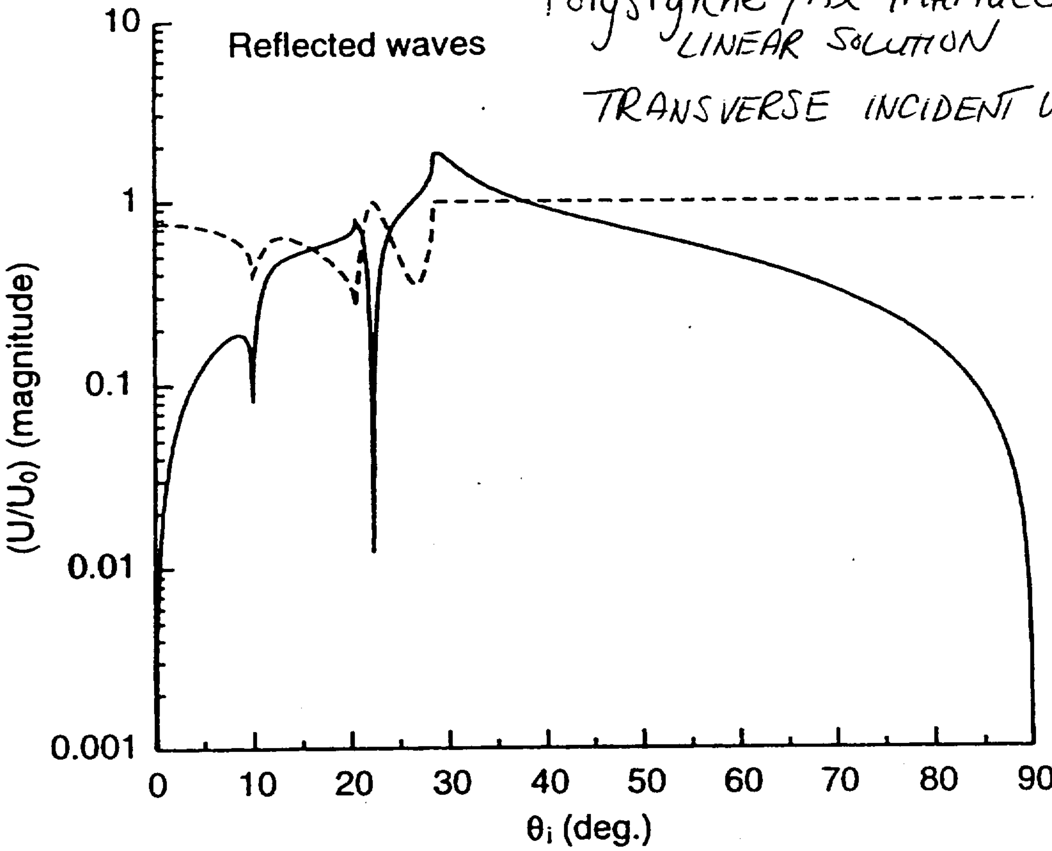
Summary

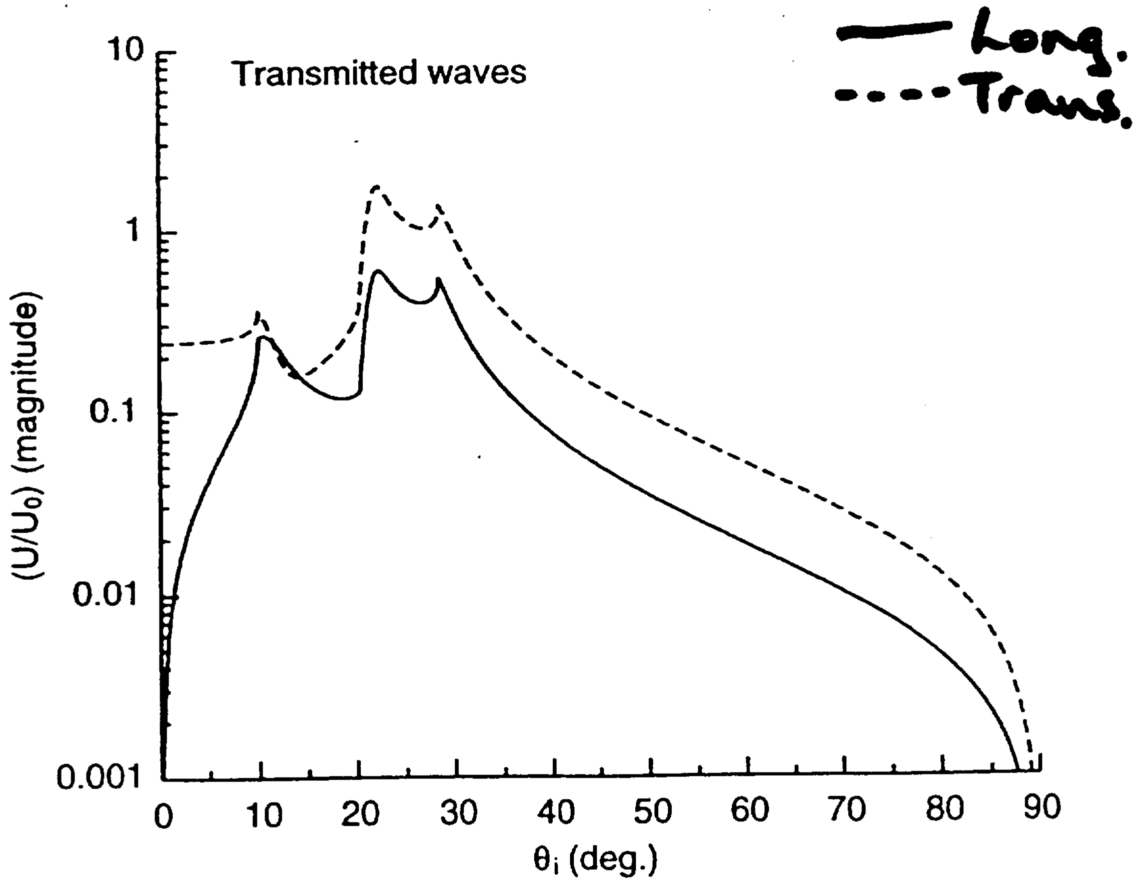

incident wave
Boundary cond^{n}s at fundamental f
Linear waves, Driven harmonics
Boundary cond^{n}s at harmonic 2f
Freely propagating harmonics


z
x
I
II
$\mathbf{U_0}$
$\mathbf{k_0}$
$\mathbf{k_T}$
$\mathbf{U_T}$
$\mathbf{k_L}$
$\mathbf{U_L}$
$\mathbf{U_L}$
$\mathbf{k_L}$
$\mathbf{U_T}$
$\mathbf{k_T}$

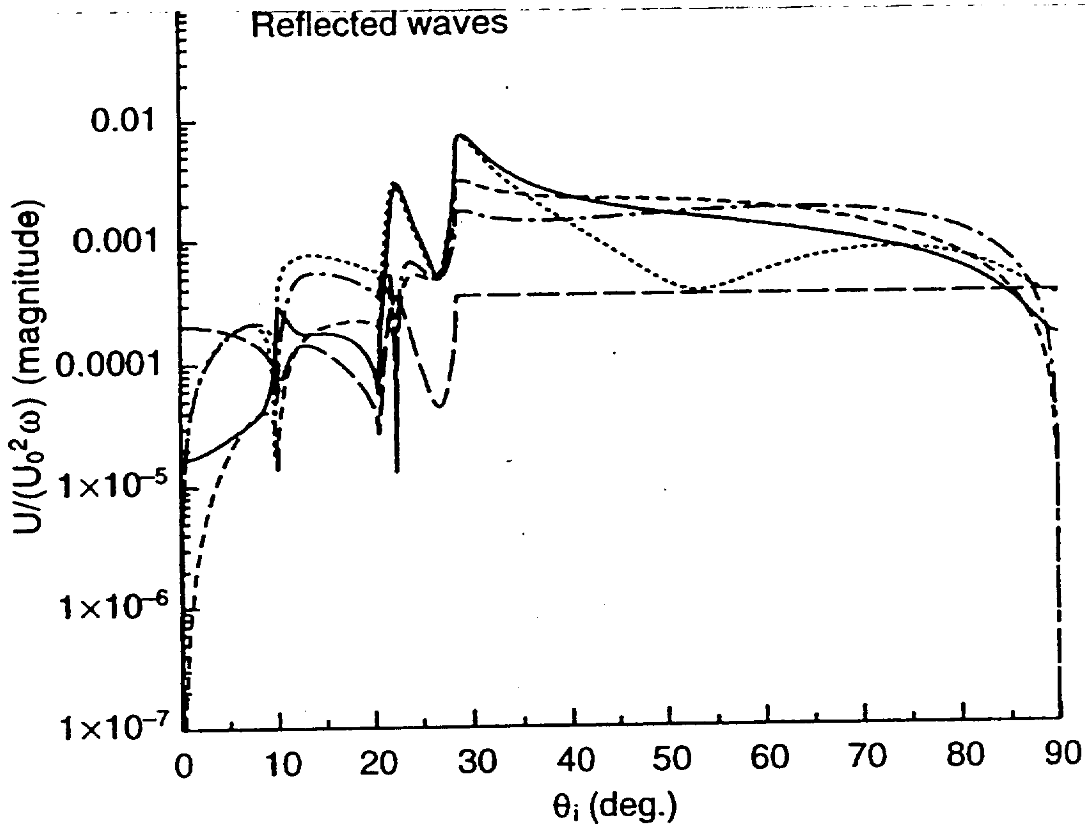

z
2kT
kL+kT
I
2kO
2kL
kO+kL
kO+kT
x
2kL
kL+kT
II
2kT

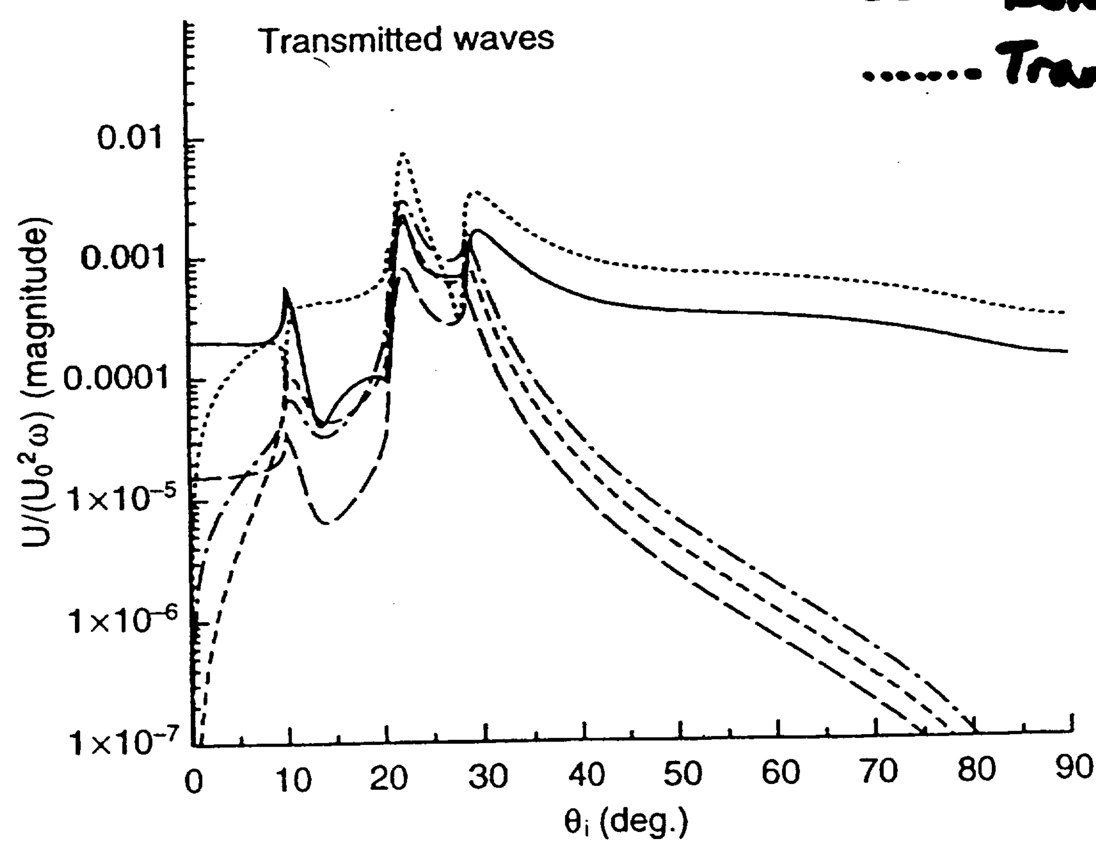
Polystyrene / Al Interface
LINEAR SOLUTION
TRANSVERSE INCIDENT WAVE





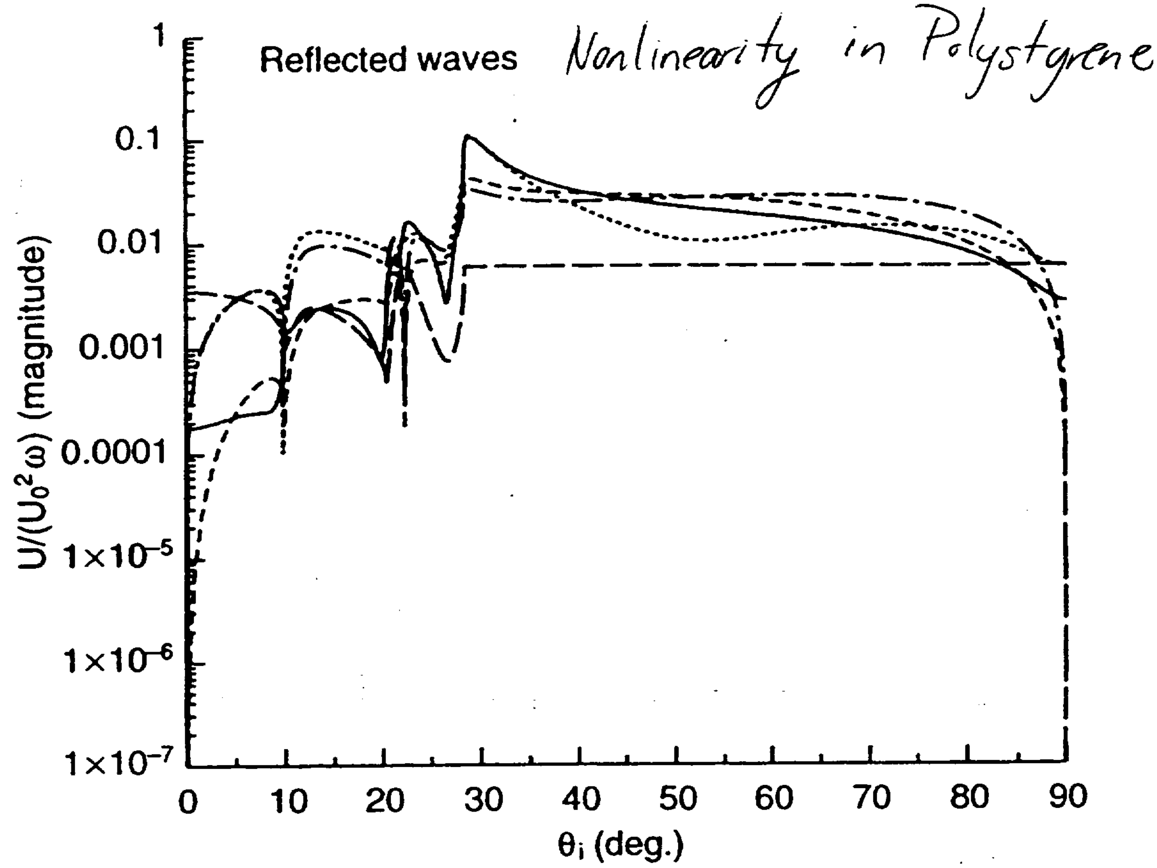
Polystyrene /AL Interface – 2F Solution
Transverse Incident Wave

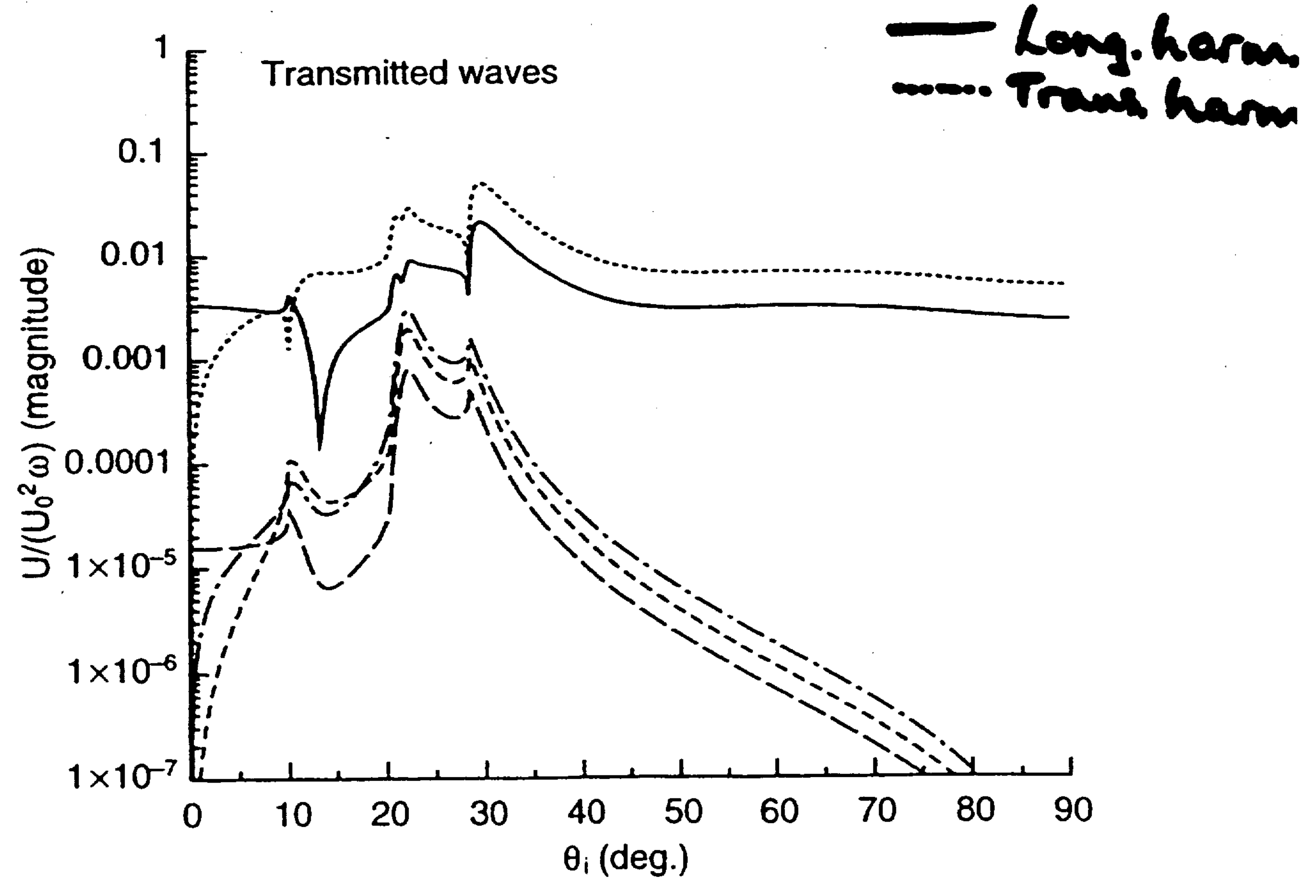


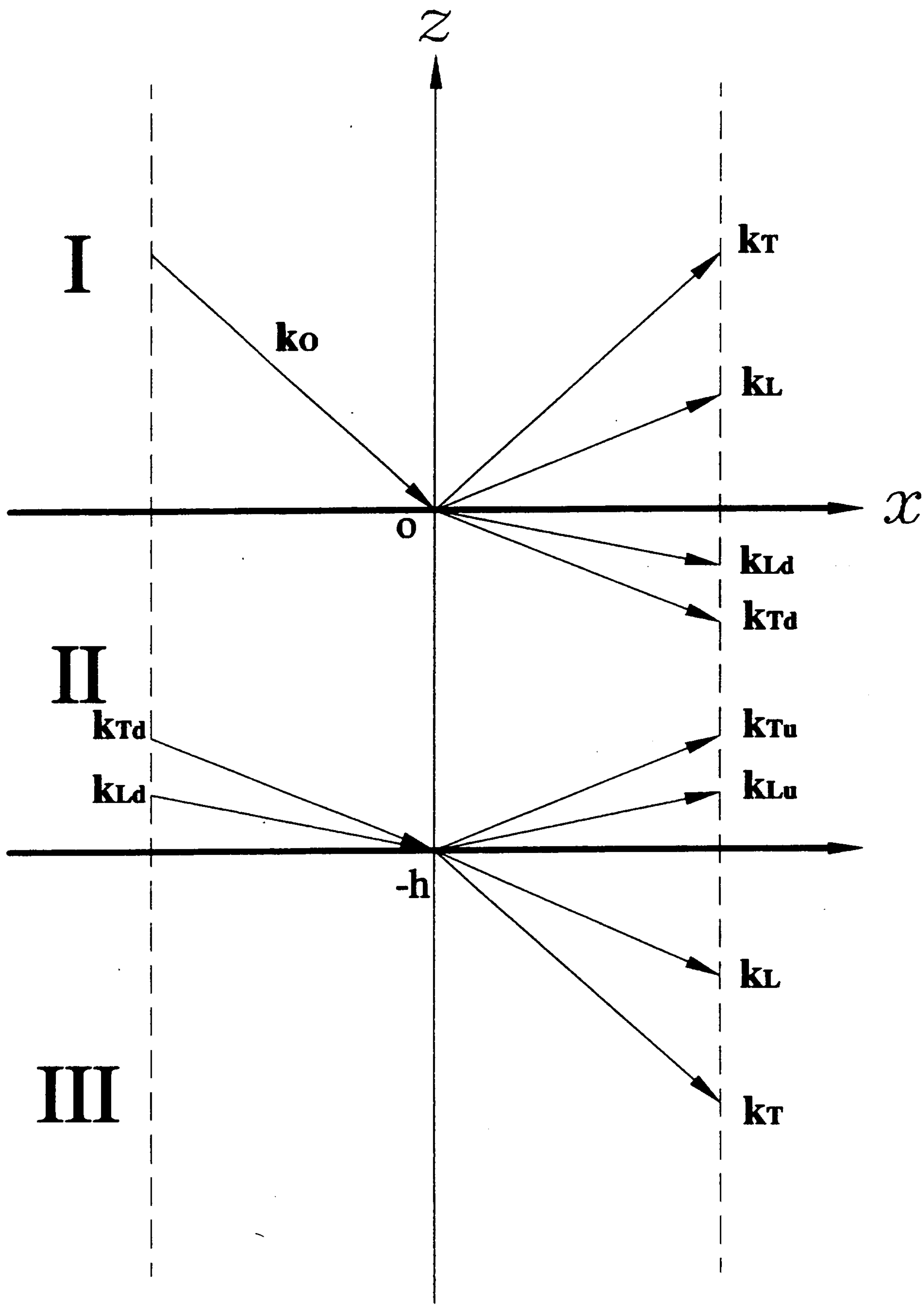


—— Long. harm.
...... Trans. harm.

Polystyrene / AL Interface

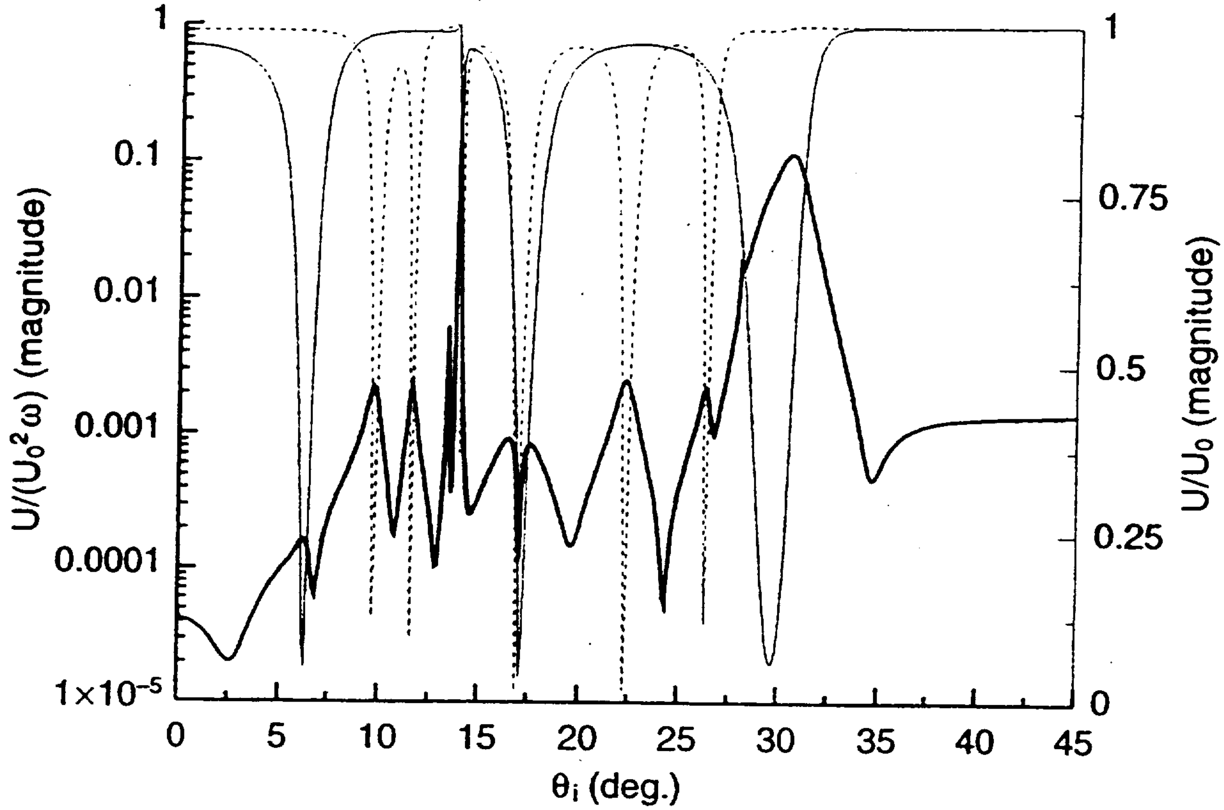




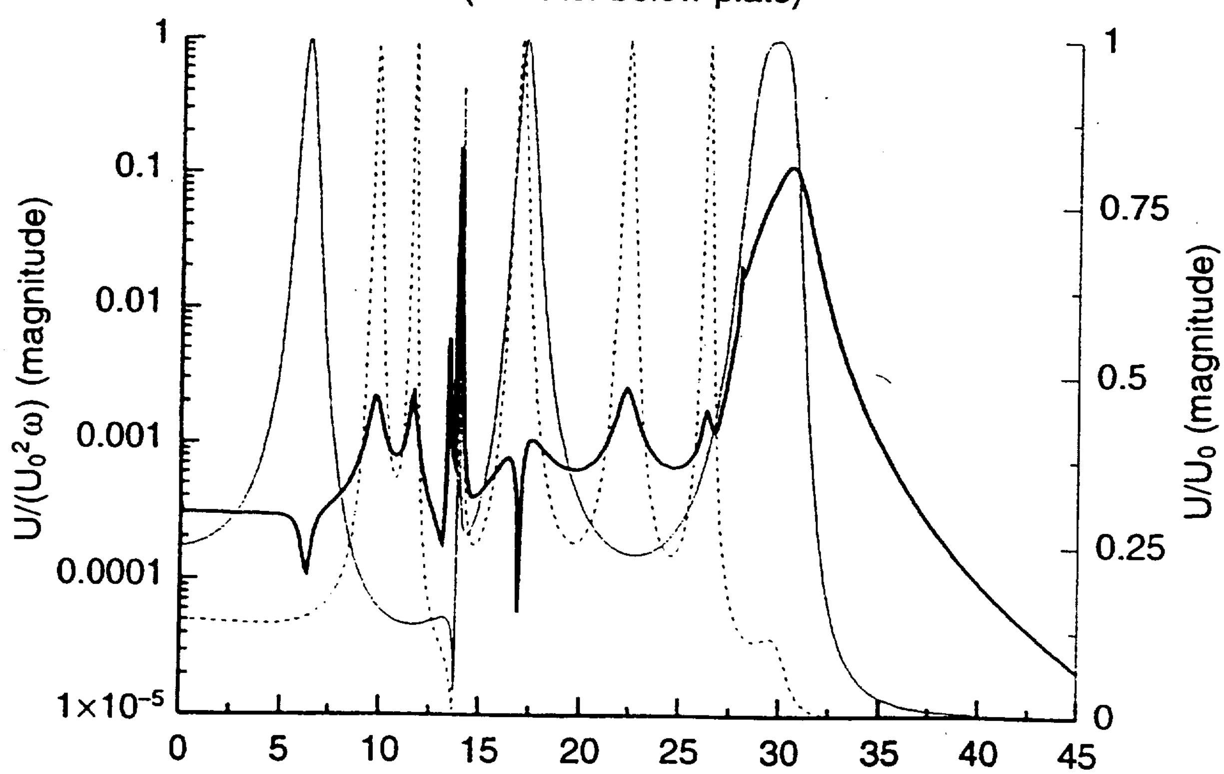

z
x
I
II
III
ko
kT
kL
o
kLd
kTd
kTd
kLd
kTu
kLu
-h
kL
kT

Aluminium plate immersed in water, 2.5 MHz incident wave.

Reflected waves (in water above plate)

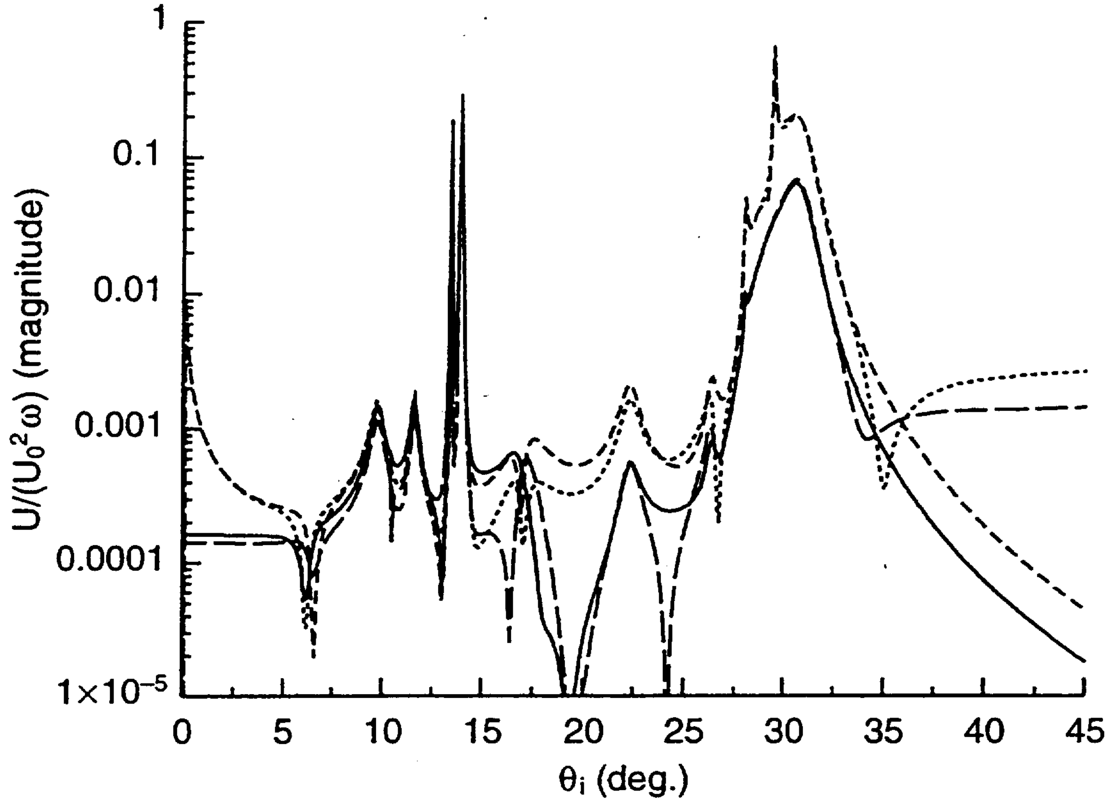


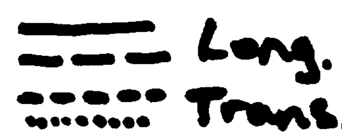
Transmitted waves (in water below plate)



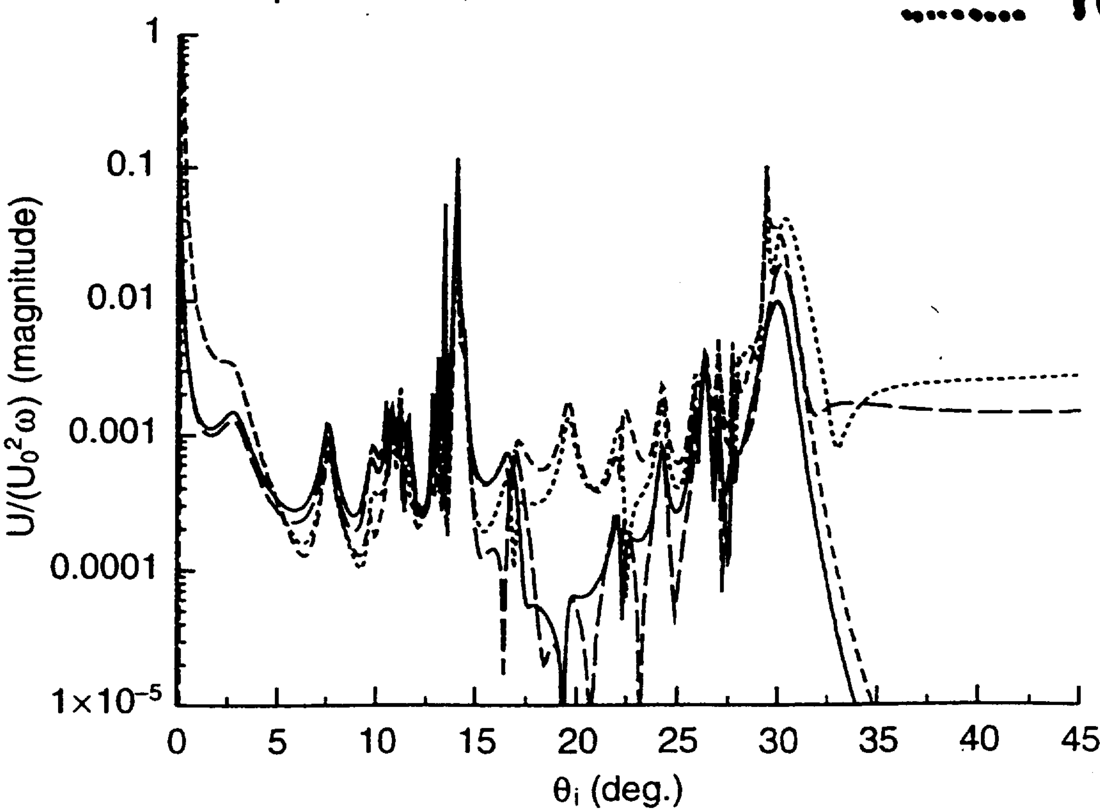
Aluminium plate immersed in water, free harmonics in plate.

Internal plate waves, f = 2.5 MHz

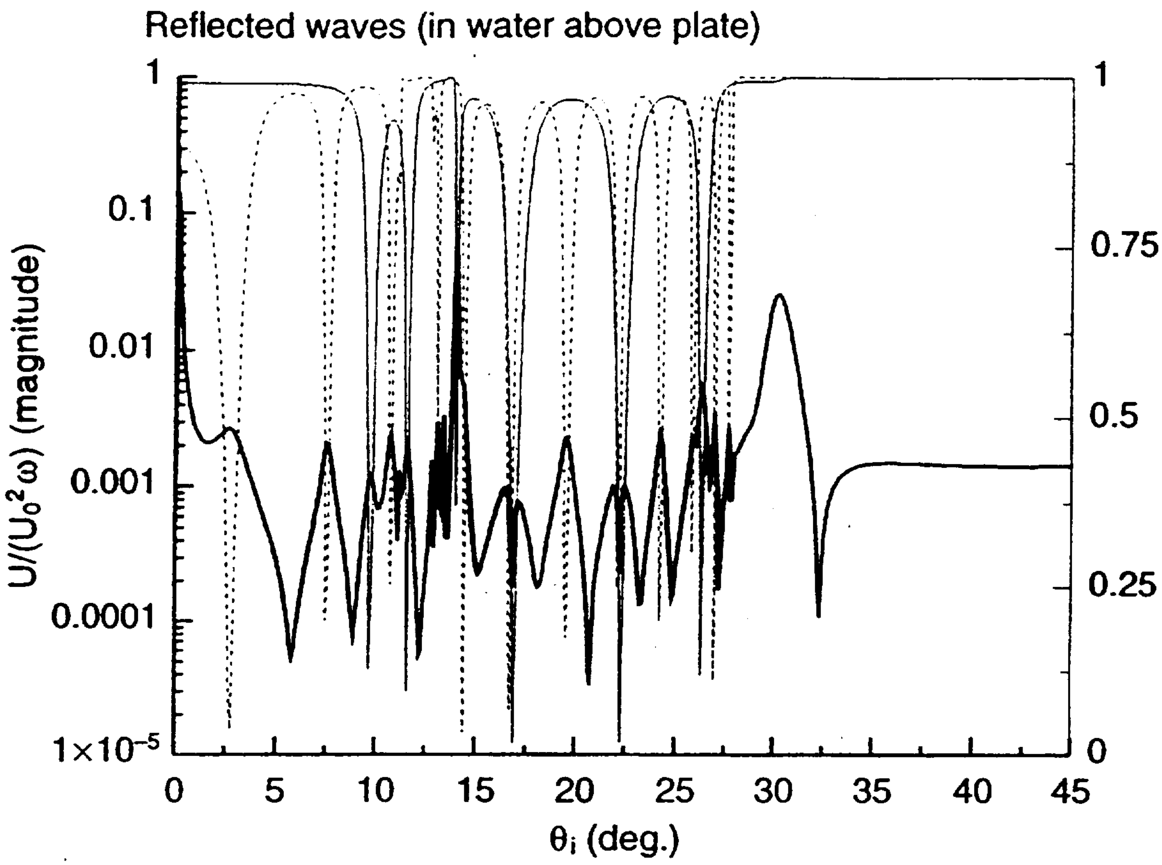


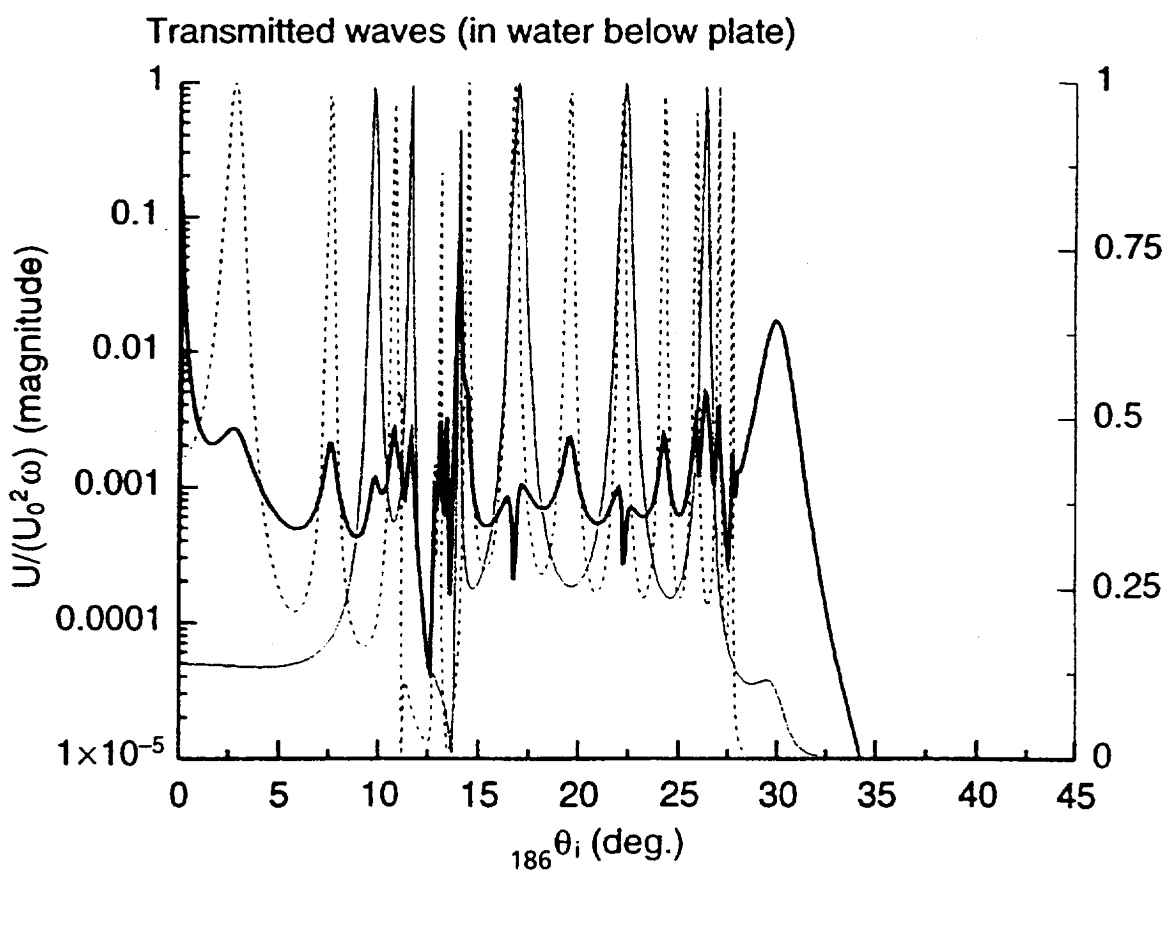


Internal plate waves, f = 5 MHz



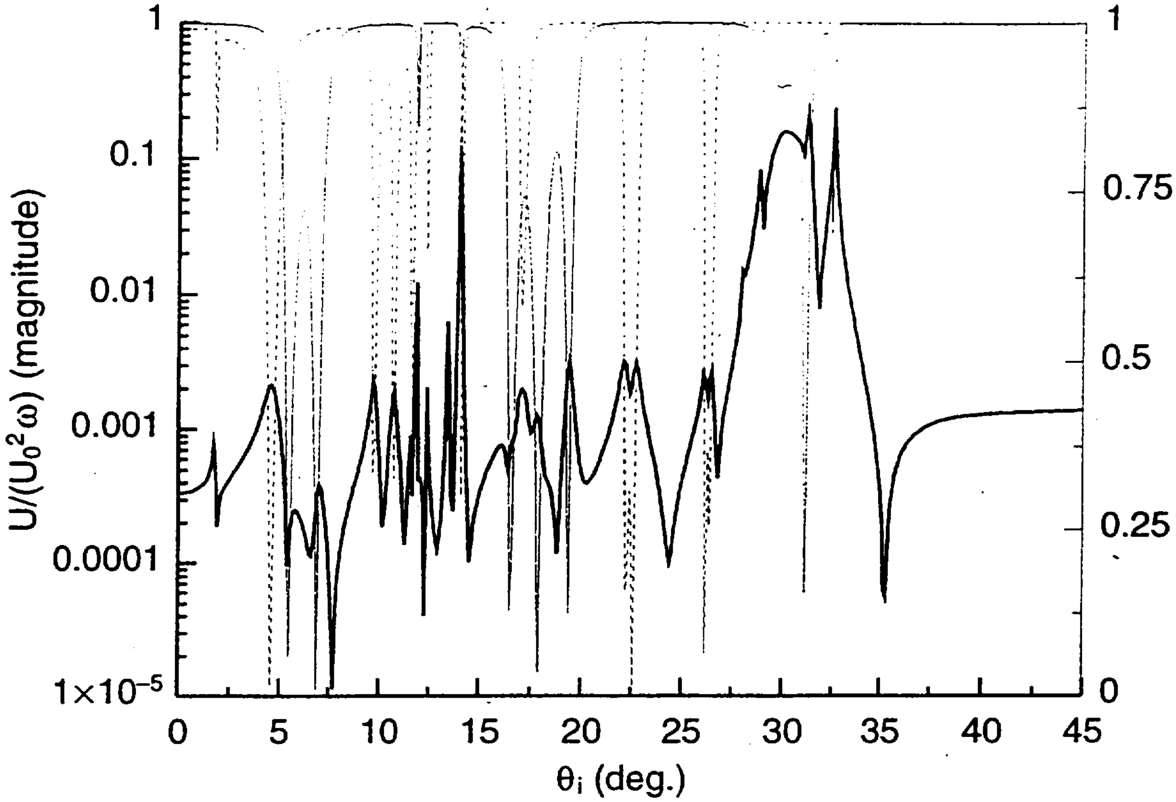
Aluminium plate immersed in water, 5 MHz incident wave.



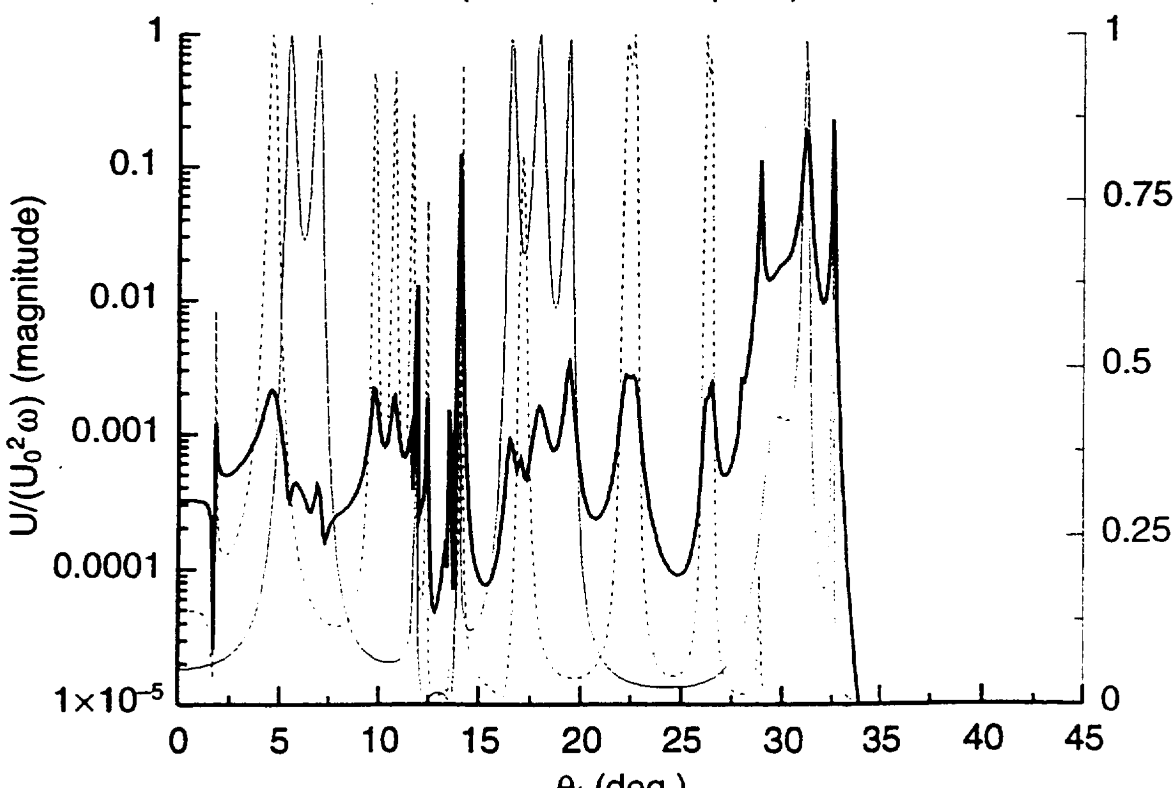


Al bonded plate immersed in water, 2.5 MHz incident wave.

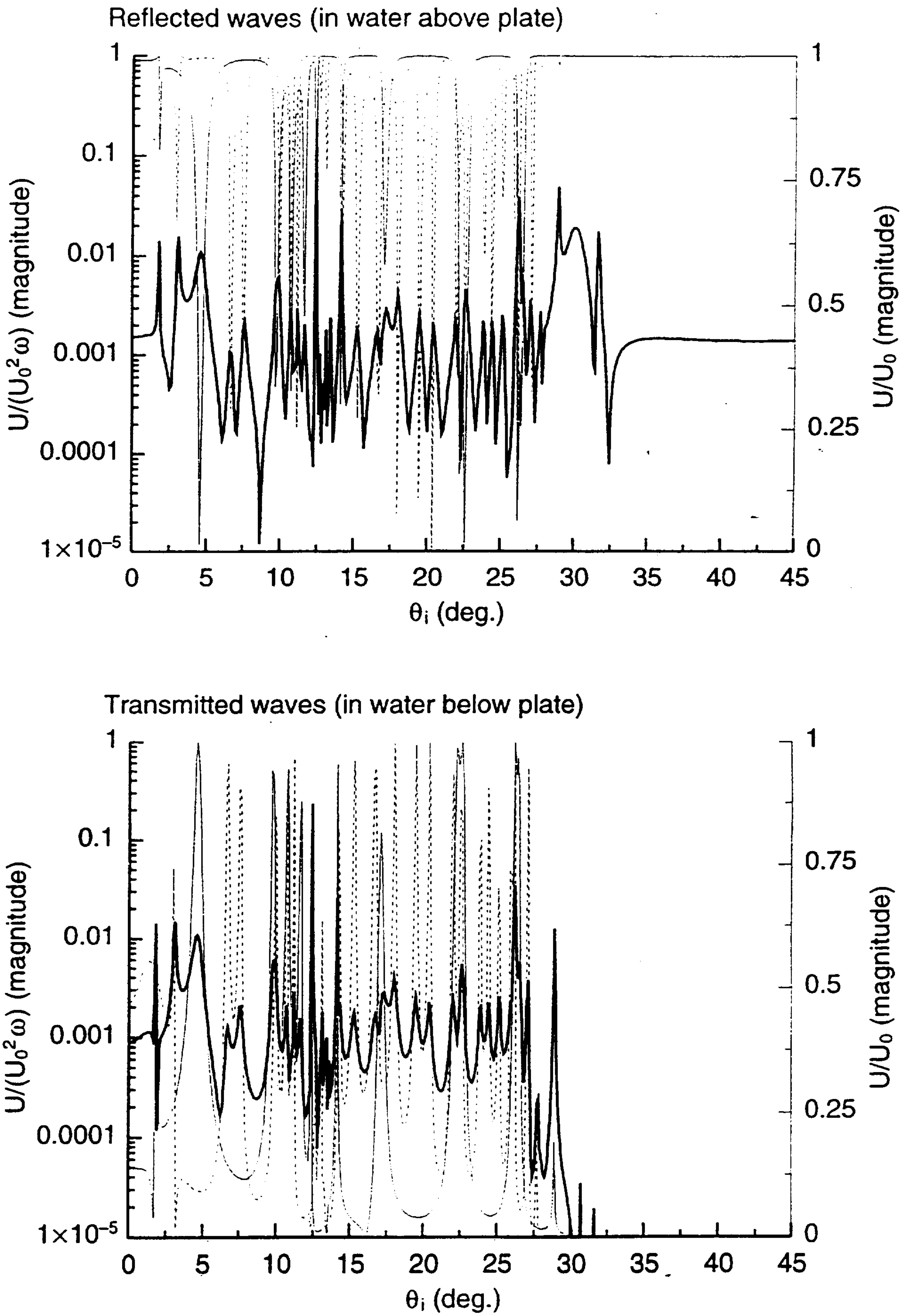
Reflected waves (in water above plate)



Transmitted waves (in water below plate)

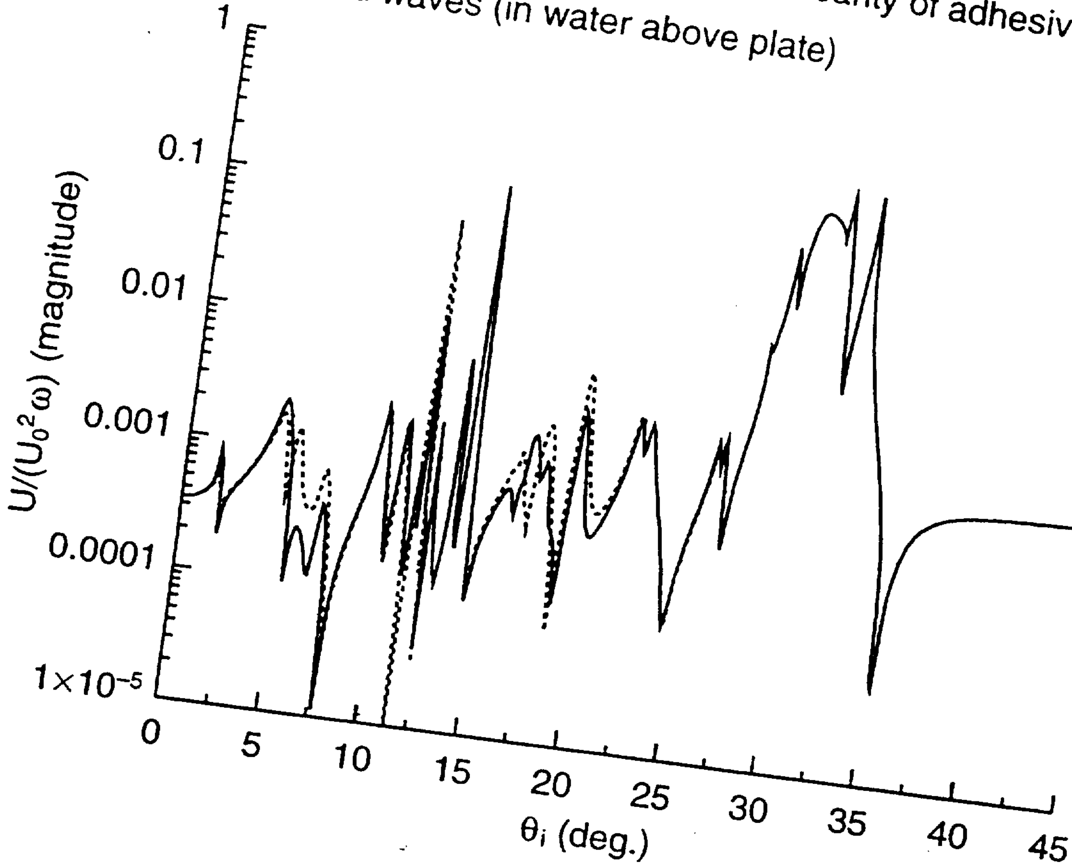


Bonded Al plate immersed in water, 5 MHz incident wave.

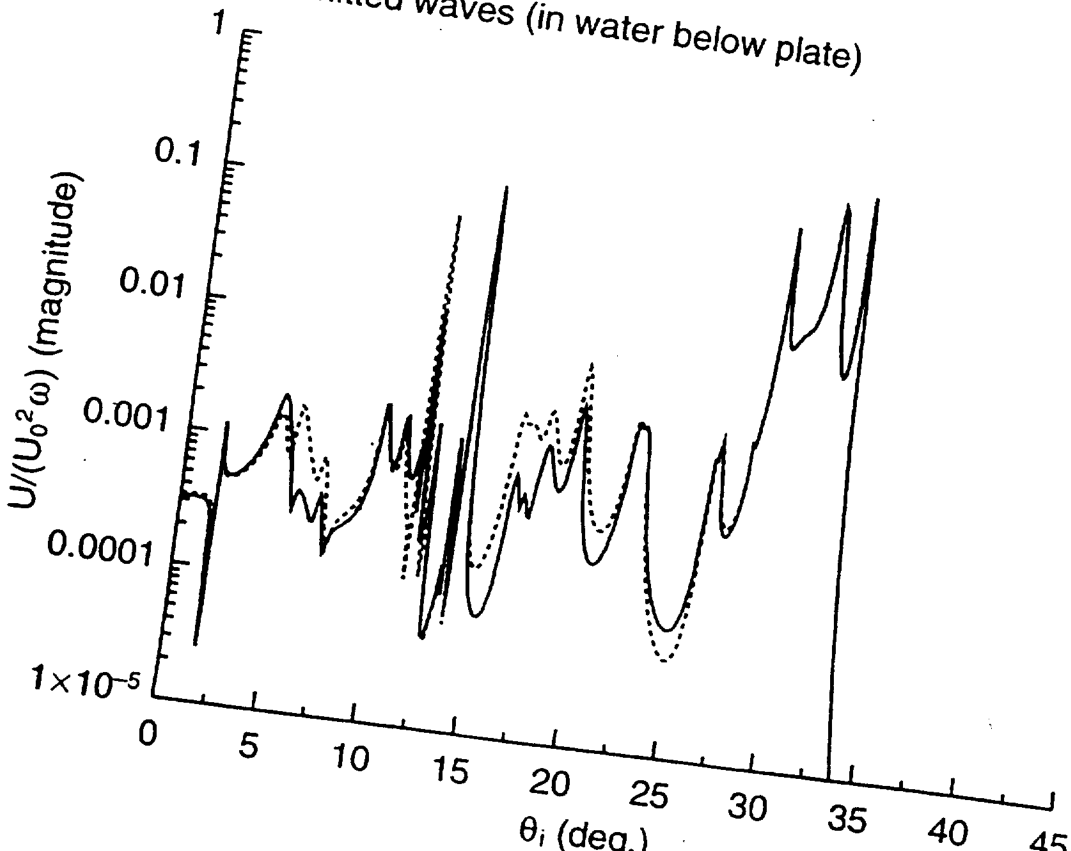


Al bonded plate immersed in water, 2.5 MHz incident wave.
Effect of increased (x2) non–linearity of adhesive

Reflected waves (in water above plate)

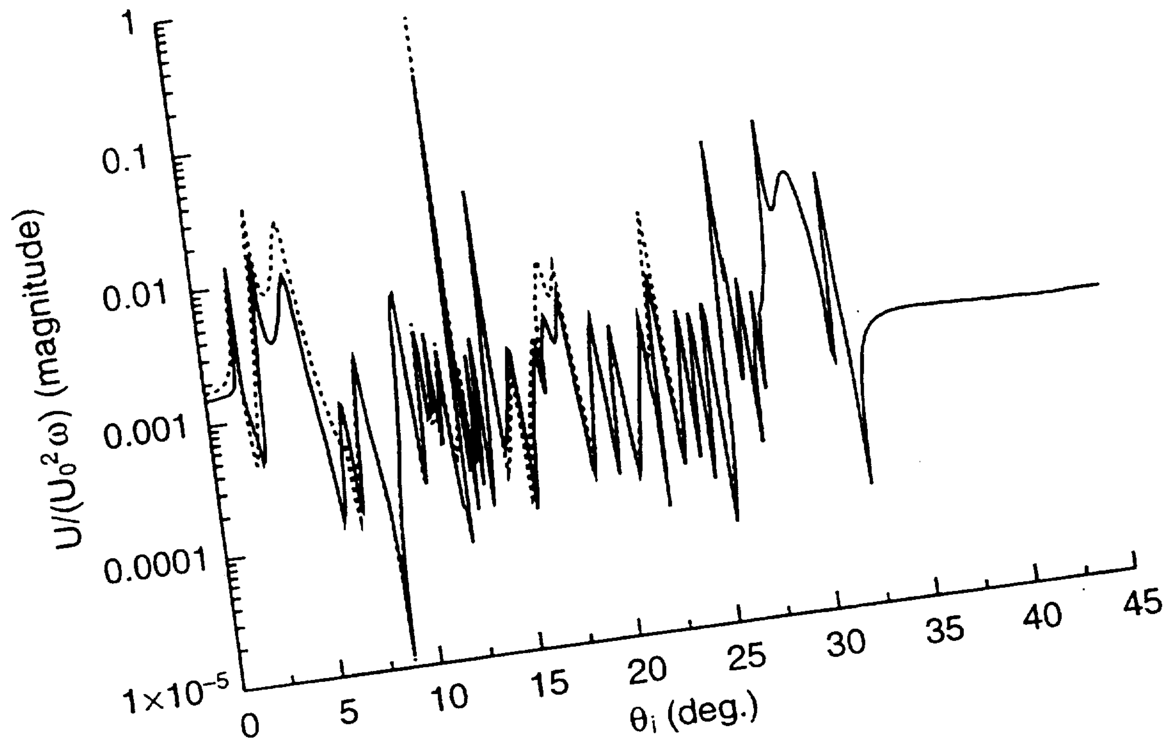


Transmitted waves (in water below plate)

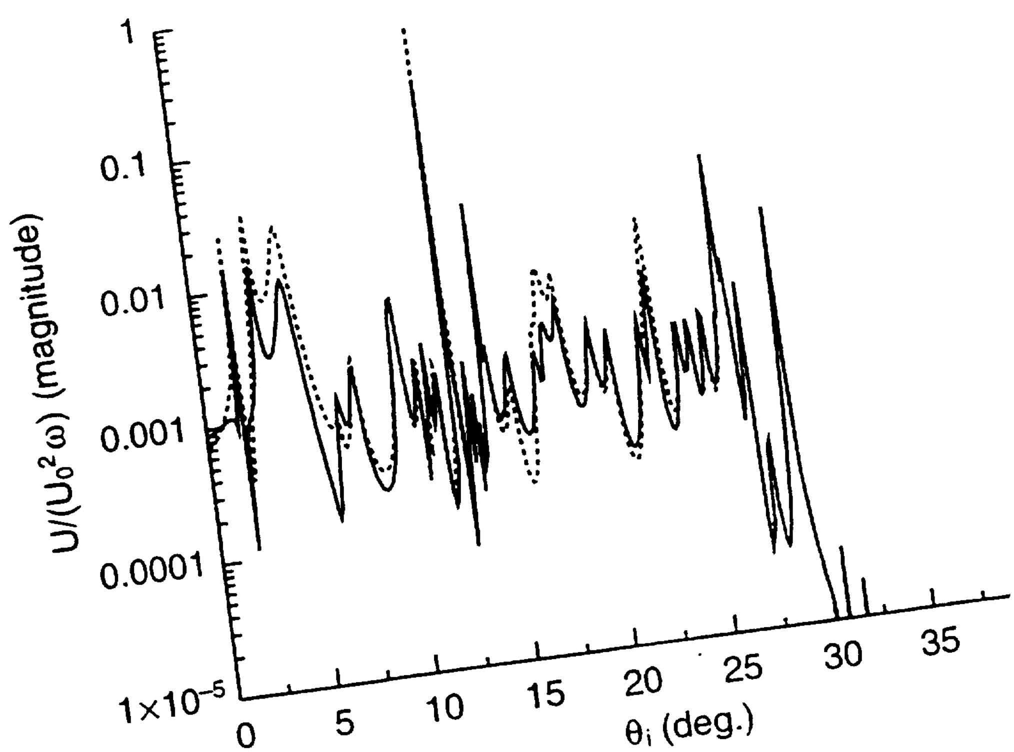


Al bonded plate immersed in water, 5 MHz incident wave.
Effect of increased (x2) non–linearity of adhesive

Reflected waves (in water above plate)



Transmitted waves (in water below plate)



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13. ABSTRACT (*Maximum 200 words*) Ultrasonics, microwaves, optically stimulated electron emission (OSEE), and computational chemistry approaches have shown relevance to bond strength determination. Nonlinear ultrasonic nondestructive evaluation methods, however, have shown the most effectiveness over other methods on adhesive bond analysis. Correlation to changes in higher order material properties due to microstructural changes using nonlinear ultrasonics has been shown related to bond strength. Nonlinear ultrasonic energy is an order of magnitude more sensitive than linear ultrasound to these material parameter changes and to acoustic velocity changes caused by the acoustoeleastic effect when a bond is prestressed. Signal correlations between non-linear ultrasonic measurements and initialization of bond failures have been measured. This paper reviews bond strength research efforts presented by university and industry experts at the Second Annual Symposium for Nondestructive Evaluation of Bond Strength organized by the NDE Sciences Branch at NASA Langley in November 1998.			
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