Structural Health Monitoring in Composite Materials Using Lamb Wave Methods

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Structural Health Monitoring

- SHM denotes a system with the ability to detect and interpret adverse “changes” in a structure in order to improve reliability and reduce life-cycle costs.

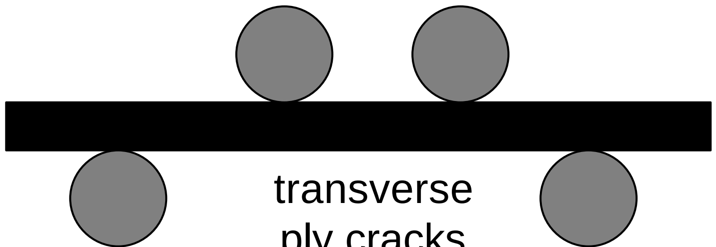
- Greatest challenge in designing a SHM system is knowing what “changes” to look for, and how to identify them

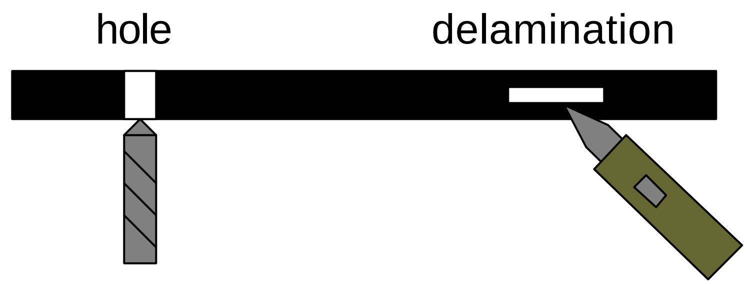
- Reduces inspection and maintenance expenses and increases the reliability of damage detection and failure prediction
  - currently 27% of aircraft life cycle cost is spent in inspections
  - avoid tear-down of built up structures for required inspections
  - much of the airline and military fleet are aging aircrafts, fatigue and corrosion become a problem

Motivation and Research Goals

- Status quo of SHM research
  - several projects investigating particular methods on ideal coupons
  - investigators are often over-sold on their own detection method
  - little presented on limitations of methods or pertinence to SHM
- Proposed research
  - investigate potential sensing methods and combinations
  - report on strengths and limitations of methods
  - implementation potential for a real structure (conformability, size, etc.)
  - show progression of detection reliability through building block
- Focus on composite materials — high pay-off area
  - easy to adhere or embed, can tailor material to suit needs
  - practical for new programs, can help to relax fears of “BVID”

Experimental Approach

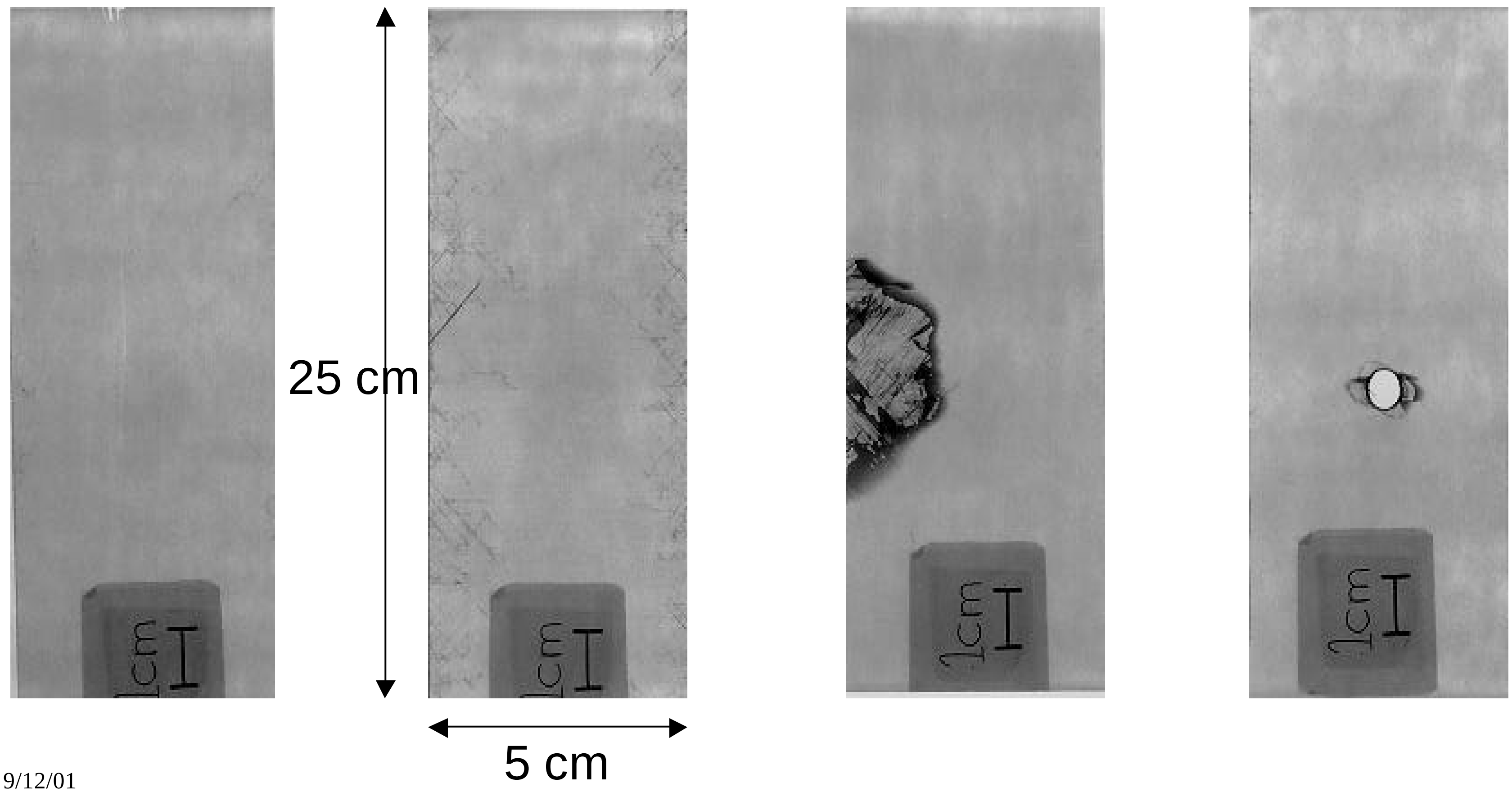




- AS4/3501-6 quasi-isotropic [90/?45/0]s laminates
- Introduced representative damage to composite specimens
  - delamination — 2.5 cm cut w/utility knife, or teflon strip in middle
  - transverse ply cracks — 4-pt fatigue on center of specimen
  - fiber fracture — 4-pt bend until audible damage
  - stress concentration — drilled hole through specimen
  - impact — hammer struck against steel plate in center of sample
- Radiographs taken to verify damage

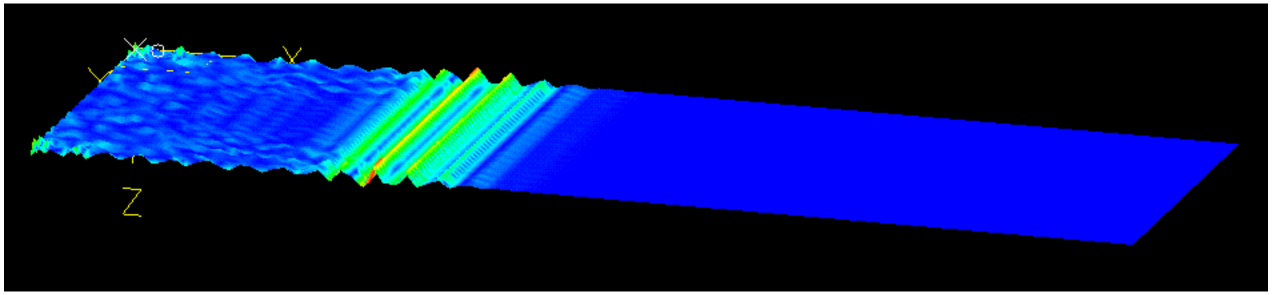
X-Ray Damage Verification

Control Specimen | Matrix Crack Specimen | Delamination Specimen | Core Drilled Specimen

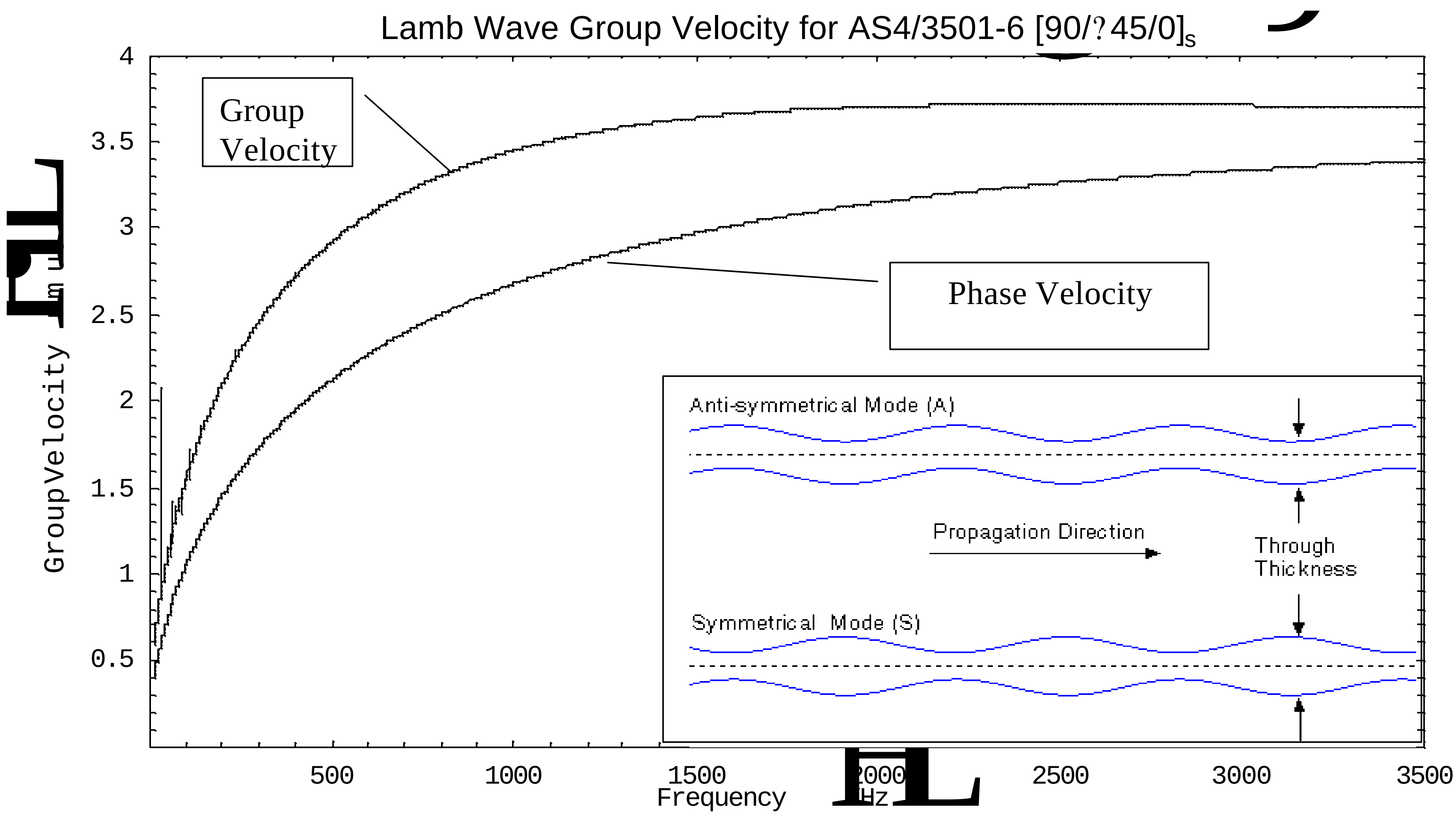


Lamb Waves

- Form of elastic perturbation that propagates in a solid medium
- First described by Horace Lamb in 1917
- Described via dispersion curves
  - plot group or phase velocity versus frequency thickness product
  - function of elastic constants and density (often use Lamé's constants)
- At a given frequency, two types of Lamb waves satisfy the wave equation – symmetric and anti-symmetric



Dispersion Curves and Wave Shapes



Damage Detection using Lamb Waves

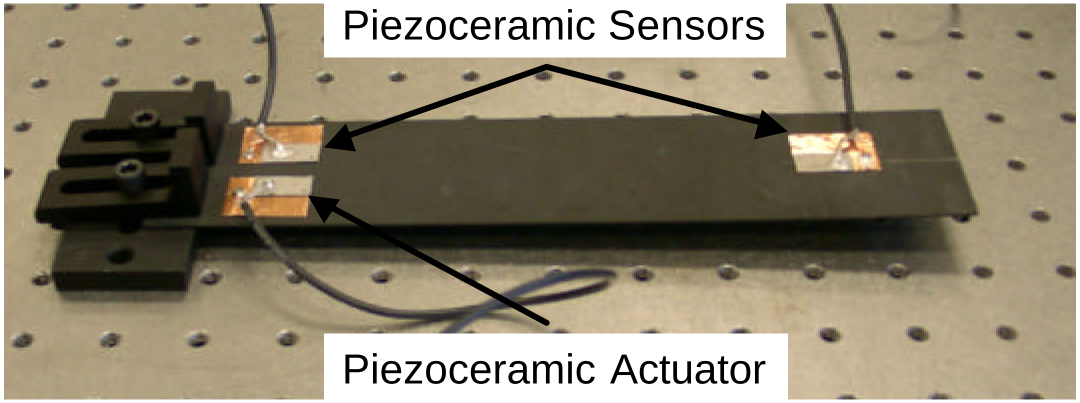
- Use specimens from previous work, improve detection capability found using frequency response methods

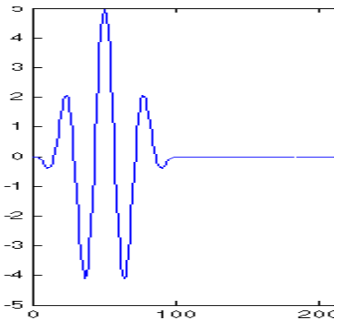
- Damage can be identified in several ways
  - group velocity determined by $(E/?)^{1/2}$, cracks slow down waves
  - reflected wave from damage can be used to determine locations

- Levels of damage detection in a structure
  - identify presence of known damage in specimens
  - differentiate between types of damage
  - estimate damage location on specimen
  - quantify extent of damage

Experimental Setup

- Setup determined from conclusion of studies
  - from material properties dispersion curves are calculated
  - from group velocity dispersion curve, operating frequency selected
  - from operating wavelength, actuator size is selected
- PZT piezoceramic patches used for actuators and sensors
- Excite A_o wave for long travel distances and to minimize clutter
- Driving signal of 3.5 sine waves under a Hanning window
  - 15 kHz for narrow specimen
  - 50 kHz for sandwich beams



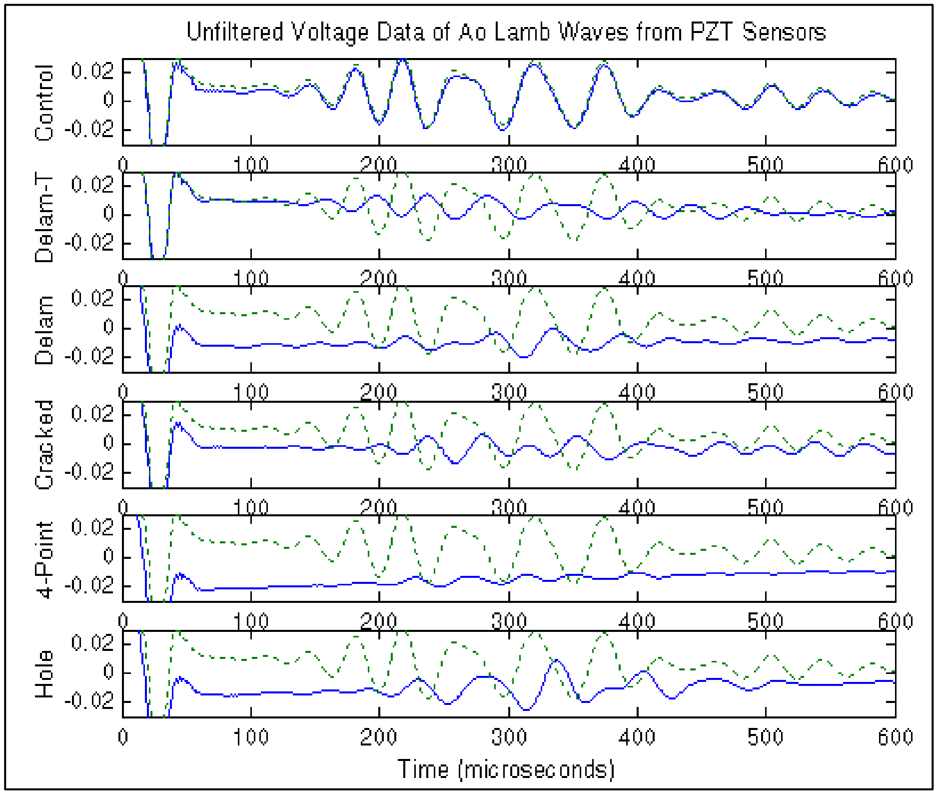


Sent Signal

Building Block Approach

- Coupon level laminate tests
  - consistency amongst control specimens
  - effects of various types of damages
- Narrow sandwich beam specimens
  - effects of various types of cores
  - delamination between laminate and core in different locations
- Complex structures
  - micro-satellite tube with honeycomb core
  - built-up structures with bonded ribs
- Future work with flat plate specimens
  - actuating in center with sensors around edges
  - “self-sensing” actuators in corners

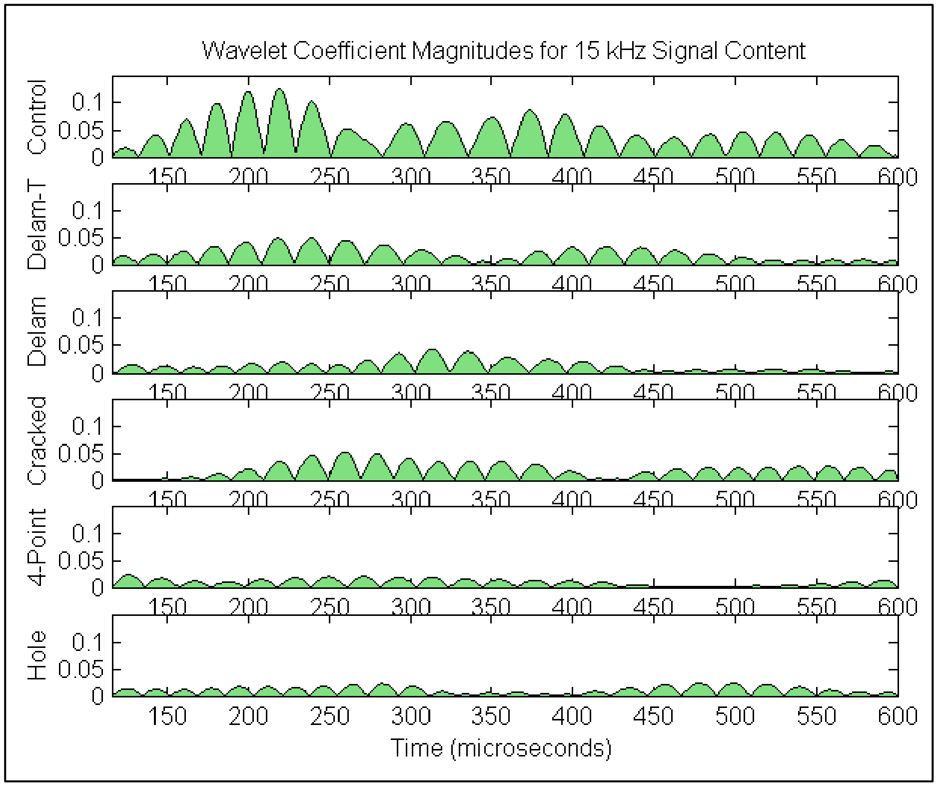
Thin Laminate Results: Time of Flight



- Time-trace of voltage signal from PZT sensor 20 cm from actuator driving at 15 kHz
- High degree of consistency between all control traces
- All damaged traces show a delay in time of arrival, and smaller amplitude responses
- Since these are short specimens, many reflections combine quickly
- While TOF is easily reproduced, difficult to measure accurately

Specimen labeled on plot
Superimposed control specimen

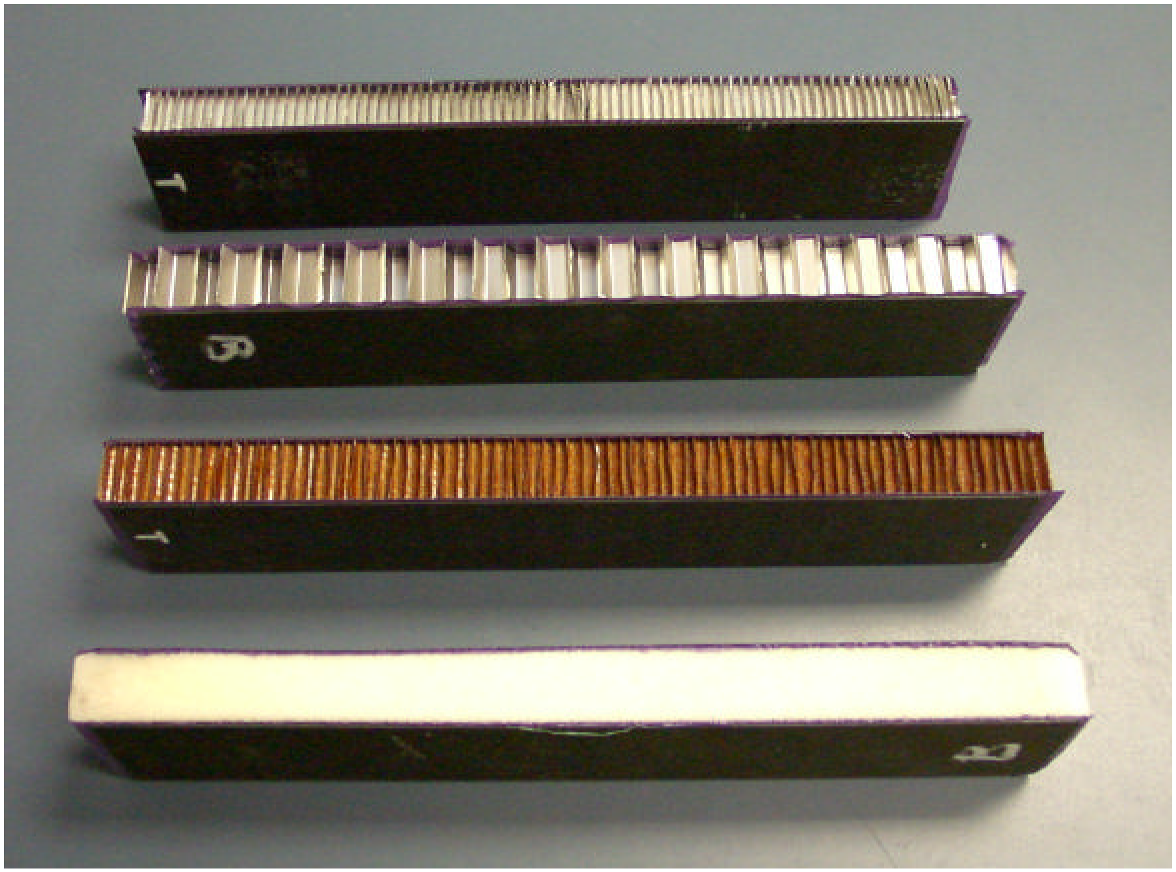
Thin Laminate Results: Wavelet Analysis



- Wavelet decomposition performed using Morlet signal, similar to FFT
- Compare received signal's energy content at dominant frequency
- Control specimen clearly has the most energy transmitted
- Appears that as damage becomes more severe, more energy is lost
- Differences seem obvious enough for process to be automated
- Still not much information about damage type and location

Demonstrates ability to detect presence of damage and judge severity

Narrow Sandwich Beams



25 cm

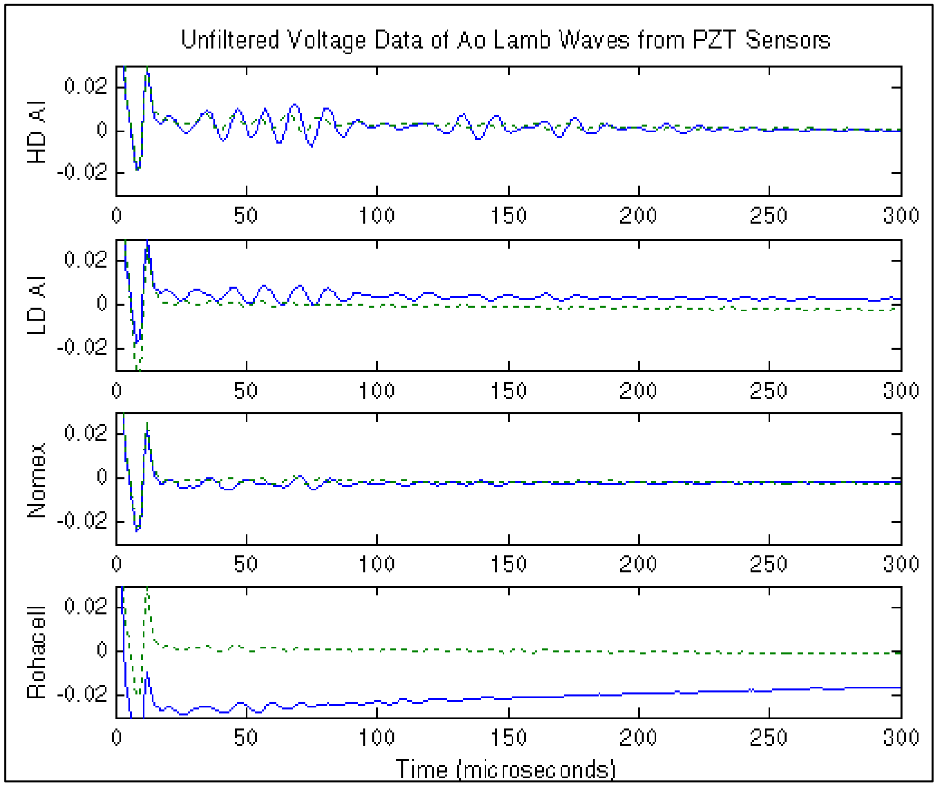
High density aluminum honeycomb (HD Al)

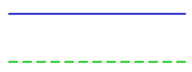
Low density aluminum honeycomb (LD Al)

Nomex core

Rohacell core

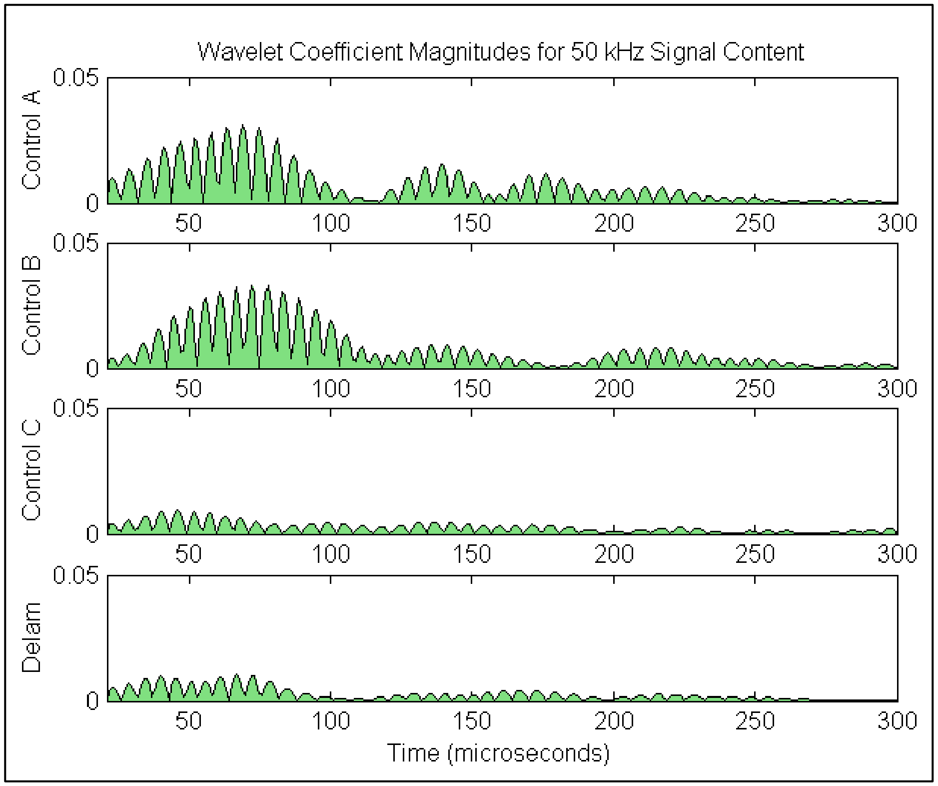
Sandwich Beam Results





- Time-trace of voltage signal from PZT sensor 20 cm from actuator driving at 50 kHz
- Stiffer panel requires higher driving frequency for clear results
- Core causes damping in the signal, softer core? smaller signal
- Again, good consistency between all control traces
- Very small signal in all damaged cases, difficult to compare with undamaged specimen

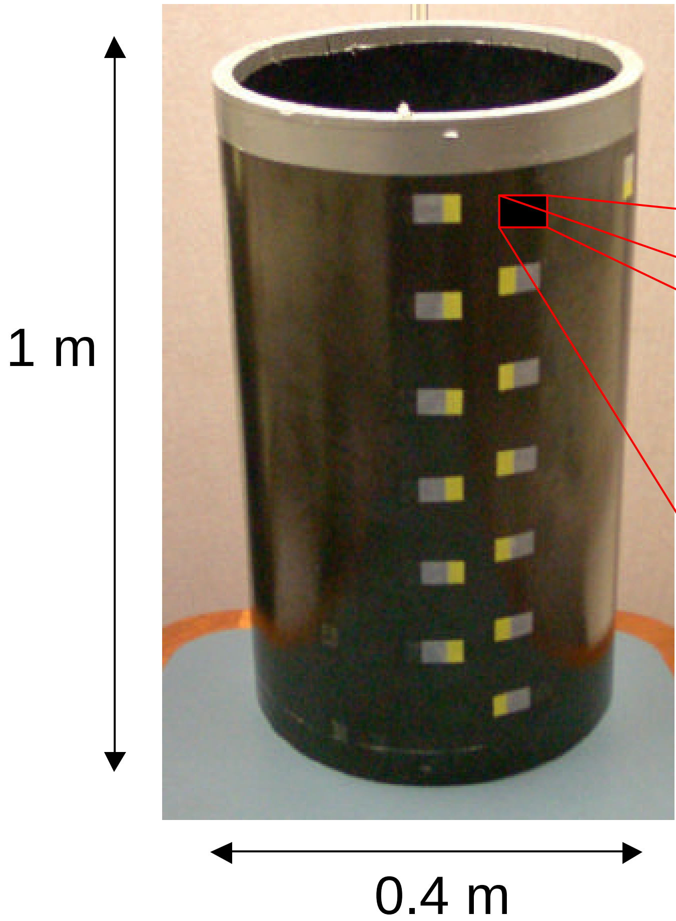
Blind-Test Beam Results



- Wavelet coefficient plot for beam "blind test" compares energy content for 50 kHz
- Three "control" specimens with high density Al core, one has an unknown delamination
- Controls compared to a specimen with a known delamination
- Top two clearly have more energy present, and are the controls
- Bottom two with little energy present are debonded specimen

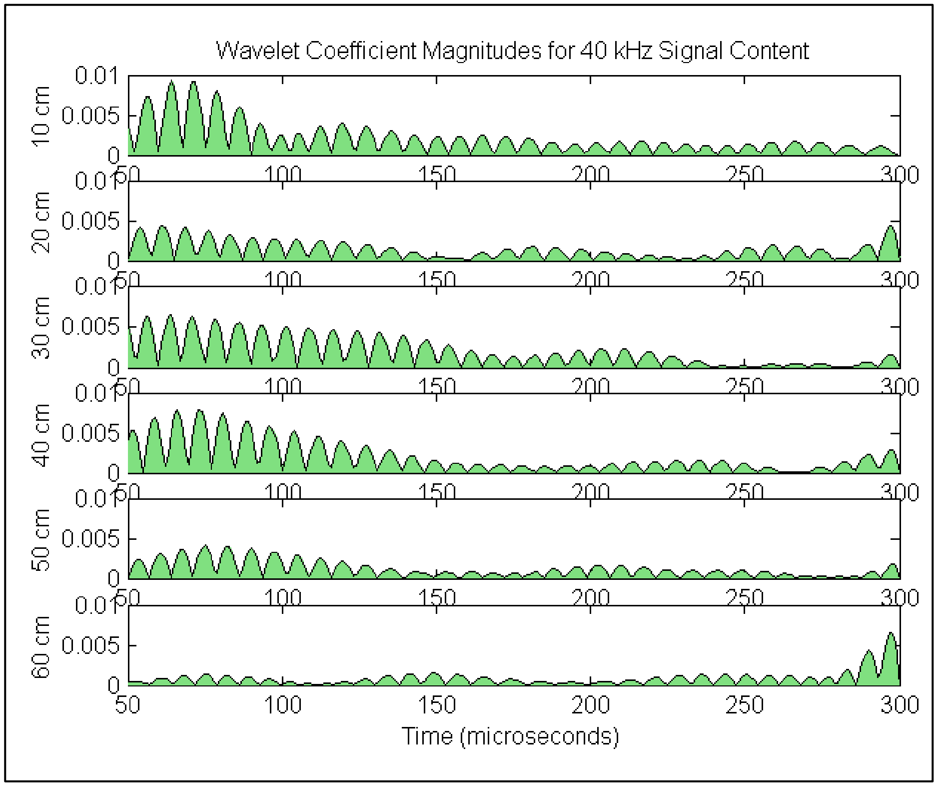
Indicates viability of wavelet method for use in at least simple structures

Composite Micro-Satellite



2.5 cm^2 impact region

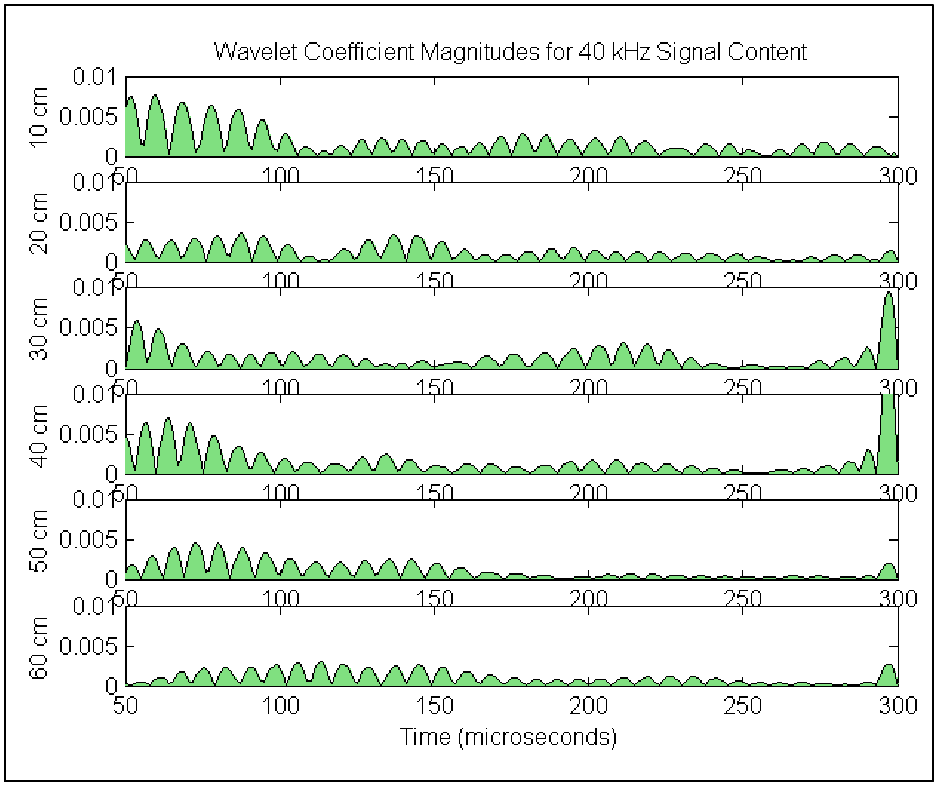
Satellite Control Region 1



- CFRP tube, 4-plies surrounding low-density anticlastic Al core
- Test two apparently undamaged areas and compare to known impact damage region
- Wavelet coefficient plot compares energy content for 40 kHz
- Determine axial and circumferential signal transmission limitations

Lamb waves are capable of traveling at least 0.5 m in sandwich structure

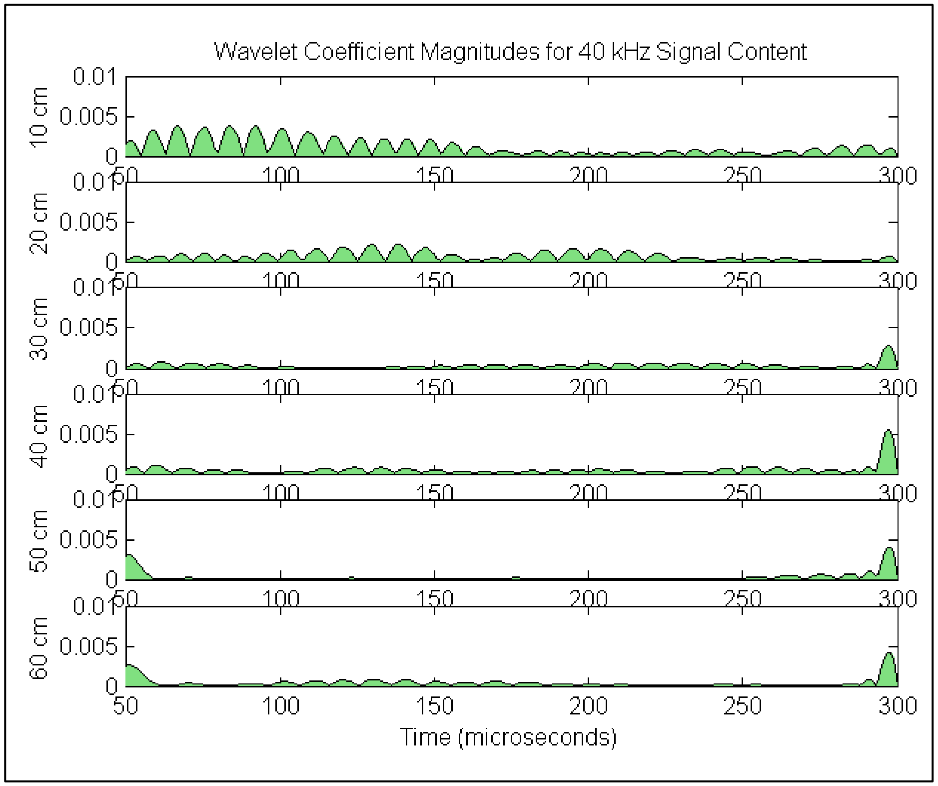
Satellite Control Region 2



- Demonstrates reproducible level of energy in Lamb wave signature for two undamaged areas
- Axial signal transmission limitation appears to be about 0.5 m
- Circumferential transmission limit of 0.2 m; curvature causes more dispersion in signal (not shown)
- Lamb waves could potentially travel even further in a large structure without damping core

Demonstrates consistency of control signal sent in complex structure

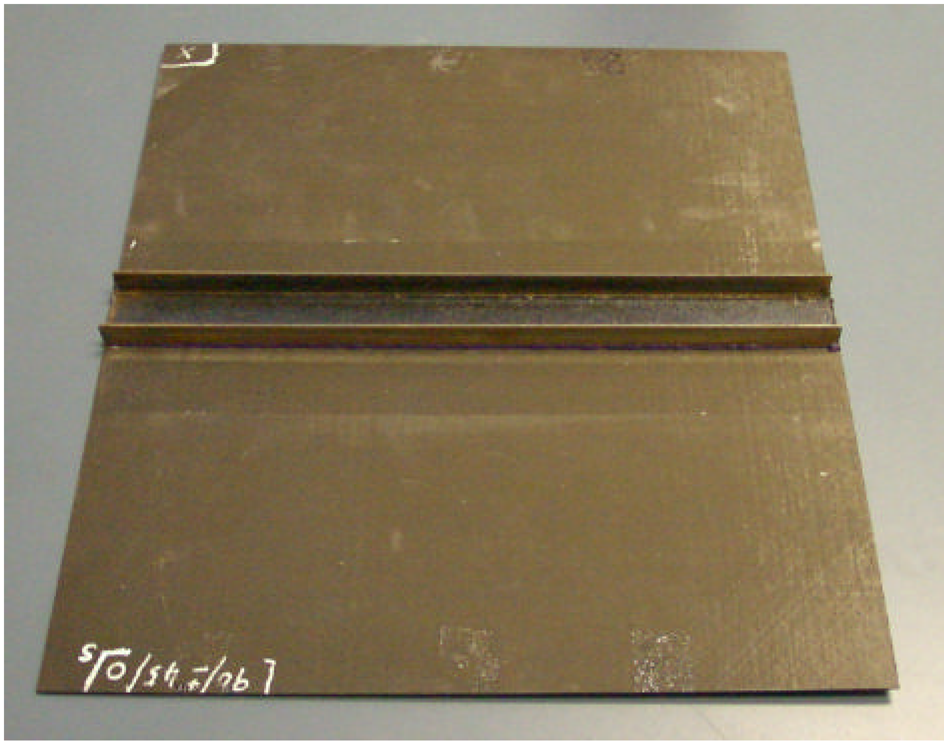
Satellite Damaged Region



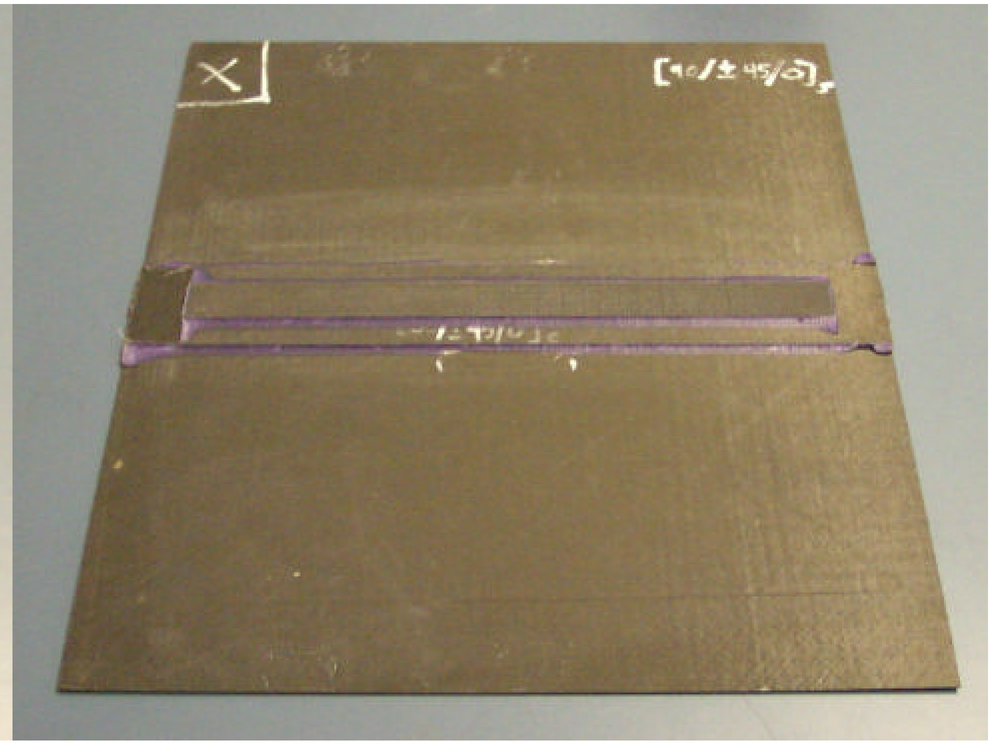
- Known impact damage region in tube of 2.5 cm diameter (damage visible on surface of outer ply)
- Energy content in first 10 cm is greatly reduced
- Signal is practically lost due to dispersion after 20 cm
- Can readily confirm presence of damage, however axial damage location information not present with current setup

Small impact damage near actuator deflects much of the sent energy

Stiffened Composite Plates

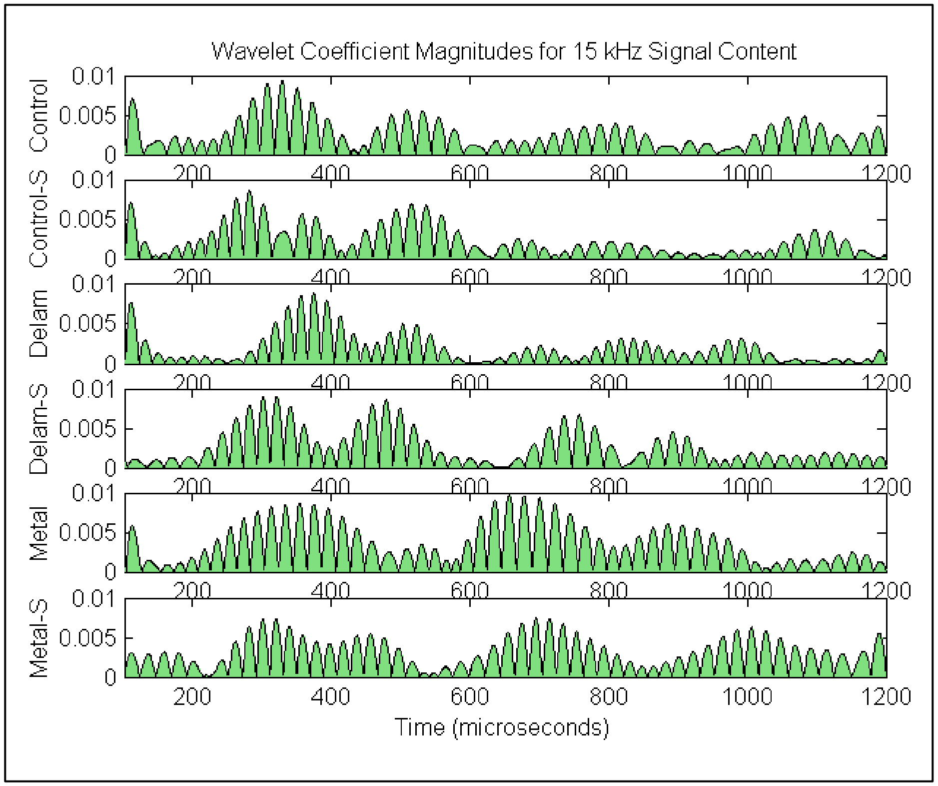


Bonded 2.5 cm aluminum C-channel



Bonded composite 2.5 & 5 cm strips

Bonded Stiffener Results



- Quasi-isotropic laminated plates with thick Gr/Ep strips bonded in center of laminates
- One plate with teflon strip inserted between adhesive and stiffener
- Observe transmitted wavelet energy passing through stiffener
  - measurement taken in center
  - measurement taken on side (S)
- Delaminated region slows wave
- Similar results observed with metallic c-channel stiffener

Lamb wave method viable for detecting delamination in built-up structure

Preliminary Lamb Wave Conclusions

- Method shows great detection sensitivity to damage
  - has demonstrated presence and severity of damage capabilities
  - potential for damage location with self-sensing actuators
- Method must be tailored for particular material and application
  - combination of models and tests to determine driving frequency
  - patch size and location depends upon material, thickness, curvature
- Several limitations exist
  - active power requirement
  - complex results caused by need for high sensitivity
  - results are localized to straight path and max traveling distances
- Possible strategy for implementation in SHM system
  - also light, conformal, but requires small voltage for actuating
  - could use same sensors as FRM and AE to produce Lamb waves
  - groups of sensors to be placed in areas of concern for triangulation

Future Work

- Finite element representations of all tests
- Combined testing using several co-located methods
  - Lamb wave
  - frequency response
  - acoustic emission
  - strain based
- Refine analysis procedures for reliable automated detection of presence of damage
- 2-D testing of plate sections