SPIE Smart Structures/NDE
March 11, 2010, San Diego, CA
Session 10: Civil Infrastructure Health Monitoring I

University of Massachusetts UMASS Lowell

Damage Inspection of Fiber Reinforced Polymer-Concrete Systems using a Distant Acoustic-Laser NDE Technique

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Outline

- Motivation and Objective
  - Delamination/debonding problem in multi-layer fiberglass-concrete systems
- Distant Inspection – Acoustic-Laser NDE Technique
- Experimental Result
- Summary

Motivation and Objective

- Deterioration and degradation of civil infrastructure




Motivation and Objective

- Sudden failures of civil infrastructure systems
  - Significant impacts
    - EX: I-35 Highway Bridge Collapse, Minneapolis, Minnesota (6:05pm, Wed., Aug. 1, 2007)

(Source: Security camera by the Army Corps of Engineers)

(Source: www.gettyimages.com)

Motivation and Objective

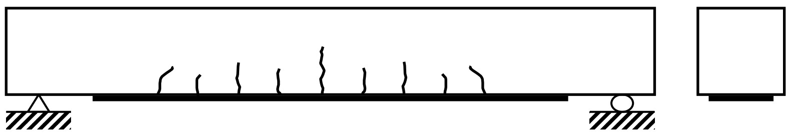
- Deterioration/degradation is inevitable, but sudden failure must be prevented.
- Among various strengthening and repairing techniques, externally-wrapped strengthening technique provides a rapid and effective solution.

(Source: Fyfe Co. LLC, 2005)

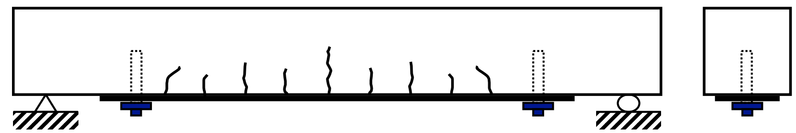
- After strengthening, a multi-layer fiberglass-concrete system is formed. → *Less ductile than the original reinforced concrete system*

Motivation and Objective

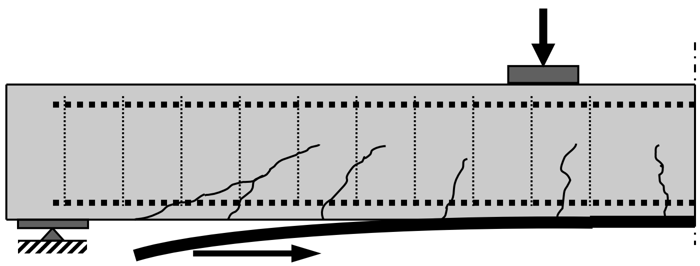
- Delamination/debonding in a strengthened reinforced concrete beam:



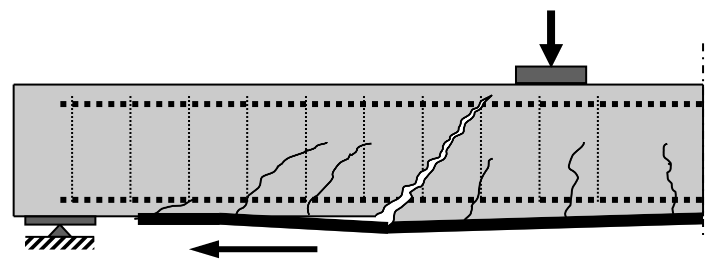
FRP reinforcement bonded to soffit



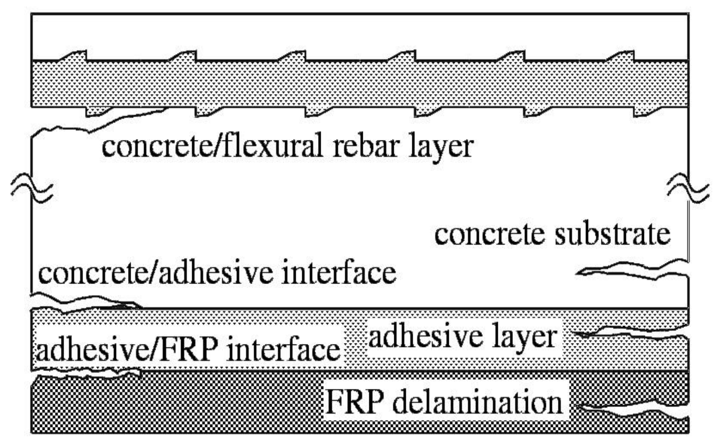
Anchorage with bolts



Debonding from laminate end



Debonding from flexural-shear crack

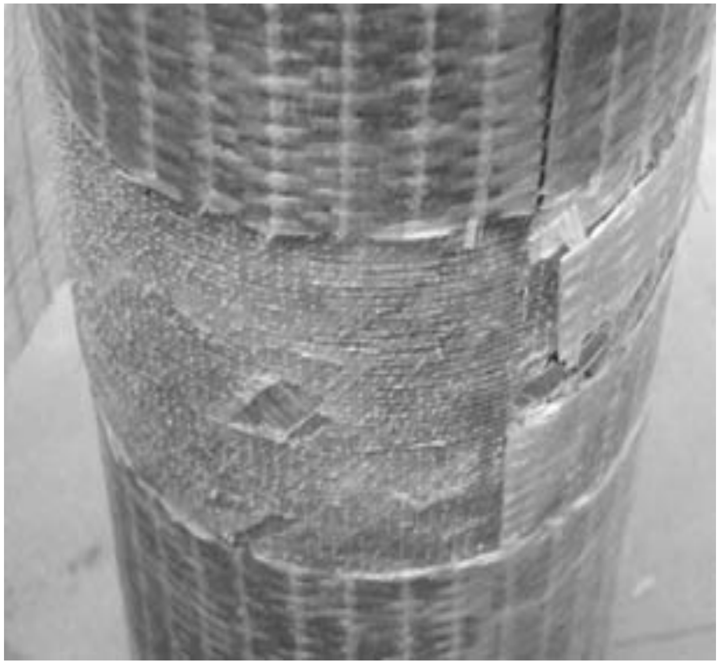


FRP(fiber reinforced polymer/plastic)

Motivation and Objective

- Delamination/debonding in a strengthened reinforced concrete column:

a) Bond delamination between plies



b) Overlap joint debonding

[Au (2001)]

Motivation and Objective

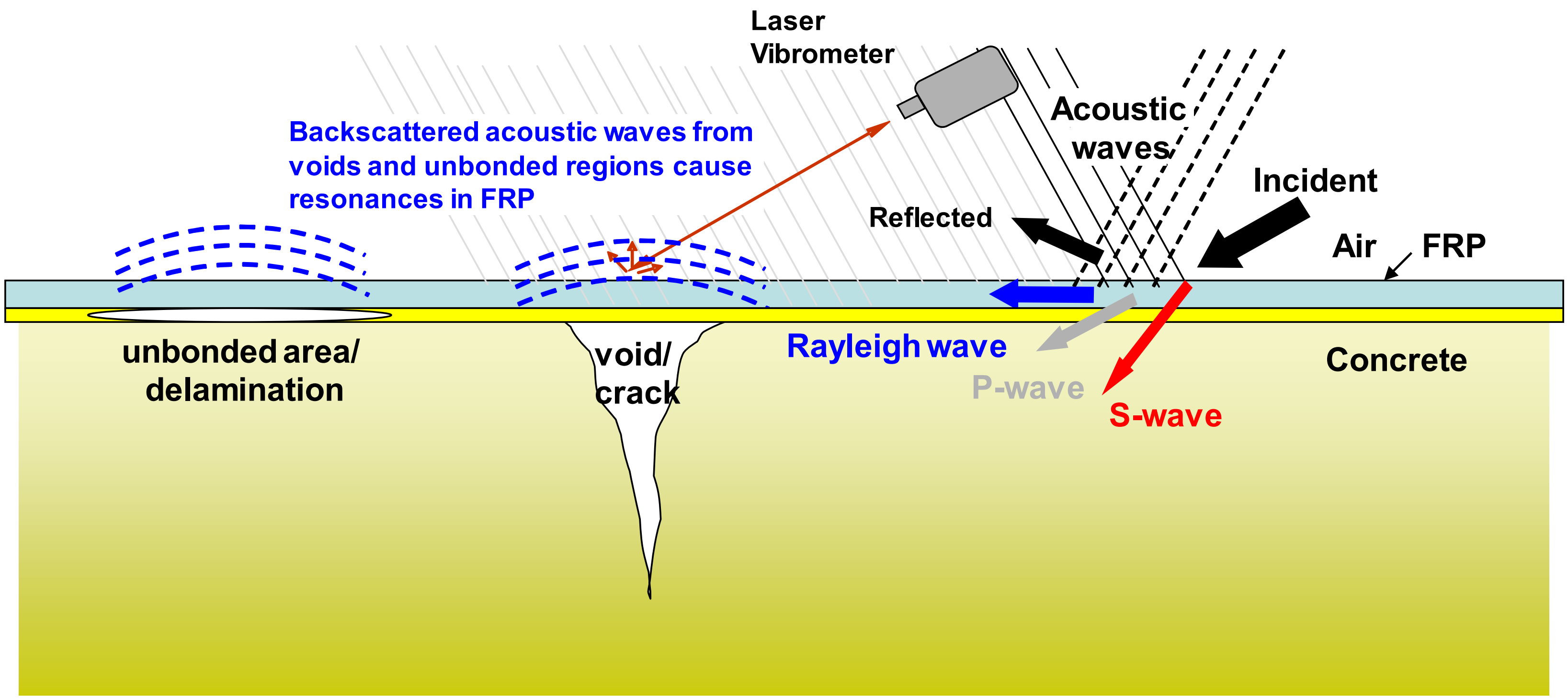
- Strengthening techniques are used –
- For new constructions to upgrade their design capacity
- For damaged structures to restore their design capacity

- Inspection needs:
  - Need to determine the level of strengthening
  - Need to evaluate the quality of strengthening construction
  - Need to monitor the long-term performance of the strengthened system

- Objective:
  - To develop a distant/standoff technique for the inspection of delamination/debonding

Acoustic-Laser NDE

- Inspection scheme:



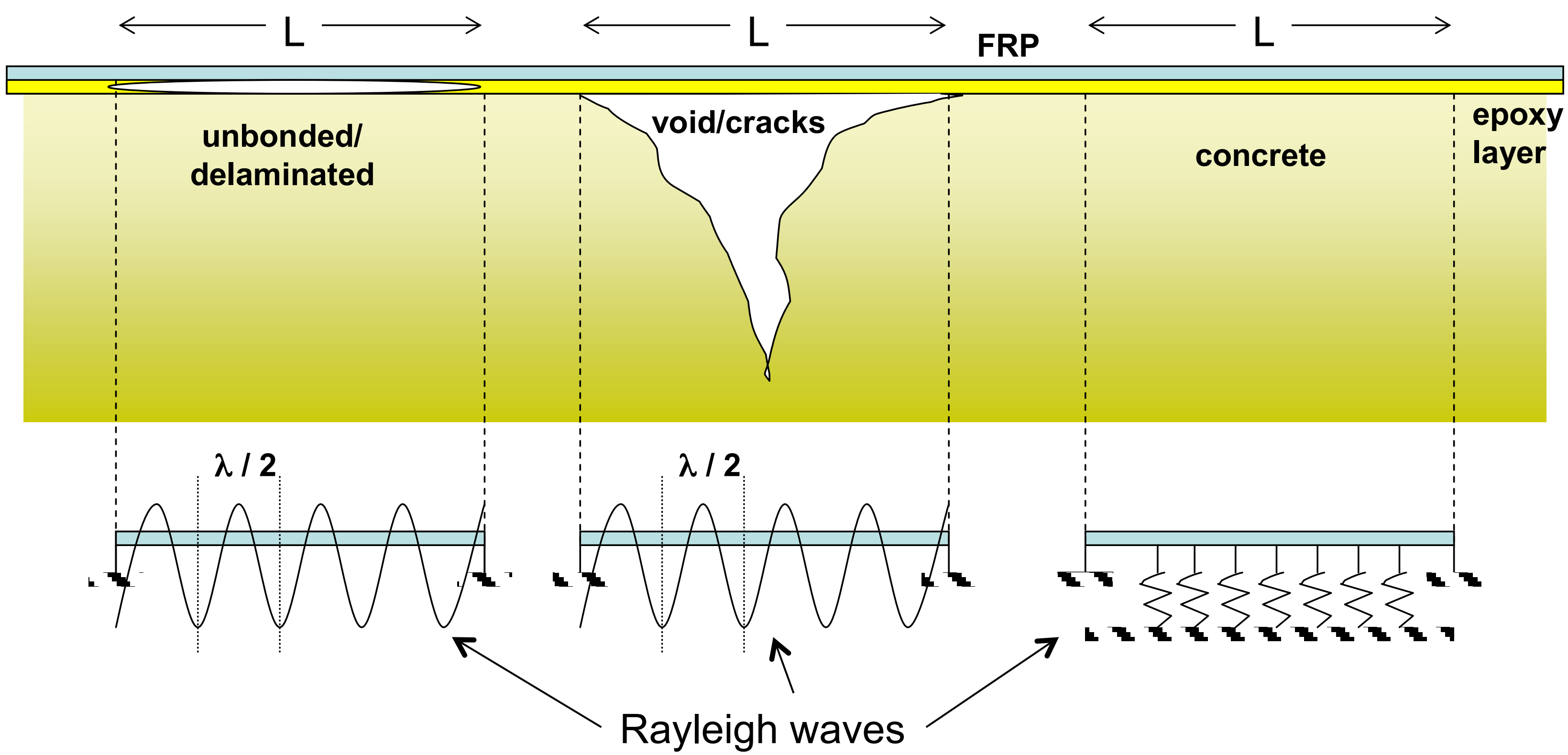
Acoustic-Laser NDE

- Proposed acoustic-laser NDE technique
  - Is a standoff inspection technique
  - Has a high powered parametric acoustic array (PAA) that can excite the structure from ranges exceeding 30 meters
  - Has a laser vibrometer that collects the surface dynamic signature of the multi-layer structure

- Principle:
  - Dynamic signature of an intact multi-layer system is different from the one of an damaged multi-layer system.

Acoustic-Laser NDE

- Simplified models of delamination and concrete cracking:



Acoustic-Laser NDE

- Theoretical basis:
  - Difference in natural frequencies of the damaged and intact regions
- Governing equation of an intact region – 2D beam model:

$$EI\frac{\partial^4 y}{\partial x^4} + \rho A\frac{\partial^2 y}{\partial t^2} + ky = 0$$

where E = Young's modulus, I = moment of the inertia, ρ = density of the material (fiberglass), A = cross sectional area, $y(x,t)$ = transverse displacement of the beam at position x and time t, and k = distributed stiffness coefficient characterizing the connection between FRP and concrete.

- Governing equation of a damaged region (clamped beam):

$$EI\frac{\partial^4 y}{\partial x^4} + \rho A\frac{\partial^2 y}{\partial t^2} = 0$$

Acoustic-Laser NDE

- Natural frequencies of the intact and damaged regions:
  - Intact –

$$\omega_i = \sqrt{\frac{K_i}{M_i}} = \sqrt{EI\int_0^L \left[\frac{d^2\phi_i(x)}{dx^2}\right]^2 dx + \int_0^L k\left[\phi_i(x)\right]^2 dx \Bigg/ \rho A\int_0^L \left[\frac{d\phi_i(x)}{dx}\right]^2 dx}$$

where M_i = the generalized mass of the *i-th* mode, and $\phi_i(x)$ = shape function.

  - Damaged (with void) –

$$\left(\omega_{void}\right)_i = \sqrt{\frac{K_i}{M_i}} = \sqrt{EI\int_0^L \left[\frac{d^2\phi_i(x)}{dx^2}\right]^2 dx \Bigg/ \rho A\int_0^L \left[\frac{d\phi_i(x)}{dx}\right]^2 dx}$$

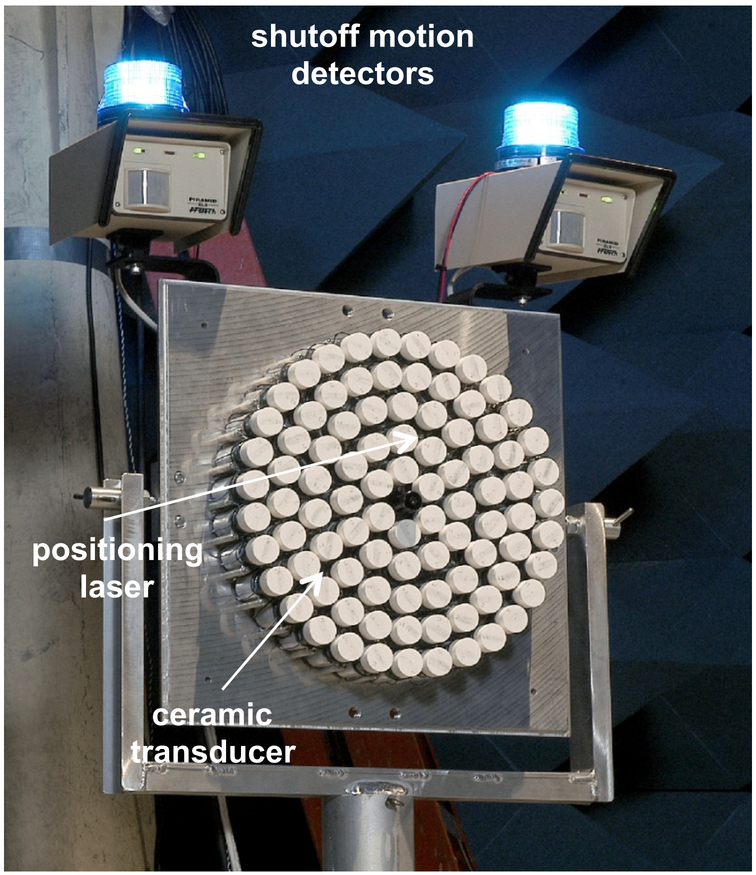
- The Rayleigh wave over a finite length void can be described in terms of two harmonic waves traveling in opposite directions.

$$y(x,t) = Ae^{j(\omega t - kx)} + Be^{j(\omega t + kx)}$$

where A and B are complex amplitudes.

Acoustic-Laser NDE

- Parametric acoustic array (PAA):



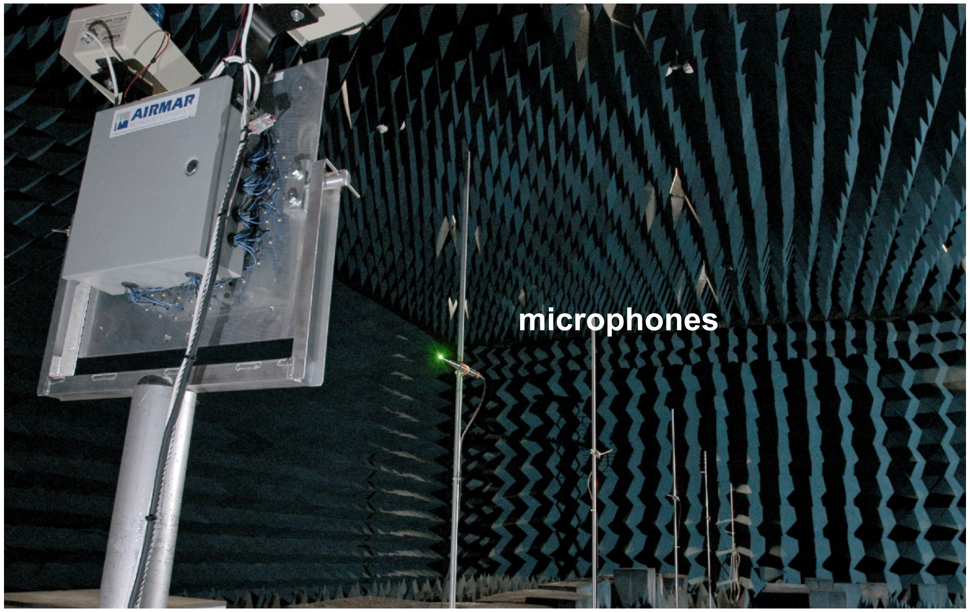
[Courtesy of MIT Lincoln Laboratory]

3000 Watt Power Supply

Safety Lockout Switches

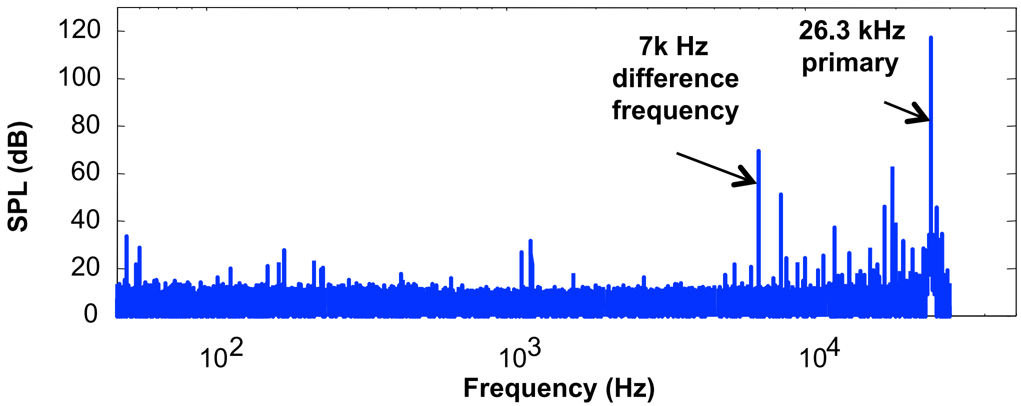
Acoustic-Laser NDE

- Acoustic radiation pattern of the developed PAA:



RF Anechoic Chamber Measurements

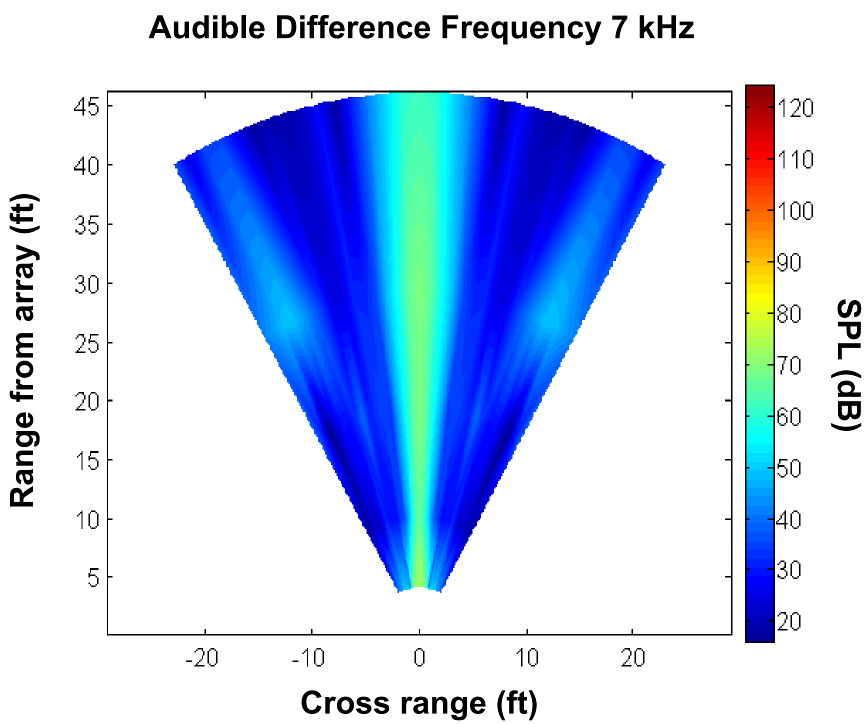
[Courtesy of MIT Lincoln Laboratory]

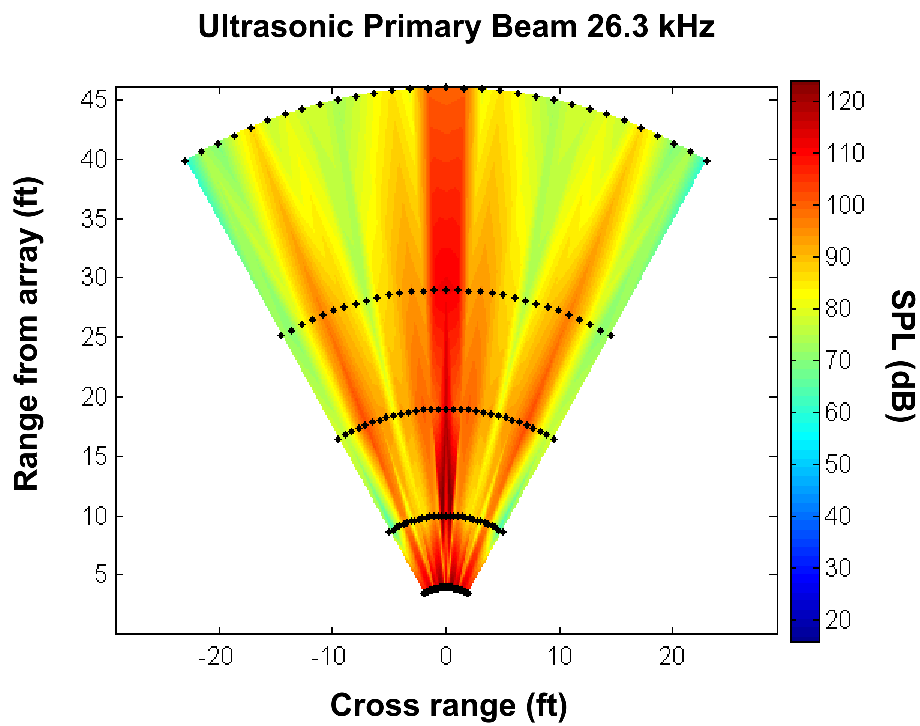


Acoustic Spectrum
mic #3 on boresight

Acoustic-Laser NDE

- PAA radiation patterns at 7 kHz and 26.3 kHz:

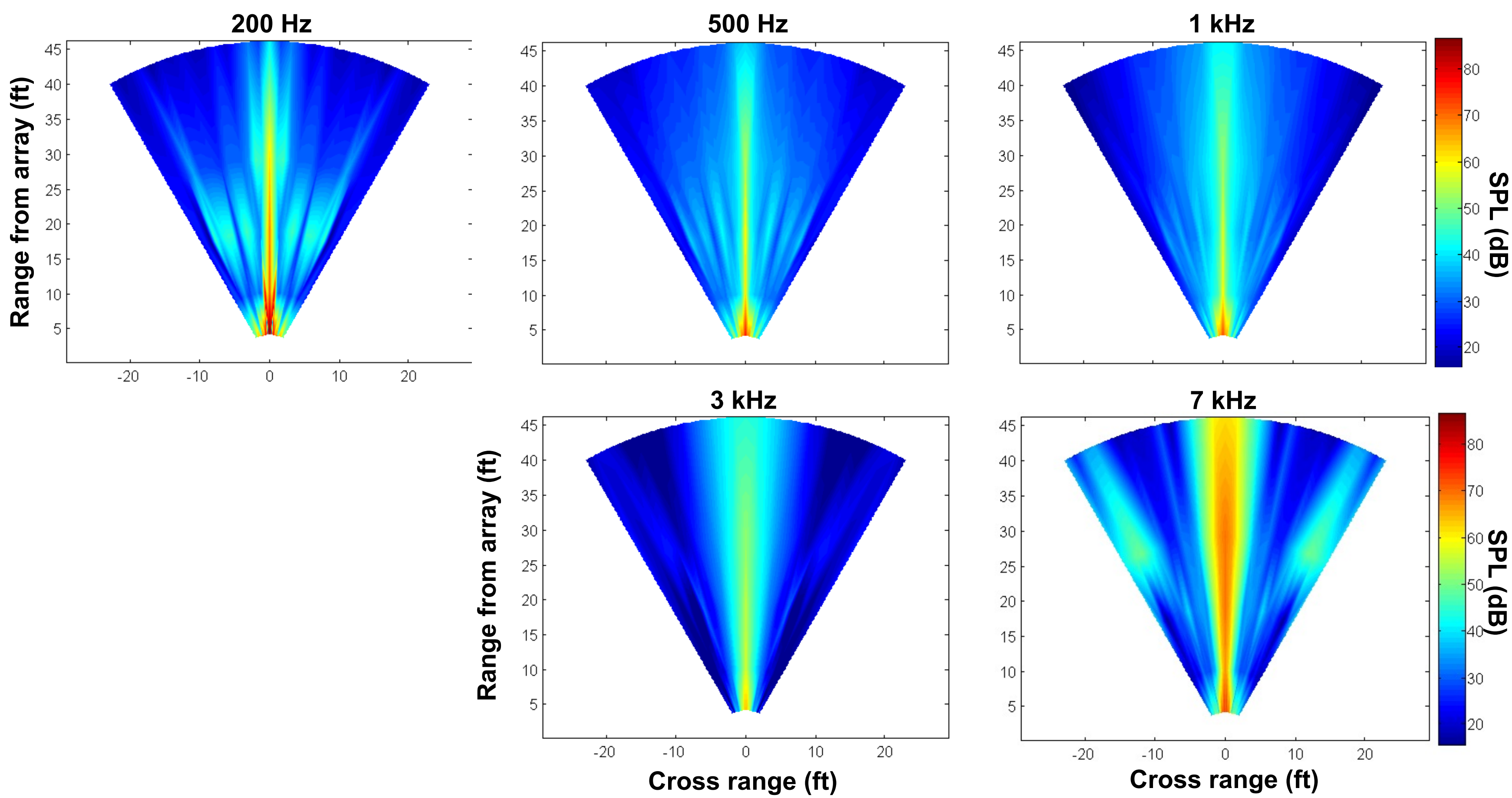




→ Acoustic waves by PAA is focused.

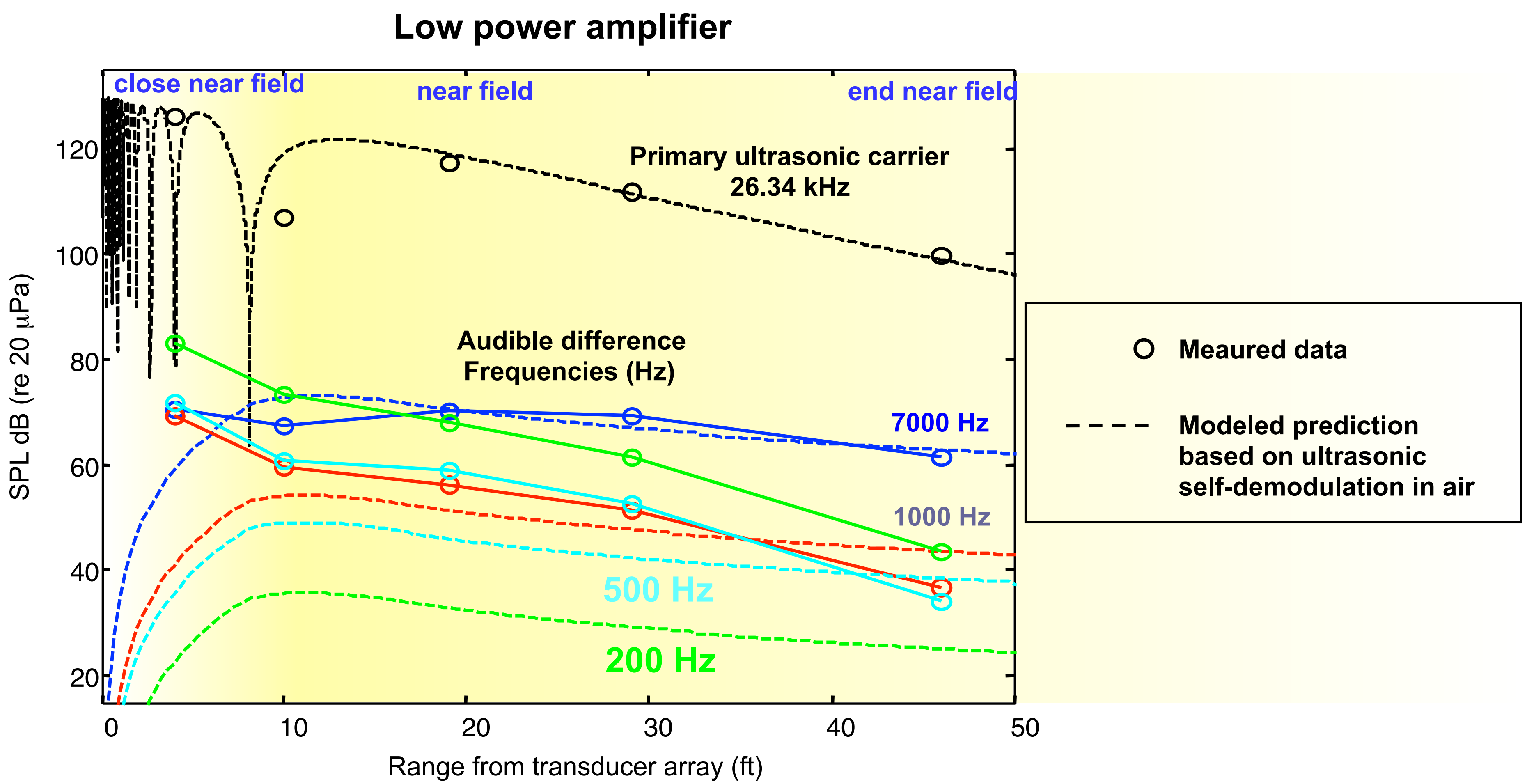
Acoustic-Laser NDE

- Acoustic radiation patterns at different frequencies:



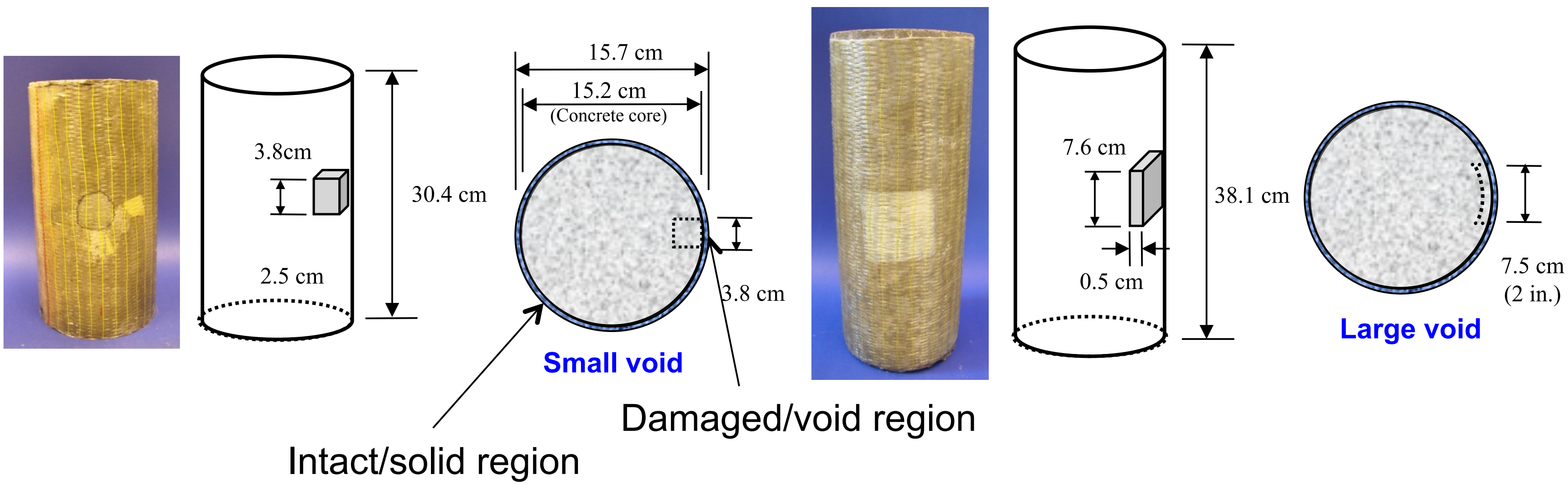
Acoustic-Laser NDE

- Acoustic power from PAA:



Experimental Result

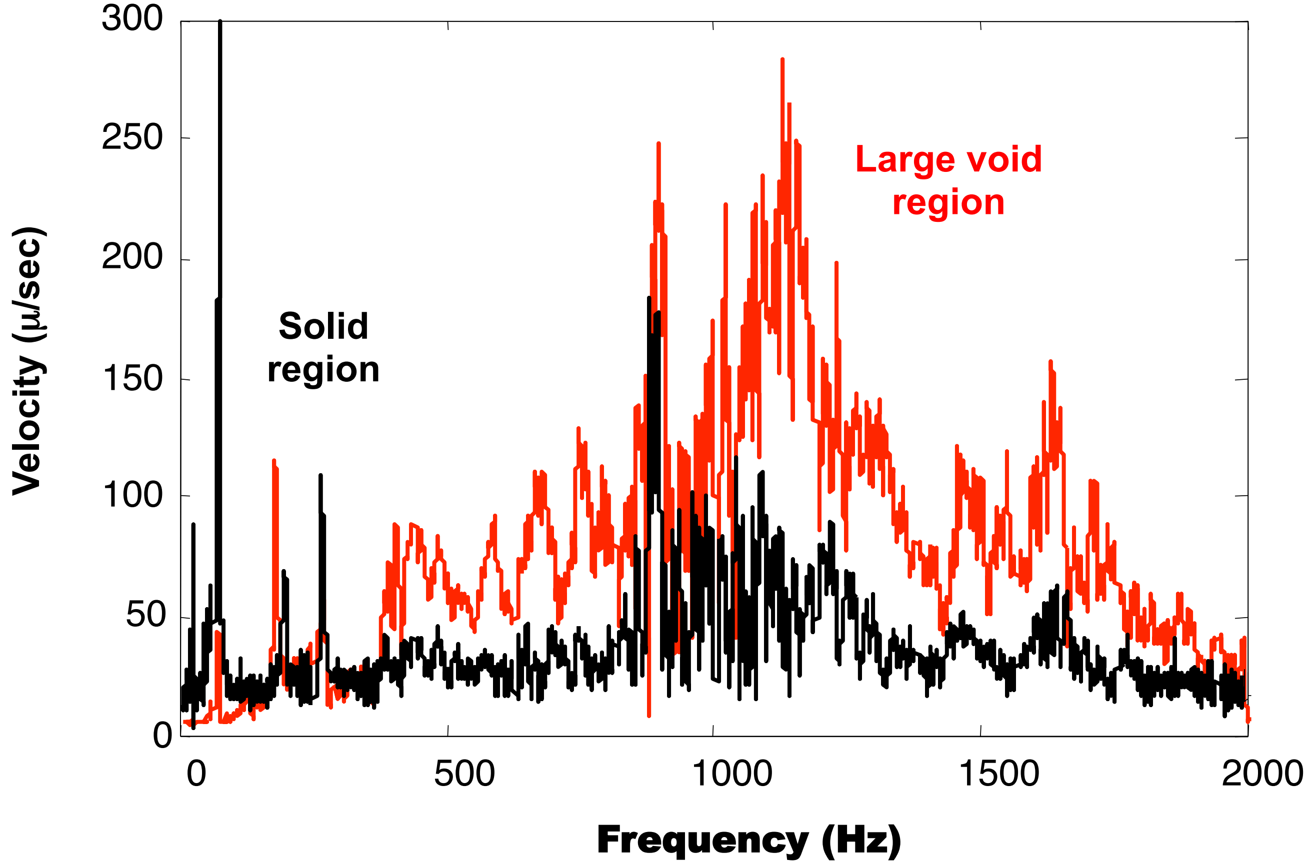
- Specimen description



- Concrete mix ratio = water : cement : sand : aggregate = 0.45 : 1 : 2.52 : 3.21
- Glass FRP (GFRP) mix ratio = epoxy : glass fiber = 0.645 : 0.355
- GFRP type = Tyfo SHE-51A by Fyfe
- Epoxy = Tyfo S epoxy by Fyfe
- GFRP sheet thickness = 0.25 cm (0.1 in)

Experimental Result

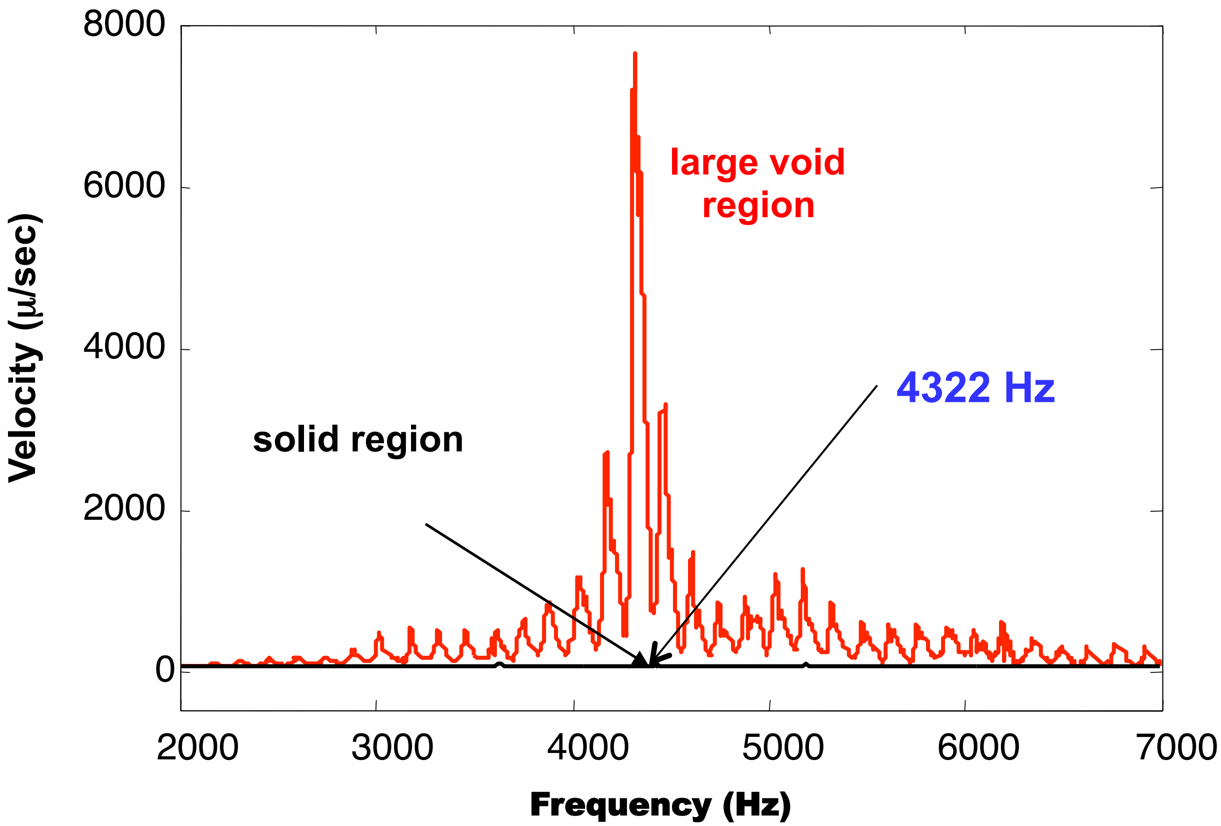
- Low frequency acoustic response using a loudspeaker source:



(Measurements were made at a distance of 30 m in an open area in Lexington, MA.)

Experimental Result

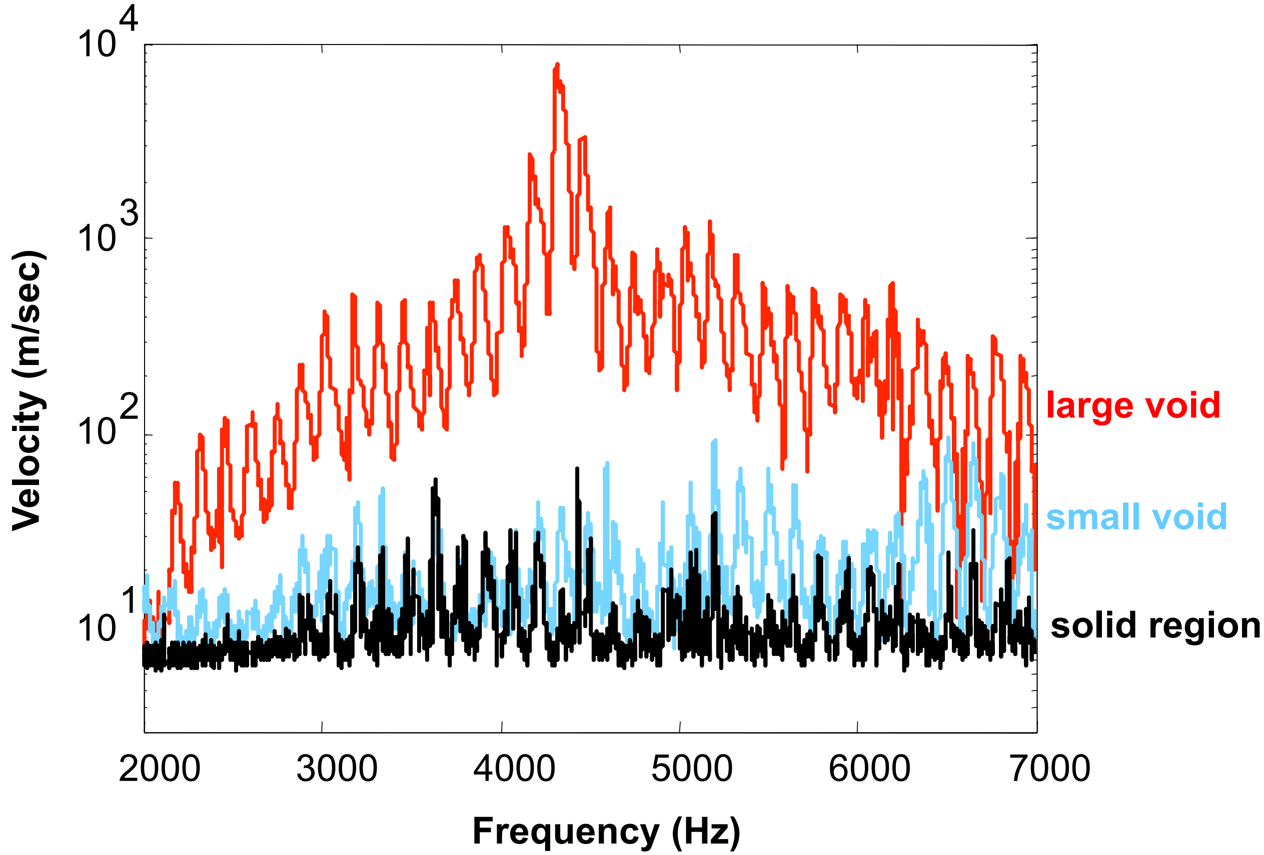
- High frequency acoustic response using the PAA:



→ Using a sound speed of 340 m/s shows that the ½ wavelength of the resonance is approximately 2 inches which is the width of the large void.

Experimental Result

- High frequency acoustic response:



Experimental Result

- Approximate 3D solution:
  - Uniform circular plate with fixed edge supports in free vibration

$$\omega_{mn} = \frac{(\lambda a)_{mn}^2}{a^2}\sqrt{\frac{D}{\rho h}}$$

where $D = Eh^3/12(1-\upsilon^2)$ = flexural rigidity of the plate, E = Young's modulus, h = thickness of the plate, ν = Poisson's ratio, ρ = density of the material, $w = w(r,\theta,t)$ = transverse displacement in cylindrical coordinate as the function of spatial variables and time t. (E = 21.5 psi (148 GPa); ρ = 1.4 lb/in^3 (1.5 kg/m^3))

λa is found from the frequency equation; a = the radius of the circular plate, λ = eigenvalue of the frequency equation.

$$J_n(\lambda a)\frac{dI_n}{dr}(\lambda a) - I_n(\lambda a)\frac{dJ_n}{dr}(\lambda a) = 0$$

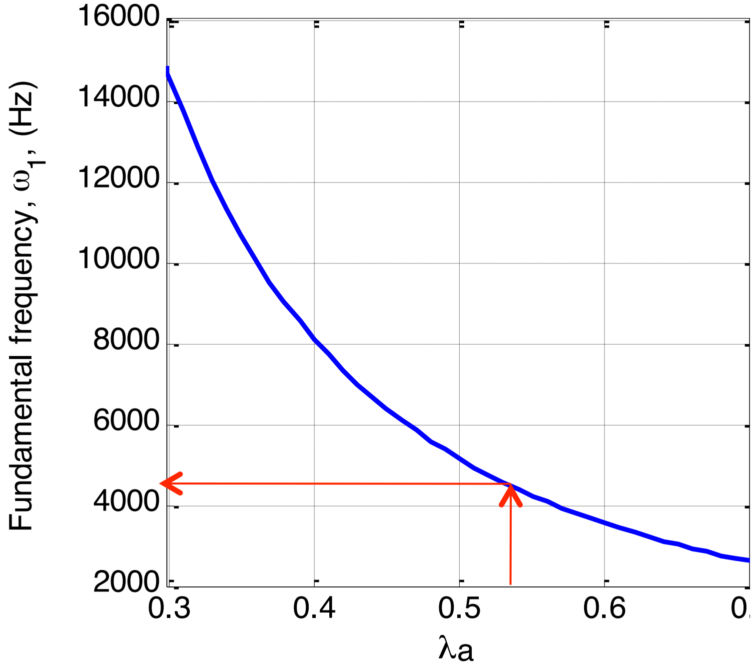
where

$J_n(\lambda a) = \left(\frac{\lambda a}{2}\right)^n \sum_{k=0}^{\infty}\left\{\left[-\frac{(\lambda a)^2}{4}\right]^k \Big/ k!\Gamma(n+k+1)\right\}$ = Bessel function of the first kind

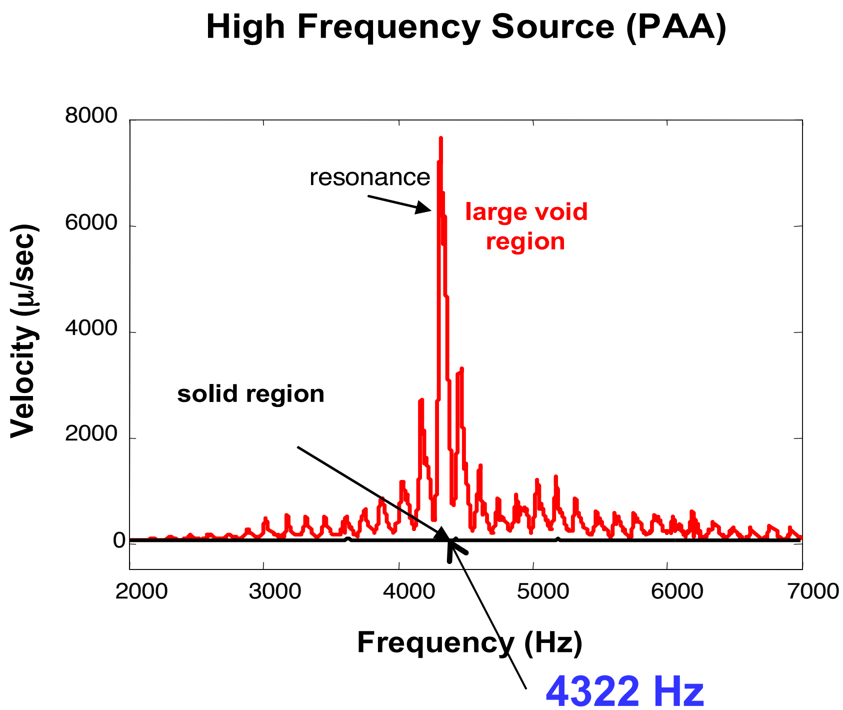
$I_n(\lambda a) = \left(\frac{\lambda a}{2}\right)^n \sum_{k=0}^{\infty}\left\{\left[\frac{(\lambda a)^2}{4}\right]^k \Big/ k!\Gamma(n+k+1)\right\}$ = modified Bessel function of the first kind

Experimental Result

- Approximate 3D solution:



λa = 0.532 → **4512 Hz**



→Difference is attributed to i) non-perfectly shape of the delamination, and ii) the variation in boundary condition.

Summary

- The proposed acoustic-laser technique is capable of remotely exciting a fiberglass-concrete system and collecting the surface dynamic signature from the system.
- Surface dynamic signature of the intact (solid) region in a multi-layer fiberglass-concrete system is different from the one of the delaminated (void) region. → A database relating surface dynamic signature and delamination/debonding characteristics can be established.
- High velocity measurements are remotely observed at the debonding location and at the resonant frequency relating to the debonding geometry.
- Possible use for detecting surface concrete cracking and steel corrosion

Thank you for your attention.

Questions?