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Structural Health Monitoring for Life Management of Aircraft

- SHM of Adhesively-bonded Composites -

Qiaojian Huang, Sridhar Krishnaswamy, Oluwaseyi Balogun and Brad Regez

Center for Quality Engineering & Failure Prevention
Northwestern University
Evanston, IL

JAMS

FAA Sponsored Project Information

- **Principal Investigators & Researchers**
  - Jan D. Achenbach
  - Sridhar Krishnaswamy
  - Qiaojian Huang, Oluwaseyi Balogun, and Brad Regez

- **FAA Technical Monitor**
  - Curt Davies

SHM of Adhesively-bonded Composites

- **Motivation:**

  Structural degradation of advanced aircraft composites caused by environment and service loads (fatigue, corrosion etc) or unpredictable external events (impact etc).

- **Goal:**

  Demonstrate an integrated diagnostic/prognostic system to make predictions of the structural health and remaining life of adhesively-bonded composite structures.

- **Approach:**

  Laser ultrasonics, selective Lamb wave sensors, and thermal imaging technique.

GLARE Laminates

- Glass-Reinforced (GLARE) laminate is a new class of fiber metal laminates, which are hybrid composites consisting of thin alternating bonded layers of metal sheets and fiber-reinforced epoxy prepreg.
- GLARE laminates provide better properties as
  - -Superior mechanical properties
  - -Weight reduction
  - -Outstanding fatigue resistance
  - -Excellent impact resistance
  - -Fire resistance

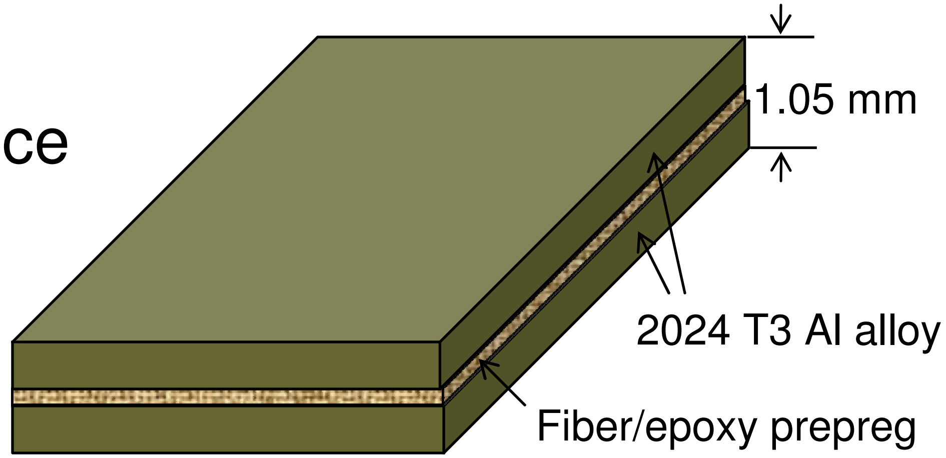
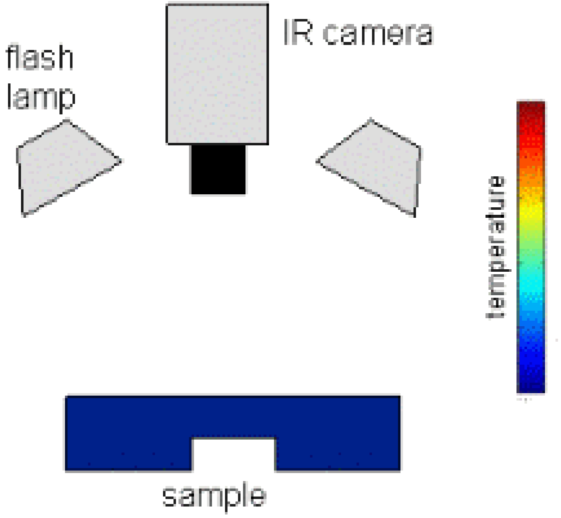


Fig.1: Configuration of GLARE 2A-2/1-0.4

Thermal Imaging Setup (Pulsed Thermography)

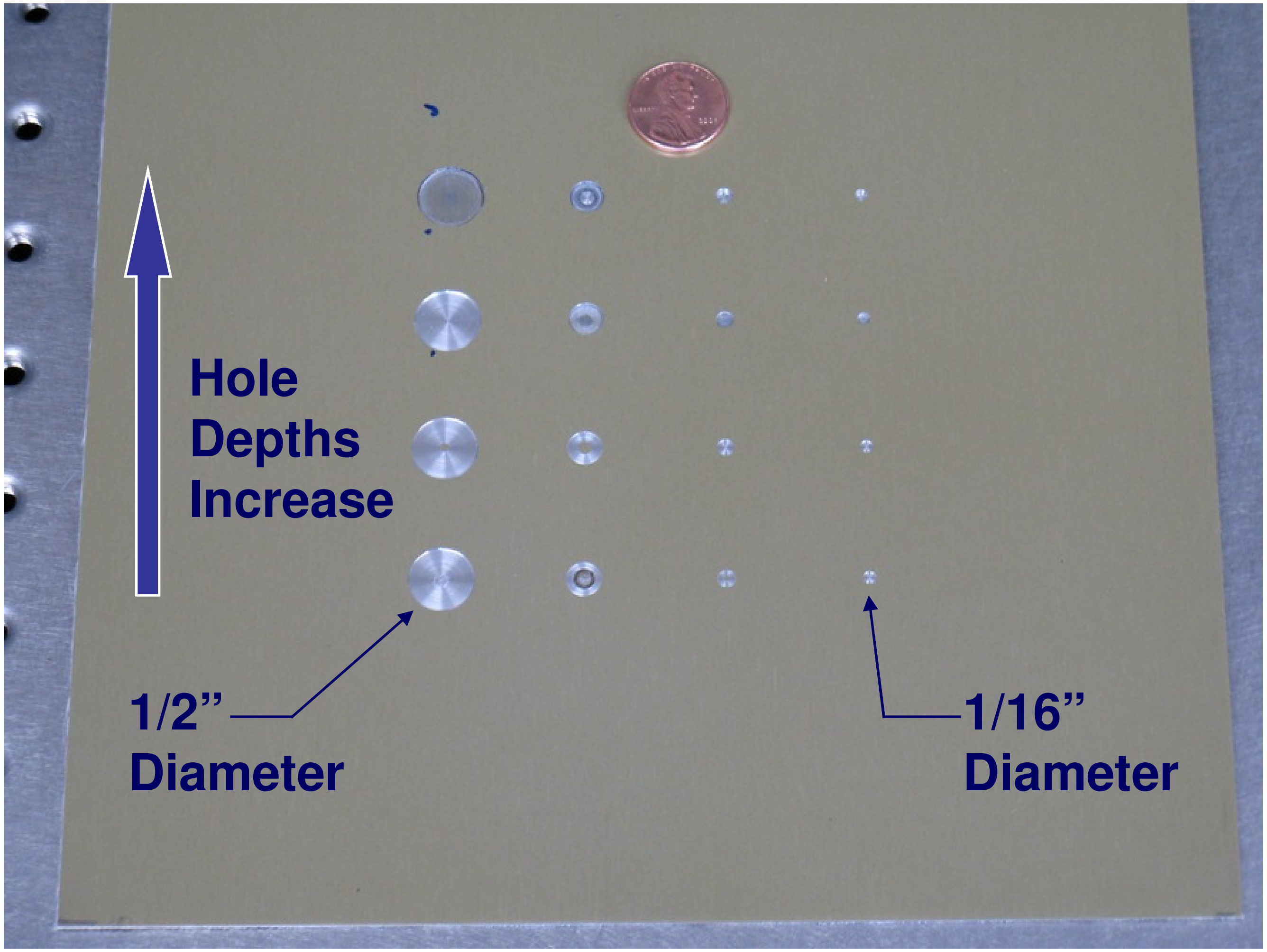
FLIR SC6000 IR Camera with
4800 Watt Flash Lamps

Setup at Northwestern University



Animation Courtesy of Thermal Wave Imaging, Inc.

Thermal Imaging GLARE Standard



Hole Depths Increase

1/2” Diameter

1/16” Diameter

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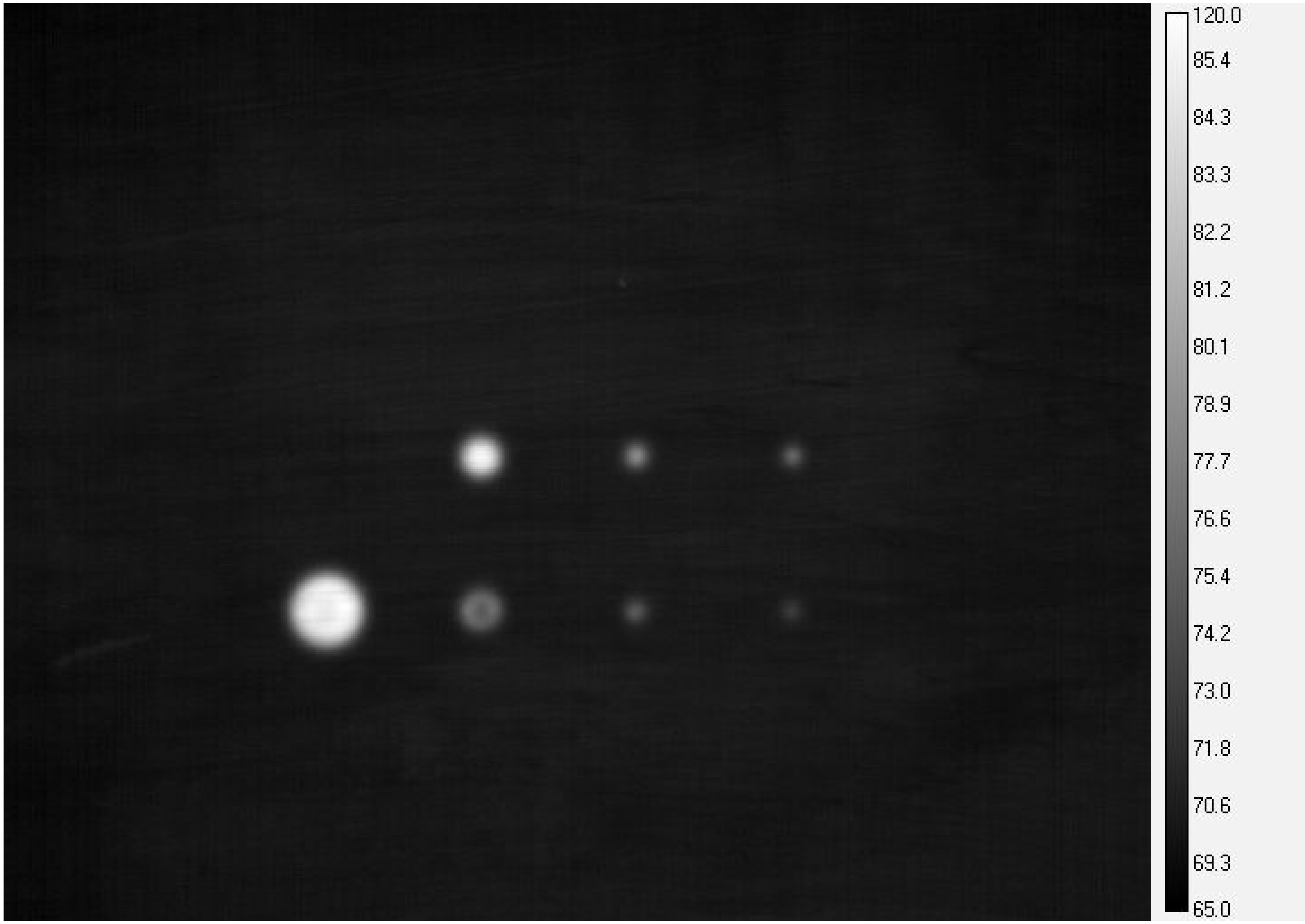
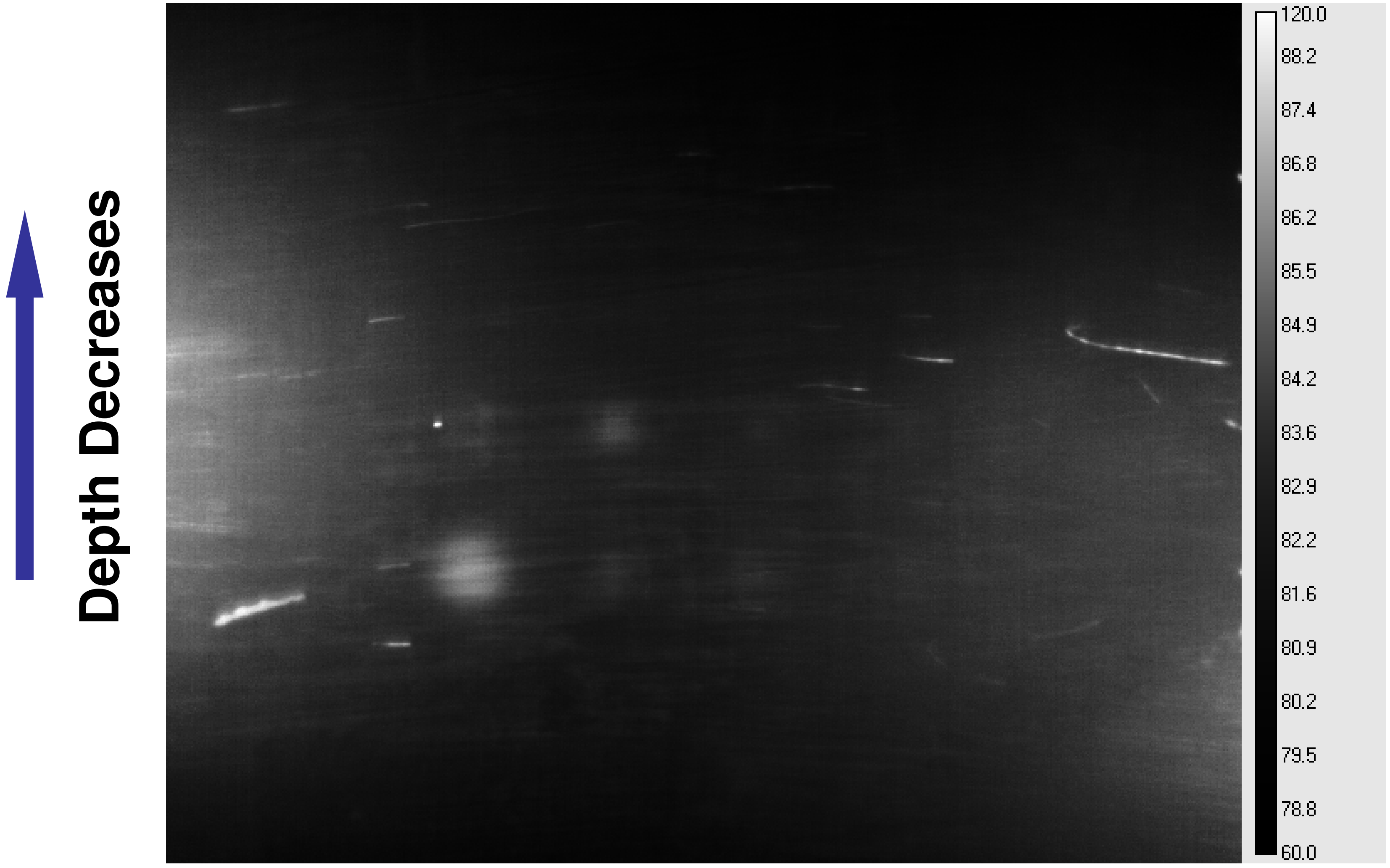
Thermal Image of GLARE Standard (Through Transmission)

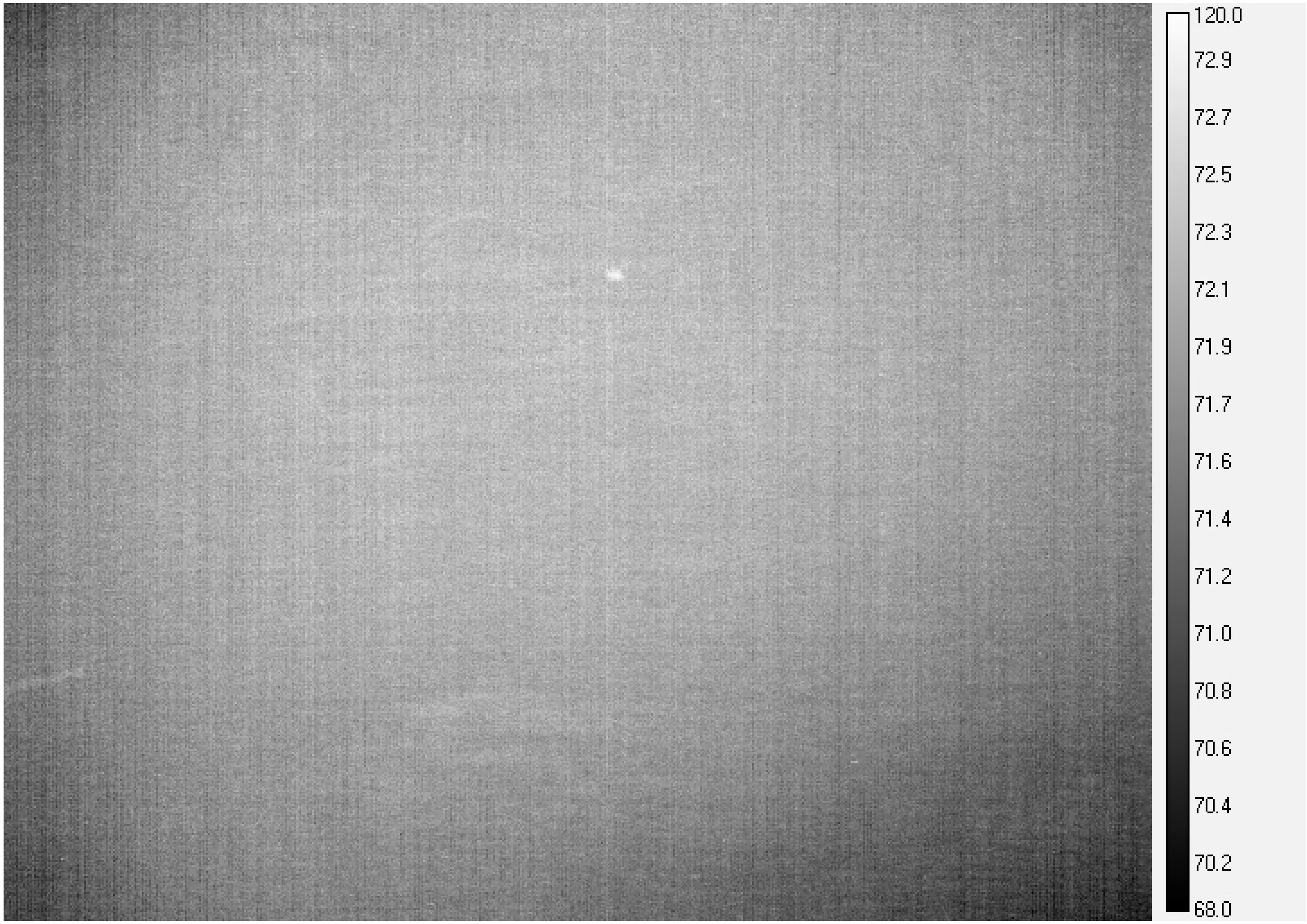
Depth Decreases



Thermal Image of GLARE Standard (Single Sided)



Thermal Image of GLARE Standard (Through Transmission)



Calculated Lamb-wave Dispersion Curves

Tab. 1: Mechanical properties of the 2024 T3 aluminum alloy and S2/FM94 glass fibre reinforced plastic lamina.

Layer	Density (kg/m³)	Elastic modulus (Gpa)	Poisson's ratio υ	Thickness (mm)
2024 T3 Al alloy [1]	2780	73.1	0.33	0.40
S2/FM94 [2]	1980	52.0	0.25	0.25

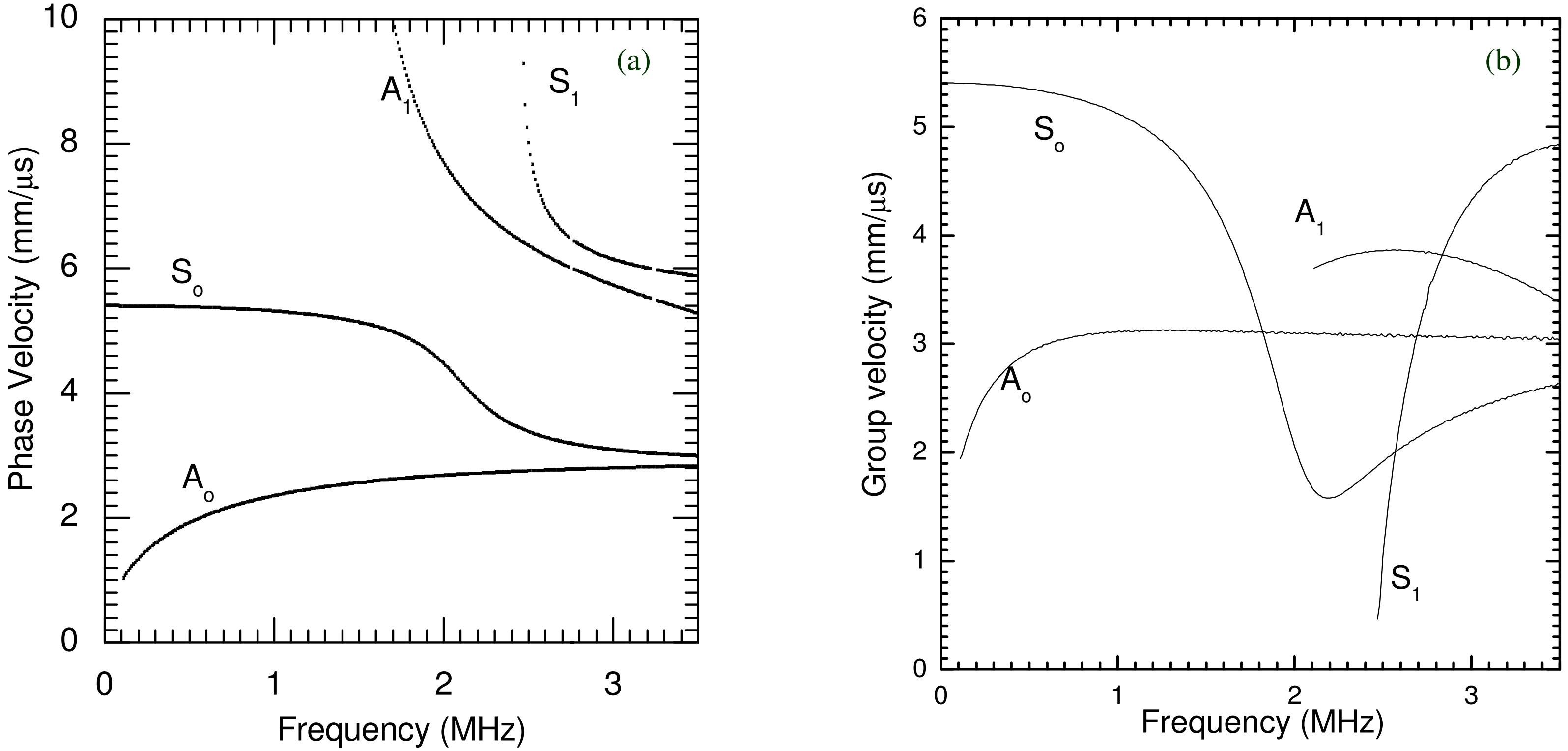


Fig. 2: Lamb-wave dispersion curves of GLARE 2A-2/1-0.4 for (a) phase velocity, and (b) group velocity.

[1] "ASM Material Data Sheet: Aluminum 2024-T3," Aerospace Specification Materials Inc.
[2] M. S. H. Fatt, C. F. Lin, D. M. Revilock, and D. A. Hopkins, "Ballistic impact of GLARE (TM) fiber-metal laminates," *Composite Structures*, vol. 61, pp. 73-88, 2003.

Setup for Lamb-wave Launching with a Pulsed Laser

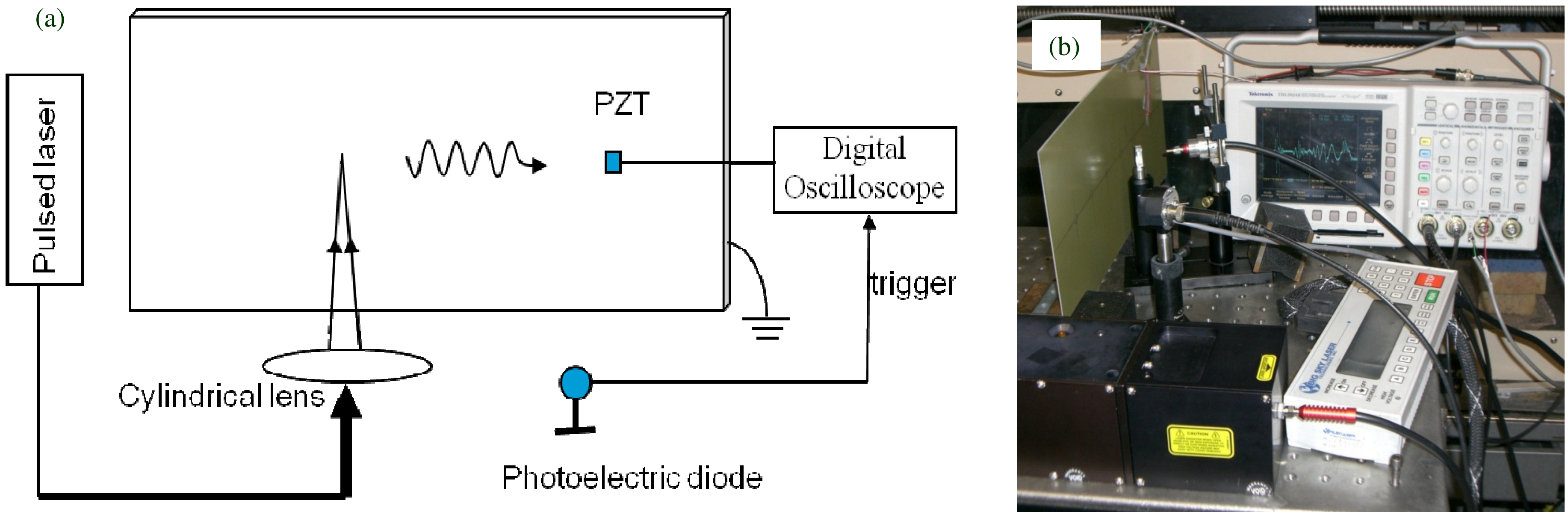


Fig. 3: An experimental system for measuring the dispersive property: (a) a schematic, (b) testing setup.

•Pulsed laser:
-wavelength: 1064 nm
-pulse width: 8 ns
-power: 5 J/30pulses

Measured Lamb-wave Signals

Lamb wave signals were recorded for various laser-PZT distances.

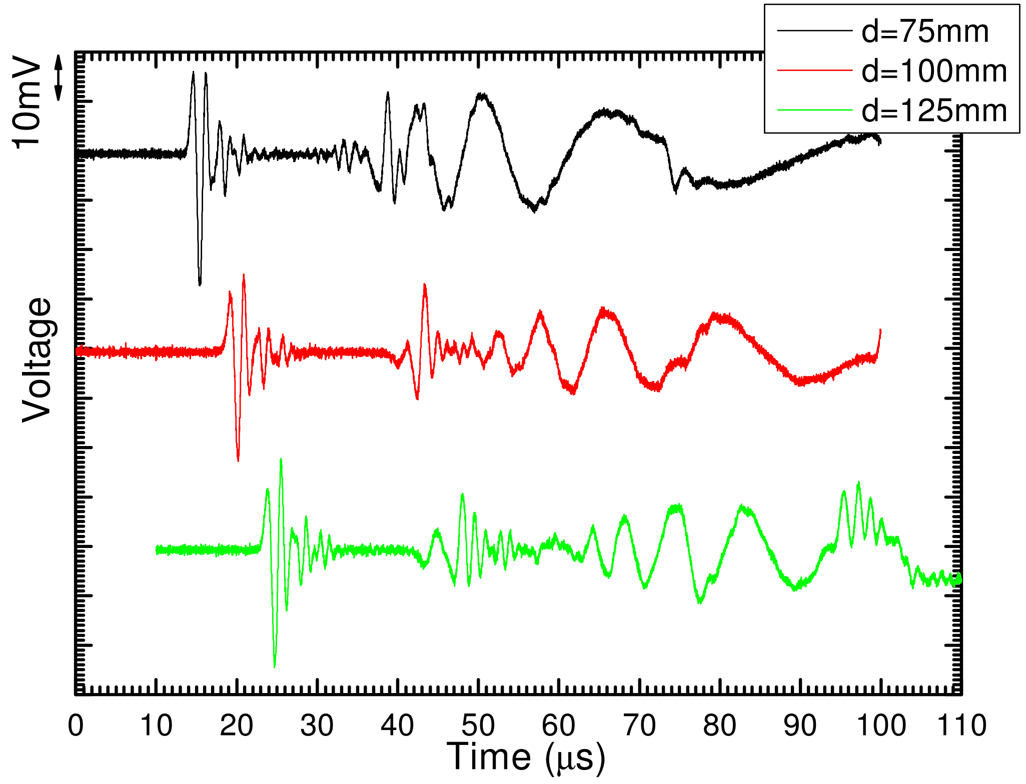


Fig. 4: Detected Lamb wave signals for various laser-PZT distances.

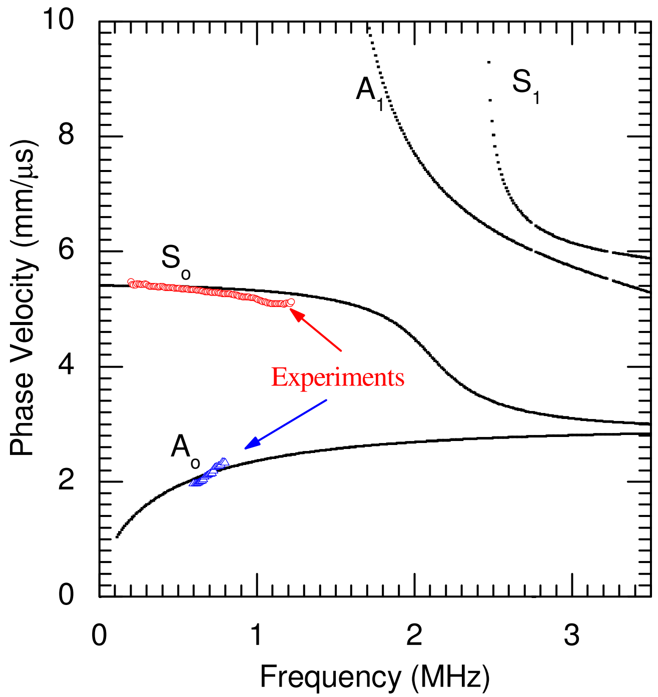
- The first arrived Lamb wave signals are for S_o mode which indicates faster velocities for lower frequencies.
- The second group of signals is a reflection from the sample edge for the S_o mode signals.
- The A_o mode signals arrive even later because they have lower speeds.
- The A_o mode is highly dispersive at low frequency range and the velocities increase as increasing of frequencies.

Measured Lamb-wave Dispersive Property

The measured Lamb wave signals were used to calculate the phase velocity by phase unwrapping. The calculation formula is given by

$$c(f) = \frac{2\pi f \cdot \Delta d}{\Delta \Phi(f)},$$

where, f, Δd, and $\Delta \Phi$ are frequency, distance, and phase difference, respectively.



- Only a part of the phase velocity for A_o mode can be obtained because the disturbing signals from the boundary reflection or other modes cause errors for the results at low frequencies.
- The measured dispersive properties are consistent with the typical characteristics of Lamb waves.

Fig. 5: Phase velocity of the GLARE plate: solid curves are from the theoretical calculations; open circles and triangles are obtained from experiments.

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Fabrication of PZT Interdigital Transducers (IDTs)

Two transducers were developed with photolithography technique:

- A thin layer of photoresist (AZ1518) was spin coated on a PZT piece and then baked on a hot plate at 95 ^{o}C for 2 minutes.
- The PZT piece was subsequently subjected to expose under ultraviolet (UV) light with a Q2000 mask aligner.
- After exposure, the PZT sample was developed in a developer (AZ 400K) to remove the exposed photoresist.
- The developed specimen was dipped into Ferric Chloride to etch away the unwanted nickel area.
- As a result, the designed pattern was then successfully transferred to the PZT electrode after cleaning off the remained photoresist with Acetone.

Fig. 6: (a) Electrode pattern design for the interdigital transducer with finger spacing of Λ=2.363 mm and finger width of 20% Λ; (b) Electrode pattern on a PZT transducer fabricated with photolithography (Dark areas: Nickel electrodes).

Lamb Waves Generated With PZT IDTs

An experimental system was set up for Lamb wave examination on the GLARE composite material.

-Two developed PZT transducers were mounted onto the GLARE panel with conductive epoxy.

-Ten cycles of tone-burst signal were generated from a function generator and were amplified by a RF amplifier.

-The amplified tone-burst signal was used to drive the transducer to launch Lamb waves.

-The detected Lamb wave signal was monitored and recorded by a digital oscilloscope.

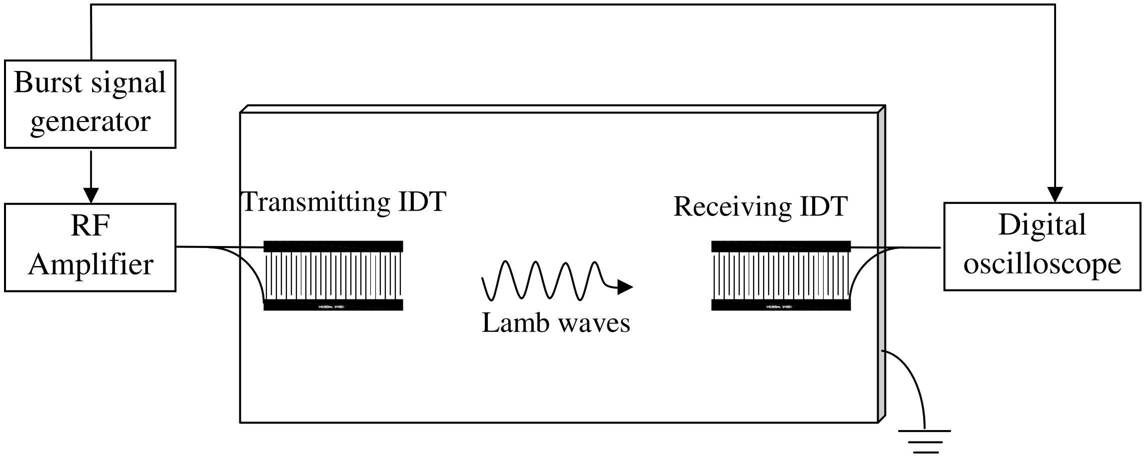


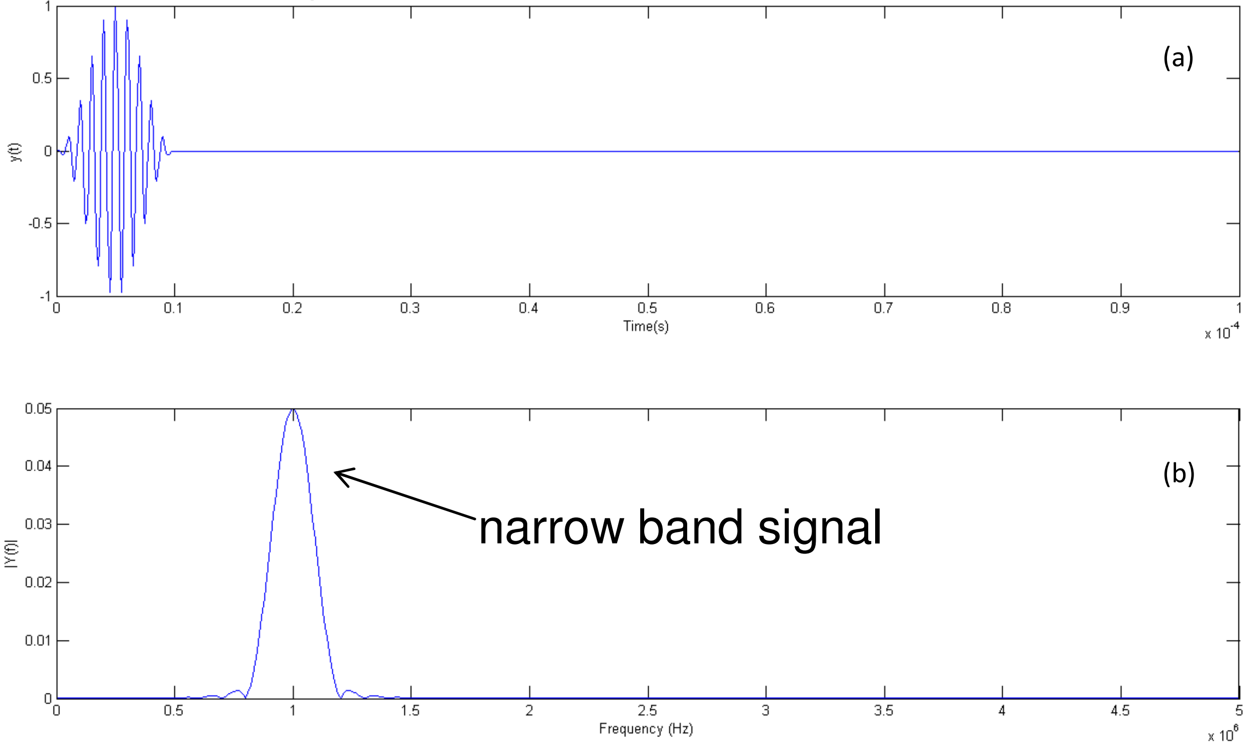
Fig. 7: a schematic of the experimental setup

Excitation Signal

The excitation sinusoidal signal with Hanning window was chosen in the form of:

$$y(t)=\begin{cases} 0.5[1-\cos(2\pi f_0 t/n_0)]\cos(2\pi f_0 t), & \mathrm{t}\le n_0/f_0 \\ 0, & \mathrm{t}> n_0/f_0, \end{cases}$$

Where f_o is the central frequency and n_o is the number of the sinusoidal cycles within the Hanning window.



narrow band signal

Fig. 8: Sinusoidal signal with a Hanning window in (a) time domain, and (b) frequency domain.

Lamb Waves Detected by a PZT IDT

Figure 9 shows the launching and detected Lamb wave signals at the frequency of f =713.0 KHz where the detected signal has maximum Lamb wave signals.

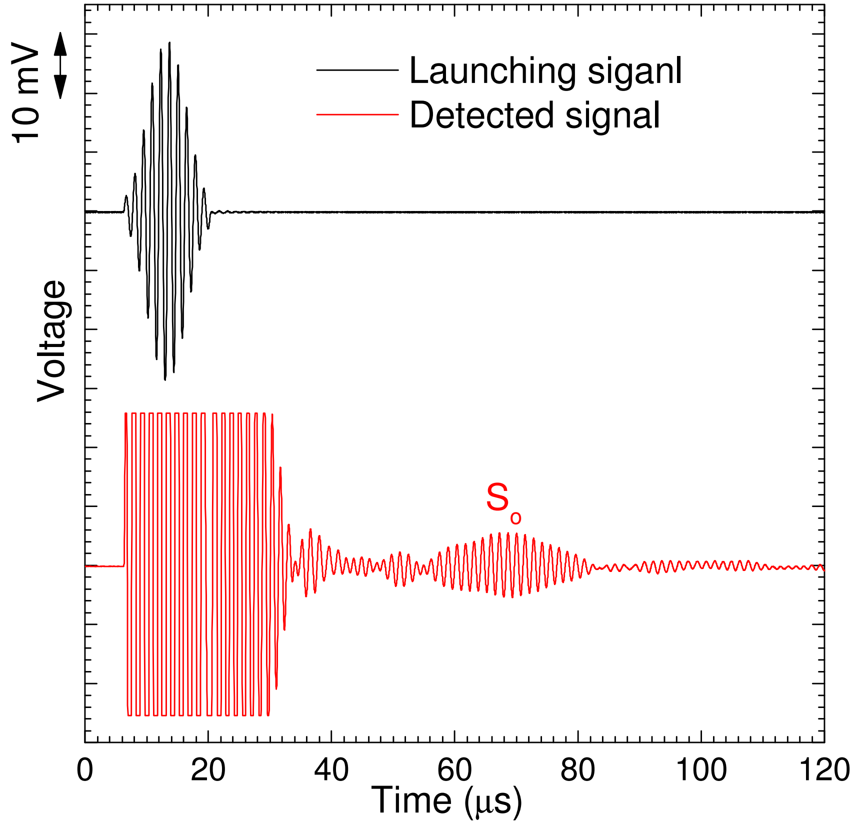


Fig. 9: Launching and detected Lamb wave signals at f = 713.0 KHz.

- •The detected signal at the very beginning is a coupling signal from the emission of the excitation source.
- •The phase velocity of the first group of tone burst signal was calculated by phase unwrapping.
- • The phase velocity of this mode was obtained as C_p = 5.103 mm/μs which is close to the phase velocity of S_o mode.
- •The experimental wavelength is 7.157 mm which is about 3 times of the designed spacing (Λ=2.363 mm) of the IDT.
- •Further research work is needed to optimize the modal selection.

Concluding remarks

1) A GLARE standard was tested using Pulsed Thermography

2) Two experimental systems were built up for launching and detecting Lamb waves in the GLARE plate.

-Lamb waves launched with a pulsed laser were used to measure the dispersive properties of Lamb waves.

-The experimental measured dispersion curves are consistent with the theoretical calculations.

-Guided Lamb waves of single mode were demonstrated to be launched successfully and which will be used for further work on debond tests.