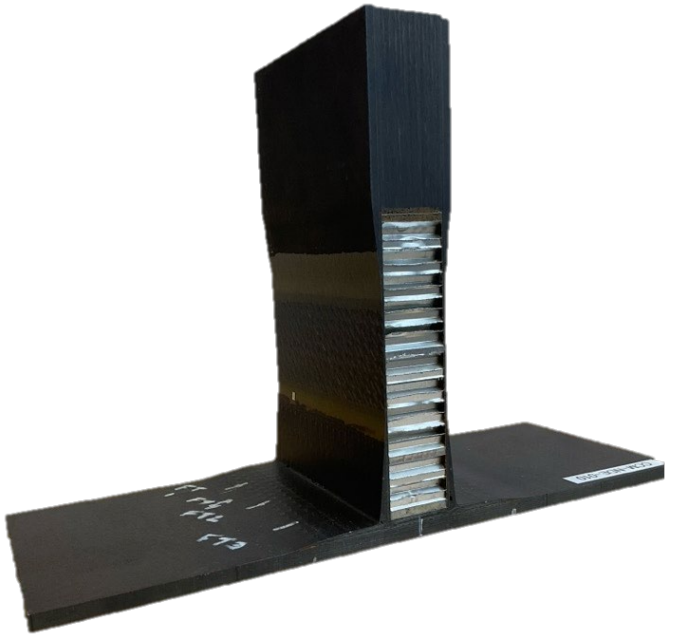
Sources of Uncertainty in Ultrasonic Phase-Based Assessment of Interfacial Stiffness in Adhesive Joints

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[1]Nondestructive Evaluation Sciences Branch
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NASA Langley Research Center
Hampton, VA 23601

Motivation

- Nondestructive evaluation (NDE) of bond strength is a major challenge
- Most industry inspections are limited to gross defects
- Bonds can be significantly weakened without apparent defects
  - Contamination
  - Kissing bonds
  - Environmental degradation

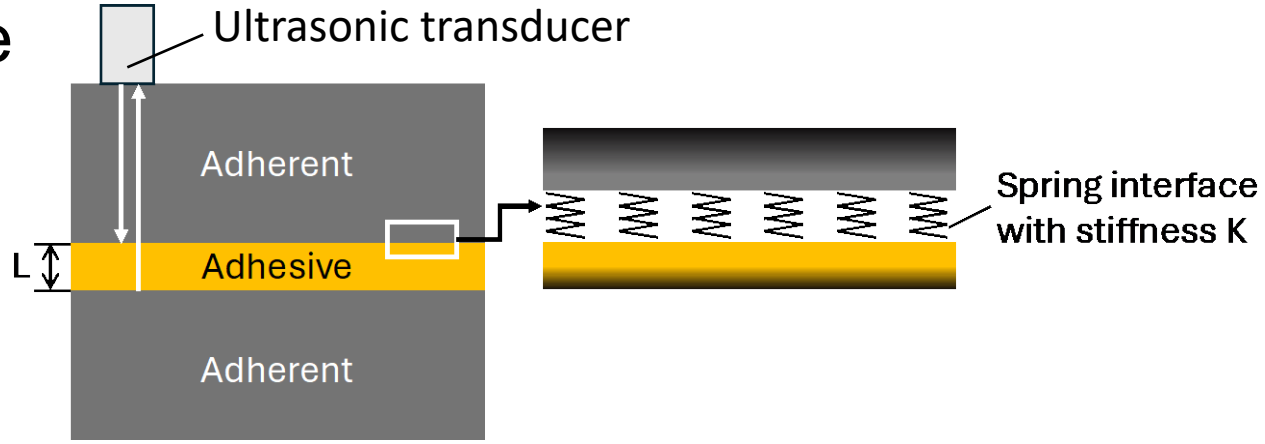


Example of complex adhesively bonded structural member

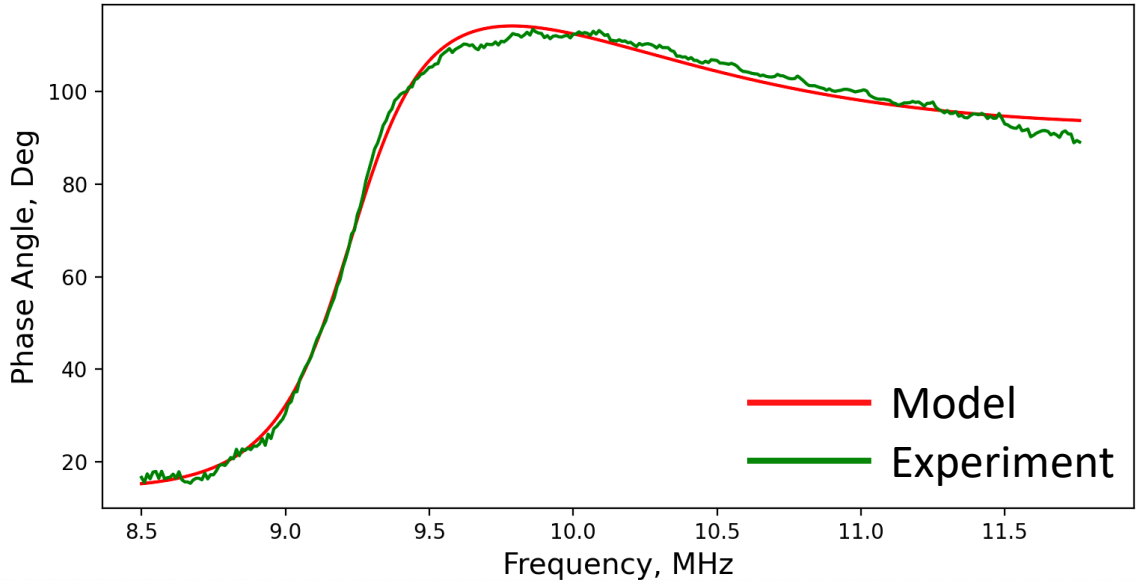
Reliable bond strength NDE is key to certifying structural bonds

Phase-Based Ultrasonic Testing (PBUT) of Bonds

- Inverse approach using spring interface model of Baik and Thompson[1]
  - Separation of bond counteracted by springs of stiffness K



- Measurement Process:
  - Frequency swept over bond resonance
  - Phase measured using phase detector
  - K found that minimizes difference between experimental and model phase response

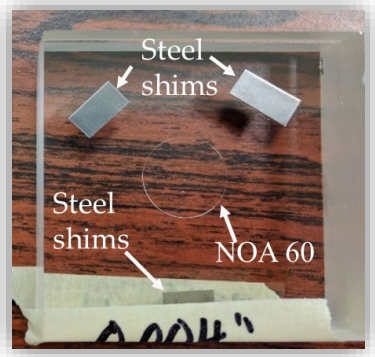


Phase response around resonance where the bond thickness is ½ the acoustic wavelength

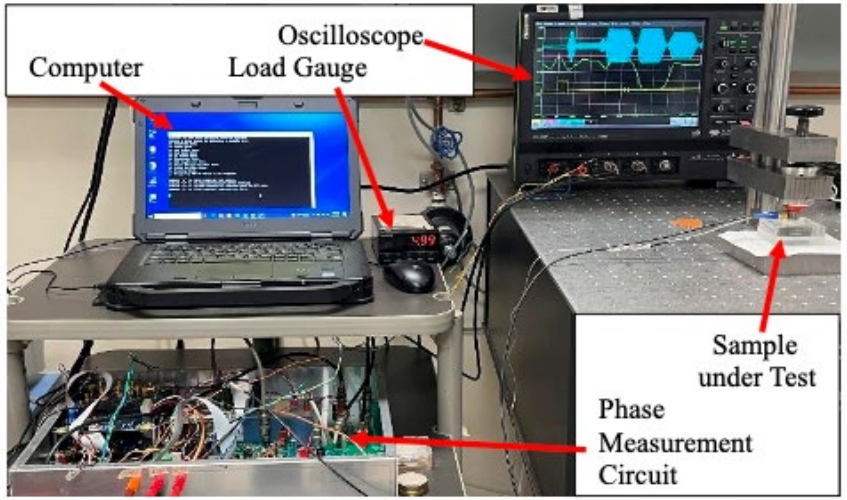
[1] Baik, J.M and Thompson, R.B.,J. NDE., 1984.

Proof of Concept Using UV-cured Adhesive

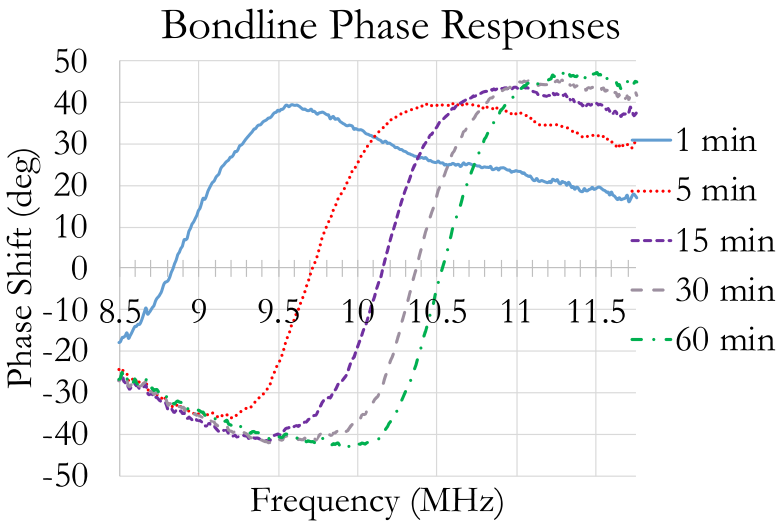
- Interfacial stiffness measured on glass specimens bonded with UV-cured adhesive at different cure states[2]
  - K increases during curing and attenuation decreases

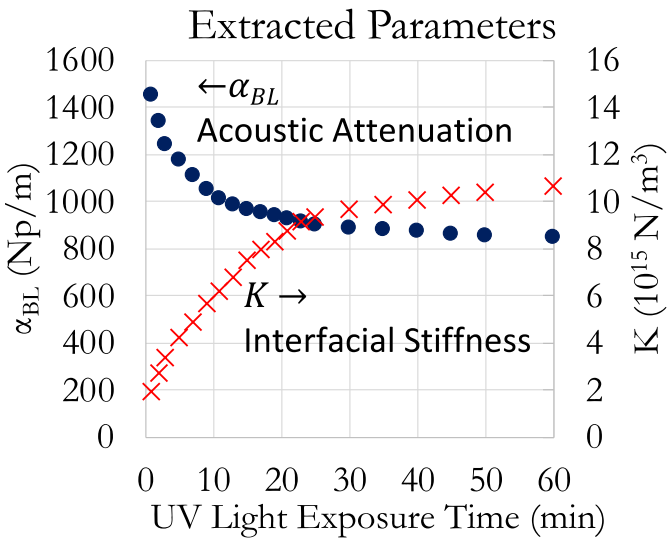


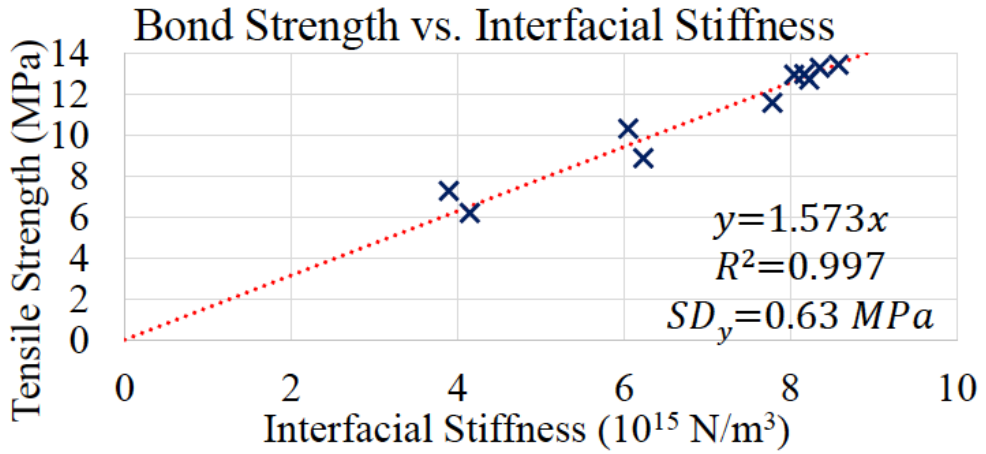
Borosilicate adherents bonded with UV-cured adhesive.



Measurement setup



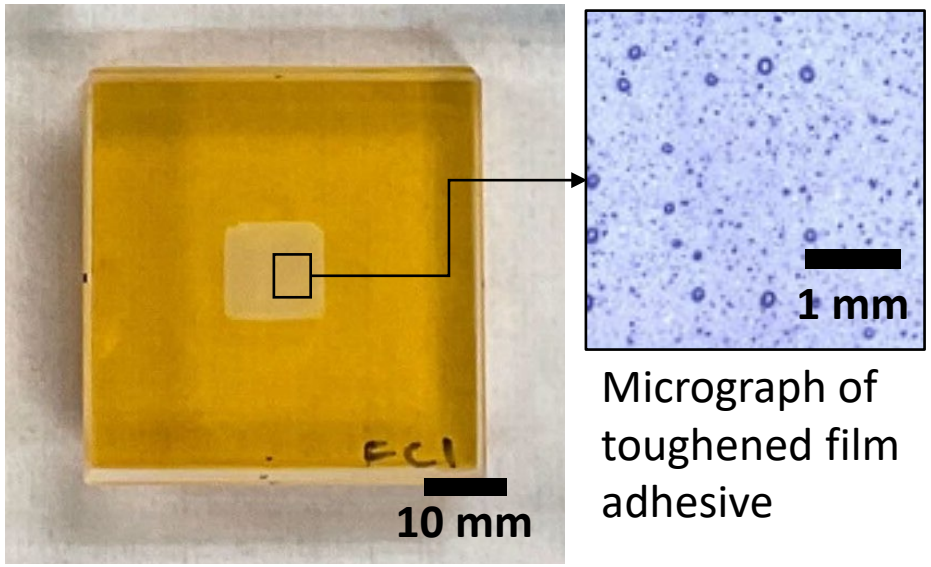




[2] Haldren, H., Perey, D., and Yost, W., JASA, 2019.

Increased Complexity with Relevant Adhesive

- Aerospace-grade toughened epoxy film adhesive under varying cure times/temperatures
  - FC1: Pristine adherents & adhesive (fully cured at 250^{0}F)
  - FC2: Pristine adherents & adhesive (fully cured at 350^{0}F)
  - FC1U: Pristine adherents & under cured adhesive
  - FC1C Contaminated adherents & adhesive (fully cured at 250^{0}F)



Micrograph of toughened film adhesive

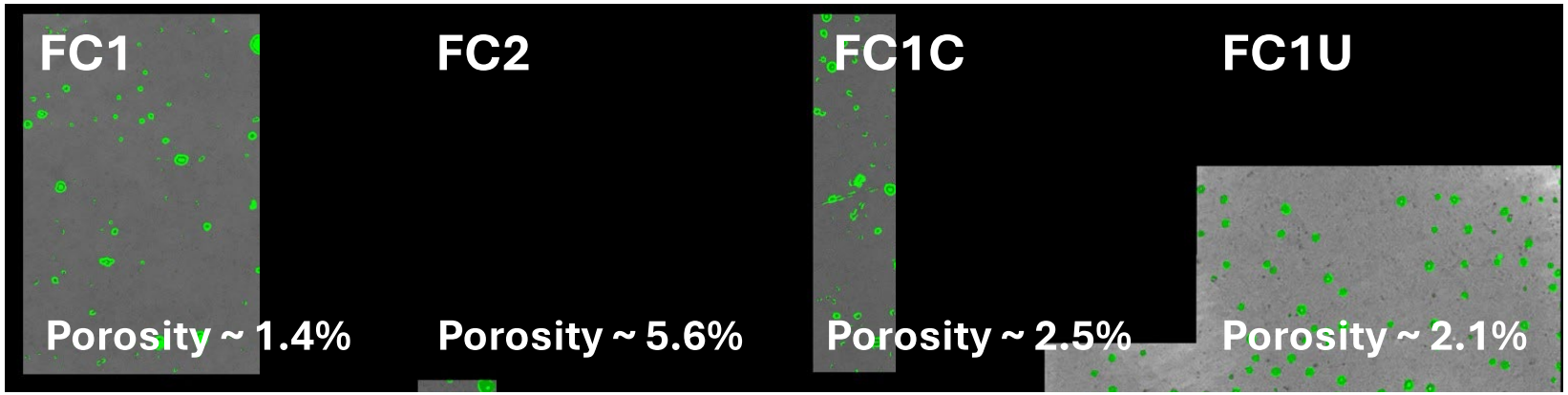
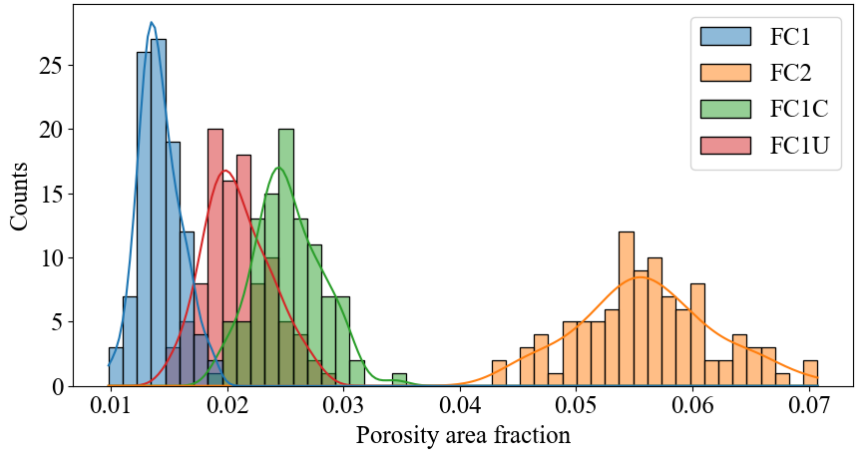


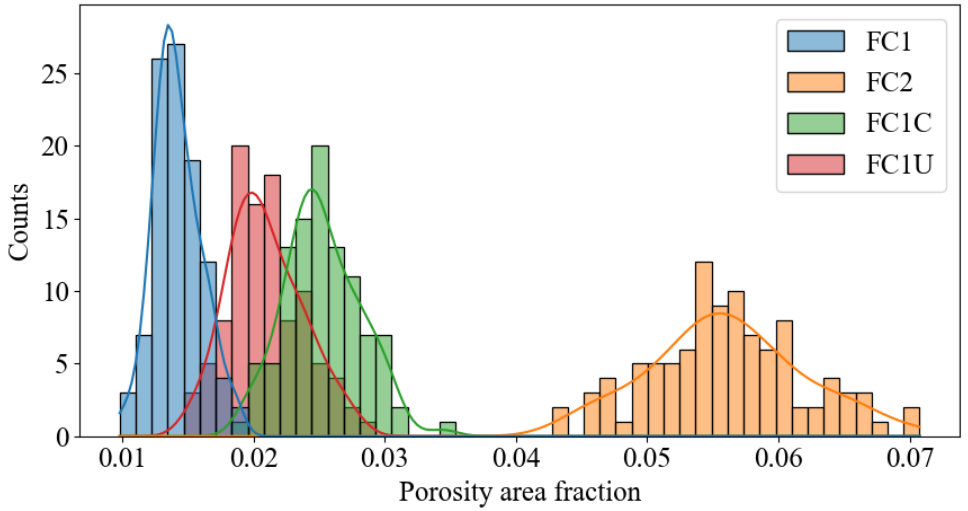
Image segmentation based on random forest classification[3]

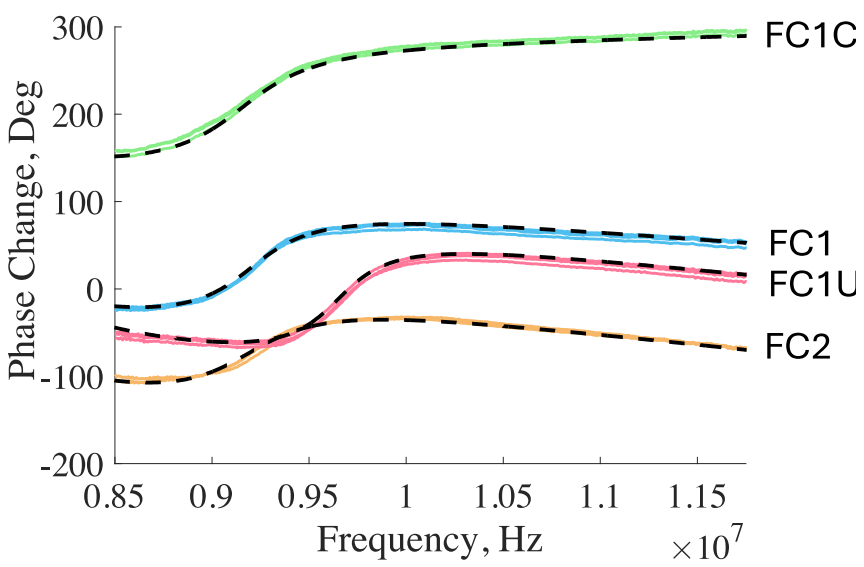


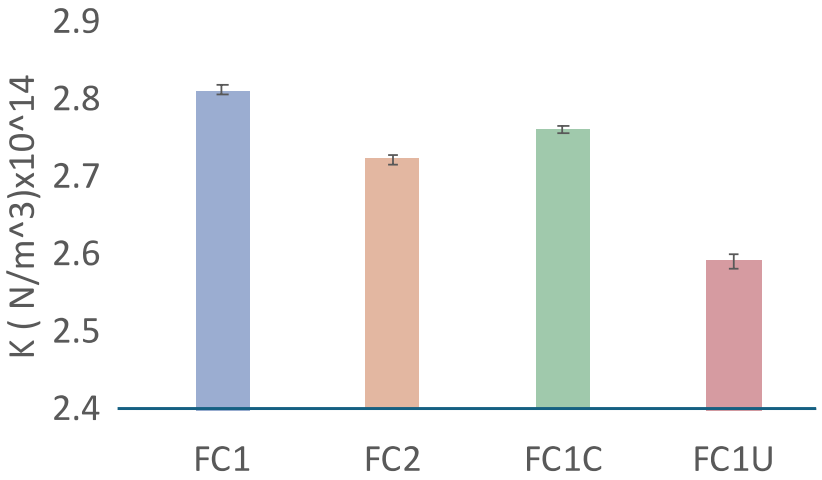
[3]Spaeth, P. and Webster, M., Proc. ASNT Research Symposium, 2023.

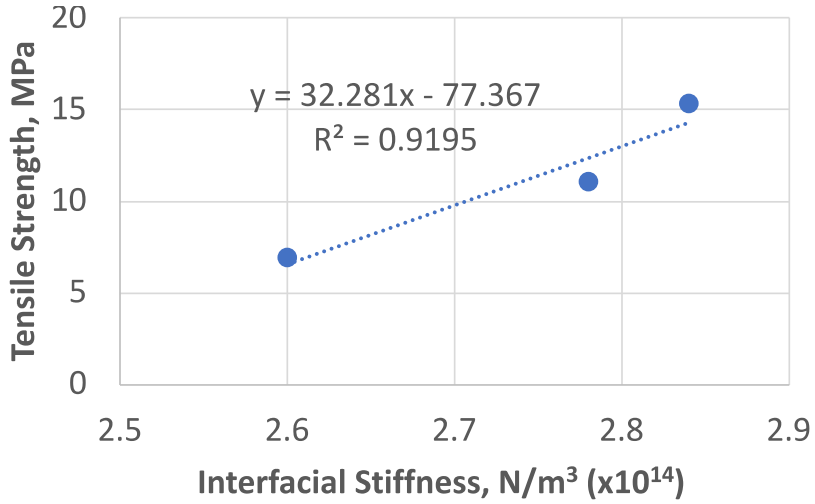
Initial Results on Aerospace Adhesive

- Phase measurements were very repeatable in triplicate measurements
- Using constant thickness and mean porosity, results correlate with strength
- Uncertainty in estimates is not known

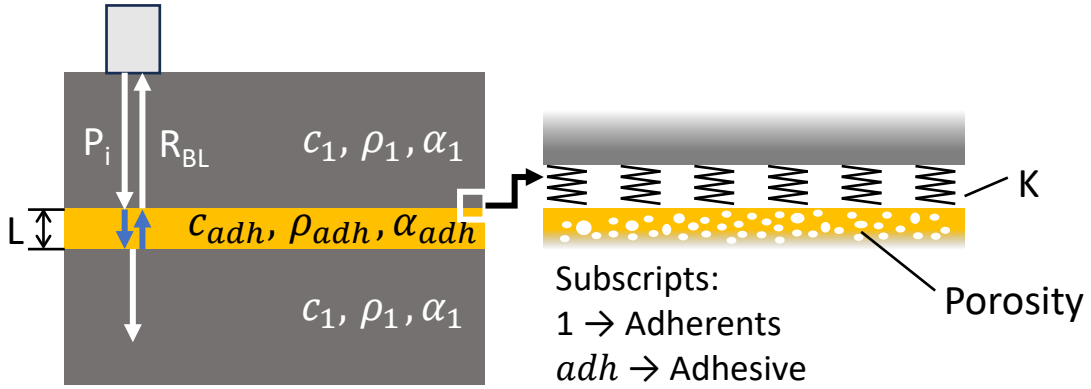








Reflection Coefficient for Tri-Layer Bond



Boundary conditions at *massless* interface:

$\sigma^+ = \sigma^- = \sigma_{interface}$

$K(u^+ - u^-) = \sigma_{int}$

σ = Stress

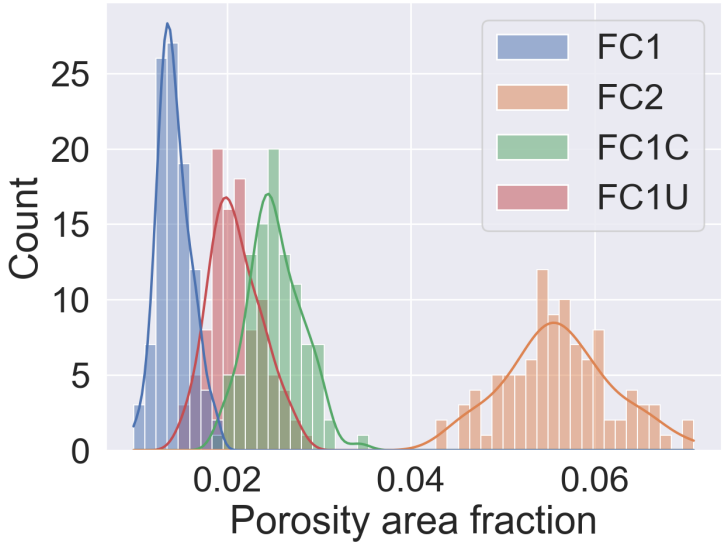
u = Displacement

P_i	Incident pressure wave
c	Wave speed
ρ	Density
α	Attenuation
L	Bond thickness
θ	Porosity

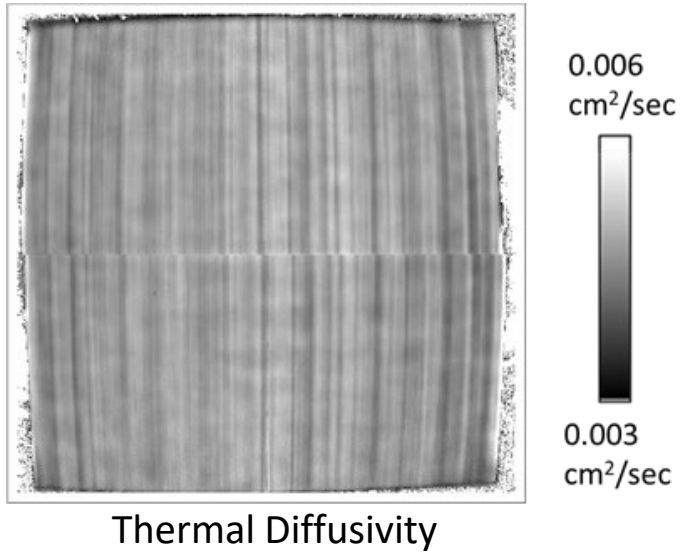
Reflection Coefficient:

$$R_{BL}(c_1, \rho_1, \alpha_1, c_{adh}, \rho_{adh}, \alpha_{adh}, \theta_{adh}, L, \omega) = |R_{BL}|e^{i\phi}$$

Porosity Distributions

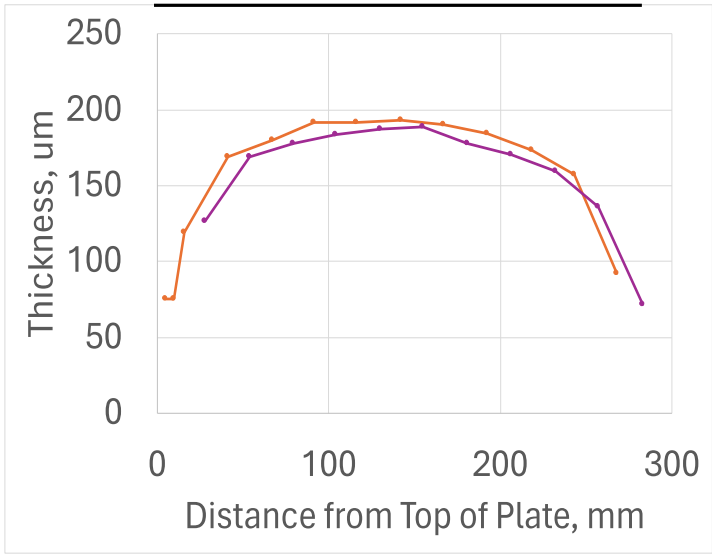


Adherent Inhomogeneity



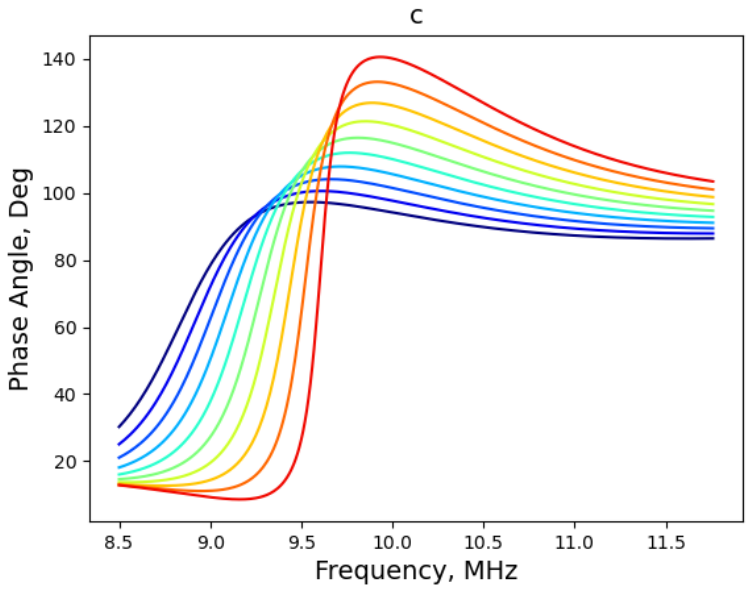
Thermal Diffusivity

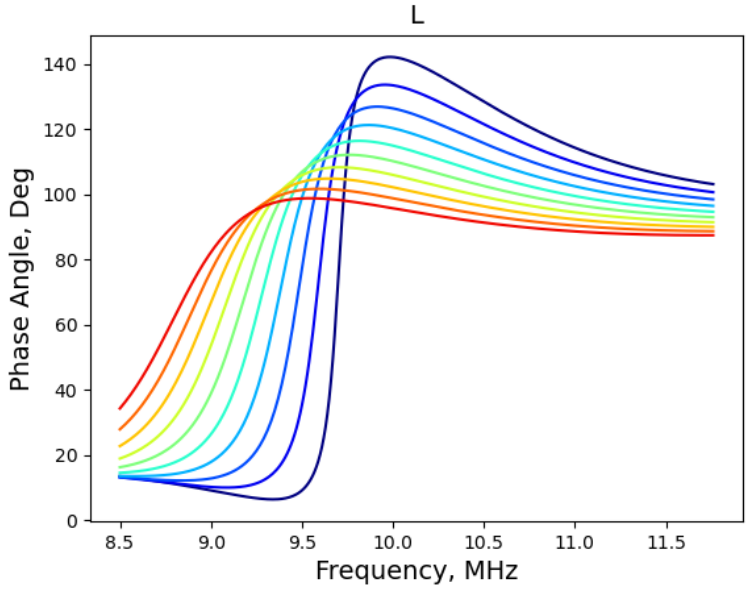
Bond Thickness Variation

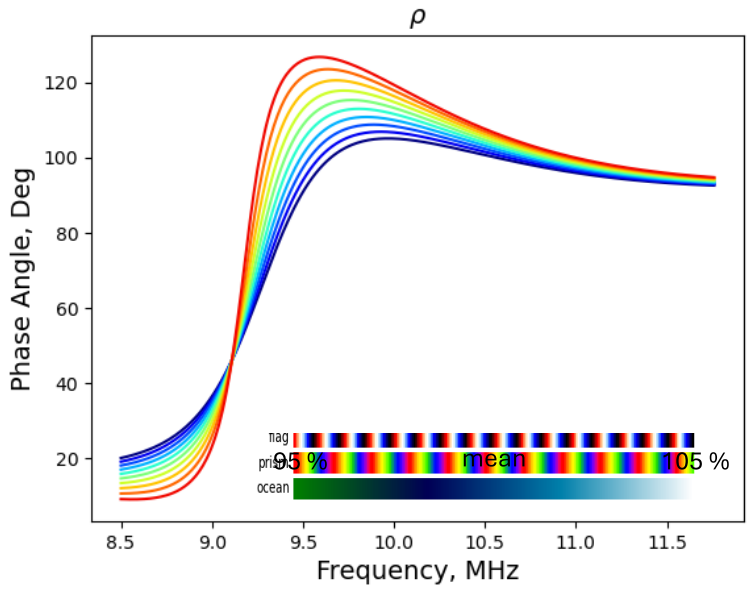


Model Response to Variation in Parameters

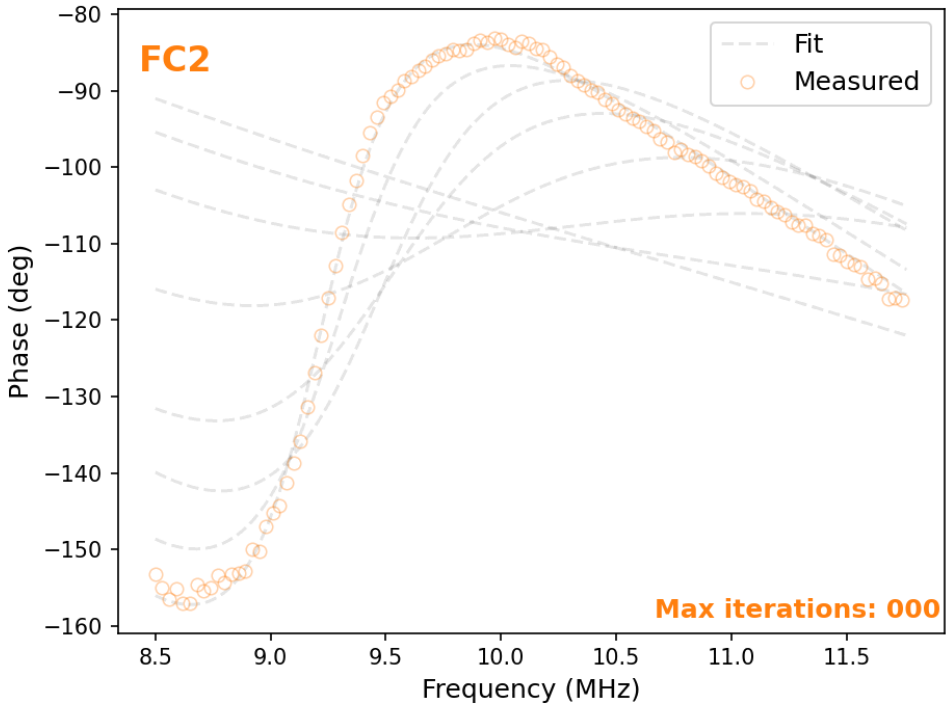
- Parameters swept by +/- 5% of mean to assess sensitivity
- Wave speed and density are influenced by porosity
- Bond thickness and wave speed have opposite effects phase response
  - $f_{resonance} = c_{adh}/2L$







Parameter Identification and Model Fitting

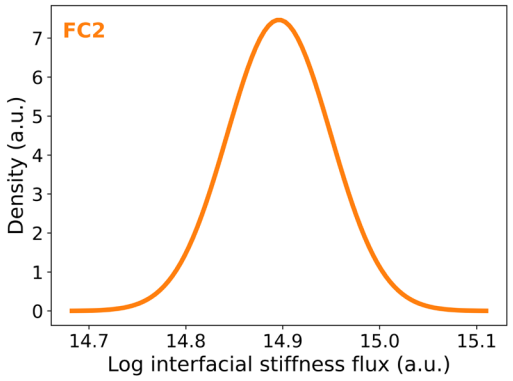


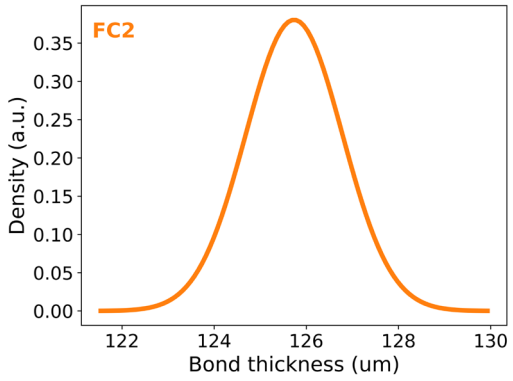
- Phase measurements g_i at input frequencies $\omega_i, i = 1, \dots, N$ used to compute parameters $\beta_1, \dots, \beta_p$ with constrained non-linear least squares:

$$\hat{\beta} = \text{argmin} \left\{ \sigma^2 = \sum_{i=1}^{N} (\phi_i(\omega_i;\, \beta) - g_i)^2 \,\middle|\, \beta_j^{\min} \le \beta_j \le \beta_j^{\max}, j = 1, \dots, p \right\}$$

- $\phi_i(\omega_i; \beta)$: predicted phase at frequency ω_i given β

- β: parameter vector consisting of (1) log interfacial stiffness, (2) acoustic attenuation, (3) slope, (4) offset, and (5) bond thickness

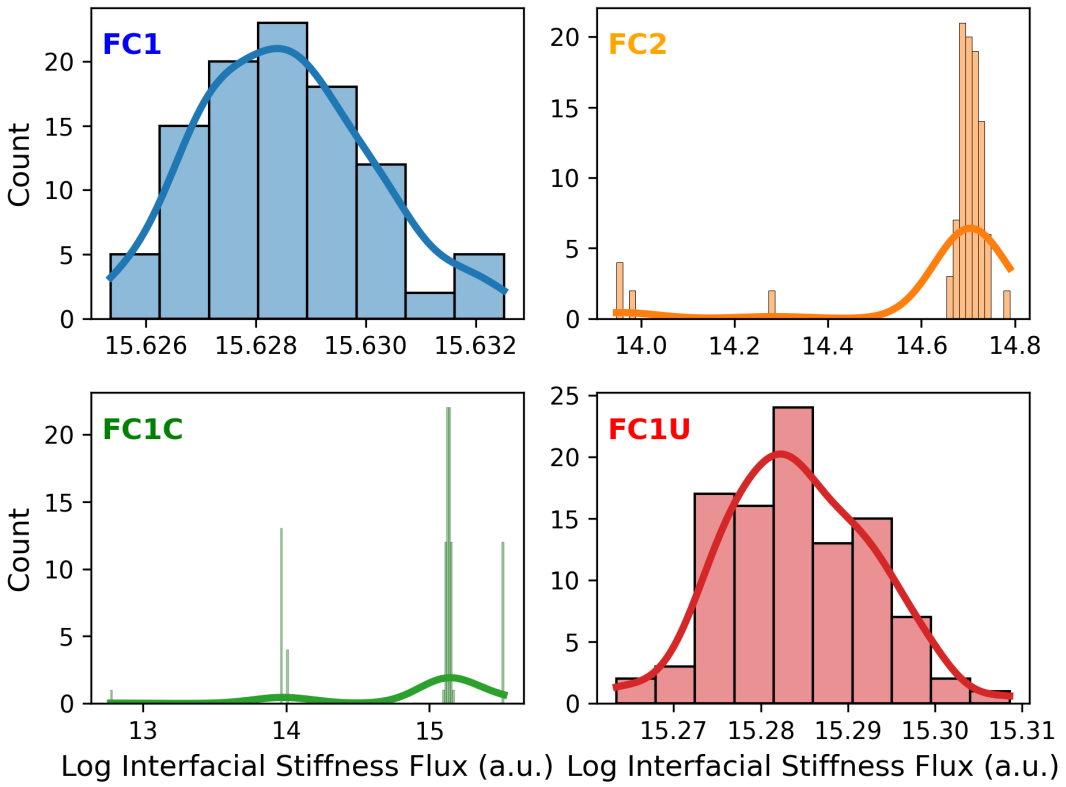




- The covariance matrix $\mathrm{V}(\hat{\beta}) = \hat{\sigma}^2[\mathrm{X}^T\mathrm{X}]^{-1}$ computed from the $N \times p$ dimensional sensitivity matrix with elements

$$\mathrm{X}_{ij}(\hat{\beta}) = \frac{\partial \phi_i}{\partial \beta_j}.$$

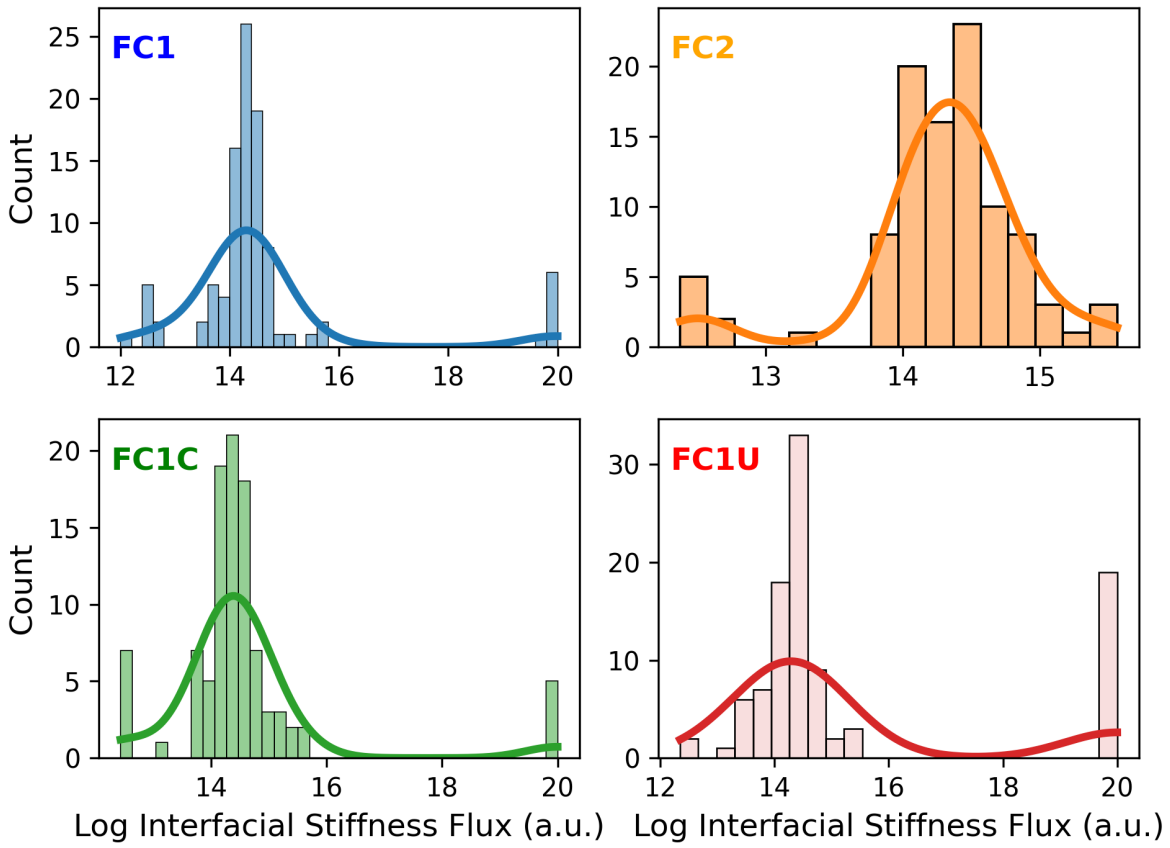
Impact of porosity on interfacial stiffness estimates



- Normal distributions for porosity area fraction[3] used to understand the impact of porosity on model fitting.
- Least-square optimal values for bond thickness, interfacial stiffness, acoustic attenuation, and the correction parameters were estimated.
- The greatest variability in estimates for interfacial stiffness occurred for specimens FC2 and FC1C.

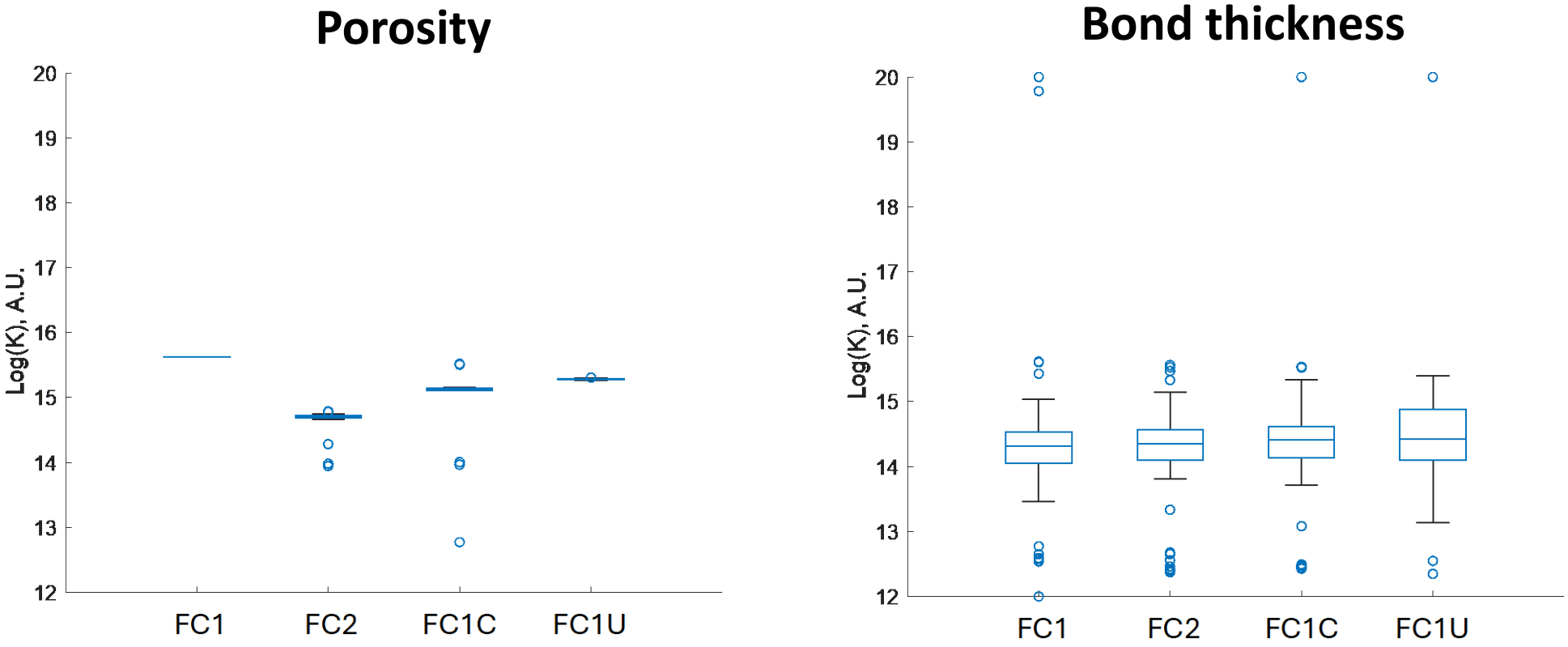
[3]Spaeth, P. and Webster, M., Proc. ASNT Research Symposium, 2023.

Impact of bond thickness on interfacial stiffness estimates



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Impact of porosity and bond thickness uncertainties on interfacial stiffness estimates



The goal is to fully characterize the joint probability distribution of parameters that affect composite bond strength.

Data Fusion and Next Steps

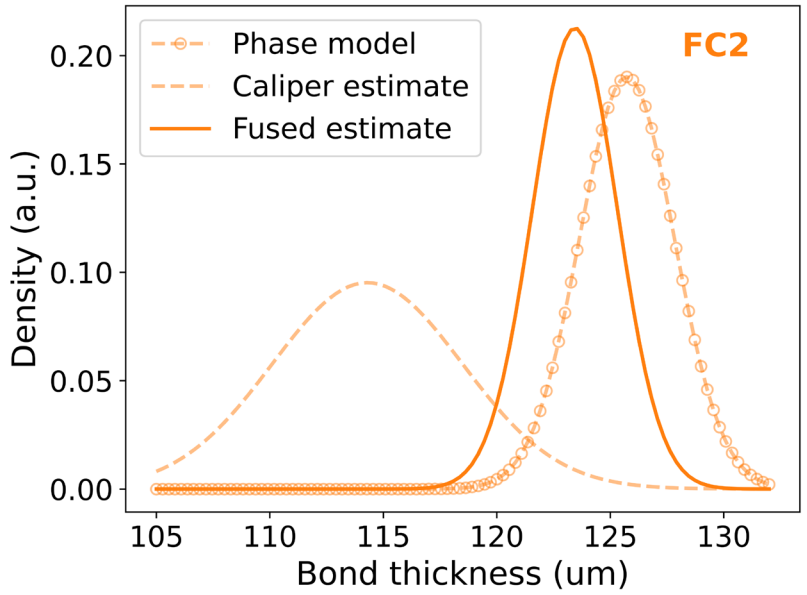
Challenges:

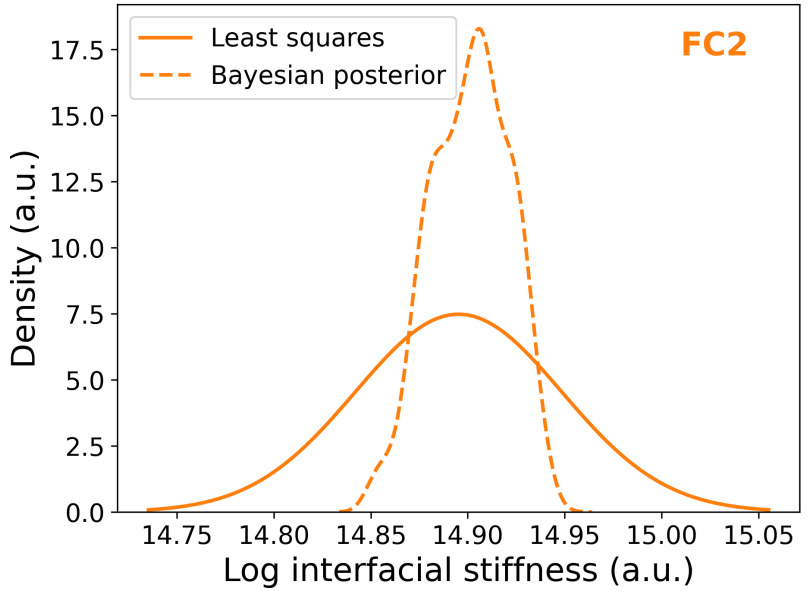
- Parameter identifiability
- Estimating additional parameters
- Combining multiple modalities

Solutions being developed:

- Reframing the problem with Bayesian estimation
- Monte Carlo methods
- Conflation of distributions technique[4,5]

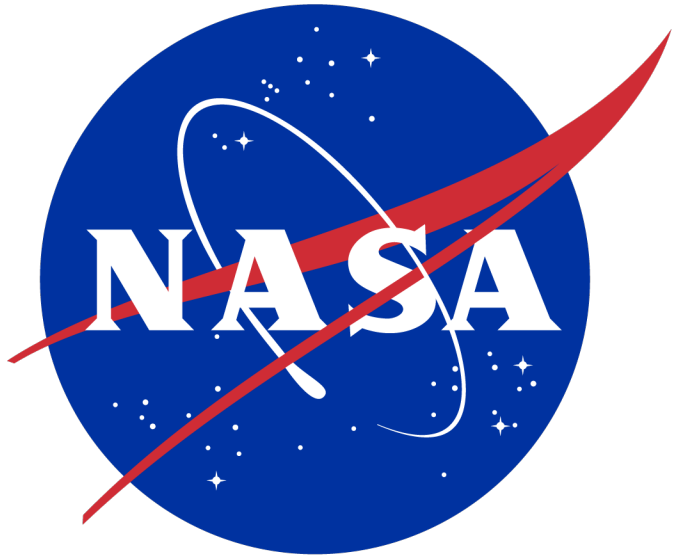
$$Q(P_1, P_2) = P(X_1, X_2 \,|\, X_1 = X_2)$$





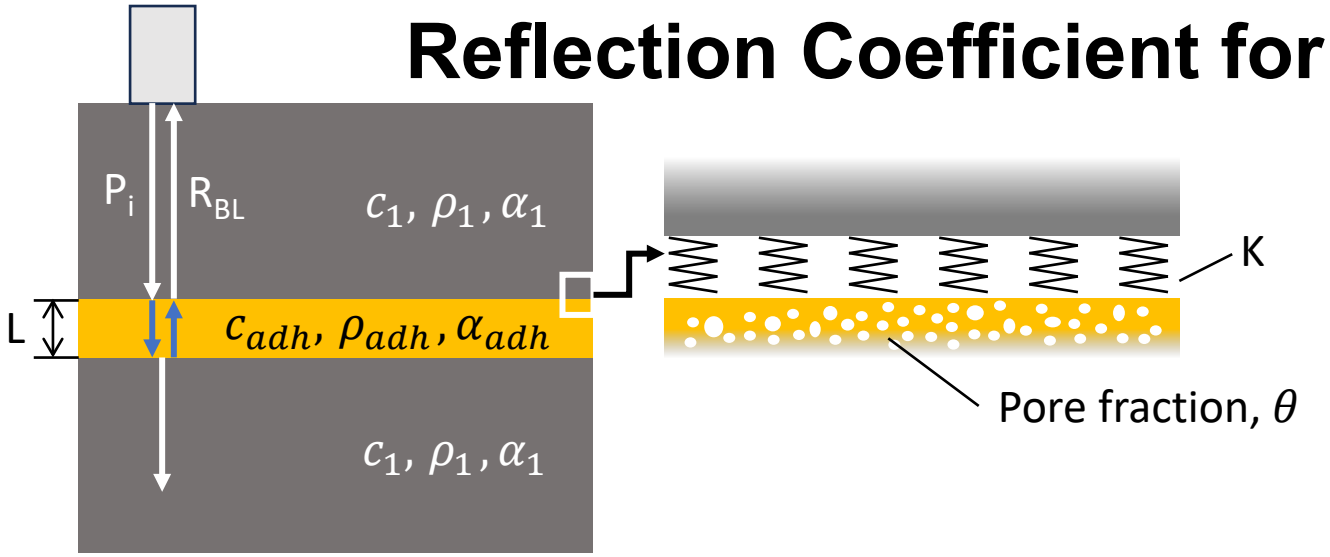
[4]Hill, T.P., Trans Amer Math Soc, **363**, 2011

[5] Spaeth, P.W., Webster, M.R., and Zalameda, J.N., Proc SPIE: Thermosense, 2024


NASA

Back up

Reflection Coefficient for Tri-Layer Bond



Boundary Conditions:

$$\sigma_1(0) + \sigma_{adh}(0) = 2K(u_{adh}(0) - u_1(0))$$
$$\sigma_1(0) = \sigma_{adh}(0)$$
$$\sigma_{adh}(L) + \sigma_2(L) = 2K(u_2(L) - u_{adh}(L))$$
$$\sigma_{adh}(L) = \sigma_2(L)$$

$$R_{BL}(c_1, \rho_1, \alpha_1, c_{adh}, \rho_{adh}, \alpha_{adh}, \theta_{adh}, L, \omega) = \frac{C_N \cos(k_{adn}L) + iS_N \sin(k_{adh}L)}{C_D \cos(k_{adn}L) + iS_D \sin(k_{adh}L)}$$

Defined Parameters:

$$C_N = \frac{2G_1^2 G_{adh}}{K}$$
$$C_D = 2G_1 G_{adh}\left(1 + \frac{G_1}{K}\right)$$
$$S_N = G_1^2 - G_{adh}^2 + \frac{G_1^2 G_{adh}^2}{K^2}$$
$$S_D = G_1^2 + G_{adh}^2 + \frac{G_1^2 G_{adh}^2}{K}\left(2 + \frac{G_1}{K}\right)$$

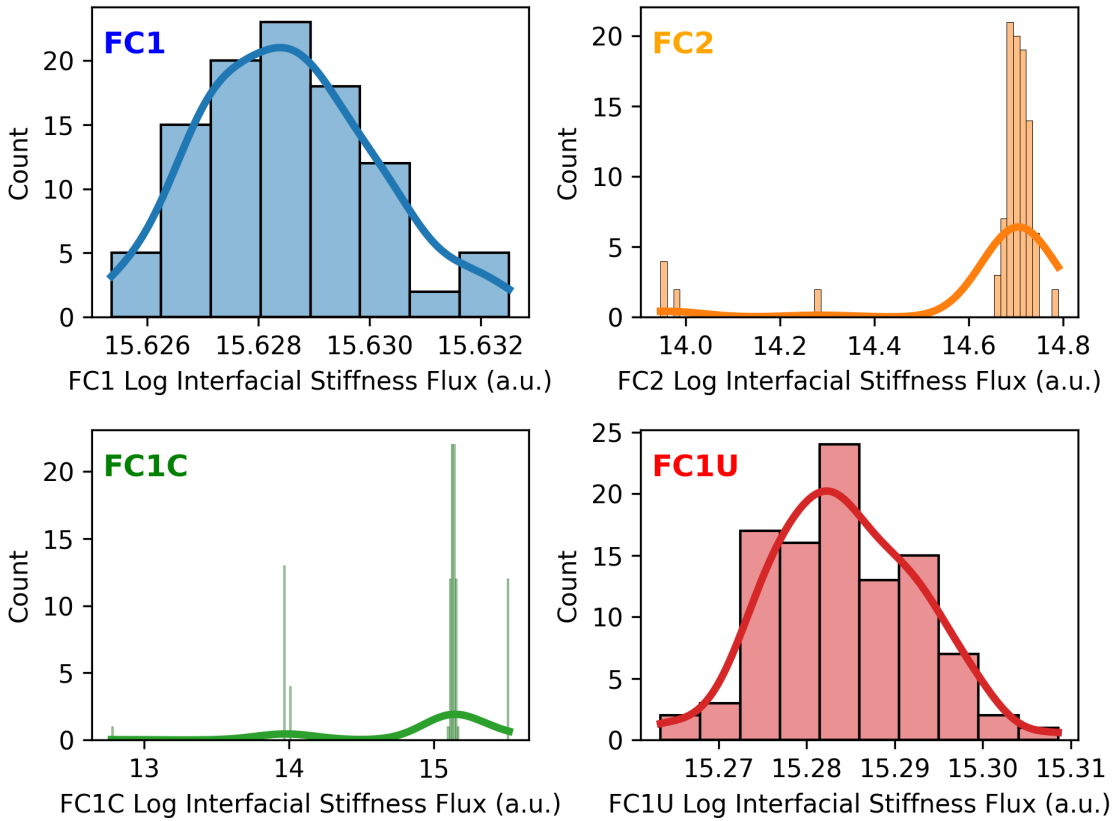
$$G_1 = \rho_1 c_1 (i\omega - \alpha_1)$$
$$G_{adh} = \hat{\rho}_{adh}\hat{c}_{adh}(i\omega - \alpha_{adh})$$
$$k_{adh} = \frac{\omega}{\hat{c}_{adh}} + i\alpha_{adh}$$

Porosity Effects[4]:

$$\hat{\rho}_{adh} = \rho_{adh}(1 - \theta_{adh})$$
$$b_K = \frac{1 + \nu_0}{(2(1 - 2\nu_0))} \qquad b_G = \frac{11 + 19\nu_0}{(4(1 - \nu_0))}$$
$$\hat{c}_{adh} = c_{adh}\left(\frac{(4 + 5\theta_{adh})(1 - \theta_{adh})}{4(1 + b_K\theta_{adh})(1 + b_G\theta_{adh})}\right)^{1/2}$$

[4]Ramakrishnan, N., "Speed of Sound in Porous Materials". Bull. Mater. Sci., 1994.

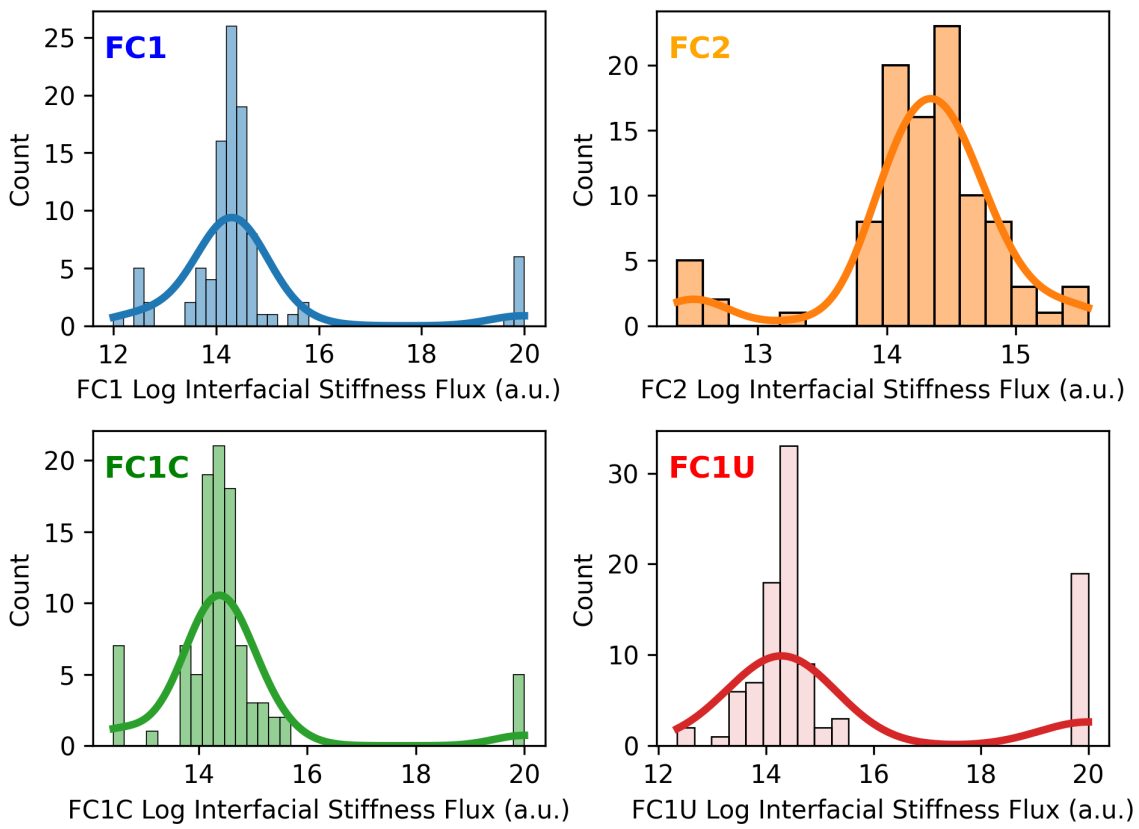
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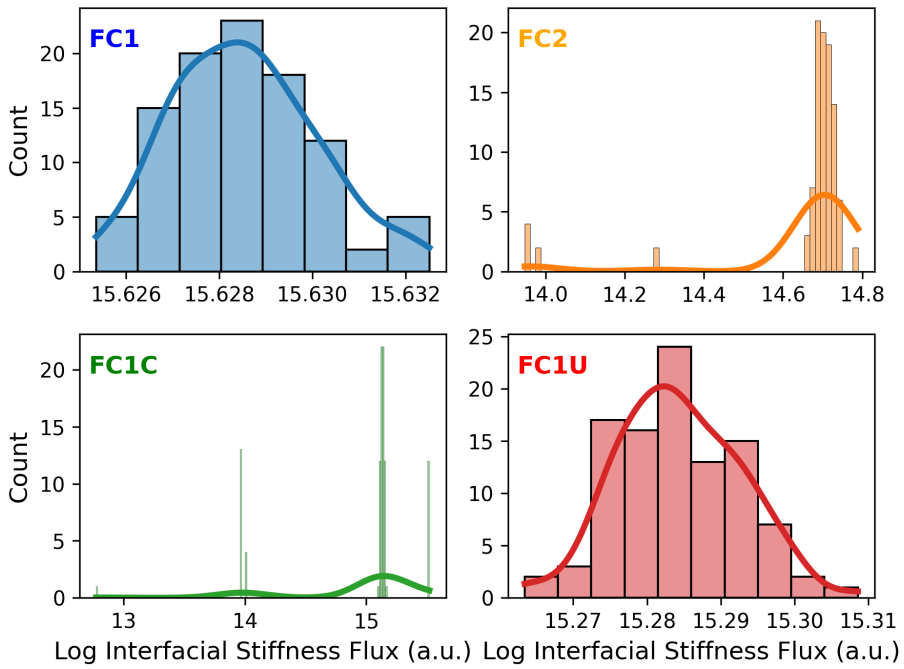
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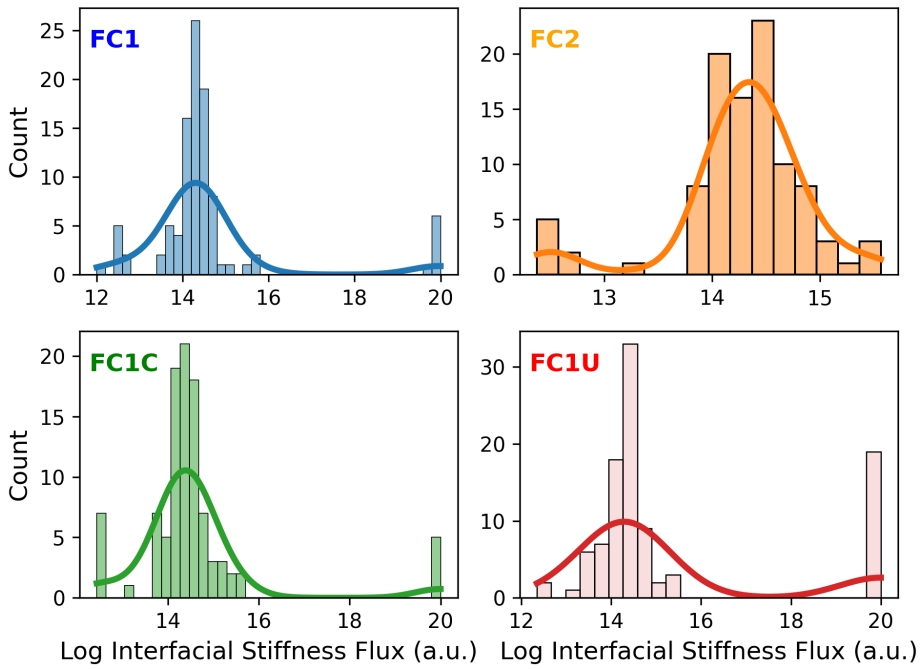
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Porosity



Bond thickness



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