Simulation of Ultrasonic Inspection of Composites Using CIVA FIDEL

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Computational Tools
Gurnee, IL USA

CIVA NA User Group Meeting
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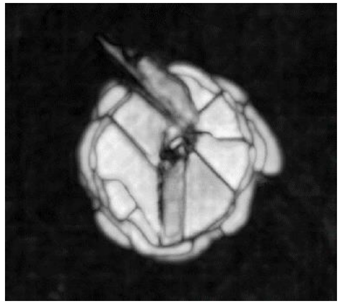
Outline

- Challenge Problem: Composite Impact Damage Characterization
  - Limitations of CIVA UT and Homogenization
- CIVA FIDEL 2D (Numerical Scheme, Problem Set-up, Applications)
- Study of Oblique UT for Hidden Impact Damage Characterization
- Alternative Uses of CIVA FIDEL

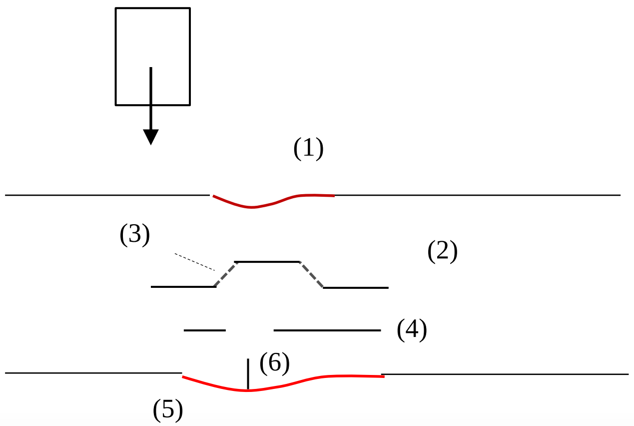
Characterization of Hidden Regions of Impact Damage in Composites

Key Features of Impact Damage:

1. Deformation of front-wall surface
2. Delamination(s), front 'profile' (delamination area, depth) →
3. Matrix cracking connecting delaminations



Impact Damage, Normal Scan AMP C-scan Map

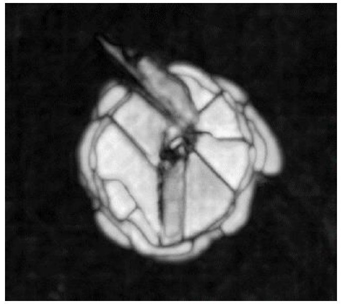


Characterization of Hidden Regions of Impact Damage in Composites

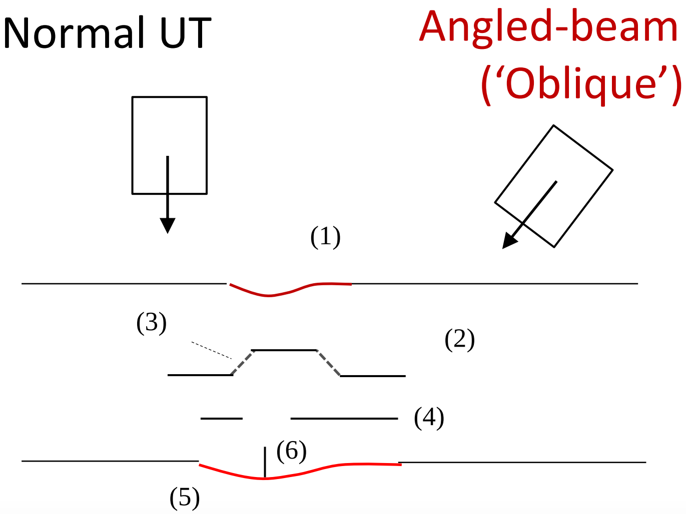
Key Features of Impact Damage:

1. Deformation of front-wall surface
2. Delamination(s), front ‘profile’ (delamination area, depth)
3. Matrix cracking connecting top delaminations
4. Extent of 3D delaminations (and matrix cracks) with depth
5. Deformation of back-wall surface
6. Backwall matrix crack

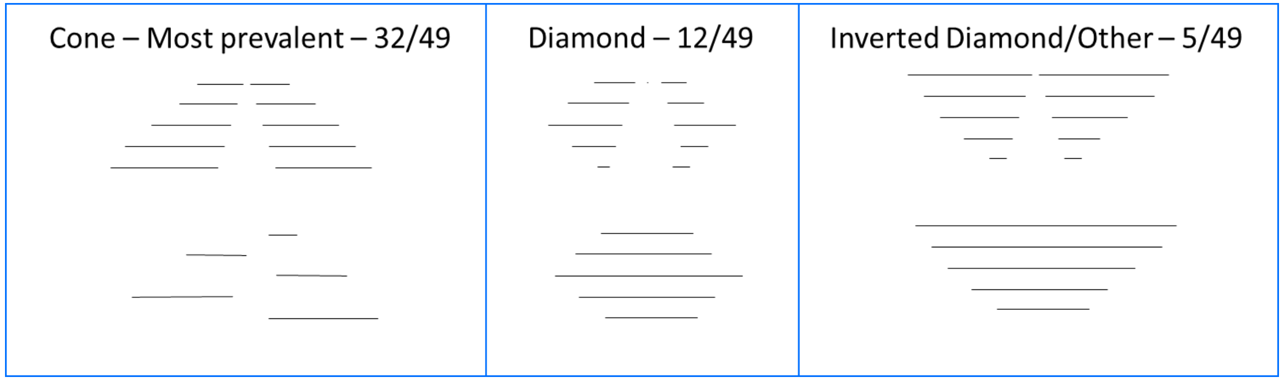
‘Hidden’ characteristics



Impact Damage, Normal Scan AMP C-scan Map



Challenge Problem: Characterize Hidden Delamination Profile

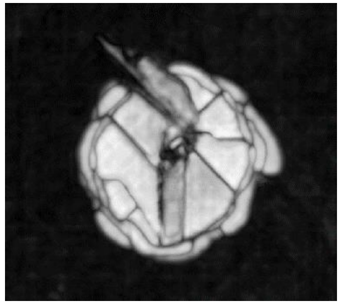


Welter, John T., PhD dissertation, University of Dayton, 2019.

Characterization of Hidden Regions of Impact Damage in Composites

Motivation:

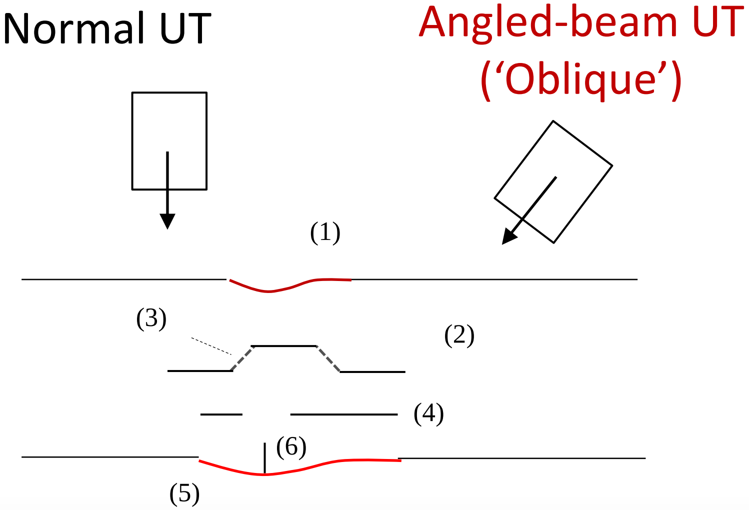
- **Improved life prediction following *slow crack growth damage tolerance,* but for polymer matrix composites**



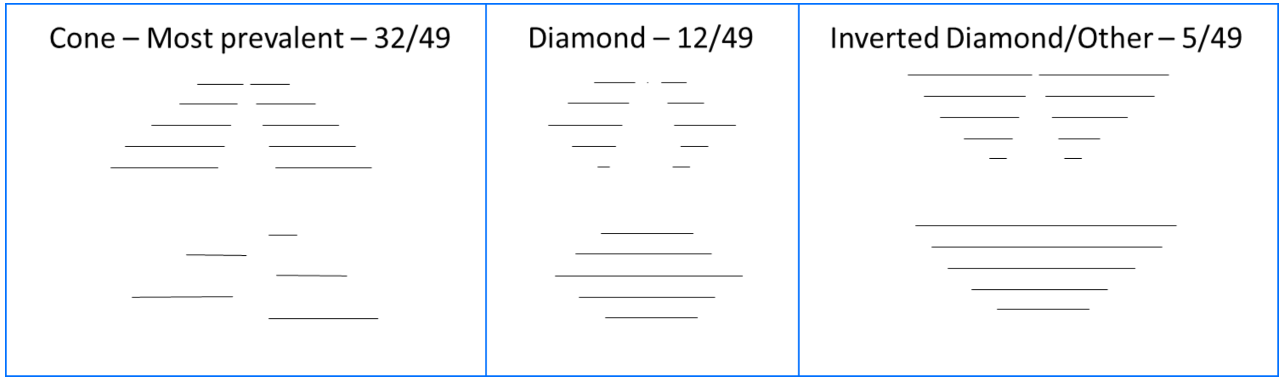
Impact Damage, Normal Scan AMP C-scan Map

Objective:

- **Develop method for field NDE to characterize 3D delamination location and extent (→ input to life prediction models)**



Challenge Problem: Characterize Hidden Delamination Profile



Welter, John T., PhD dissertation, University of Dayton, 2019.

Prior Work – Polar Backscatter UT

1. Bar-Cohen and Crane [Mat Eval., 1982]:

- Quasi-shear modes peaks at increasing angles
- Studied for glass/epoxy and SiC composites

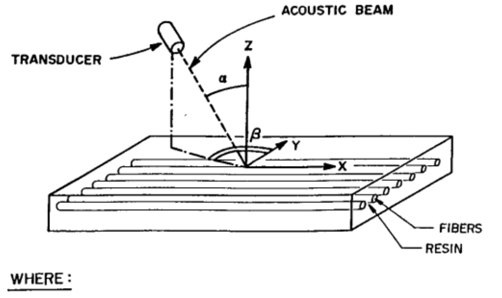


Figure 2—Schematic diagram of experimental system used to measure backscattering from composite samples.

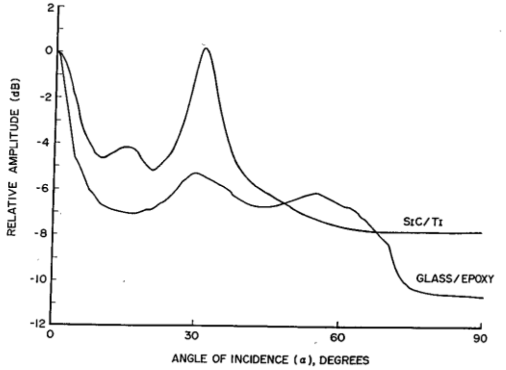
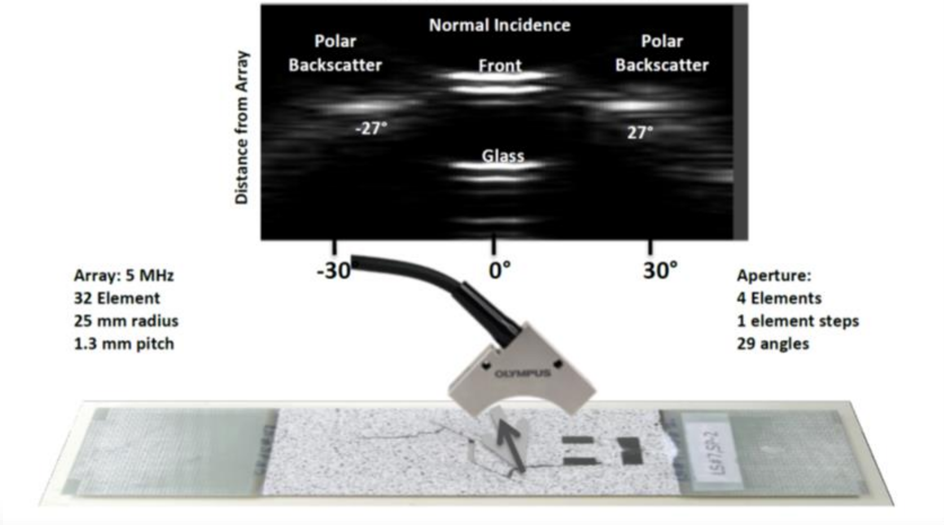


Figure 4—Comparison of backscattering from both a SiC/Ti and a glass/epoxy composite as a function of angle of incidence. Rotational angle β=0.

2. Johnston et al. [QNDE, 2013]:

- Normal front and polar backscatter at oblique angles
- For glass epoxy composite

Scattering from Crack Location



Array: 5 MHz
32 Element
25 mm radius
1.3 mm pitch

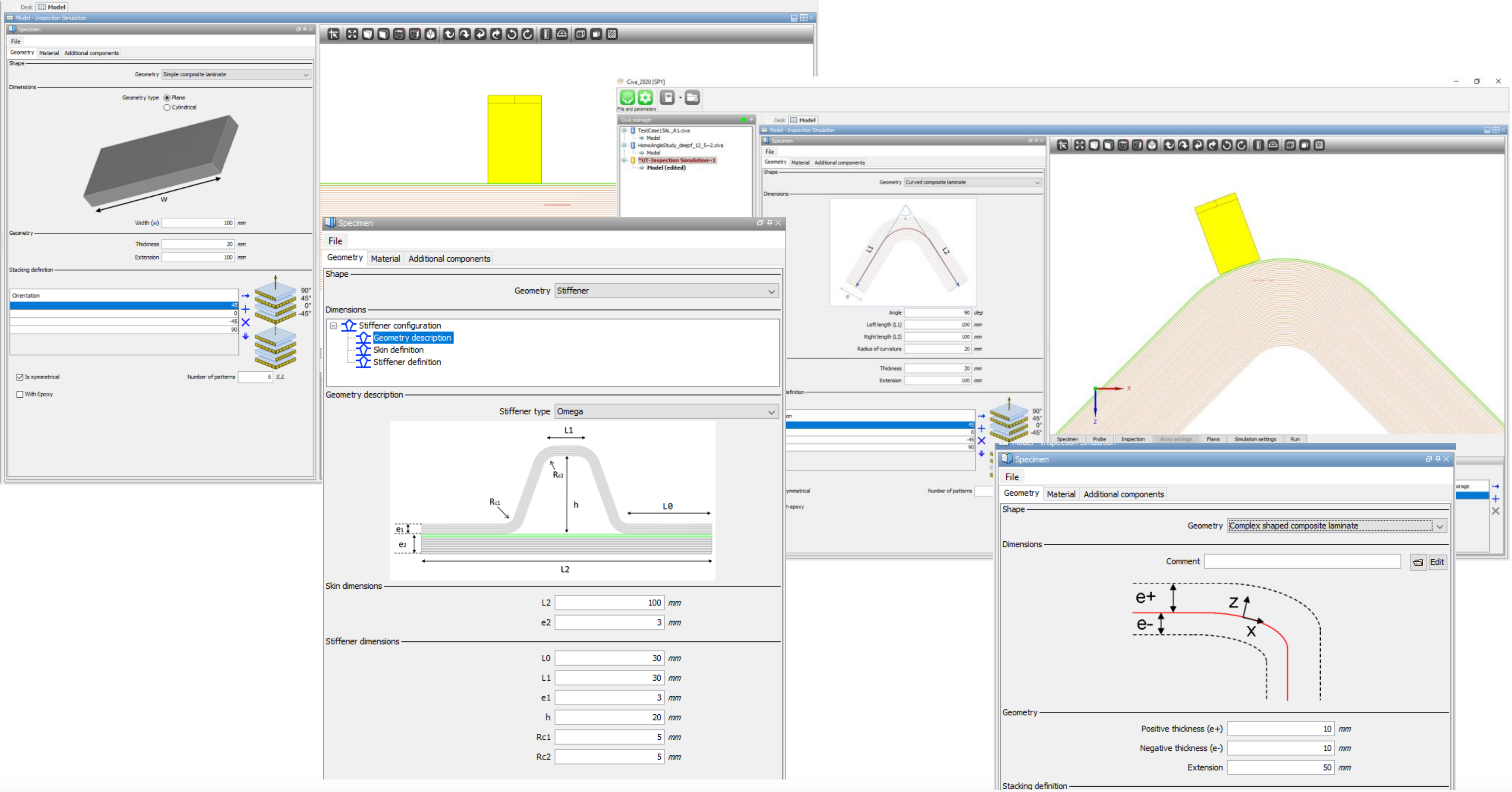
Aperture:
4 Elements
1 element steps
29 angles

Limited work on using angled-beam UT for inspection of composites

Specimen Models for Composites in CIVA UT

Specimen Geometry Options:

- Simple Composite Laminates
- Curved Composite Laminates
- Stiffener
- Complex Shaped Composite Laminate



Model - Inspection Simulation

Specimen

Geometry: Simple composite laminate

Geometry type: ● Plane ○ Cylindrical

Width (w): 100 mm

Thickness: 20 mm

Extension: 100 mm

Stacking definition

Orientation
45
0
-45
90

☑ Is symmetrical

Number of patterns: 6 S.I.

☐ With Epoxy

Specimen

Geometry: Stiffener

Stiffener configuration
  Geometry description
  Skin definition
  Stiffener definition

Geometry description

Stiffener type: Omega

Skin dimensions

L2: 100 mm

e2: 3 mm

Stiffener dimensions

L0: 30 mm

L1: 30 mm

e1: 3 mm

h: 20 mm

Rc1: 5 mm

Rc2: 5 mm

Specimen

Geometry: Curved composite laminate

Angle: 90 deg

Left length (L1): 100 mm

Right length (L2): 100 mm

Radius of curvature: 20 mm

Thickness: 20 mm

Extension: 100 mm

Specimen

Geometry: Complex shaped composite laminate

Comment:

Positive thickness (e+): 10 mm

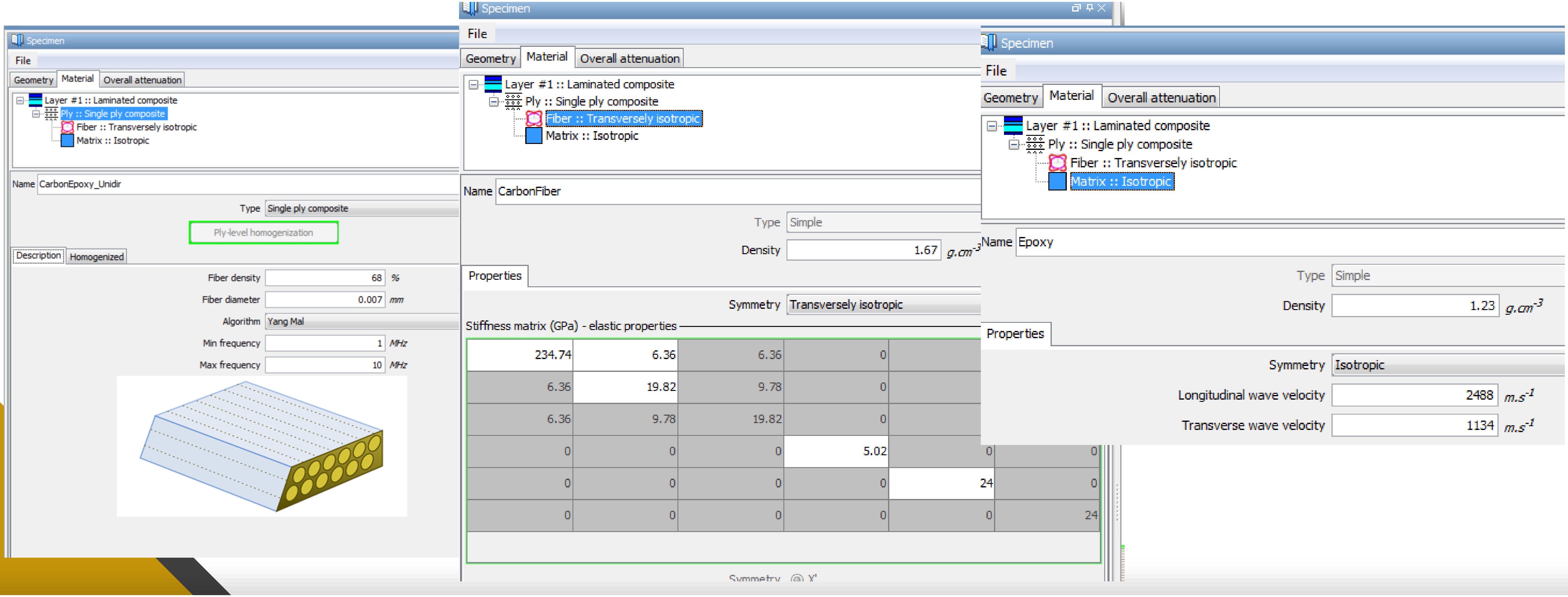
Negative thickness (e-): 10 mm

Extension: 50 mm

Stacking definition

Specimen Models for Composites in CIVA UT

- **Homogenization used to generate orthotropic representation of elastic properties for single ply**



Layer #1 :: Laminated composite
Ply :: Single ply composite
Fiber :: Transversely isotropic
Matrix :: Isotropic

Name CarbonEpoxy_Unidir
Type Single ply composite
Fiber density 68 %
Fiber diameter 0.007 mm
Algorithm Yang Mal
Min frequency 1 MHz
Max frequency 10 MHz

Name CarbonFiber
Type Simple
Density 1.67 $g.cm^{-3}$
Symmetry Transversely isotropic

Stiffness matrix (GPa) - elastic properties

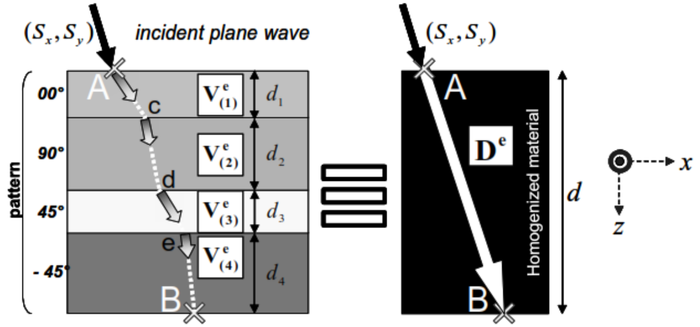
234.74	6.36	6.36	0		
6.36	19.82	9.78	0		
6.36	9.78	19.82	0		
0	0	0	5.02	0	0
0	0	0	0	24	0
0	0	0	0	0	24

Symmetry ◎ X'

Name Epoxy
Type Simple
Density 1.23 $g.cm^{-3}$
Symmetry Isotropic
Longitudinal wave velocity 2488 $m.s^{-1}$
Transverse wave velocity 1134 $m.s^{-1}$

Specimen Models for Composites in CIVA UT

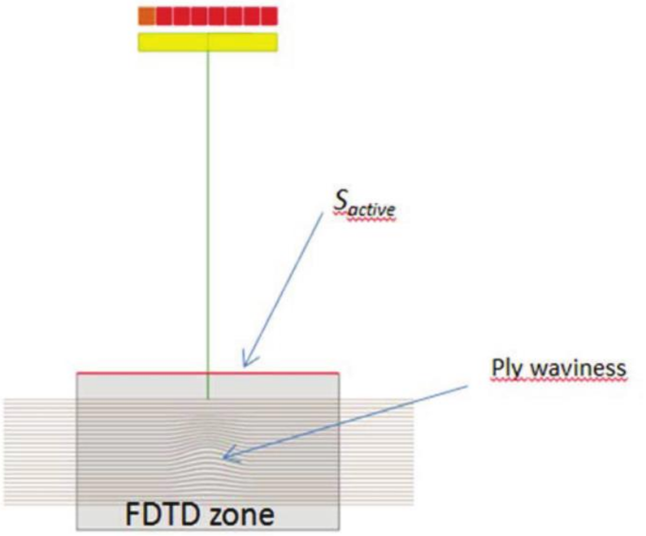
- **Homogenization used to generate orthotropic representation of elastic properties for single ply**
- **Homogenization can also be used provide equivalent material for entire composite stack-up**
  - Deydier, S., Calmon, P. and Pétillon, O., 2006, “Modeling of the Ultrasonic Propagation into Carbon-Fiber-Reinforced Epoxy Composites, Using a Ray Theory Based Homogenization Method,” ECNDT 2006. https://www.ndt.net/article/ecndt2006/doc/Mo.2.3.4.pdf



  - **Homogenization is a satisfactory approximation for normal UT inspections of flat composites**
  - ***Limitations of homogenization for full composite model:***
    - **Approximate model breaks down for oblique UT inspection**
    - **Sensitive to composite curvature and ply waviness**
    - **Neglects ply noise (requires thin intermediate epoxy layer in model)**

CIVA FIDEL 2D for Modeling Multilayer Composites with Defects

- **CIVA FIDEL 2D Uses Hybrid Numerical Model [1,2]**
  - **Finite Difference Time Domain (FDTD) formulation used to perform computation inside rectangular box surrounding specimen.**
  - **The incident wavefield on the box upper boundary (red line) is computed using fast CIVA semi-analytical incident beam model**
  - **Reciprocity principle used to evaluate pressure received by probe**
  - **Limited to pulse-echo immersion composite inspection**

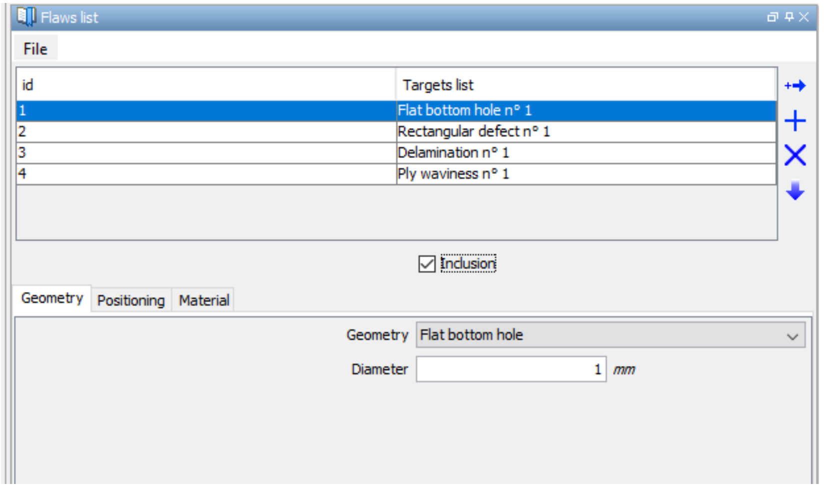


[1] Dominguez, N. and Reverdy, F., "Simulation of Ultrasonic Testing of Composite Structures," 11th European Conference on Non-Destructive Testing / ECNDT 2014, (Prague, Czech Republic, (October 6-10, 2014), http://www.ndt.net/events/ECNDT2014/app/content/Paper/344_Dominguez.pdf.

[2] Jezzine, K., Imperiale, A., Demaldent, E., Le Bourdais, F., Calmon, P., and Dominguez, N. "Modeling approaches for the simulation of ultrasonic inspections of anisotropic composite structures in the CIVA software platform." In *AIP Conference Proceedings*, vol. 1949, no. 1, p. 130003. AIP Publishing LLC, (2018). https://aip.scitation.org/doi/pdf/10.1063/1.5031598

CIVA FIDEL 2D for Modeling Multilayer Composites with Defects

- **CIVA FIDEL 2D Integrated into CIVA UT Interface**
- **Four Flaw (2D) Options:**
  - **Flat Bottom Hole**
  - **Rectangular**
  - **Rectangular**
  - **Delamination**
  - **Ply Waviness**

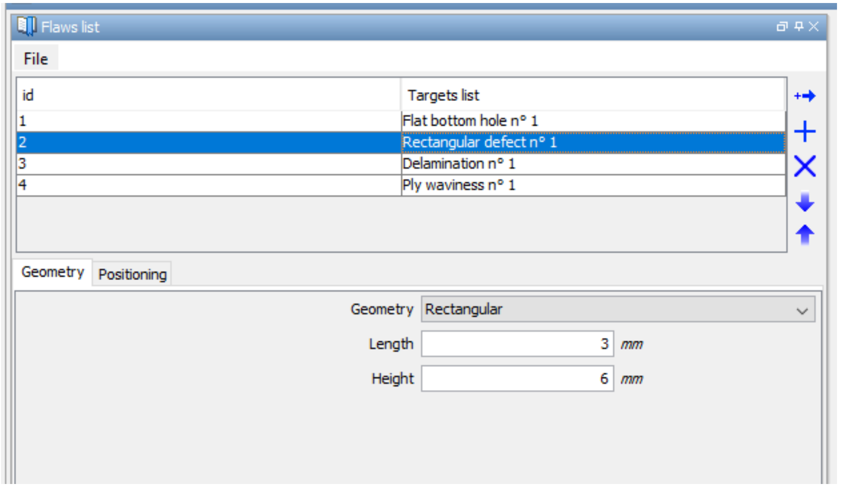


id	Targets list
1	Flat bottom hole n° 1
2	Rectangular defect n° 1
3	Delamination n° 1
4	Ply waviness n° 1

☑ Inclusion

Geometry: Flat bottom hole

Diameter: 1 mm

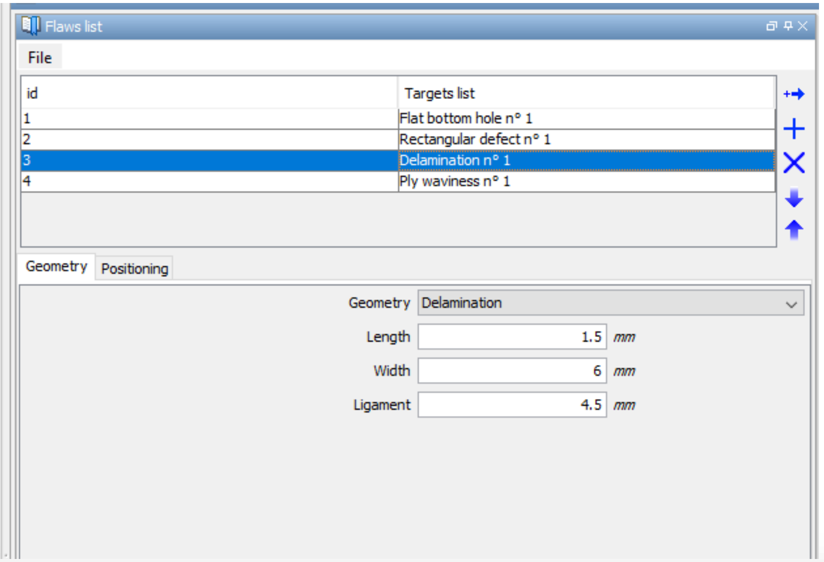


id	Targets list
1	Flat bottom hole n° 1
2	Rectangular defect n° 1
3	Delamination n° 1
4	Ply waviness n° 1

Geometry: Rectangular

Length: 3 mm

Height: 6 mm



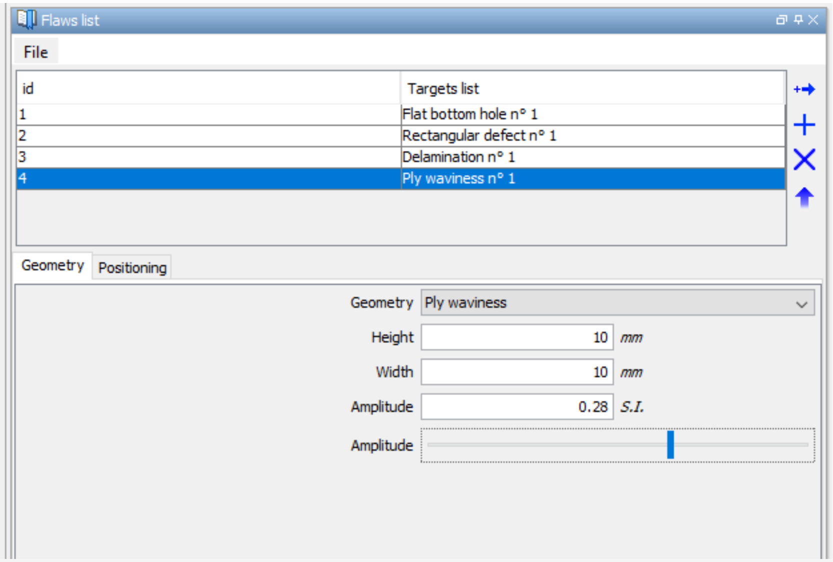
id	Targets list
1	Flat bottom hole n° 1
2	Rectangular defect n° 1
3	Delamination n° 1
4	Ply waviness n° 1

Geometry: Delamination

Length: 1.5 mm

Width: 6 mm

Ligament: 4.5 mm



id	Targets list
1	Flat bottom hole n° 1
2	Rectangular defect n° 1
3	Delamination n° 1
4	Ply waviness n° 1

Geometry: Ply waviness

Height: 10 mm

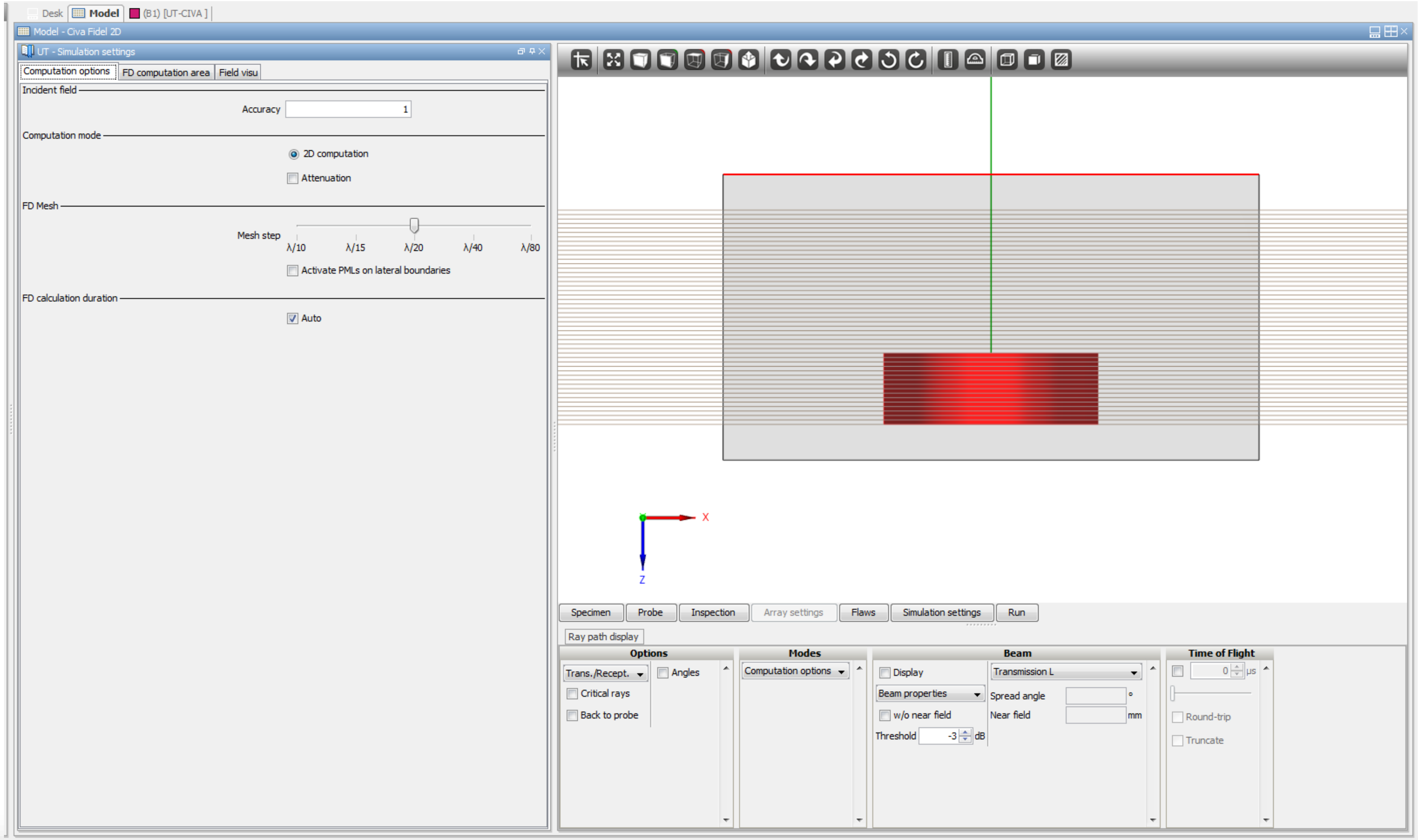
Width: 10 mm

Amplitude: 0.28 S.I.

Amplitude

CIVA FIDEL 2D for Modeling Multilayer Composites with Defects

- **CIVA FIDEL 2D Integrated into CIVA UT Interface**
- **Simulation Settings:**
  - **Define dimensions of computation zone**
  - **Option to use PML for eliminating side reflections**



Incident field

Accuracy: 1

Computation mode

● 2D computation

☐ Attenuation

FD Mesh

Mesh step: λ/10 λ/15 λ/20 λ/40 λ/80

☐ Activate PMLs on lateral boundaries

FD calculation duration

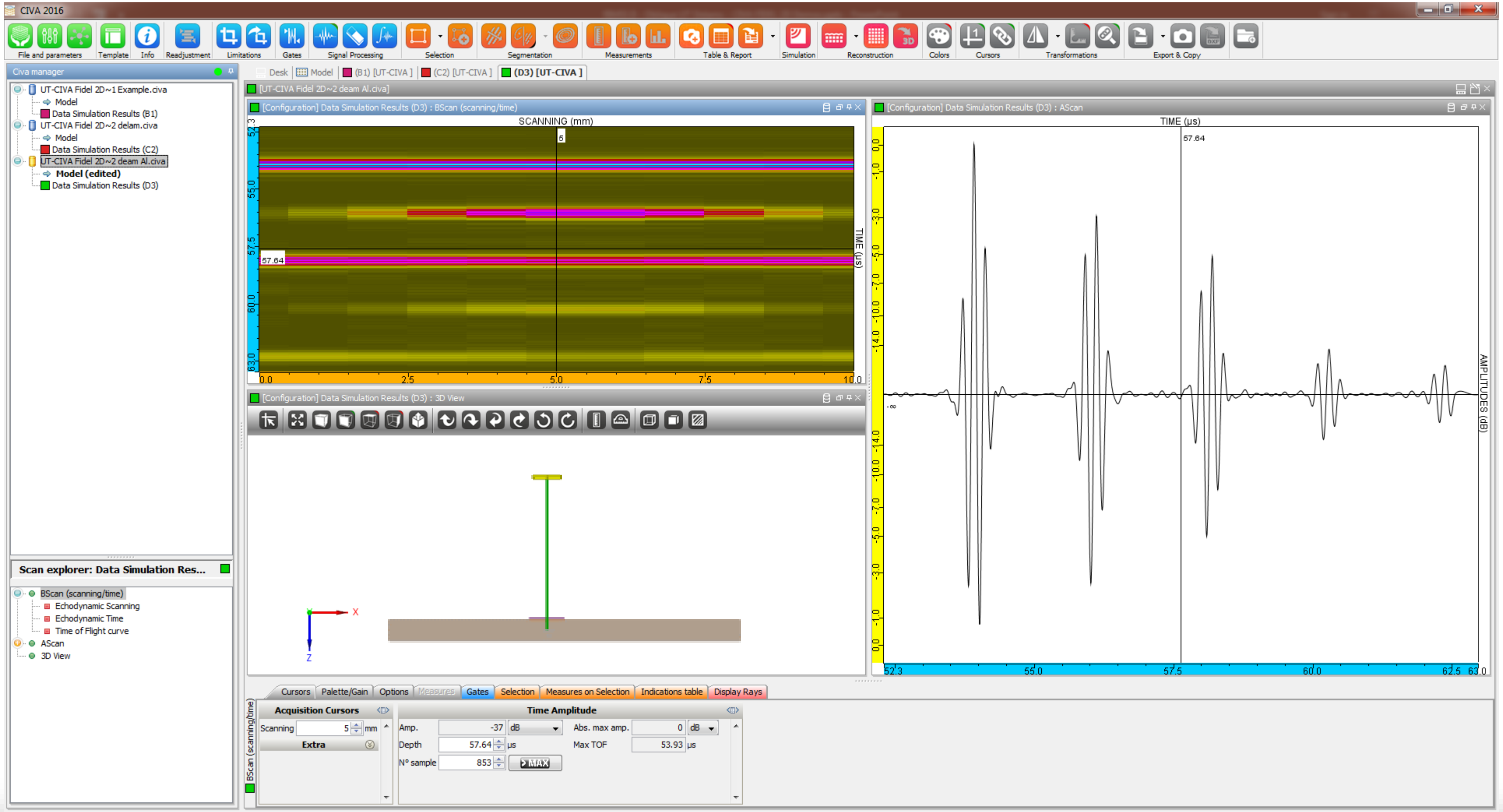
☑ Auto

Threshold: -3 dB

Time of Flight: 0 µs

CIVA FIDEL 2D for Modeling Multilayer Composites with Defects

- **CIVA FIDEL 2D Integrated into CIVA UT Interface**
- **Simulation Time:**
- **6 mm / 48 layer composite @ 5 MHz:**
  - **A-scan Time: 4 min. 12 sec.**
  - **B-scan Time: 2 hrs. 39 min (11 steps)**



Acquisition Cursors

Scanning 5 mm

Time Amplitude

Amp. -37 dB

Depth 57.64 µs

N° sample 853

Abs. max amp. 0 dB

Max TOF 53.93 µs

EXTENDE CIVA
NON ▪ DESTRUCTIVE ▪ EVALUATION

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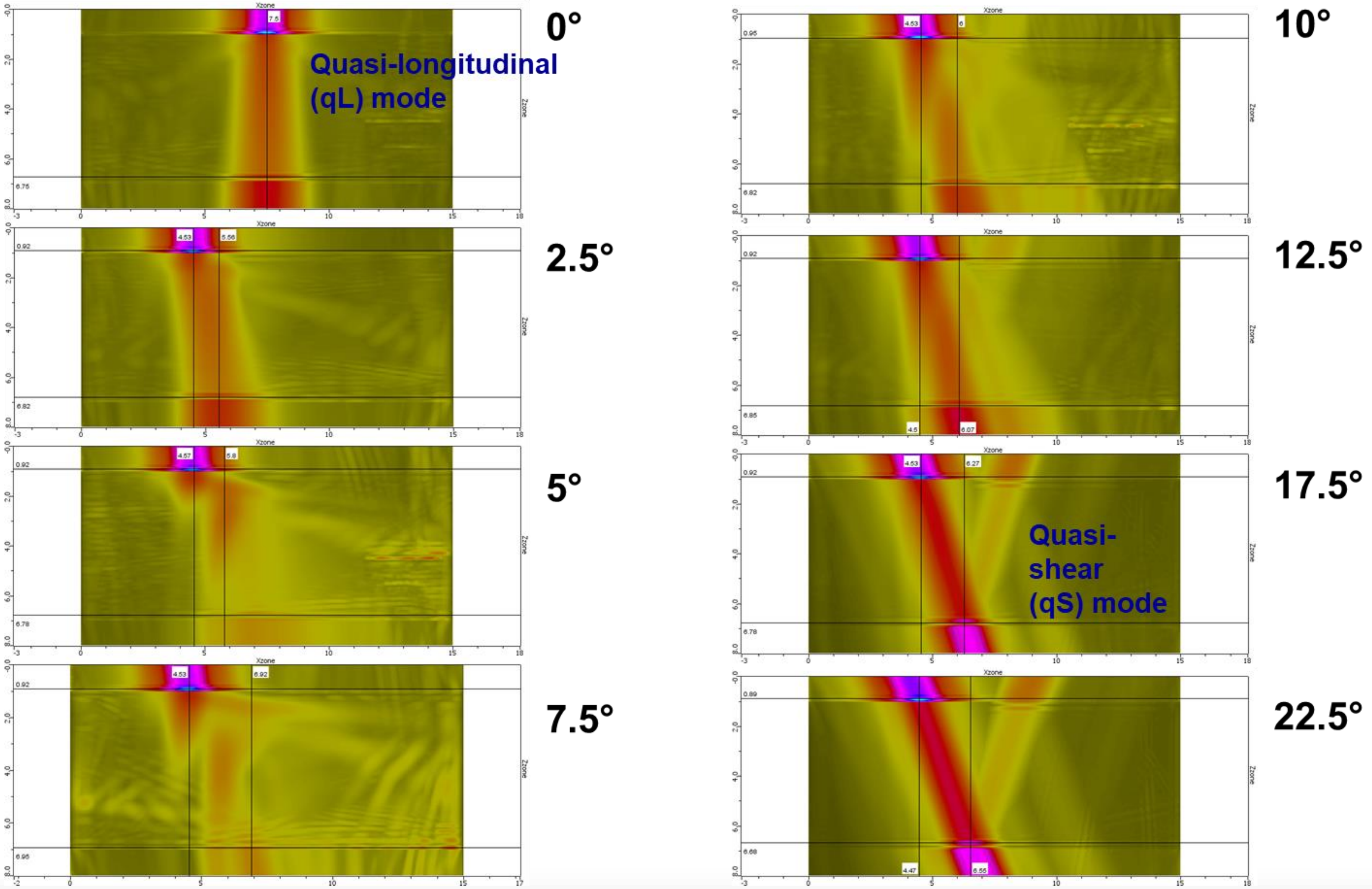
Inspection, Testing & Asset-Integrity Solutions

Study of Oblique UT for Hidden Impact Damage Characterization

- **1) Study Transition from Normal to Oblique Inspection**
- **CIVA FIDEL Provides Helpful Visualization of Wavefield Response (Max)**

Note: At small oblique angles, quasi-longitudinal (qL) mode dies, replaced by quasi-shear (qS) modes

5 MHz, 6.3 mm dia.

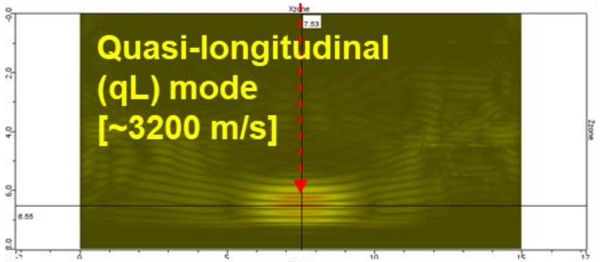


Study of Oblique UT for Hidden Impact Damage Characterization

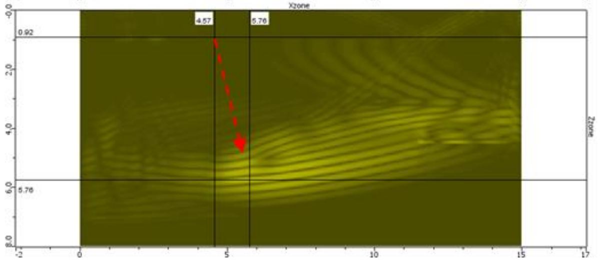
- **1) Study Transition from Normal to Oblique Inspection**
- **CIVA FIDEL Provides Helpful Visualization of Wavefield Response (in Time)**

Note: These oblique quasi-shear (qS) modes are strong, with wavespeeds slightly less than qL modes

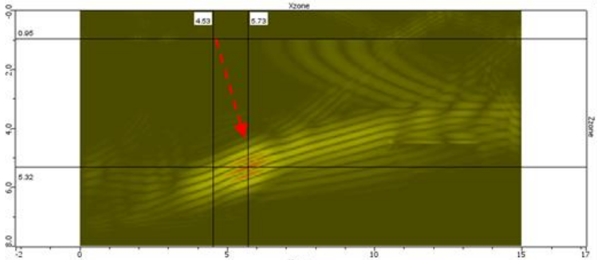
5 MHz,
6.3 mm dia.



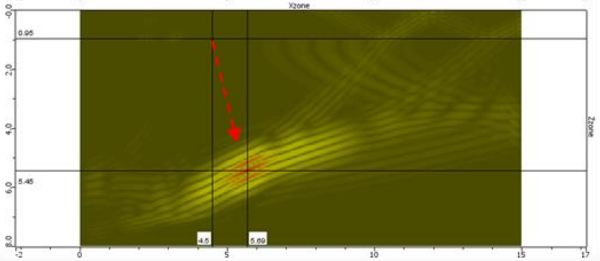
0°
Vpp=
171.1



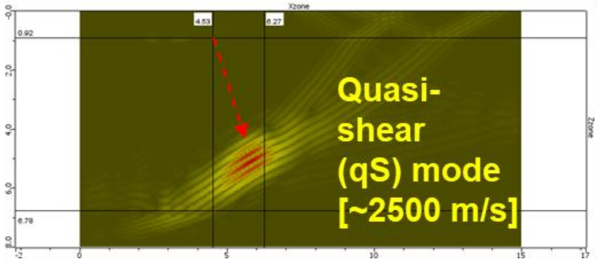
5°
Vpp=
27.63



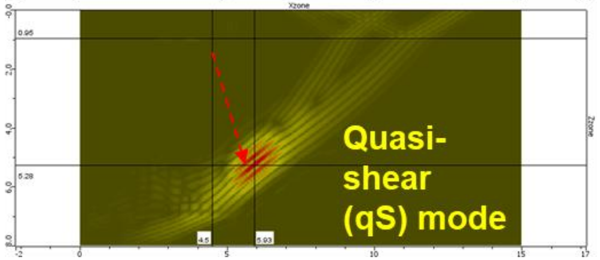
10°
Vpp=
172.2



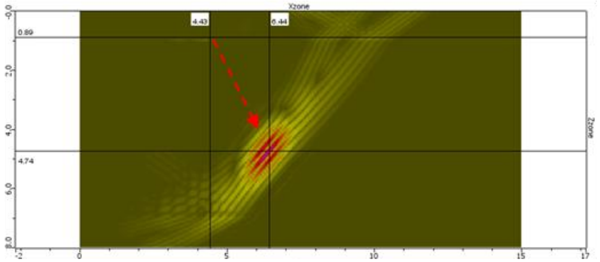
12.5°
Vpp=
190.1



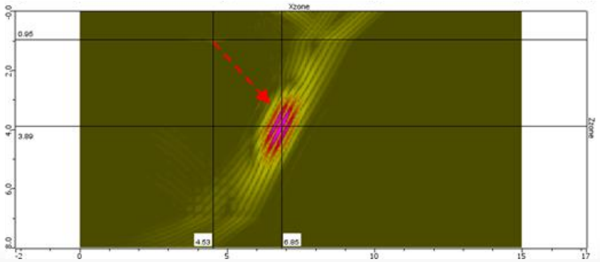
17.5°
Vpp=
233.4



22.5°
Vpp=
236.2



30°
Vpp=
258.1



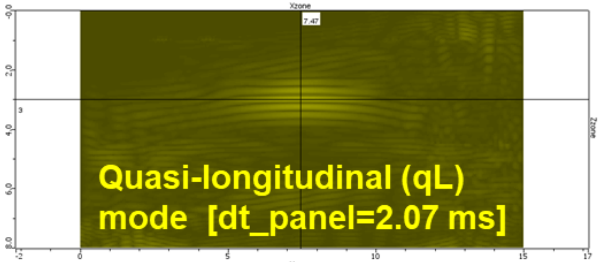
40°
Vpp=
285.6

Study of Oblique UT for Hidden Impact Damage Characterization

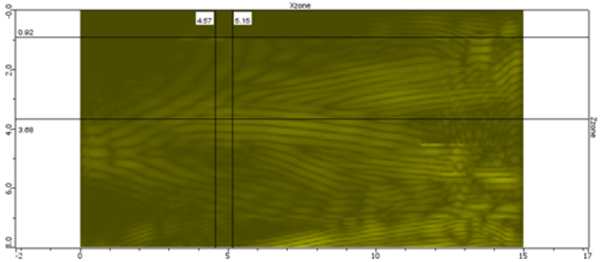
- 1) Study Transition from Normal to Oblique Inspection
- CIVA FIDEL Provides Helpful Visualization of Wavefield Response (in Time)

Note: Reflected qS modes 'off backwall' are significant, but lose energy at steeper angles into water

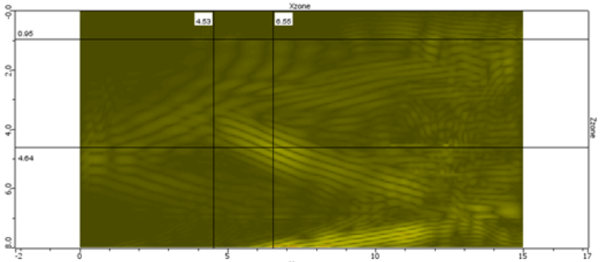
5 MHz,
6.3 mm dia.



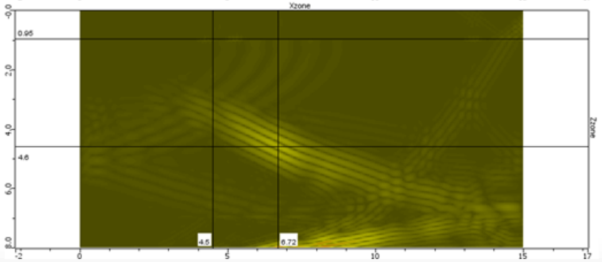
0°
Vpp=
73.0



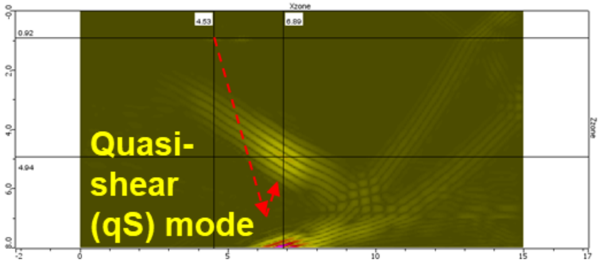
5°
Vpp=
27.63



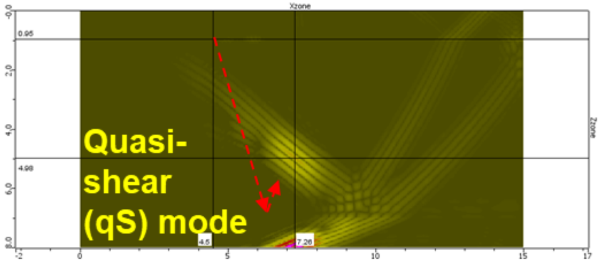
10°
Vpp=
67.3



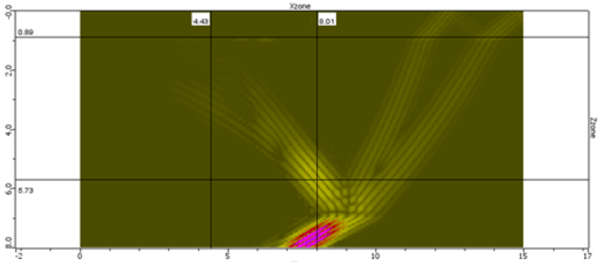
12.5°
Vpp=
85.2



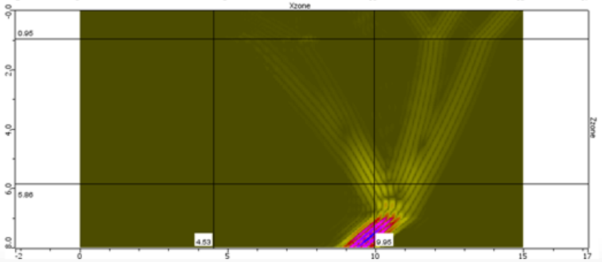
17.5°
Vpp=
110.8



22.5°
Vpp=
106.5



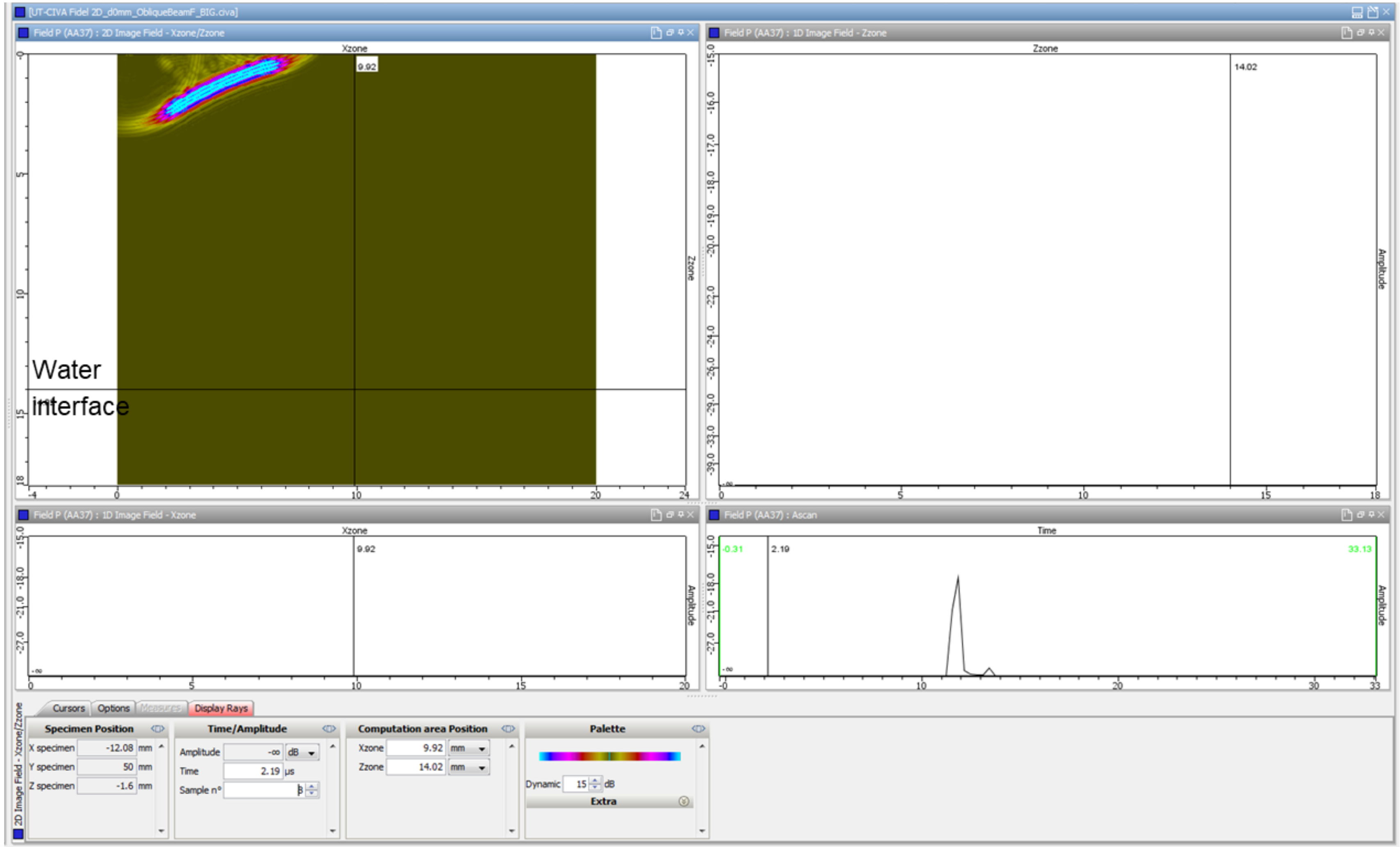
30°
Vpp=
94.3



40°
Vpp=
59.4
(@ 21.09 us)

Study of Oblique UT for Hidden Impact Damage Characterization

- **2) Model Explains Source of *Surface Noise* Signals with Oblique Inspection**
- **Simulation: 5 MHz, θ_{inc} = 24°, 0.25" dia, focal pt. 19 mm, wp = 17 mm**



Specimen Position
X specimen -12.08 mm
Y specimen 50 mm
Z specimen -1.6 mm

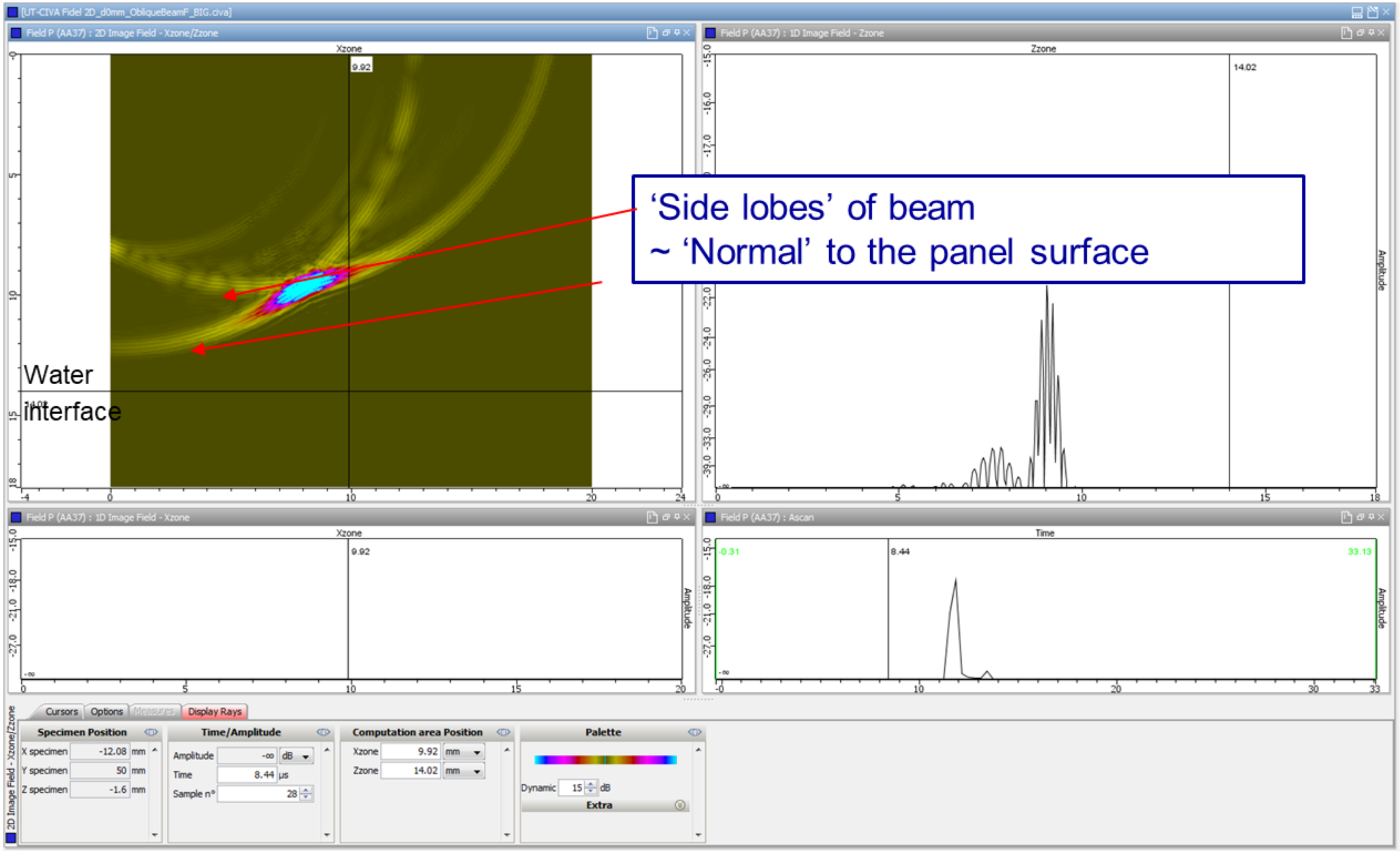
Time/Amplitude
Amplitude -∞ dB
Time 2.19 µs
Sample n° 3

Computation area Position
Xzone 9.92 mm
Zzone 14.02 mm

Dynamic 15 dB

Study of Oblique UT for Hidden Impact Damage Characterization

- **2) Model Explains Source of *Surface Noise* Signals with Oblique Inspection**
- **Simulation: 5 MHz, θ_{inc} = 24°, 0.25" dia, focal pt. 19 mm, wp = 17 mm**



‘Side lobes’ of beam
~ ‘Normal’ to the panel surface

Water interface

Specimen Position
X specimen -12.08 mm
Y specimen 50 mm
Z specimen -1.6 mm

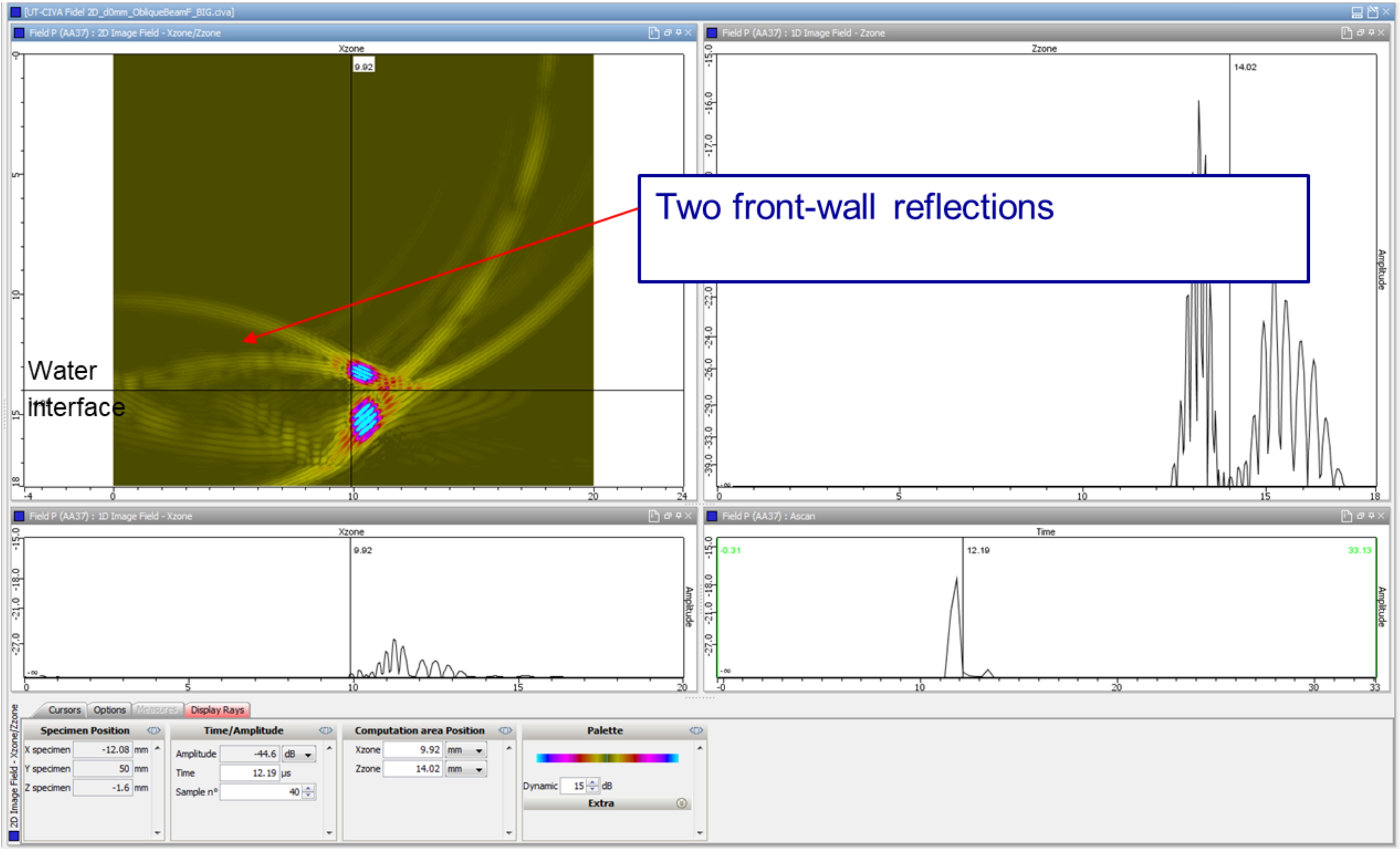
Time/Amplitude
Amplitude -∞ dB
Time 8.44 µs
Sample n° 28

Computation area Position
Xzone 9.92 mm
Zzone 14.02 mm

Dynamic 15 dB

Study of Oblique UT for Hidden Impact Damage Characterization

- **2) Model Explains Source of *Surface Noise* Signals with Oblique Inspection**
- **Simulation: 5 MHz, θ_{inc} = 24°, 0.25" dia, focal pt. 19 mm, wp = 17 mm**



Two front-wall reflections

Water interface

[UT-CIVA Fidel 2D_d0mm_ObliqueBeamF_BIG.civa]

Field P (AA37) : 2D Image Field - Xzone/Zzone

Field P (AA37) : 1D Image Field - Zzone

Field P (AA37) : 1D Image Field - Xzone

Field P (AA37) : Ascan

Specimen Position

X specimen -12.08 mm

Y specimen 50 mm

Z specimen -1.6 mm

Time/Amplitude

Amplitude -44.6 dB

Time 12.19 µs

Sample n° 40

Computation area Position

Xzone 9.92 mm

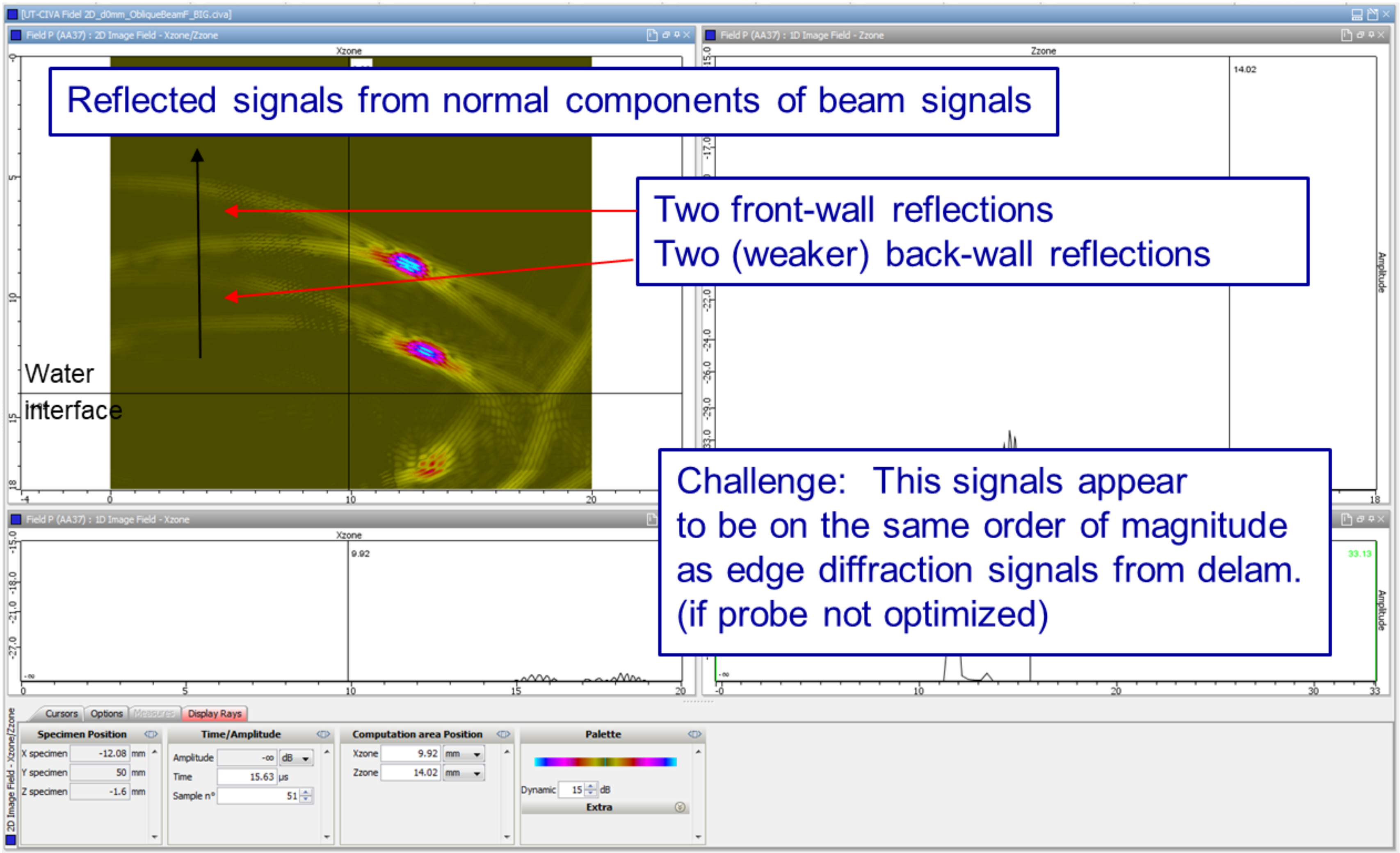
Zzone 14.02 mm

Palette

Dynamic 15 dB

Study of Oblique UT for Hidden Impact Damage Characterization

- **2) Model Explains Source of *Surface Noise* Signals with Oblique Inspection**
- **Simulation: 5 MHz, θ_{inc} = 24°, 0.25" dia, focal pt. 19 mm, wp = 17 mm**



Reflected signals from normal components of beam signals

Two front-wall reflections
Two (weaker) back-wall reflections

Challenge: This signals appear to be on the same order of magnitude as edge diffraction signals from delam. (if probe not optimized)

Specimen Position
X specimen -12.08 mm
Y specimen 50 mm
Z specimen -1.6 mm

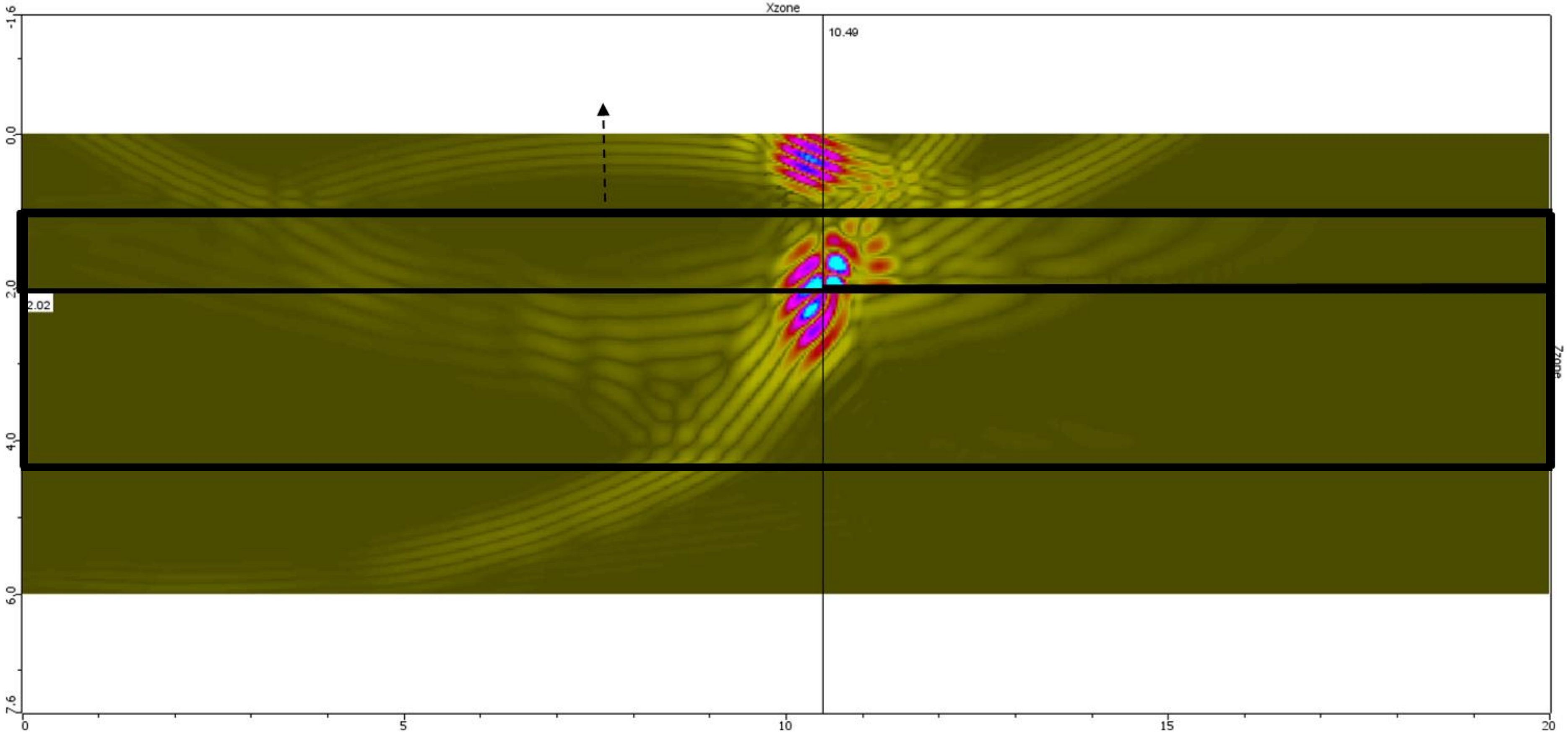
Time/Amplitude
Amplitude -∞ dB
Time 15.63 µs
Sample n° 51

Computation area Position
Xzone 9.92 mm
Zzone 14.02 mm

Palette
Dynamic 15 dB
Extra

Study of Oblique UT for Hidden Impact Damage Characterization

- **3) Investigate Diffraction from Delamination Edge**
- **Simulation: 5 MHz, θ_{inc} = 24°, 0.25" dia, focal pt. 19 mm, wp = 17 mm**
- **Delamination Position:**
  - **d_z = 1.0 mm (from top)**



Study of Oblique UT for Hidden Impact Damage Characterization

- **3) Investigate Diffraction from Delamination Edge**
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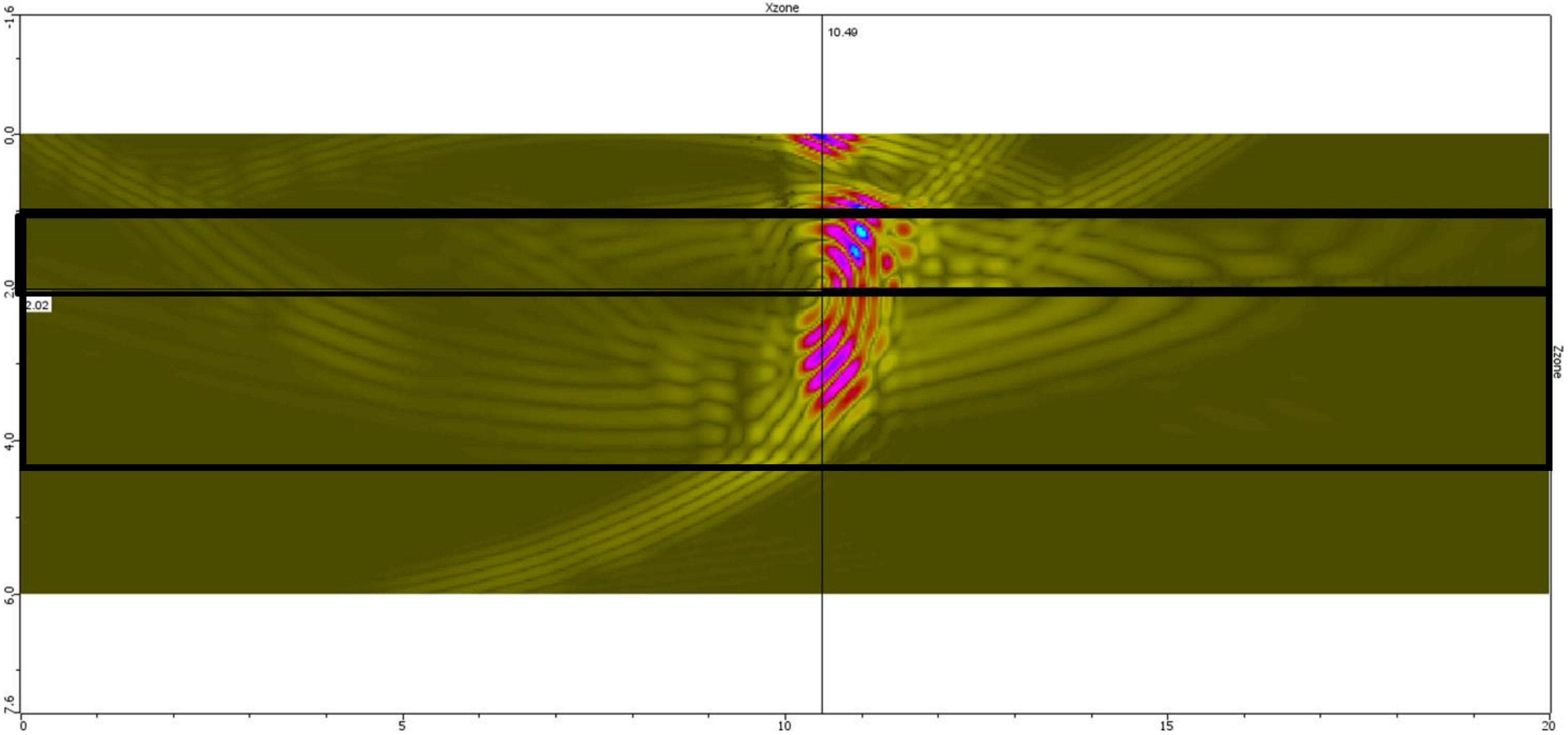

Study of Oblique UT for Hidden Impact Damage Characterization

- **3) Investigate Diffraction from Delamination Edge**
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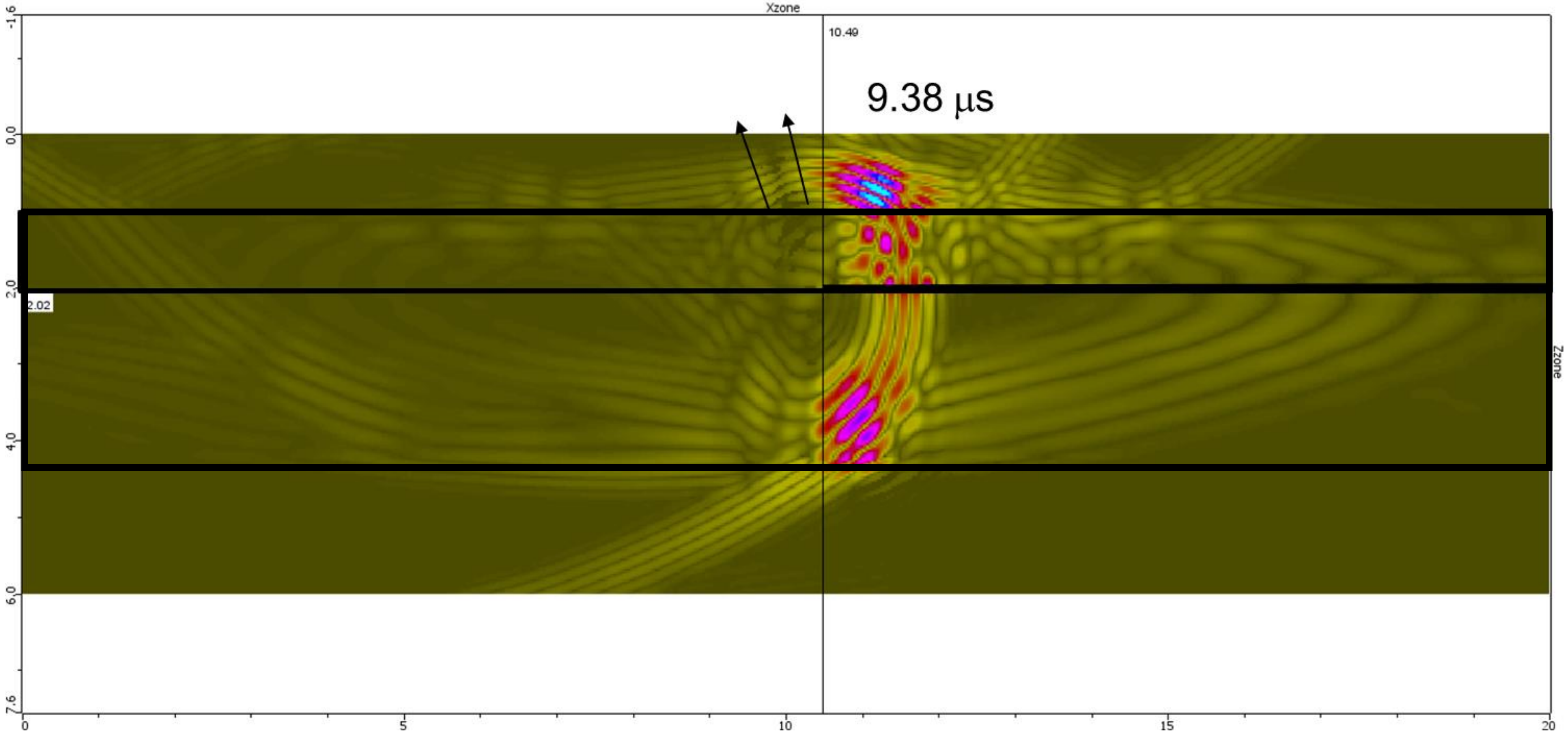

Study of Oblique UT for Hidden Impact Damage Characterization

- **3) Investigate Diffraction from Delamination Edge**
- **Simulation: 5 MHz, θ_{inc} = 24°, 0.25" dia, focal pt. 19 mm, wp = 17 mm**
- **Delamination Position:**
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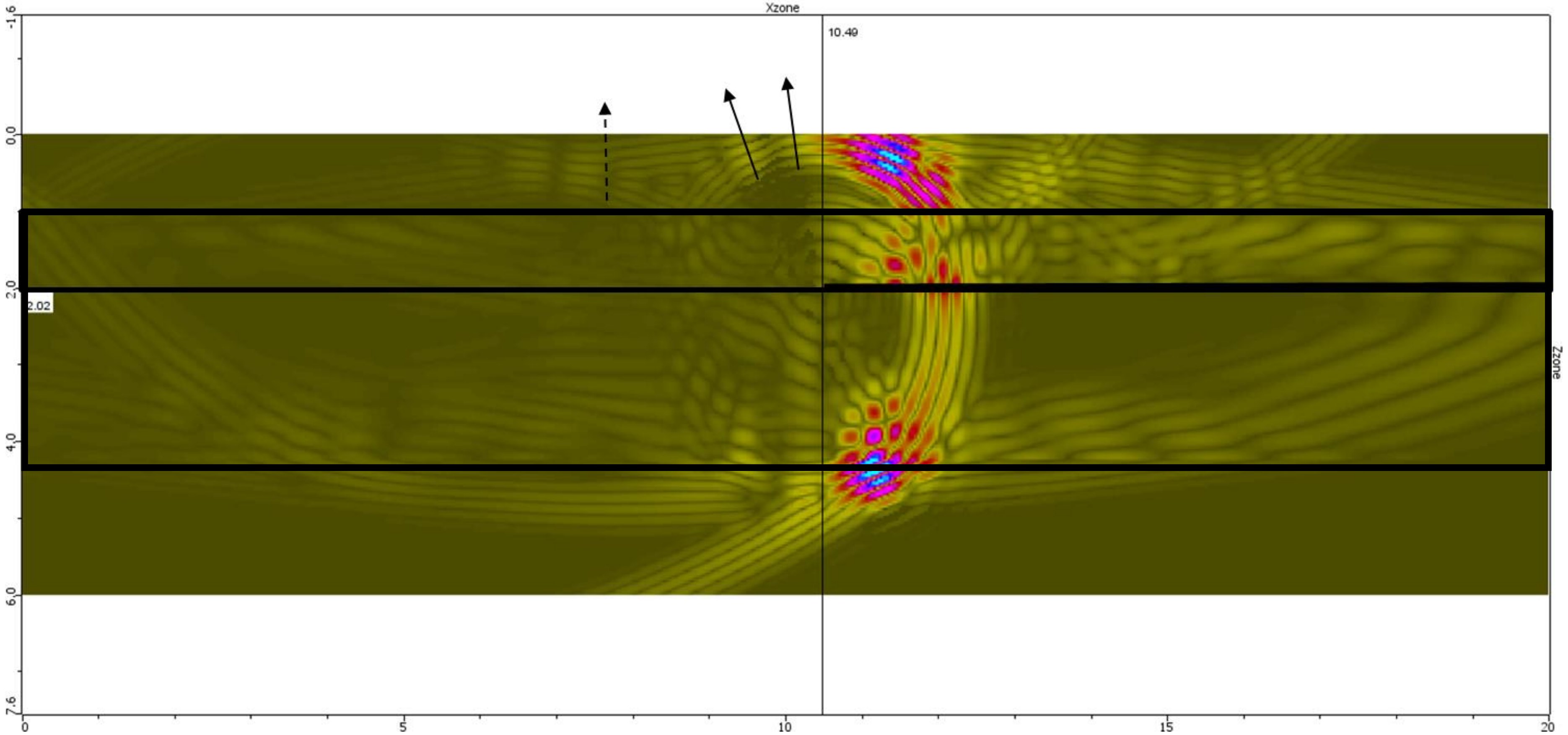
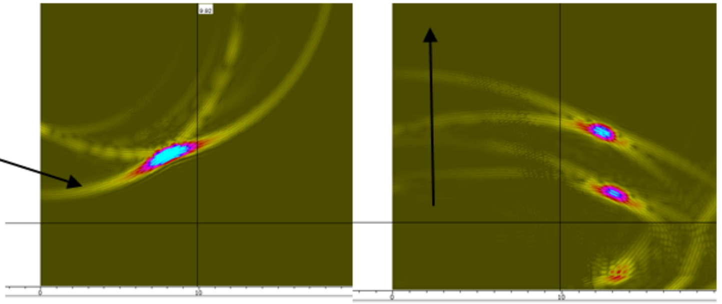


Signal Paths for Oblique UT Inspection of Delaminations in Composites

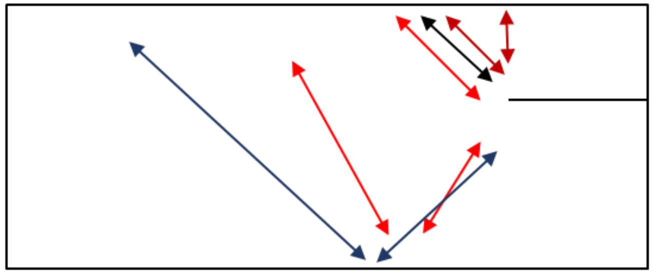
A. **Reflections from Normal Beam Components (NBC) of Angled Beam**
   1. **Top surface (usually a pair)**
   2. **Back surface (usually a pair)**



B. **Scattering from Top Surface Roughness (N_TOP)**

C. **Scattering from Internal Material Noise (N_INT) (porosity, fiber noise)**

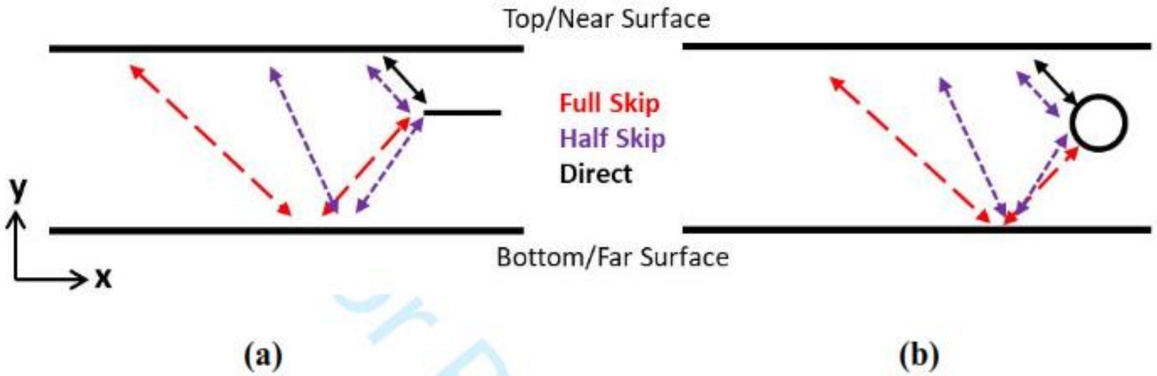
D. **Delamination Edge Response – Multiple Paths:**



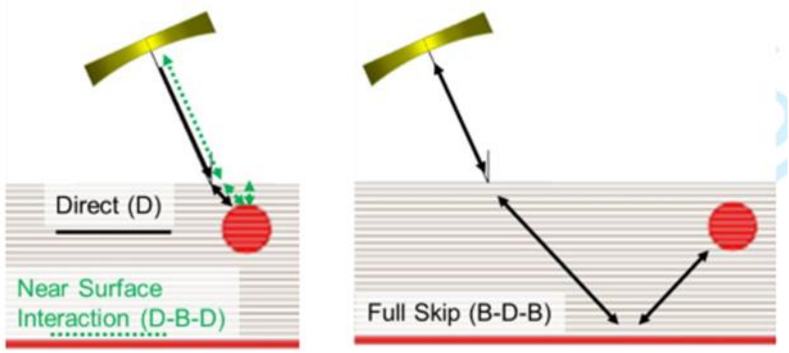
   1. **Direct Reflection (d)**
   2. **1st Diffraction → Top surface → 2nd Diffraction (d - b - d)**
   3. **1st SDH Diffraction → Backwall; Backwall → 1st SDH Diffraction [Half Skip] (d - b)**
   4. **Backwall → 1st SDH Diffraction → Backwall [Full Skip] (b - d - b)**

Observations on Pulse-Echo Oblique UT Response from Delaminations and Side Drilled Holes (SDHs)

- **Model Benchmark Study with Experimental Verification for Delaminations and SDHs [1]**
  - **Simulation: 2.25 MHz, $\theta_{inc} = 18°$,**
    6.3 mm dia, focal pt. 11.4 mm, wp = 7 mm
  - **Good agreement (model to exp.) for SDH full skip to direct reflection response**
  - **Direct reflection from 'ideal' delamination 39% of SDH direct signal**
  - ***Not confidently seeing delamination edge diffraction in exp.***



	SDH Amplitude		Delamination Amplitude	
	Model	Experiment	Model	Experiment
Direct/Direct SDH	1.00	1.00	0.39	-
Full Skip/Direct SDH	0.38	0.37	0.10	-

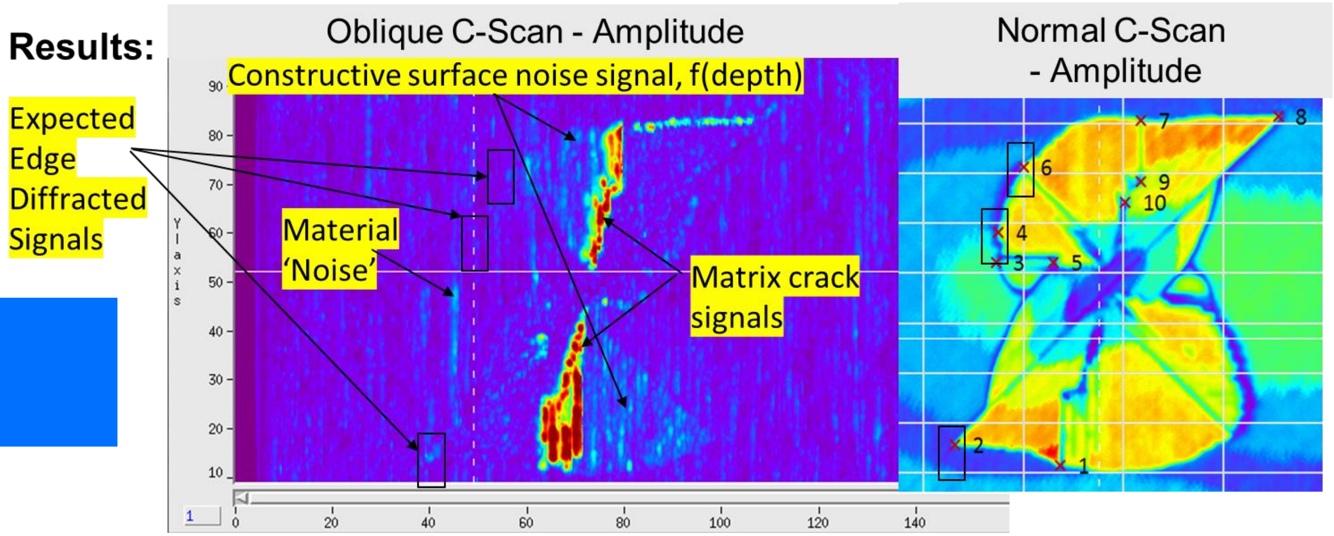


[1] Welter, J. T., Aldrin, J. C., Wertz, J. N., Kramb, V. and Zainey, D., 2020, "Model Benchmarking Studies of Angle Beam Pulse Echo Ultrasonic Inspection of Composites," *Materials Evaluation*, 78(1).

Observations on Pulse-Echo Oblique UT Response from Delaminations and Side Drilled Holes (SDHs)

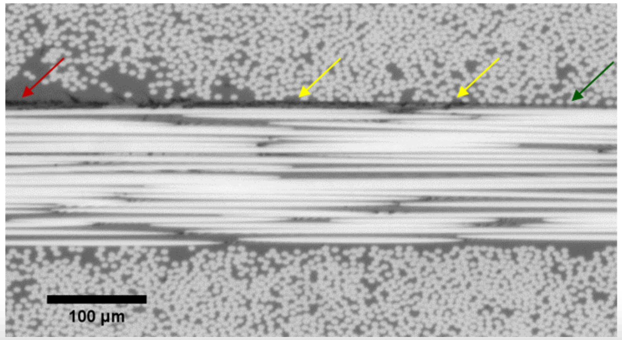
- **Model Benchmark Study with Experimental Verification for Delaminations and SDHs** [1]
  - **Experiment performed using delamination edges present in impact damage specimen**

Results:



- Experiments fail to resolve clear 'direct' delamination edge signals with oblique UT

- Delamination edge has complex transition of scattered voids in matrix between plies
  - Edge not well defined



Contact PAUT Approach for Hidden Impact Damage Characterization

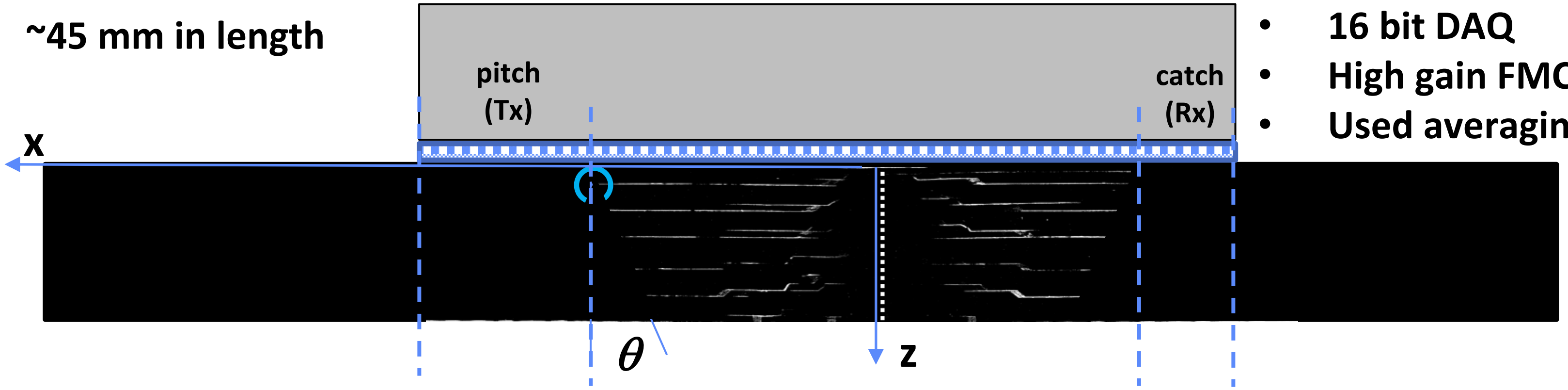
Direct contact avoids repeated reflections between array and top surface

64 (and 60) element PAUT

- 5 MHz
- ~45 mm in length

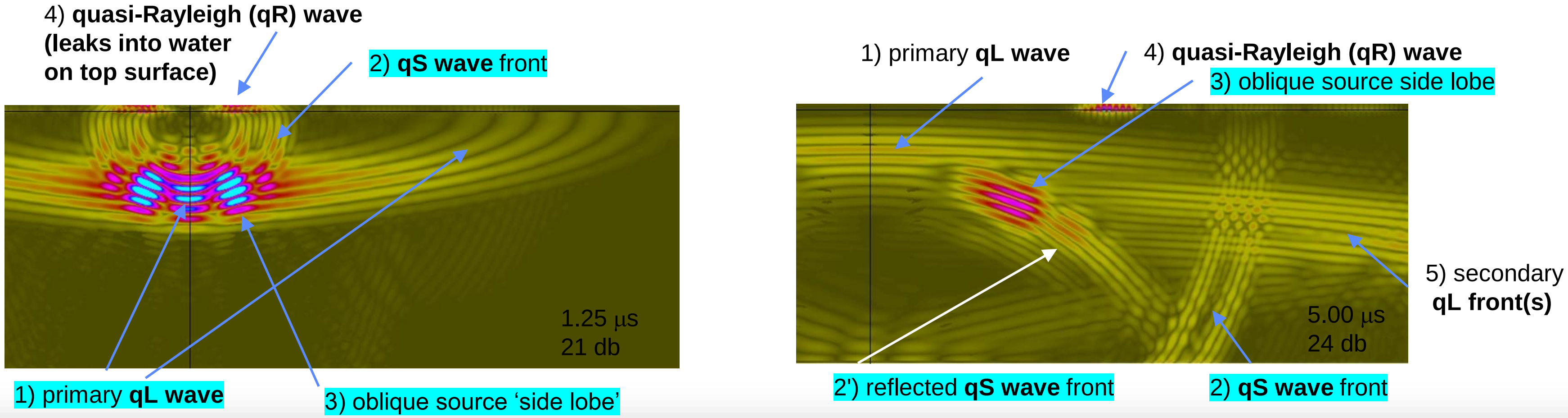
Best PAUT Test Configuration:

- Contact Array
- 16 bit DAQ
- High gain FMC DAQ
- Used averaging (4-8)



6.03 mm, 48 Ply PMC
[Quasi-isotropic layup]

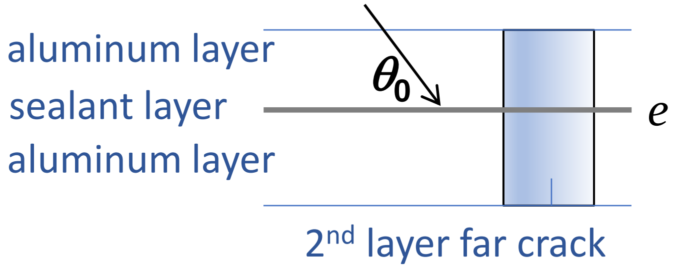
CIVA FIDEL (2D) Wavefield Simulations for Single PAUT Element Source



Oblique quasi-longitudinal (qL) and quasi-shear (qS) waves can be generated by single PAUT element

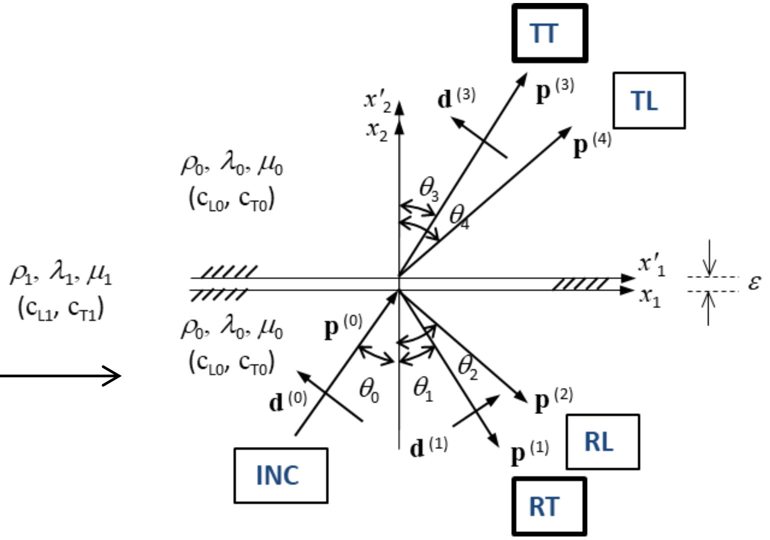
Sensitivity Study of Sealant State for Multilayer Structure Inspections

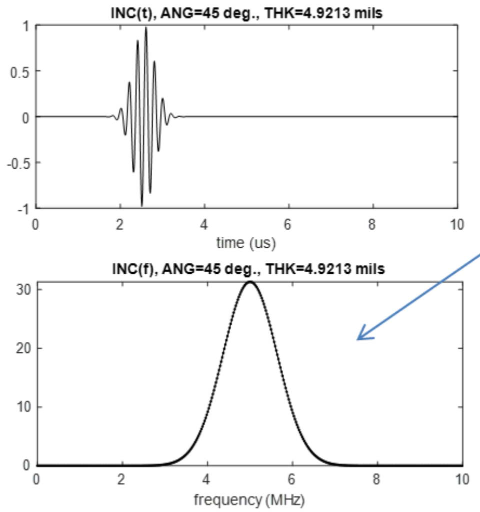
- **Difficult for ray-theory based model to accurately simulate response through sealant layer in metallic structures *(due to repeated reflections)***



- **Objective: Evaluate Sensitivity to Oblique UT Inspection and Varying Sealant Condition [1]:**
  - **Incidence Angle, θ_0**
  - **Sealant Layer Thickness, e**

- **Model Approaches:**
  - **Analytical model [2]** →
  - **CIVA FIDEL**





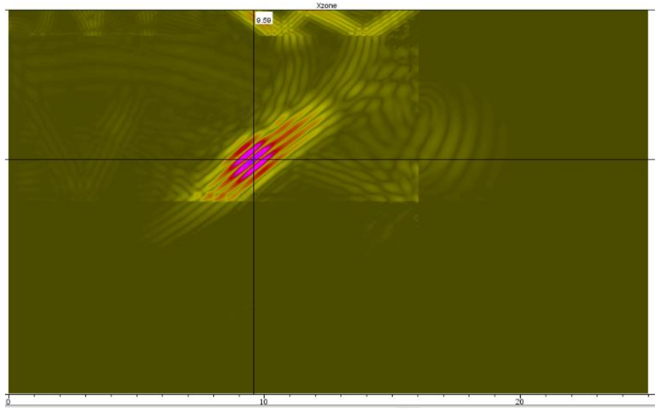
1. *Solve INC(f)*RT(f) [in freq. domain]*
2. *Apply IFFT to evaluate RT(t)*

[1] Aldrin, J. C., Forsyth D. S., and Lindgren, E. A. "Case study of model-assisted probability of detection (MAPOD) evaluation for manual ultrasonic inspection of fastener sites for fatigue cracks." *Review of Progress in Quantitative Nondestructive Evaluation* (2019).

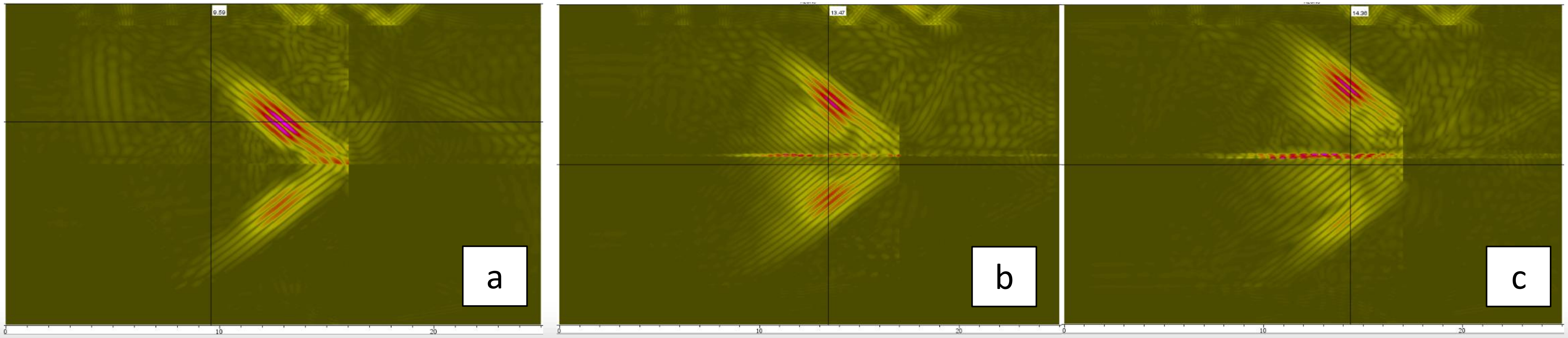
[2] Lowe, M. J. S. "Matrix techniques for modeling ultrasonic waves in multilayered media." *IEEE UFFC,* 42, no. 4 (1995): 525-542.

Sensitivity Study of Sealant State for Multilayer Structure Inspections

- **Objective: Evaluate Sensitivity to Varying Sealant Layer Thickness,** e:
- **Results: 5 MHz, 45 deg shear wave in aluminum, incident at sealant layer**
  a. 0.05 mm layer of sealant: Reflected -2.1 dB (0.79), Transmitted -6.5 dB (0.47)
  b. 0.125 mm layer of sealant: Reflected -3.8 dB (0.65), Transmitted -6.5 dB (0.47)
  c. 0.25 mm layer of sealant: Reflected -4.1 dB (0.62), Transmitted -9.5 dB (0.33)
- **Observations:**
  - **Thinnest sealant layers produce largest reflected and transmitted signals**
  - **With increasing thickness, sealant produces repeated reflections with varying interference and delay**



Aldrin, J. C., Forsyth D. S., and Lindgren, E. A. "Case study of model-assisted probability of detection (MAPOD) evaluation for manual ultrasonic inspection of fastener sites for fatigue cracks." *Review of Progress in Quantitative Nondestructive Evaluation* (2019).



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- Welter, J. T., Aldrin, J. C., Wertz, J. N., Kramb, V., Zainey, D., Schehl, N., Uchic, M. D. and Wallentine, S. M., "Oblique angle pulse echo ultrasound for delamination characterization." *45th Annual Review of Progress in QNDE*, AIP, 2102, p. 100001. AIP Publishing LLC, (2019). https://aip.scitation.org/doi/pdf/10.1063/1.5099829
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- John Welter, AFRL [Dissertation, University of Dayton, 2019]
- John Wertz, Sarah Wallentine, Eric Lindgren, Michael Uchic, AFRL
- David Zainey, Norman Schehl, Victoria Kramb, Tyler Lesthaeghe, UDRI
- EXTENDE

About Computational Tools

- **Dr. John C. Aldrin – Consultant / Principal of Computational Tools since 2001**
  - **PhD (1998-2001) at Northwestern University with Major Professor Jan Achenbach**

Computational Tools

- **Focus on Applications of Computational Methods in NDE R&D**
  - ***Specialize in NDE modeling and simulation, data analysis, inverse methods, and reliability (POD) assessment***
  - **Work Primarily as Visiting Scientist at Air Force Research Laboratory, Material State Awareness Branch, Materials and Manufacturing Directorate (AFRL/RXCA) – WPAFB, Ohio, USA, since 2001**
  - **Participate as member of NASA Engineering and Safety Center (NESC) TDT on NDE, since 2004**

- **Work Between *Research and Application* Community on NDE Technology Transition:**
  - **USAF/AFRL, SAIC, NASA, UTC (ARCTOS), UDRI, UES, ISU, TRI/Austin, Victor Technologies, KBR, Southern Research, Vibrant, Mistras, Orbital Transports, and BP**