Simulation of Ultrasonic Inspection of Composites Using CIVA FIDEL

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Computational Tools
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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

Normal UT

(1)

(2)

(3)

(4)

(5)

(6)
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

Challenge Problem: Characterize Hidden Delamination Profile

Characterization of Hidden Regions of Impact Damage in Composites

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

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

Challenge Problem: Characterize Hidden Delamination Profile

- Cone – Most prevalent – 32/49
- Diamond – 12/49
- Inverted Diamond/Other – 5/49

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

2. Johnston et al. [QNDE, 2013]:
   - Normal front and polar backscatter at oblique angles
   - For glass epoxy composite

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
Specimen Models for Composites in CIVA UT

- Homogenization used to generate orthotropic representation of elastic properties for single ply
Specimen Models for Composites in CIVA UT

- Homogenization used to generate orthotropic representation of elastic properties for single ply
- Homogenization can also be used to provide equivalent material for entire composite stack-up


- 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


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
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
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:
    - B-scan Time: 2 hrs. 39 min (11 steps)
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.
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.
Study of Oblique UT for Hidden Impact Damage Characterization

- 2) Model Explains Source of Surface Noise Signals with Oblique Inspection

- Simulation: 5 MHz, $\theta_{inc} = 24^\circ$, 0.25" dia, focal pt. 19 mm, wp = 17 mm
Study of Oblique UT for Hidden Impact Damage Characterization

- 2) Model Explains Source of *Surface Noise* Signals with Oblique Inspection

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Study of Oblique UT for Hidden Impact Damage Characterization

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• Simulation: 5 MHz, $\theta_{inc} = 24^\circ$, 0.25" dia, focal pt. 19 mm, wp = 17 mm
Study of Oblique UT for Hidden Impact Damage Characterization

• 3) Investigate Diffraction from Delamination Edge

• Simulation: 5 MHz, \( \theta_{inc} = 24^\circ \), 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

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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. 1\textsuperscript{st} Diffraction → Top surface
      → 2\textsuperscript{nd} Diffraction (d - b - d)
   3. 1\textsuperscript{st} SDH Diffraction → Backwall;
      Backwall → 1\textsuperscript{st} SDH Diffraction [Half Skip] (d - b)
   4. Backwall → 1\textsuperscript{st} 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, $\theta_{\text{inc}} = 18^\circ$, 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.

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<th>SDH Combination</th>
<th>Amplitude Model</th>
<th>Amplitude Experiment</th>
<th>Amplitude Model</th>
<th>Amplitude Experiment</th>
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<td>Direct/Direct SDH</td>
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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

- 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

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)

Direct contact avoids repeated reflections between array and top surface

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

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

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

1) primary qL wave
2) qS wave front
3) oblique source side lobe
4) quasi-Rayleigh (qR) wave (leaks into water on top surface)
5) secondary qL front(s)

1.25 µs 21 db
5.00 µs 24 db
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, $\theta_0$
  - Sealant Layer Thickness, $e$

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

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CIVA NA User Group Meeting
August 19, 2020
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

References – Oblique UT Inspection of Impact Damage in Composites


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  • 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

• 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