AM.6 Numerical modelling (ID637)

Benefits of new Finite Elements models available for Ultrasonic NDE simulations

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EXTENDE CIVA

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OUTLINE

- Modeling Strategies available for Ultrasound Testing
- Experimental validation of FEM models
  - Beam propagation
  - Defect response
  - Shadowing effect
- Conclusion

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- **Modeling Strategies available for Ultrasound Testing**
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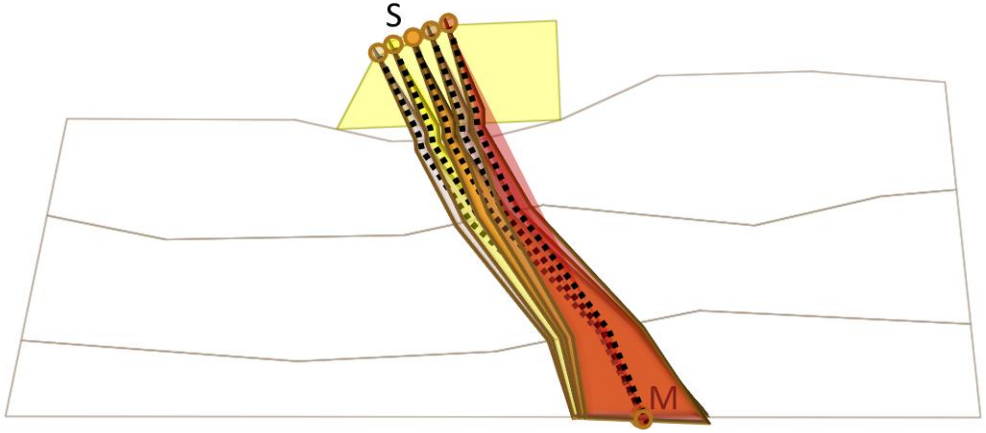
Modeling Strategies in UT

- Our scope is based on the available models within the software platform CIVA:
  - Software platform **dedicated** to NDE simulation & analysis
  - Developed by **CEA LIST** and distributed by **EXTENDE**
  - Multi-technique **simulation**:
    - UT: Ultrasounds (Simulation & Analysis)
    - RT-CT: Radiography (Gamma and X Rays) & Computed Tomography
    - ET: Eddy Current
    - GWT: Guided Waves
    - SHM-GWT: Structural Health Monitoring by Guided Waves
    - TT: Thermography
- For each technique, different modeling approaches are available, this is particularly the case for UT in CIVA 2025.

Modeling Strategies in UT

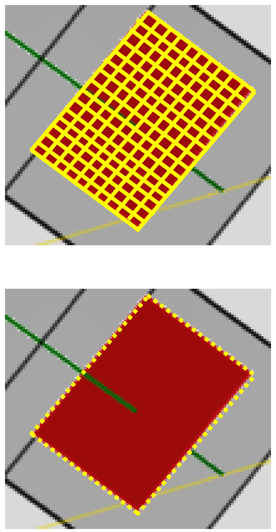
- **Three main modeling strategies:** Semi-Analytical models (***SA***)
  - UT field predicted using a semi-analytical model (*‘Pencil Method’*)
  - Beam interaction with flaws and geometry computed using dedicated interaction models:
    - Kirchhoff&GTD, Kirchhoff, SOV, Born…

Beam propagation computation



→ Discretized source points on the crystal surface and observation points on the flaw surface and edge

Flaw interactions computation



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- **Modal** approach allowing detailed analysis and understanding of each mode
- ‘**Very fast**’ simulations compared to fully numerical approaches
- A lot of industrial ‘use cases’ can be covered **efficiently and accurately**

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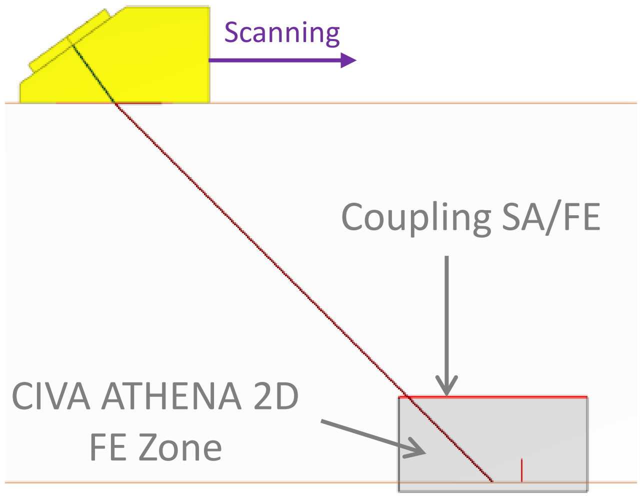
- **Limitations** in capacities (e.g., mainly bulk waves, no multiple scattering between defects, …)
- **Validity domains** (e.g., flaw height vs λ)

Modeling Strategies in UT

- **Three main modeling strategies:** Hybrid models
  - UT field predicted using a semi-analytical model (*'Pencil Method'*)
  - Beam interaction between flaws and geometry computed using local Finite Elements (FE)

CIVA ATHENA 2D*



→ FE computation of the beam propagation and interactions from the coupling SA/FE zone

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- Intermediate computation time
- More accurate for small flaws (vs λ) and specific wave phenomena, interaction between flaws

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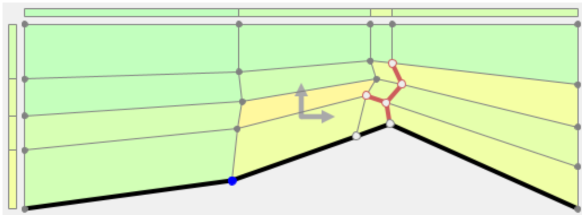
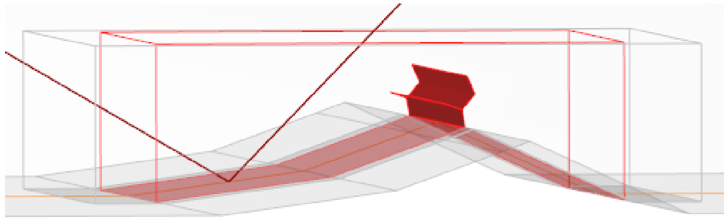
- Less adapted for 'big' scene and complex material propagation
- Potential iterations to define the FE zone
- Only 2D computation for ATHENA

FE Grid





→ SA incident beam propagation computation on the defect and backwall (in the FEGrid area) and local FEM computation for the interactions

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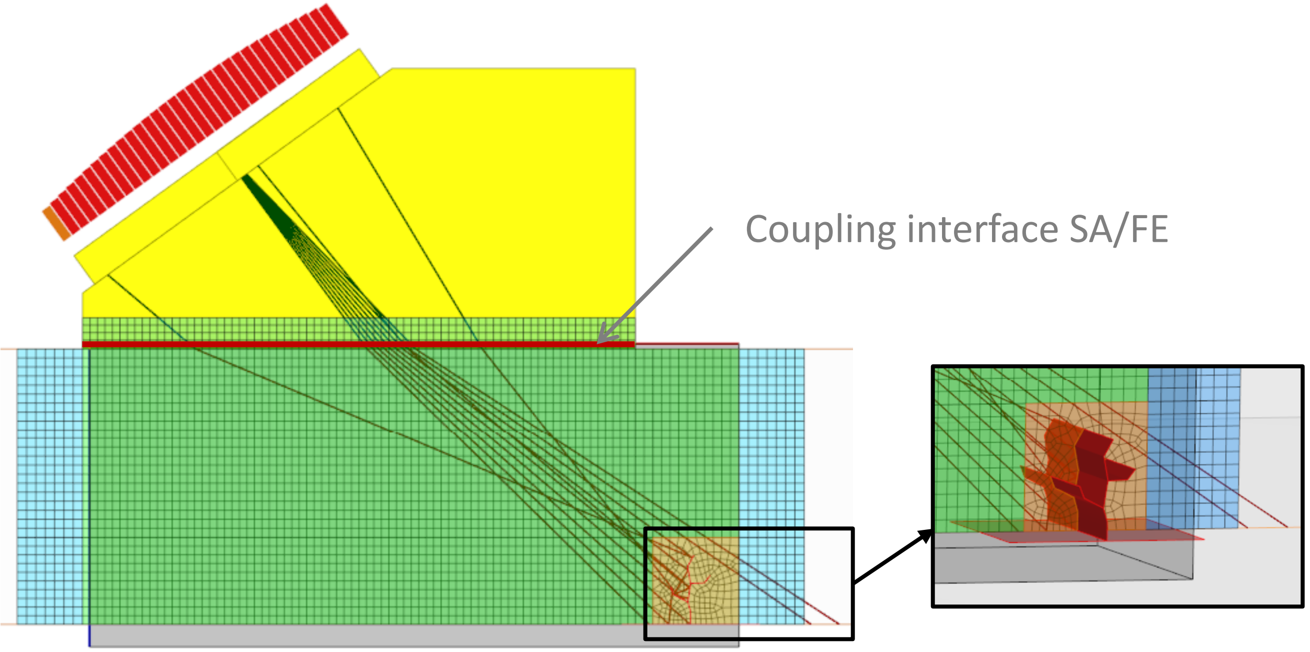
* *Electricité De France (EDF) code*

Modeling Strategies in UT

- **Three main modeling strategies:** Full component FEM (***FFEM***)
  - Beam propagation modelled by SA models at the interface of the component only
  - Inside the component, everything is computed with FE



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- FEM approach applied to the entire part, enabling the simulation of all physical wave types and their interactions with the material, geometry and defects
- Visualization of the wave propagation and interaction with discontinuities

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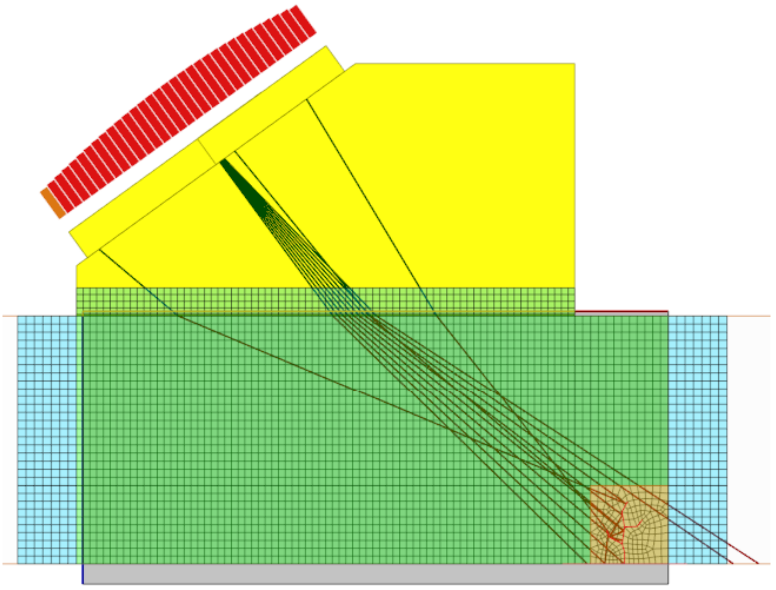
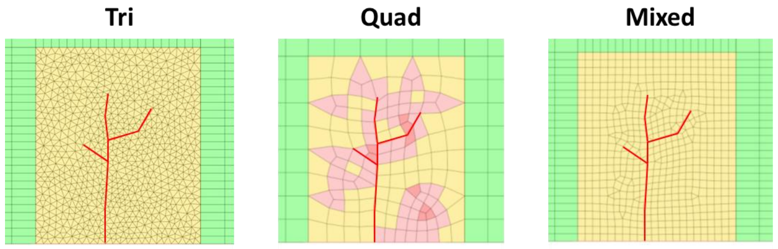
- Computation time
- Some parameters to optimize accurately to limit computation time

Modeling Strategies in UT

FFEM implementation in CIVA:

- Automatic strategy of domain decomposition:
  - Emission source region and/or absorbing zones
  - Structured mesh (quad)
  - Unstructured mesh (tri, quad, mixed)
- Element sizes automatically adapted in each domain vs λ_{min} to ensure accuracy and stability
- User-assistance tools for model setup and optimization:
  - Simulation time window
  - Region Of Interest size
  - Mesh quality:
    - Elements with good quality
    - Elements with moderately, highly and severely degraded elements





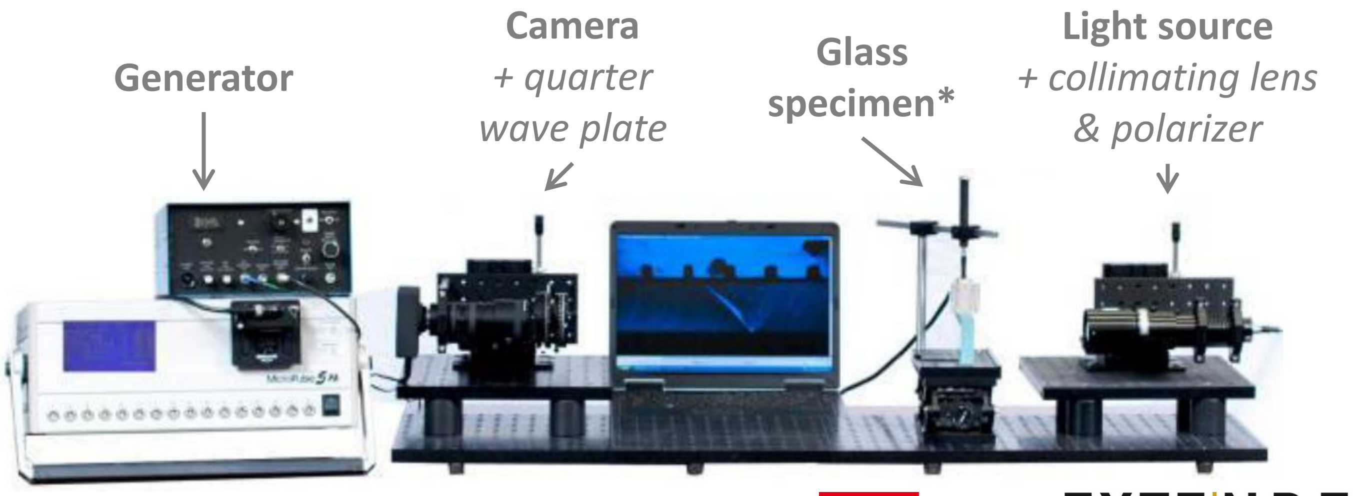
OUTLINE

- Modeling Strategies available for Ultrasound Testing
- **Experimental validation of FEM models**
  - **Beam propagation**
  - **Defect response**
  - **Shadowing effect**
- Conclusion

Experimental validation

Beam propagation: Experimental set-up description

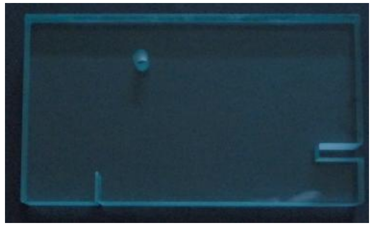
- Experimental UT beam propagation highlighted using <u>photoelastic technique</u>
  → UT waves induce local stress that alters light polarization, enabling direct visualization of wave propagation using a cross-polarized optical setup
- Some key points:
  - Image intensity $\nearrow$ when probe frequency $\nearrow$ and or excitation voltage $\nearrow$
  - Weaker L-mode contrast vs S-mode (L stress gradient lower than S)



*Glass acoustic properties
Density: 2.2 ; v_L = 5850 m/s ; v_S = 3450 m/s

- 3 parts tested:

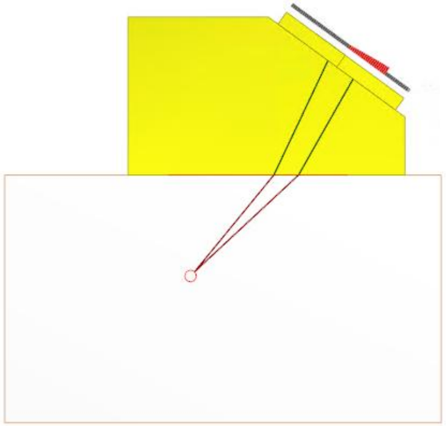
Side Drilled Hole



'T' weld

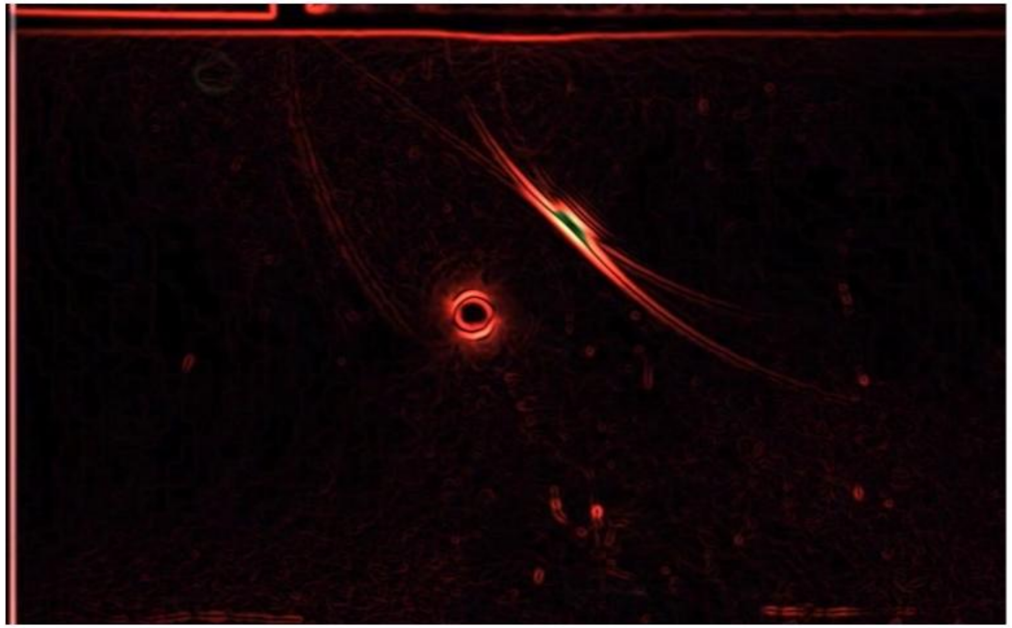
TOFD on a subsurface notch

Experimental validation

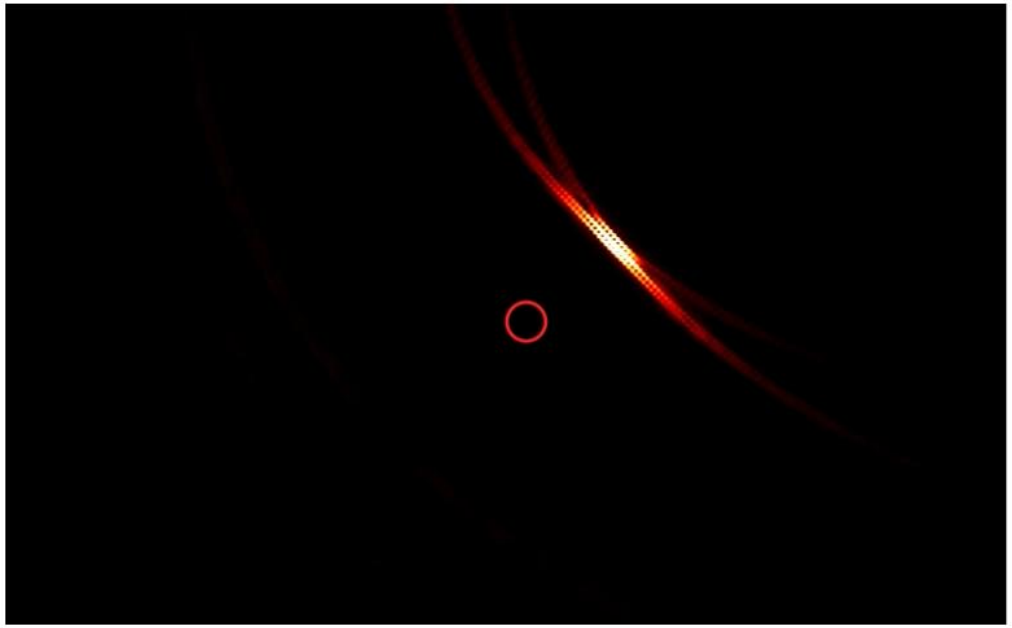


- **Beam propagation:** Side Drilled Hole

Photoelastic results



Simulation results (FFEM)



Configuration details:
Probe '5L64'
20 elts. sub-aperture, S45° focusing 50 mm depth
SDH Ø3mm, depth 25 mm

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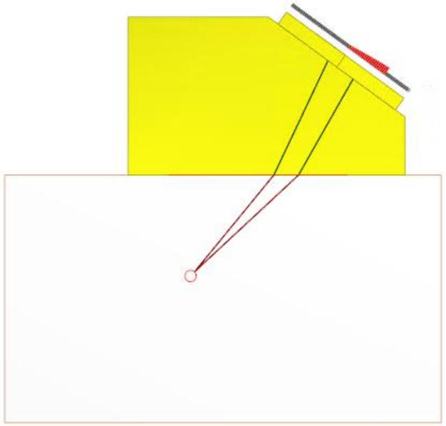
Experimental validation



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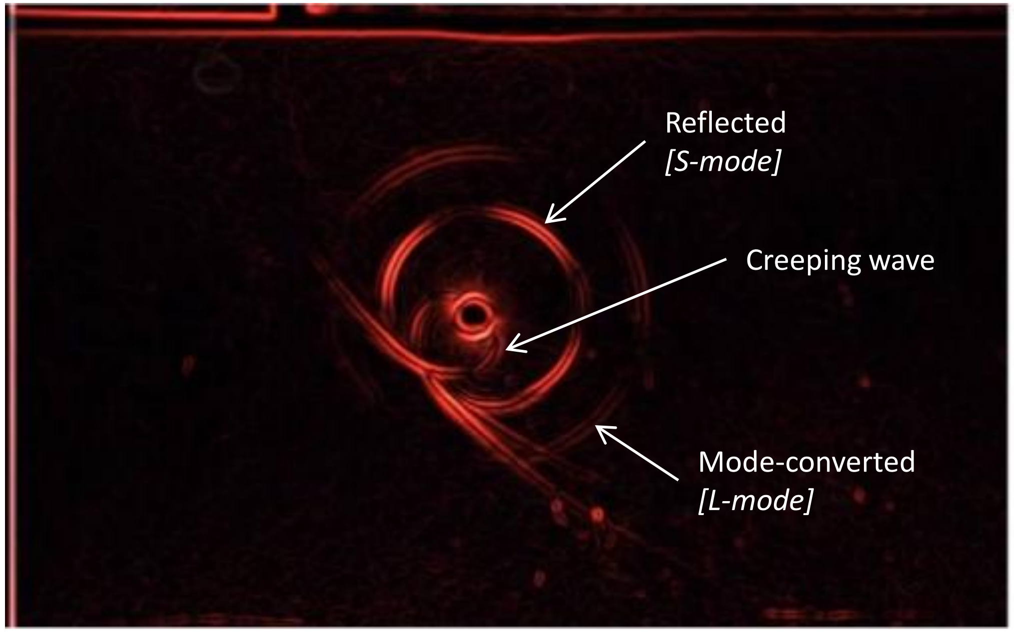
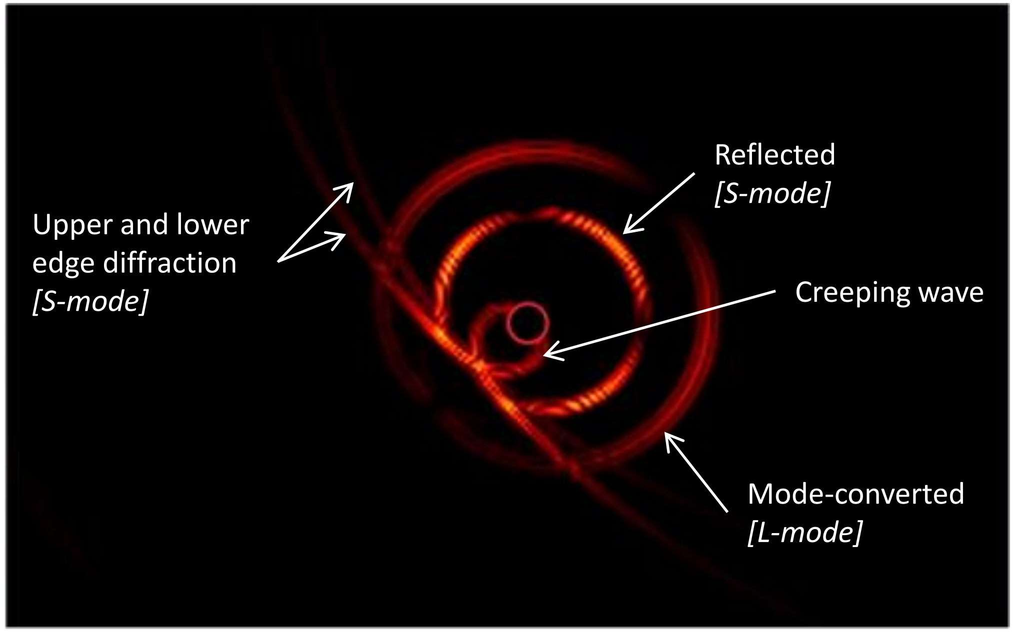
Photoelastic results

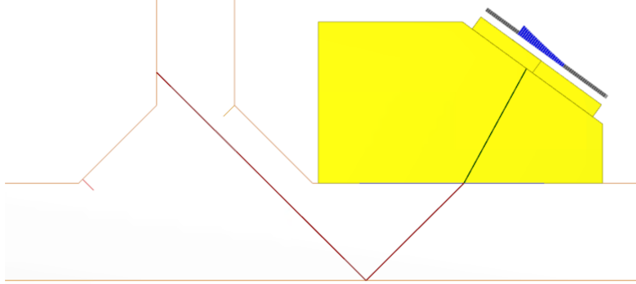


Simulation results (FFEM)



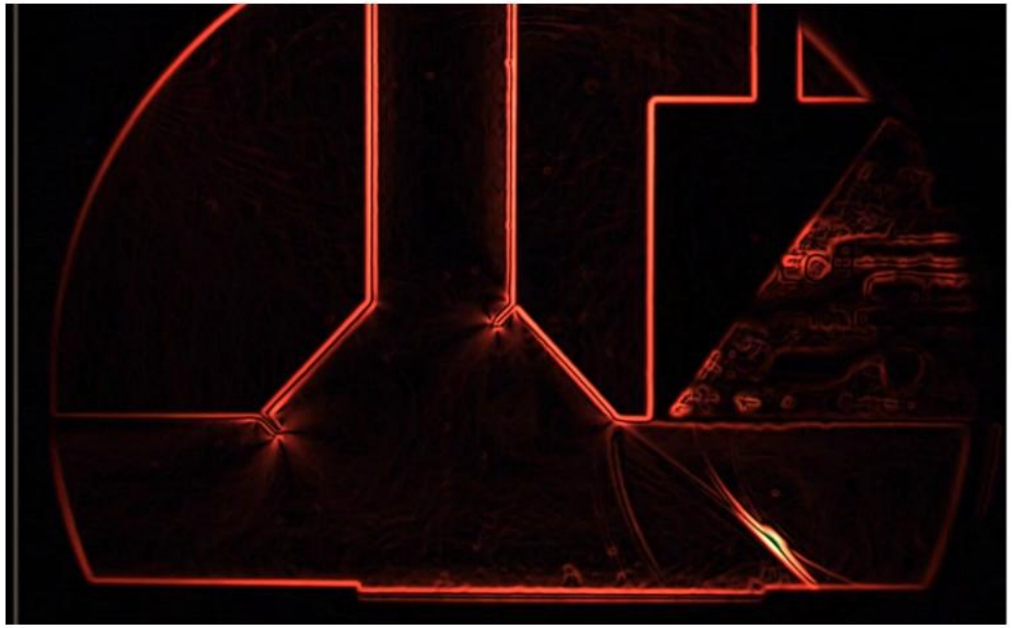
Configuration details:
Probe '5L64'
20 elts. sub-aperture, S45° focusing 50 mm depth
SDH Ø3mm, depth 25 mm

Experimental validation

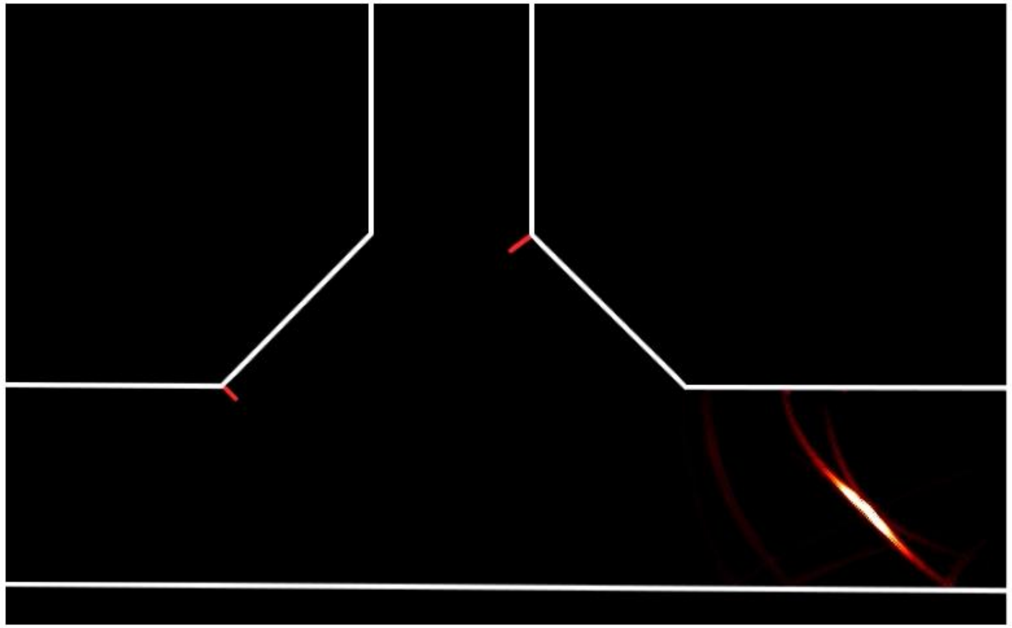


Beam propagation: T-Weld

Photoelastic results

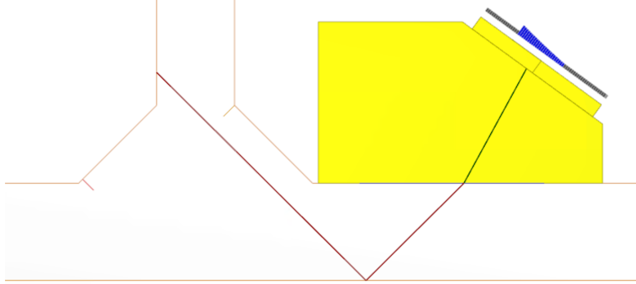


Simulation results (FFEM)



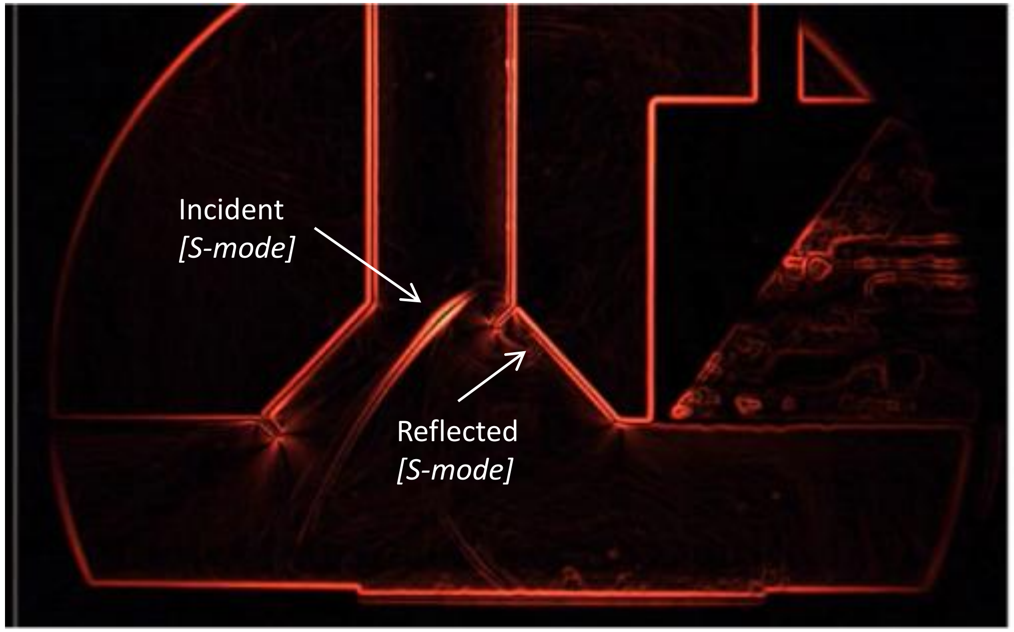
Configuration details:
Probe ‘5L64’
24 elts. sub-aperture, S45° focusing 50 mm depth
2 * cracks like flaws, height = 4 mm

Experimental validation

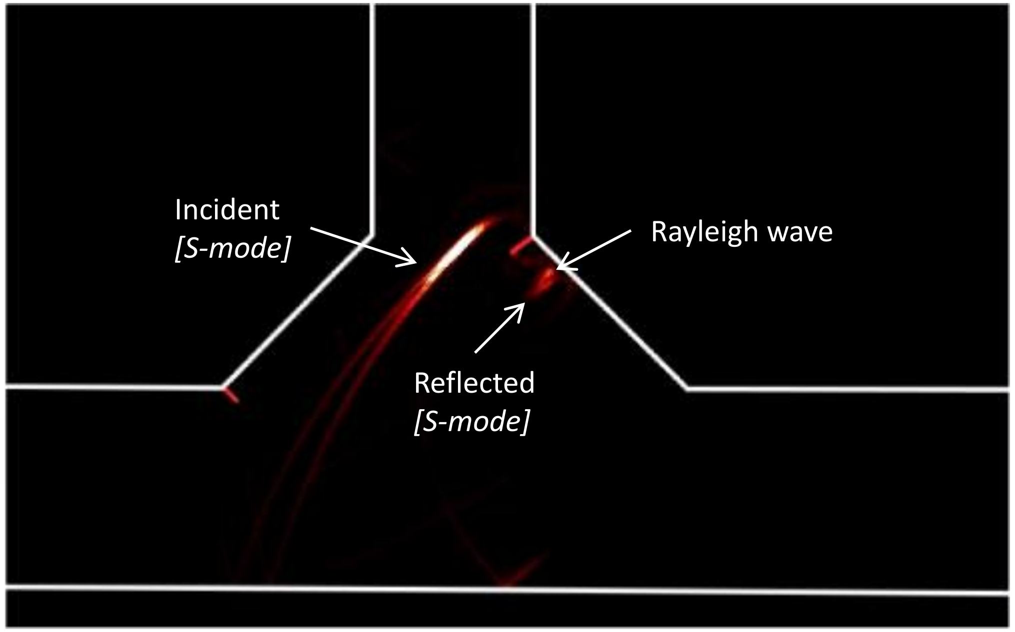


- **Beam propagation:** T-Weld

Photoelastic results



Simulation results (FFEM)



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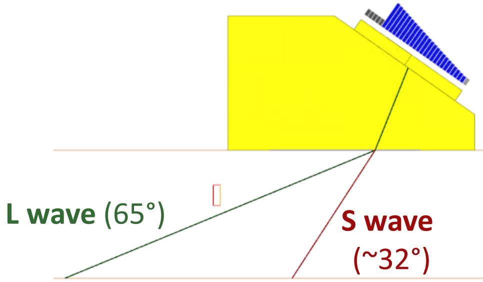
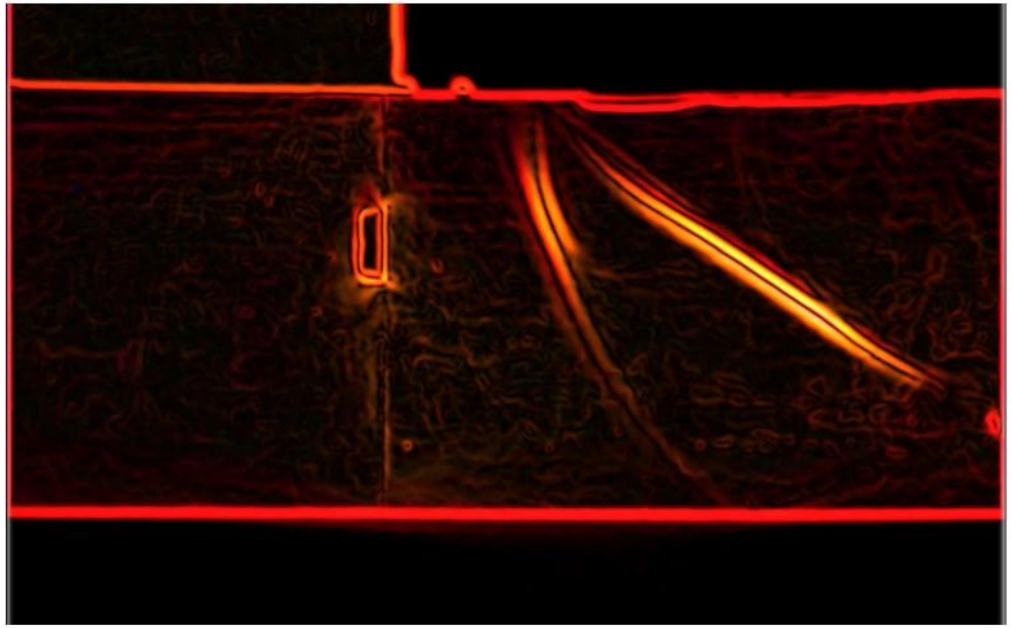


- **Beam propagation:** TOFD on a subsurface notch

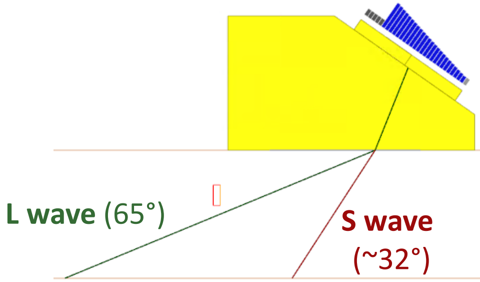
Photoelastic results



Simulation results (FFEM)

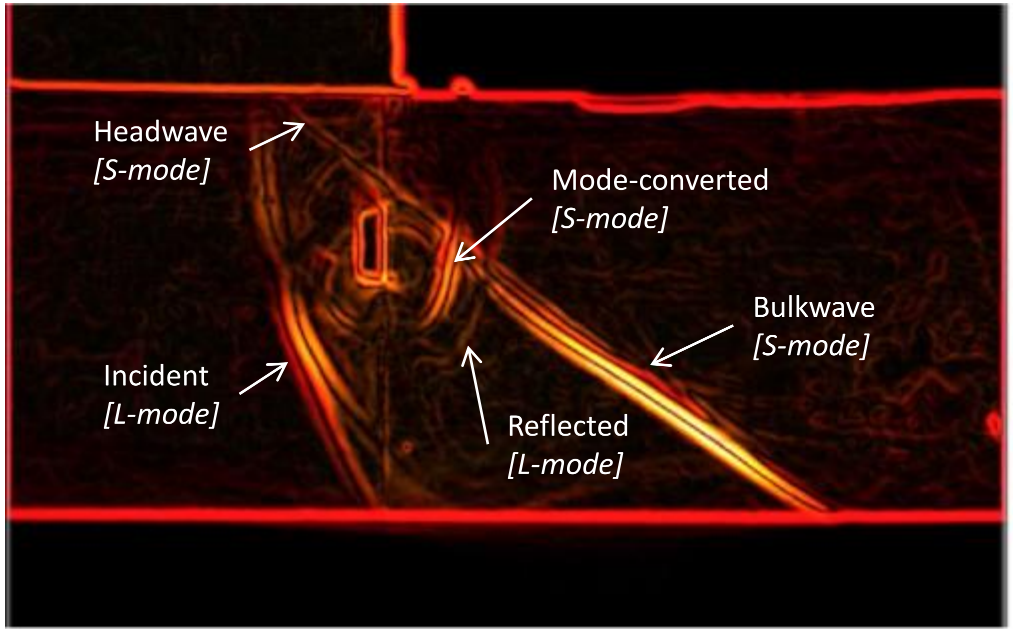
Configuration details:
Probe 'DAAH 7.5L30'
24 elts. sub-aperture, L65° focusing 10 mm depth
Notch 3*1 mm², ligament 5 mm vs surface

Experimental validation

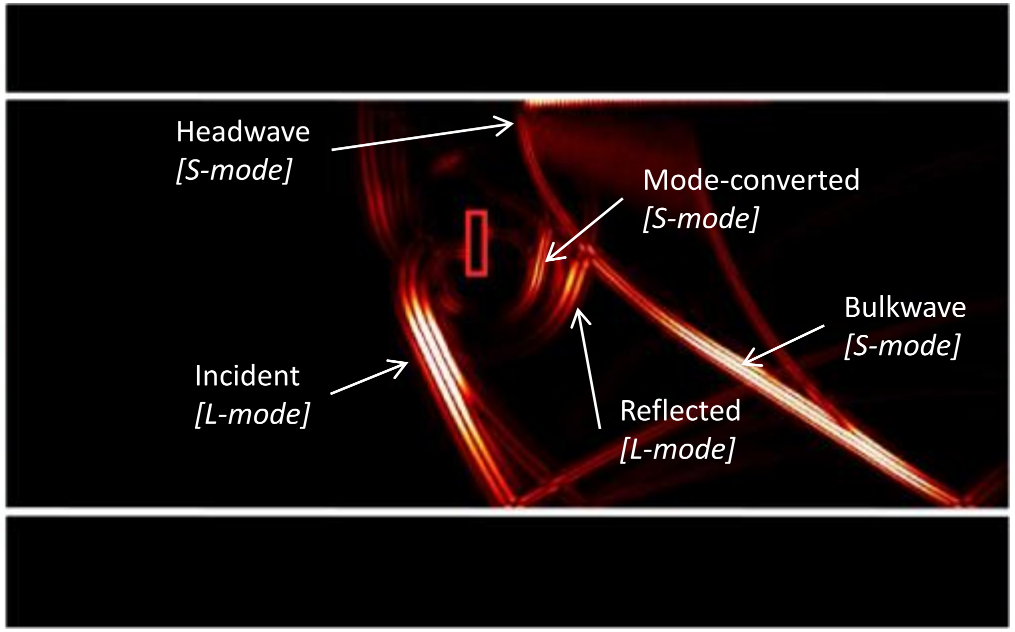


- **Beam propagation:** TOFD on a subsurface notch

Photoelastic results



Simulation results (FFEM)



Configuration details:
Probe 'DAAH 7.5L30'
24 elts. sub-aperture, L65° focusing 10 mm depth
Notch 3*1 mm², ligament 5 mm vs surface

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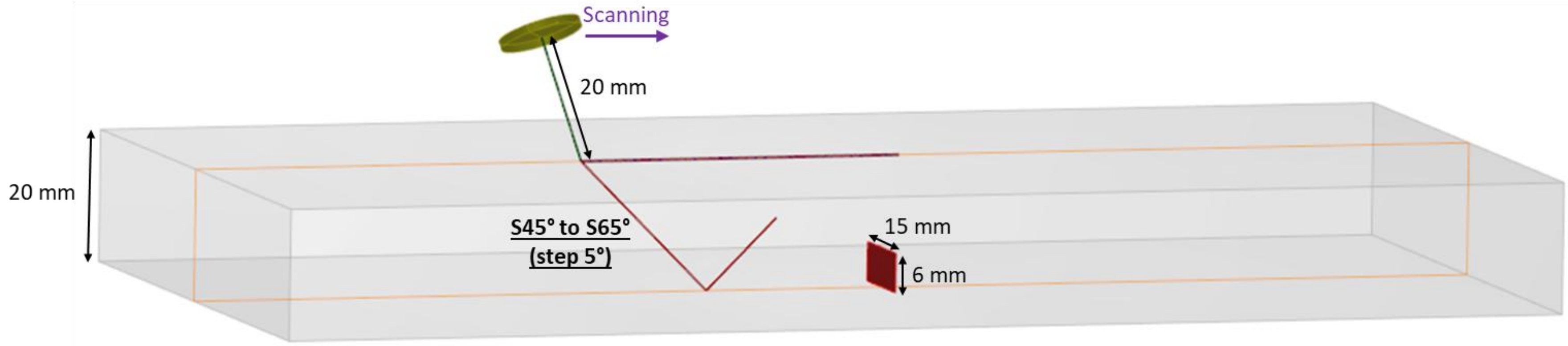
Experimental validation

- **Defect response:** Refraction angle impact
  - Planar specimen made of carbon steel (density: 7.8 ; v_L = 5900 m/s ; v_S = 3230 m/s)
  - Immersion inspection:
    - Conventional probe: Ø12.7 mm ; f = 4.5 MHz
    - Water path = 20 mm
    - Refraction angle: **S45° to S65° (step 5°)**
  - Backwall breaking flaw 6x15 mm²
  - Calibration (each angle): SDH Ø2 mm, depth 15 mm



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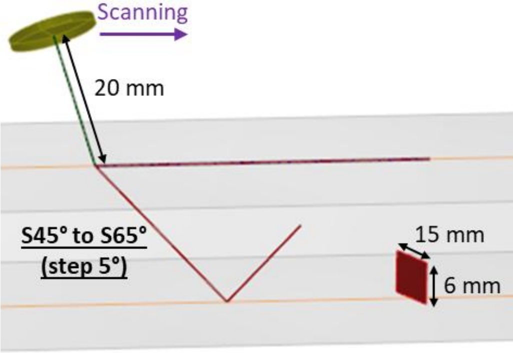
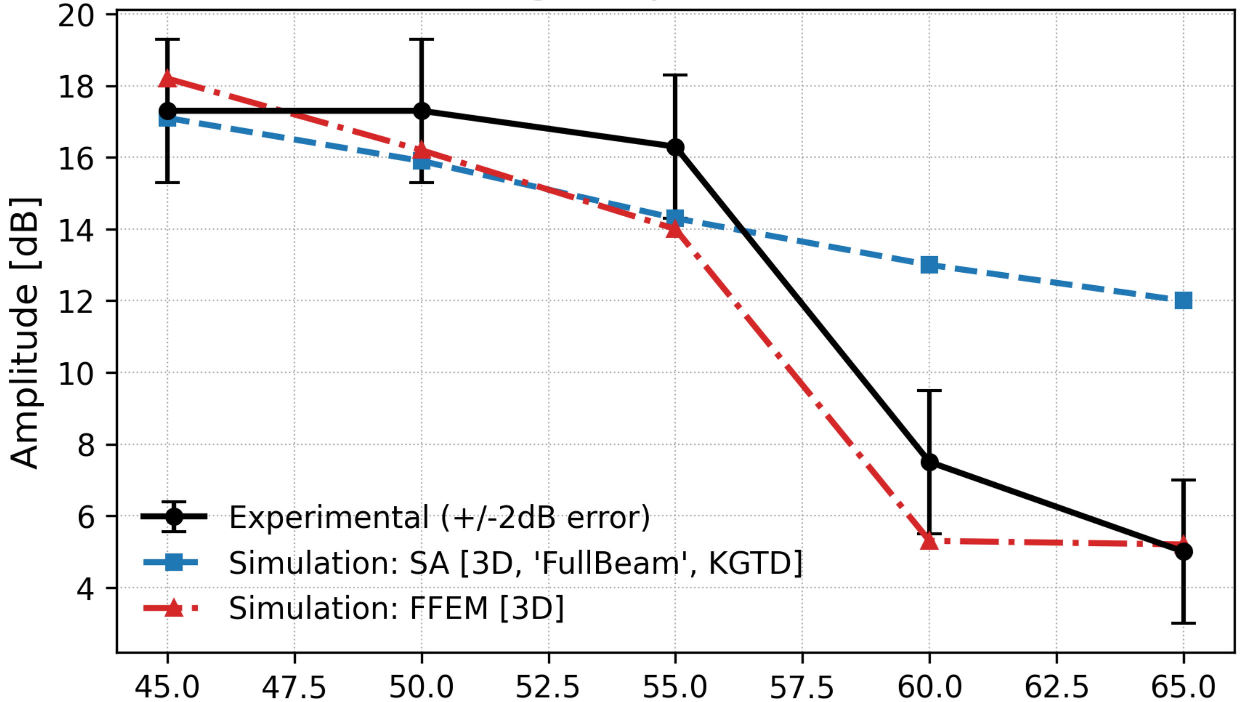


Defect response: Refraction angle impact

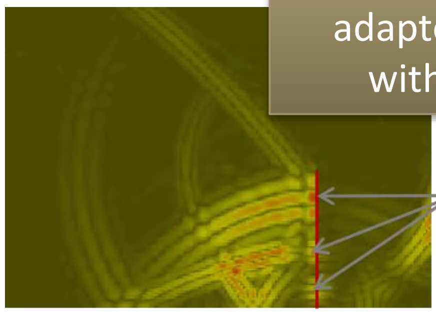


Refraction angle [°]	S45	S50	S55	S60	S65
SA [3D, 'FullBeam', KGTD]	-0.2	-1.4	-2.0	+5.5	+7.0
FEM [3D]	+0.9	-1.1	-2.3	-2.2	+0.2

Error in dB (simulation - experimental)

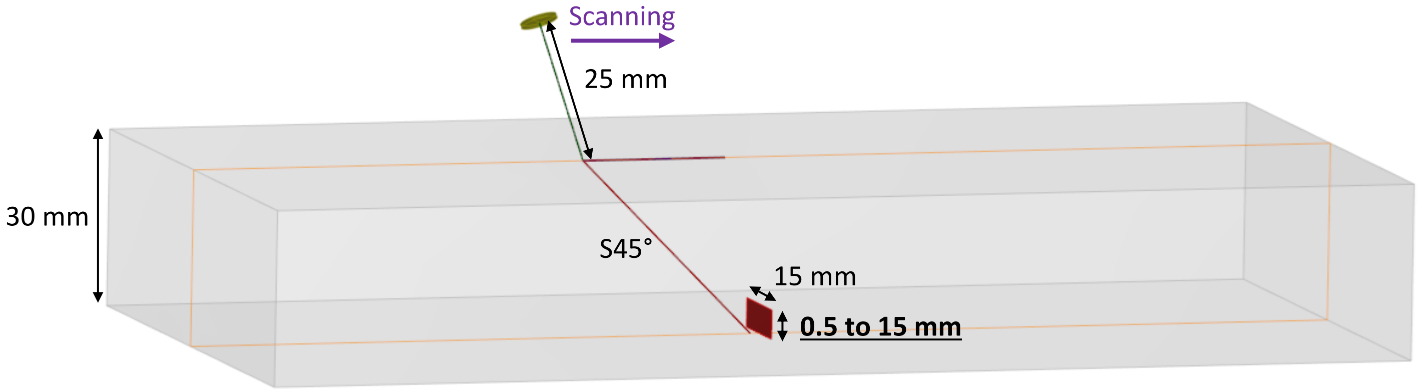
- Good agreement between SA and FFEM for the first three angles.
- Significant discrepancies in SA beyond 60°, while FFEM shows consistent trends.
  → Around 60°, close to critical angle on the vertical flaw, complex phenomena are generated (creeping waves…) and interfere with the main S-mode corner echo ; these are predicted in FFEM but not in SA explaining the discrepancies.

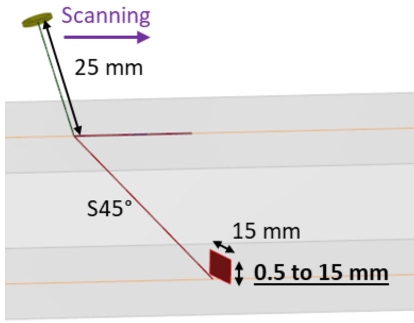
Application case also well adapted and validated with hybrid model



Experimental validation

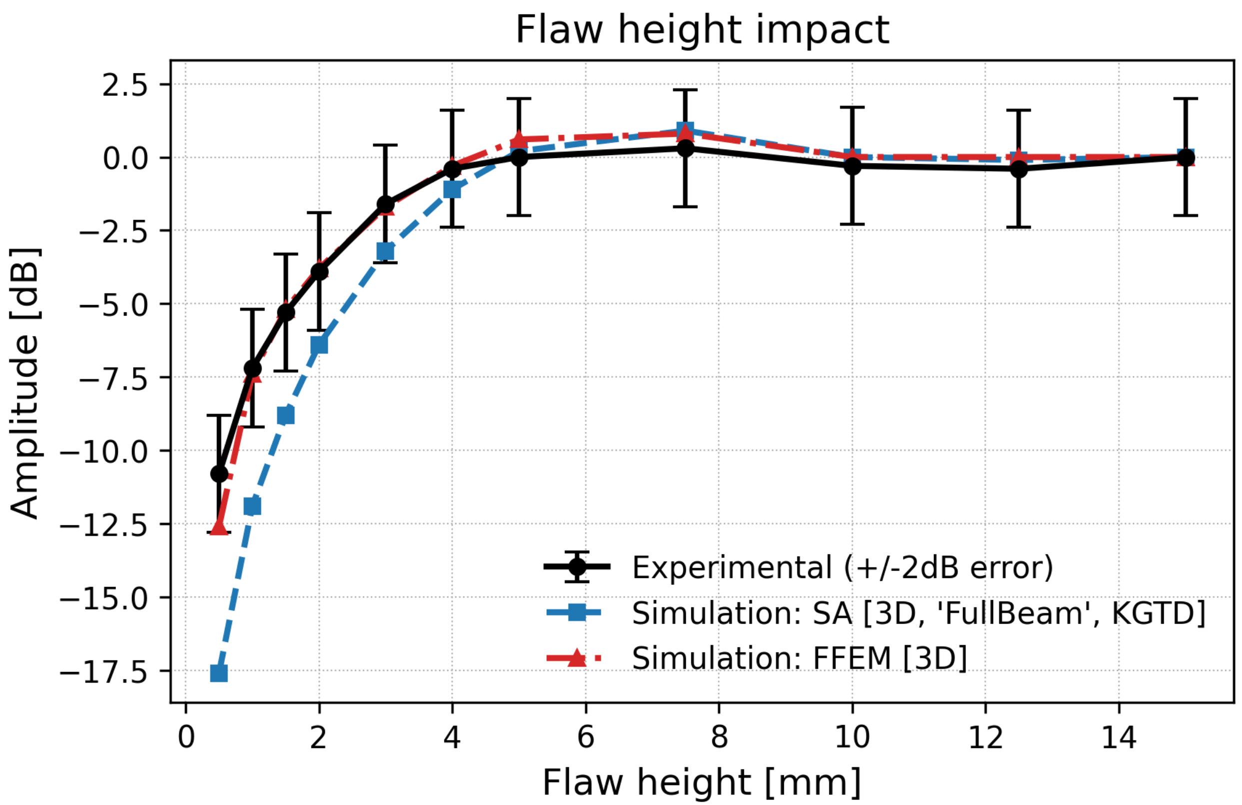
- **Defect response:** Flaw height impact
  - Planar specimen made of carbon steel (density: 7.8 ; v_L = 5900 m/s ; v_S = 3230 m/s)
  - Immersion inspection:
    - Conventional probe: Ø6.35 mm ; f = 2.25 MHz
    - Water path = 25 mm
    - Refraction angle: S45°
  - Backwall breaking flaw: length 15 mm, **height 0.5 to 15 mm**
  - Calibration: bigger flaw (15x15 mm²)





Experimental validation

Defect response: Flaw height impact



- SA models (KGTD) not valid for small flaws (vs λ), this explains why discrepancies are observed for flaws smaller than 2 mm height
- Better prediction for small flaws with FFEM

Flaw height [mm]	0.5	1	1.5	2	3	4	5	7.5	10	12.5	15
SA [3D, FullBeam, KGTD]	-6,8	-4,7	-3,5	-2,5	-1,6	-0,7	0,2	0,6	0,3	0,3	0,0
FFEM [3D]	-1,8	-0,2	0,1	0,1	-0,1	0,1	0,6	0,5	0,3	0,4	0,0

Error in dB (simulation - experimental)

Application case also well adapted and validated with hybrid model

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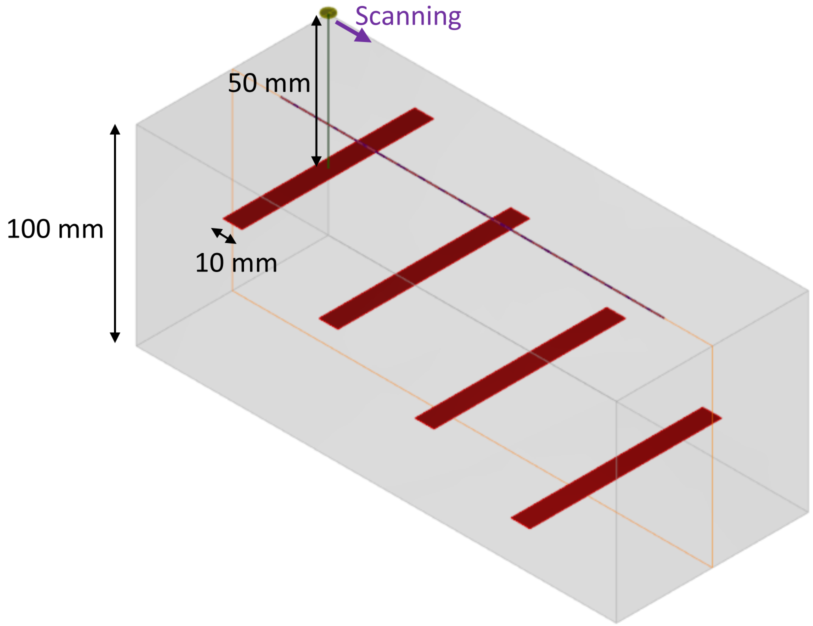
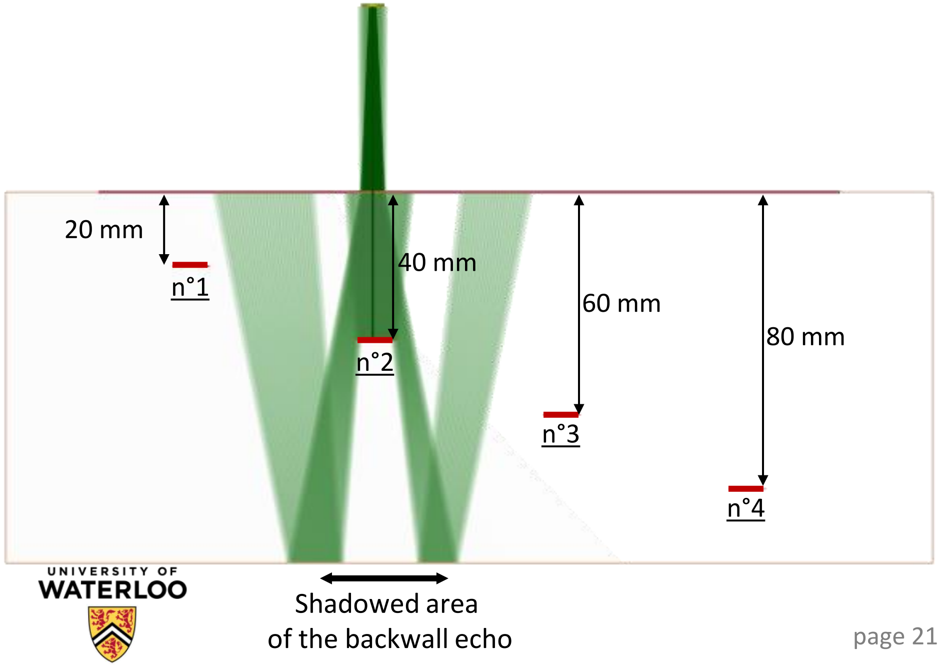
Experimental validation

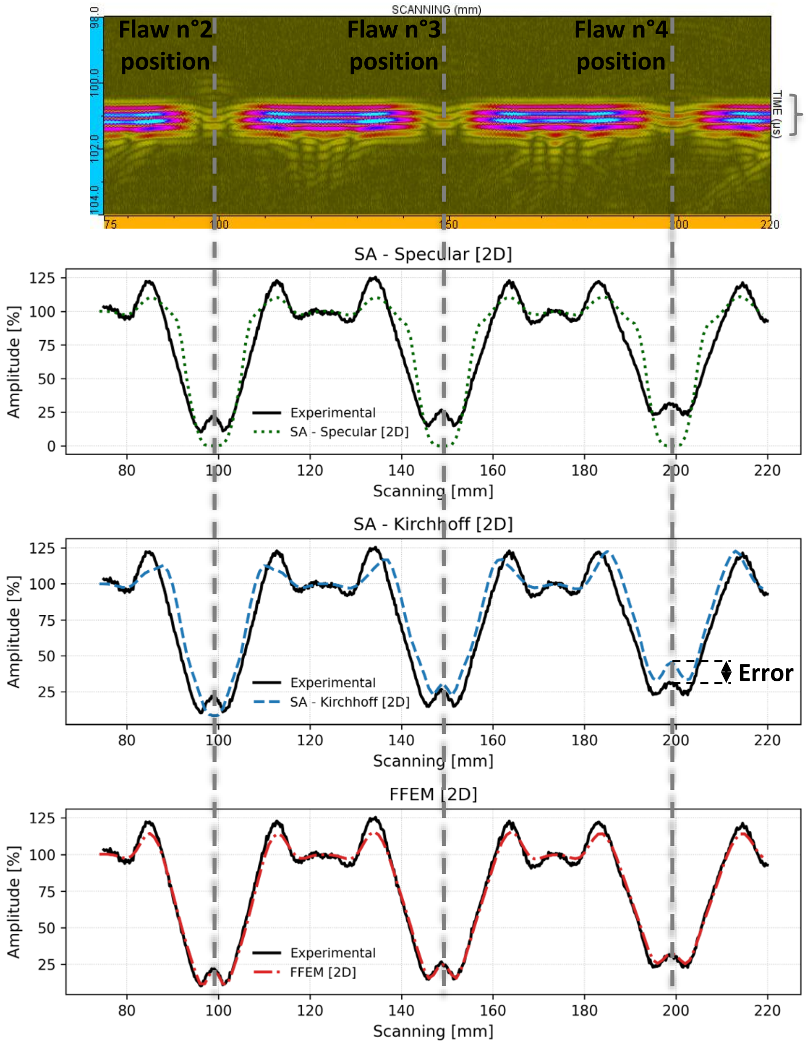
- **Shadowing effect:** Impact of delaminations on backwall echoes
  - Planar specimen made of carbon steel (density: 7.8 ; v_L = 5900 m/s ; v_S = 3230 m/s)
  - Immersion inspection:
    - Conventional probe: Ø6.35 mm ; f = 2.25 MHz
    - Water path = 50 mm
  - 4 ‘delamination’ flaws: 10 mm wide at 4 depths from 20 mm to 80 mm





Experimental validation

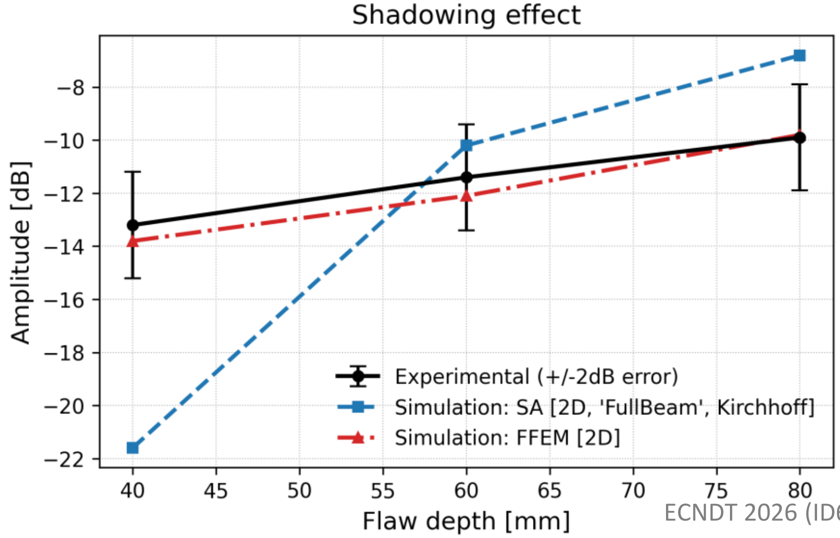
Shadowing effect: Impact of delaminations on backwall echoes



- 2 Semi-Analytical models for the geometry:
  - **Specular model:** Total shadowing, no amplitude below the flaw → not relevant in this case.
  - **Kirchhoff model:** Improved agreement, but amplitude discrepancies remain on the shadowed backwall echo, varying with defect depth
- **FFEM model:** Good agreement with experiment regarding the amplitude of the shadowed backwall echo beneath each defect

Defect depth [mm]	40	60	80
SA [2D, Kirchhoff]	-8.4	+1.2	+3.1
FFEM [2D]	-0.6	-0.7	+0.1

Error in dB (simulation - experimental)



OUTLINE

- Modeling Strategies available for Ultrasound Testing
- Experimental validation of FEM models
  - Beam propagation
  - Defect response
  - Shadowing effect
- **Conclusion**

Conclusion

- With the new Full FEM model, CIVA becomes a **complete multi-model** UT simulation platform: Semi-Analytical (SA) + Hybrid (SA + local FE) + ‘Full component FEM’ (FFEM)

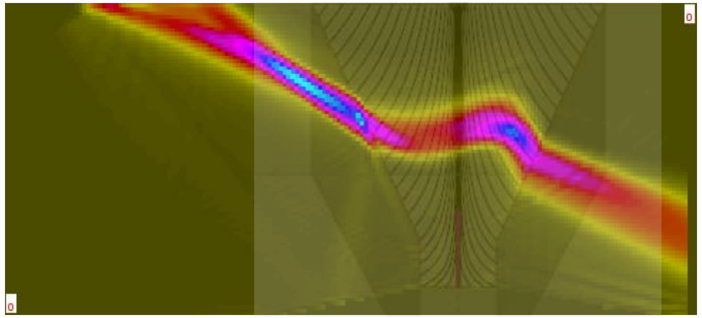
- FFEM model gives **a new possibility for cross-validation of SA models** so that you can use them in their application domain with confidence and benefit from its intensive computation capabilities

- Where you reach limits of SA models, CIVA FFEM (and/or hybrid models) is now available to **overcome these limits** and expand the range of applications for modeling

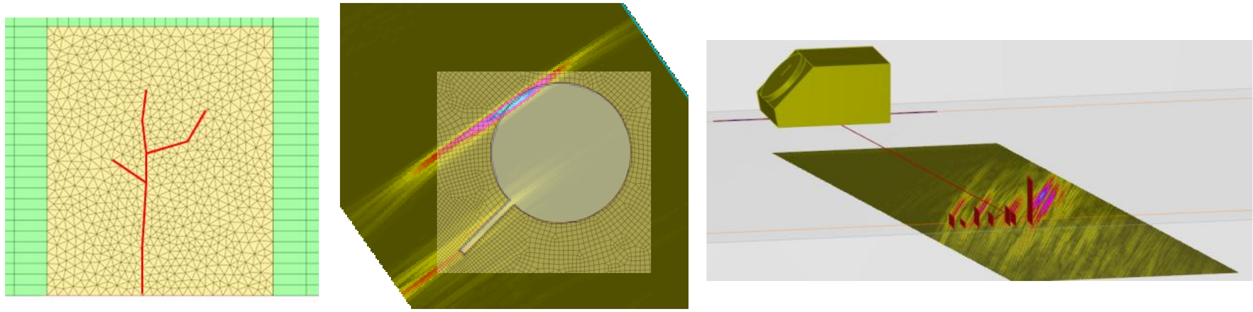
Conclusion

Full FEM expands the range of possible modeling applications

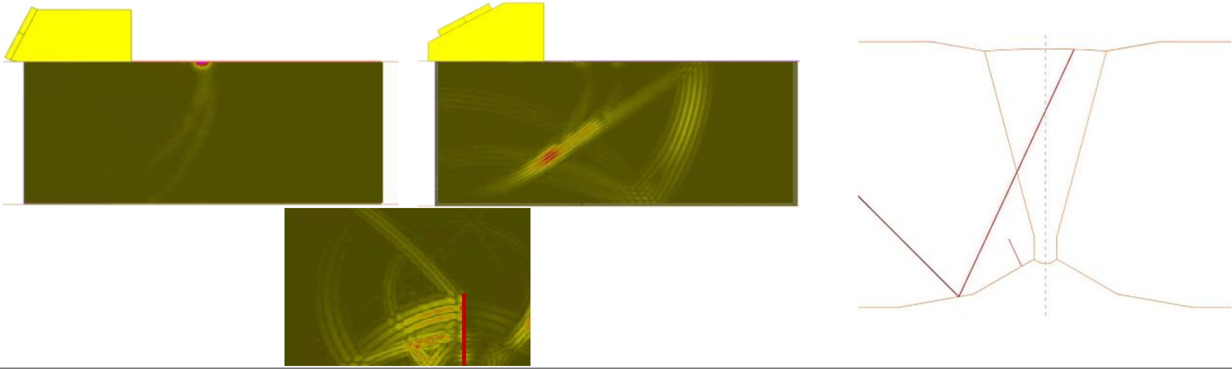
Propagation in complex materials (anisotropic, heterogeneous…)



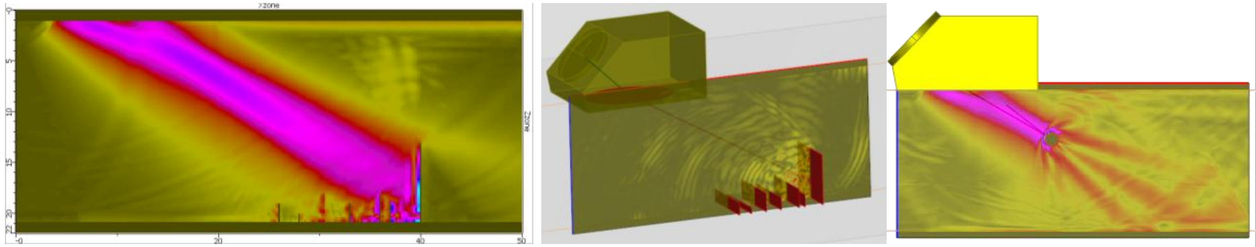
'Complex' defects (specific profiles, small height, 'cluster'…)



Applications cases with surface wave (Rayleigh, creeping waves…)



Accurate shadowing effect modeling



Appendix: Computation time

Key parameters influencing computation time:

- Probe frequency
- Simulation time window
- Region Of Interest size
- Mesh quality
- Computation mode: 2D or 3D

$$CPU\ Time = F^{d+1} \times C(config) \times Q(mesh)$$

Inspection frequency
$d = 2$ or 3

Fluid-solid, Viscosity,
Thin layers, Anisotropy,
Heterogeneity …

Distorted finite elements,
small edges…

	1 MHz	5 MHz
2D	10 sec	20 min
3D	10 min	4 days

up to $\times$ 1000 !
(most often $\times$ 2 to 10)

Appendix: Computation time

- **FFEM 3D computation time:**
  - *Defect response – Refraction angle impact*: f = 4.5 MHz
    - Highly dependent on the refraction angle → impact on the simulation time window
    - On average, one A-scan position requires ~10 h of computation *(AMD Ryzen 9 16-core @ 4.2 GHz)*
    - This corresponds to ~6 days per configuration, with an average of 15 mechanical positions
  - *Defect response – effect of defect height*: f = 2.25 MHz
    - One A-scan position requires ~3 h of computation *(AMD Ryzen 9 16-core @ 4.2 GHz)*
  - In 2D, all computation times are below 1 h

Appendix: Kirchhoff limit on small flaws

- **Defect response > Flaw height impact:** Kirchhoff algorithm limit
  - 'ka' product vs 1
    - k: wave number ($\frac{2\times\pi}{\lambda}$)
    - a: defect half-height

Flaw height [mm]	0.5	1	1.5	2	3	4	5	7.5	10	12.5	15
SA [3D, 'FullBeam', KGTD]	-6,8	-4,7	-3,5	-2,5	-1,6	-0,7	0,2	0,6	0,3	0,3	0,0
FFEM [3D]	-1,8	-0,2	0,1	0,1	-0,1	0,1	0,6	0,5	0,3	0,4	0,0
'ka' product	1,1	2,2	3,3	4,4	6,6	8,8	10,9	16,4	21,9	27,4	32,8

Appendix: Overview and Perspectives

- FFEM currently available for 2D and 3D simulations limited to 2.5D-symmetric geometries (constant cross-section profile along the extrusion).

- Ongoing developments include the following perspectives:
  - HPC capabilities to reduce computation times (particularly for 3D FFEM simulations)
  - Further optimization of the FFEM model implementation
  - New capabilities: 3D defects (e.g., FBH), complex geometries, composites, concrete, through-transmission technique, and more