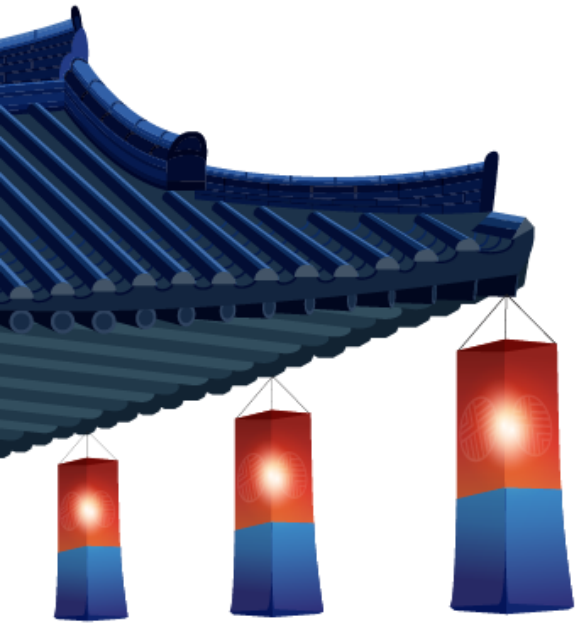


HYBRID & SURROGATE MODELS
-
NEW TRENDS AND APPLICATIONS OF SIMULATION SOFTWARE FOR NDT

Fabrice FOUCHER (EXTENDE),
Roman FERNANDEZ (EXTENDE), Stéphane LE BERRE (CEA)

Exclusive Sponsor
EVIDENT

20th WCNDT
20th World Conference on Non-Destructive Testing
Songdo Convensia, Incheon, Korea
27-31 May 2024

Ministry of Science and ICT
Incheon Metropolitan City
Incheon Tourism Organization
KOREA TOURISM ORGANIZATION

OUTLINE

- Context
- Metamodels
- Hybrid Models
- Finite Element Models
- Conclusion

Context : Simulation for NDE

Why using simulation in NDT ?

- Evaluate **feasability**, **design** and **optimize** inspections
  Better understanding, less iterations before physical tests on mock-ups

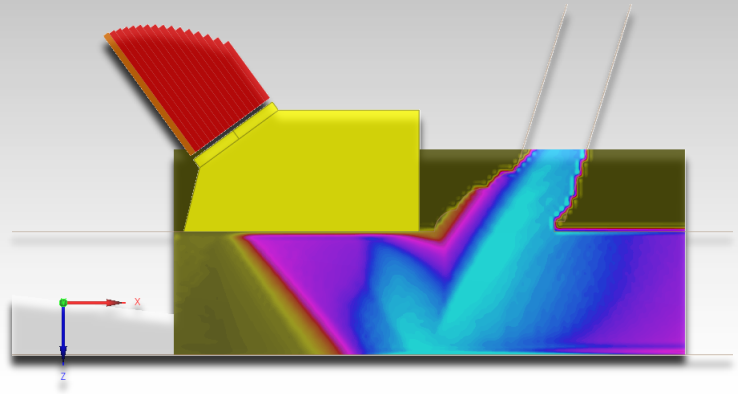
- Support **performance demonstrations**:

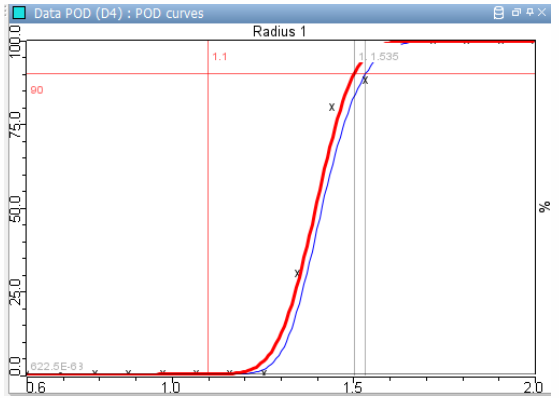
Capacity to run large parametric studies to provide
data for technical justifications /reliability/POD studies

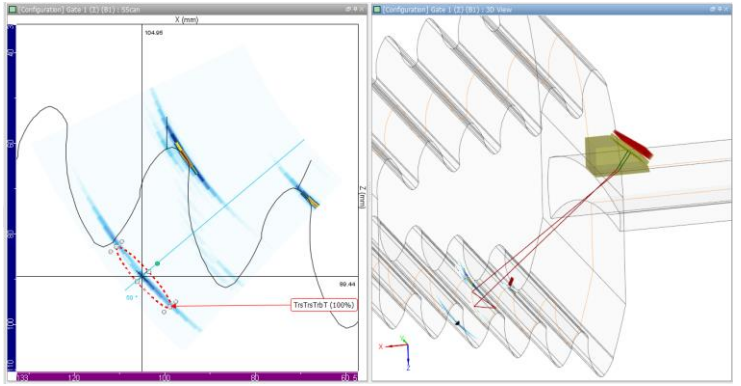
- **Expertise**:

To explain complex situations and confirm or disprove a diagnosis

- **Convince** and **train :**
  Illustrate inspections set-up to support technical discussions



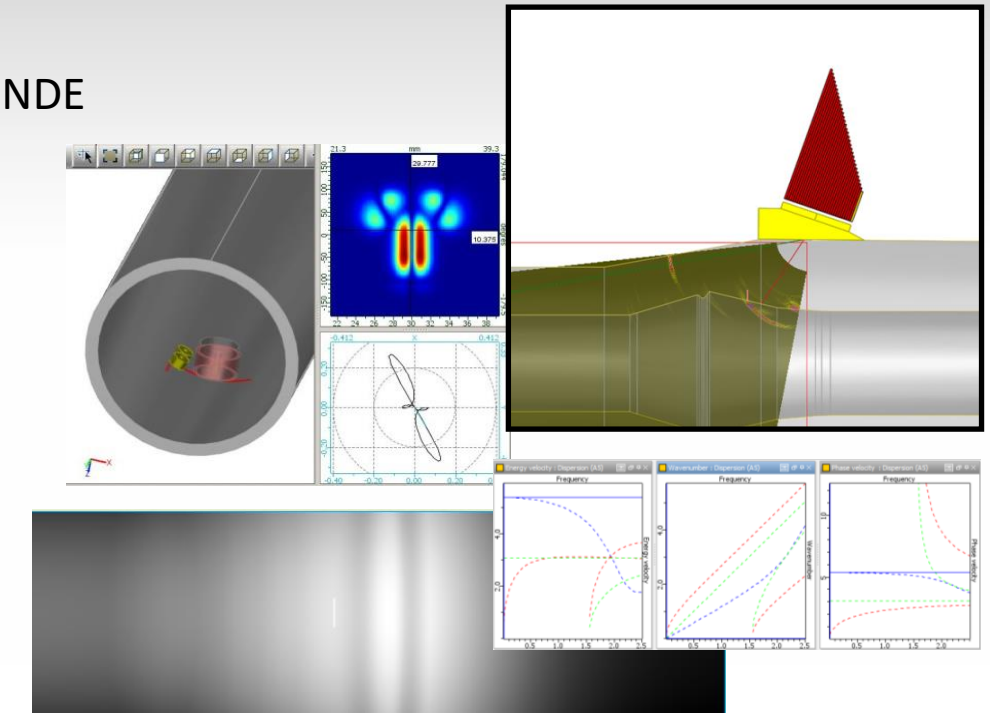


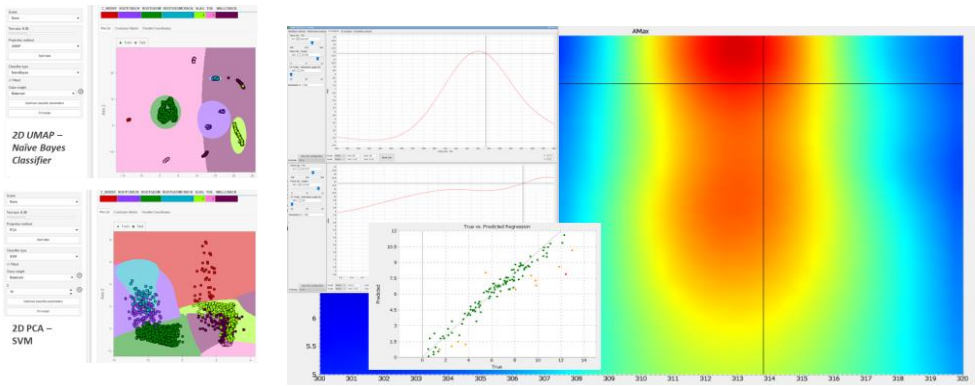


Context: CIVA Modeling Platform

About CIVA software :

- Developed by CEA LIST and distributed worldwide by EXTENDE
- Multi-technique:
  - UT - Ultrasound Testing
  - SHM / GWT - Guided Waves Testing and SHM by guided waves
  - RT - Radiography (X & Gamma) – Tomography
  - ET - Eddy Current Testing
  - TT - Thermographic Testing
- Parametric studies, Sensitivity and POD analysis
- UT Analysis (Real acquisition data)
- Data Science
  (to develop machine-learning based detection and classification tools)

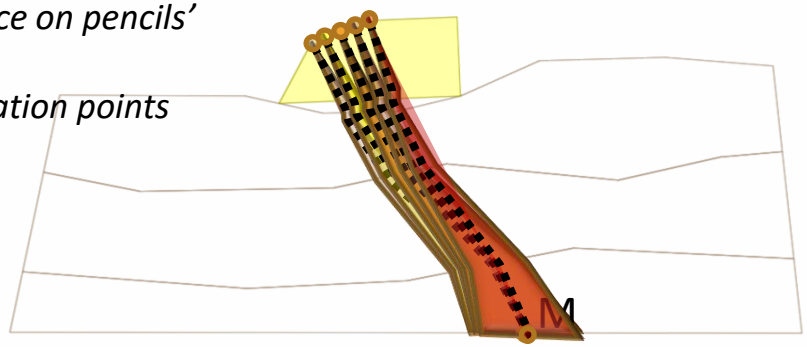


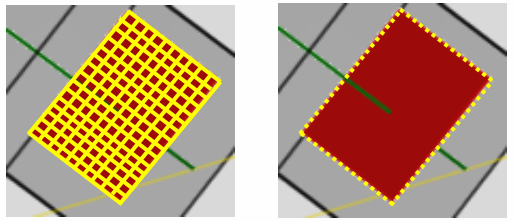


Context

- CIVA mainly based on semi-analytical models. For instance, **in CIVA UT**:
  - Has been historically based on “Ray-based” methods:
    - Pencil models for beam propagation
    - Kirchhoff & GTD beam/flaw interaction models (among others)

Integration over probe surface on pencils’ contributions to compute field at observation points





Integration on flaw surfaces and edges of beam/flaw reflection and diffraction coefficients

ADVANTAGES:

- “**Very Fast**” simulations compared to fully numerical approaches,
- A lot of industrial “use cases” can be covered efficiently

DRAWBACKS:

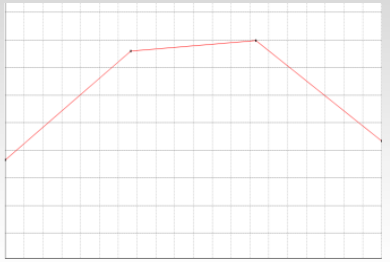
Some limitations in capacities and validity domain

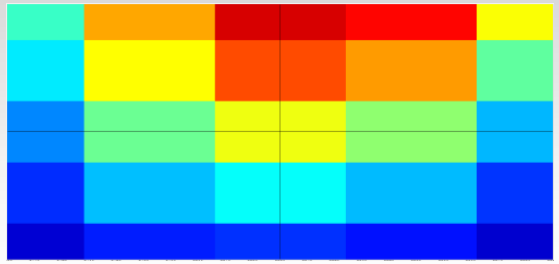
NEEDS:

- Overcome limitations and increase accuracy for wider acceptance and more applications
- Needs for “even more” data generation (IA - Machine Learning, Optimization, Reliability)

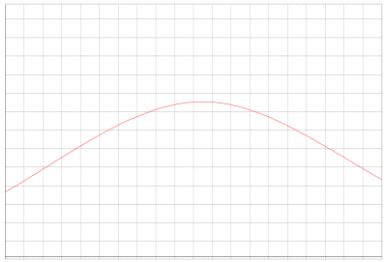
Metamodels

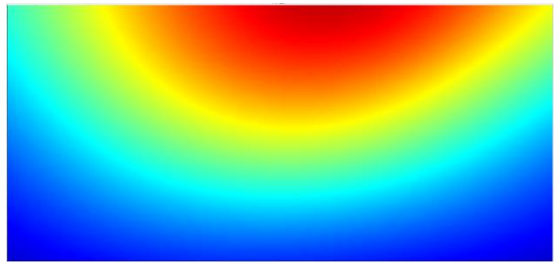
- CIVA includes metamodelling capabilities:
  - Based on an initial set of computed cases with variable parameters:
    The “database” (discrete grids)



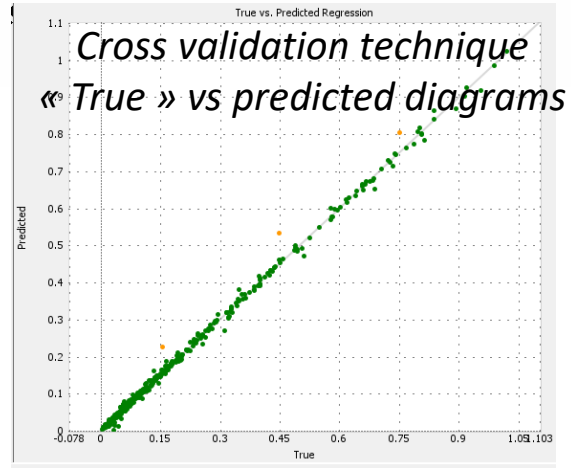


  - Application of smart interpolation algorithms to build a **surrogate model** which provides a **continuum** of results for **all parameters combination**





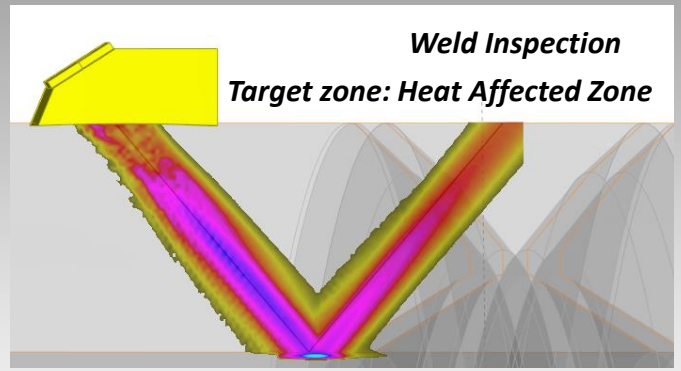
  - Once available, you can explore multiple scenarios in the defined range → **“Real time” simulations, massive data** production



Cross validation technique
« True » vs predicted diagrams

  - Metamodels needs a simulation database based on physical models with enough samples.
  - Metamodel “error” shall be assessed prior to use

Metamodels: Applications

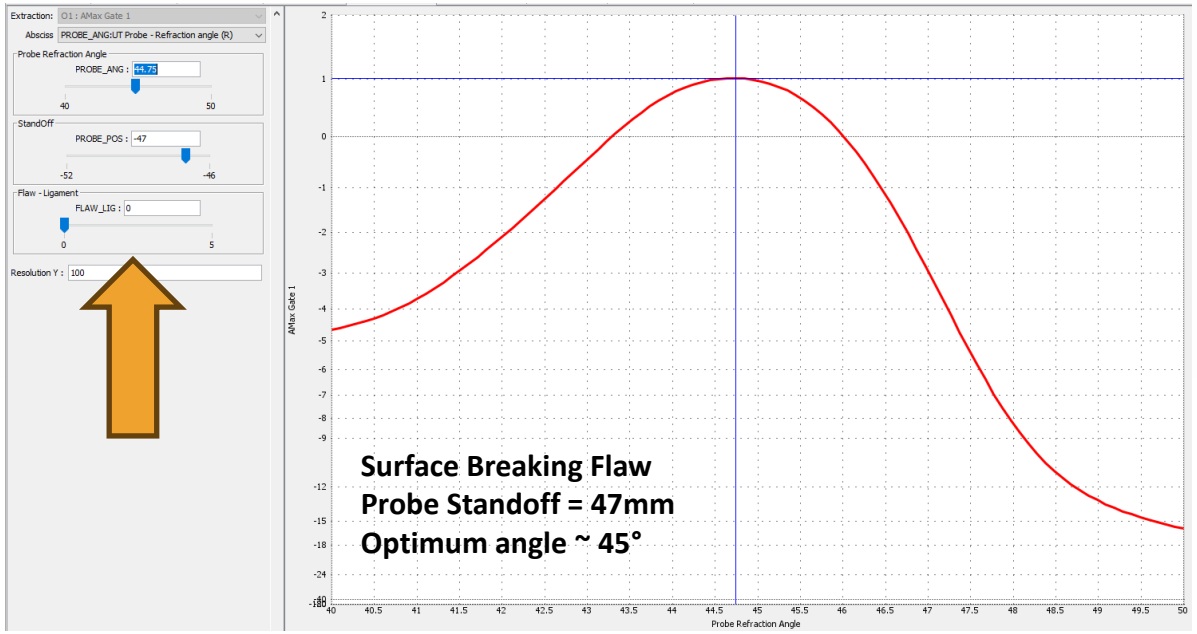


Design/Optimization and reliability studies :

Explore any combination of parameters' values, i.e., any inspections scenarios

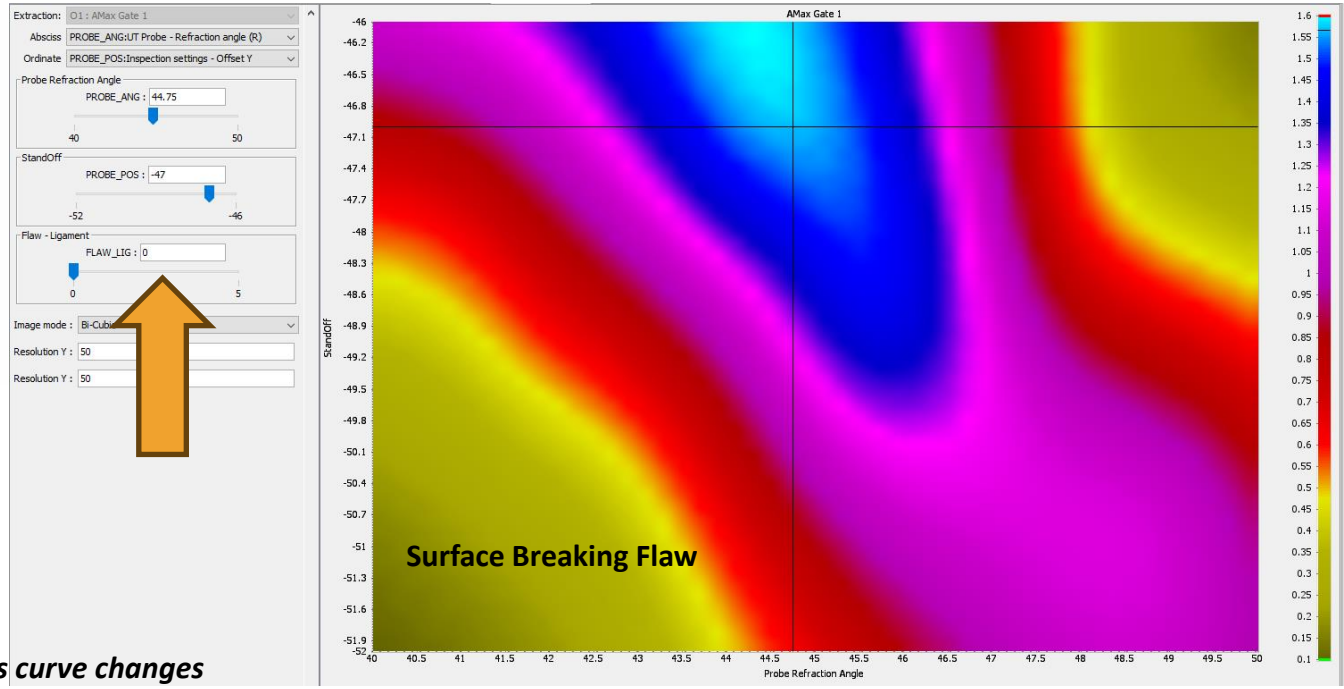
- Variable parameters: Refraction angles, Flaw location, probe location (standoff)
- Impact of 1 parameter on signal amplitude:

Impact of Probe angle on the sensitivity



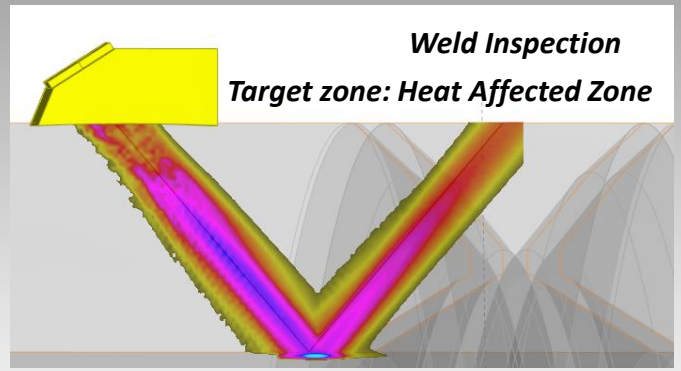
- 2D Viewer: See the "optimum" at a glance

Impact of Probe standoff and Refraction angle on the sensitivity



Sliders available to see how this curve changes other values of the 2 other parameters

Metamodels: Applications



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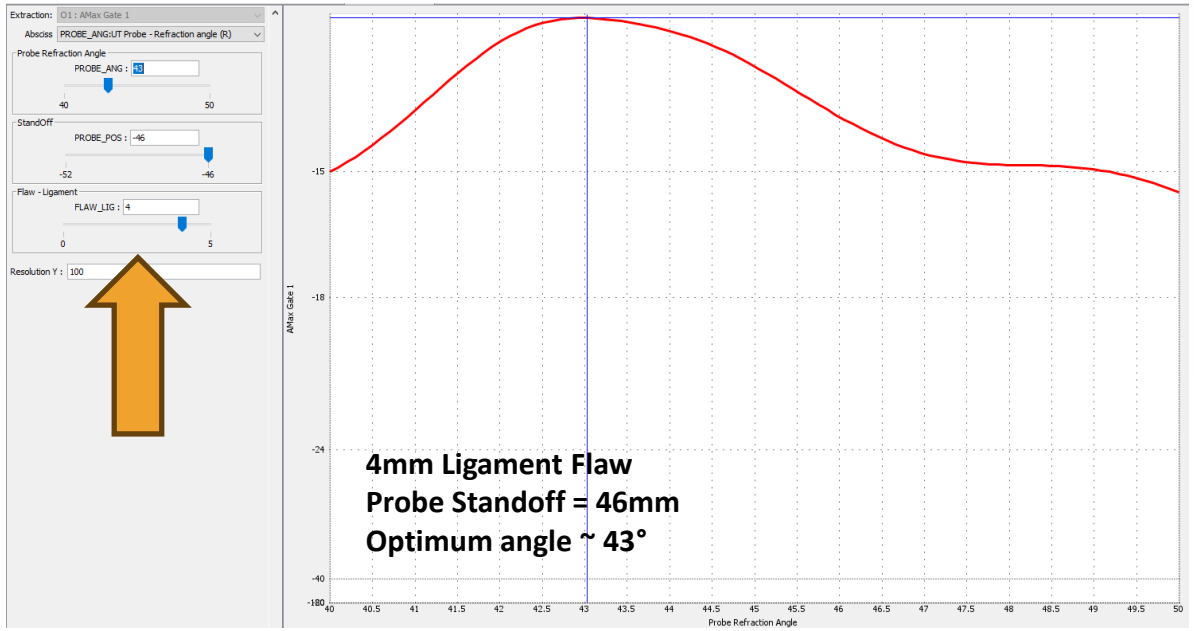

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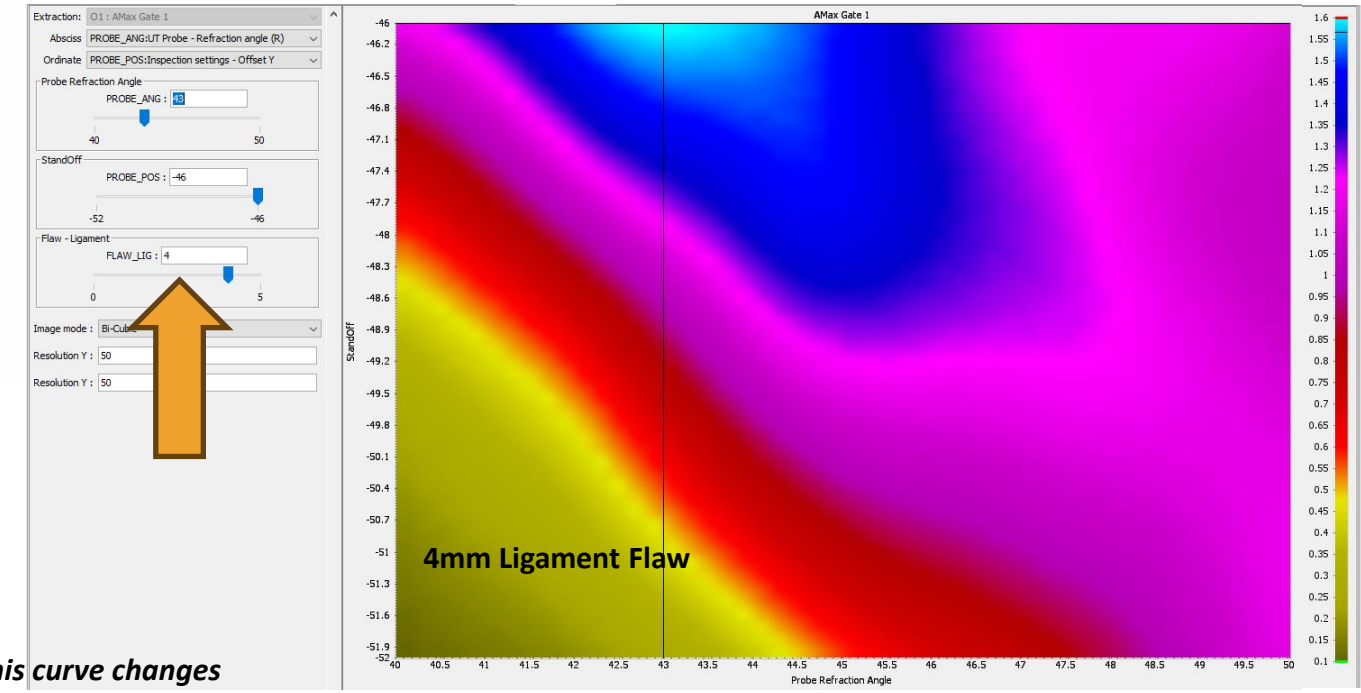
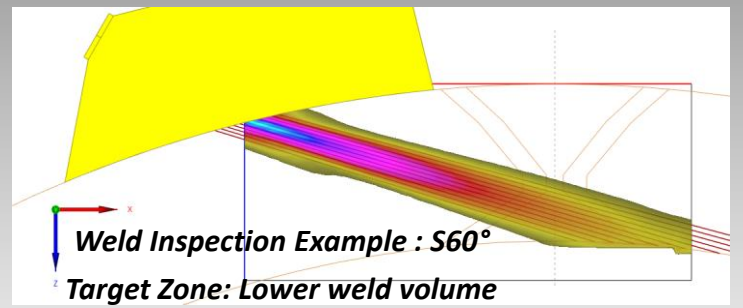


Sliders available to see how this curve changes other values of the 2 other parameters

Metamodels: Applications

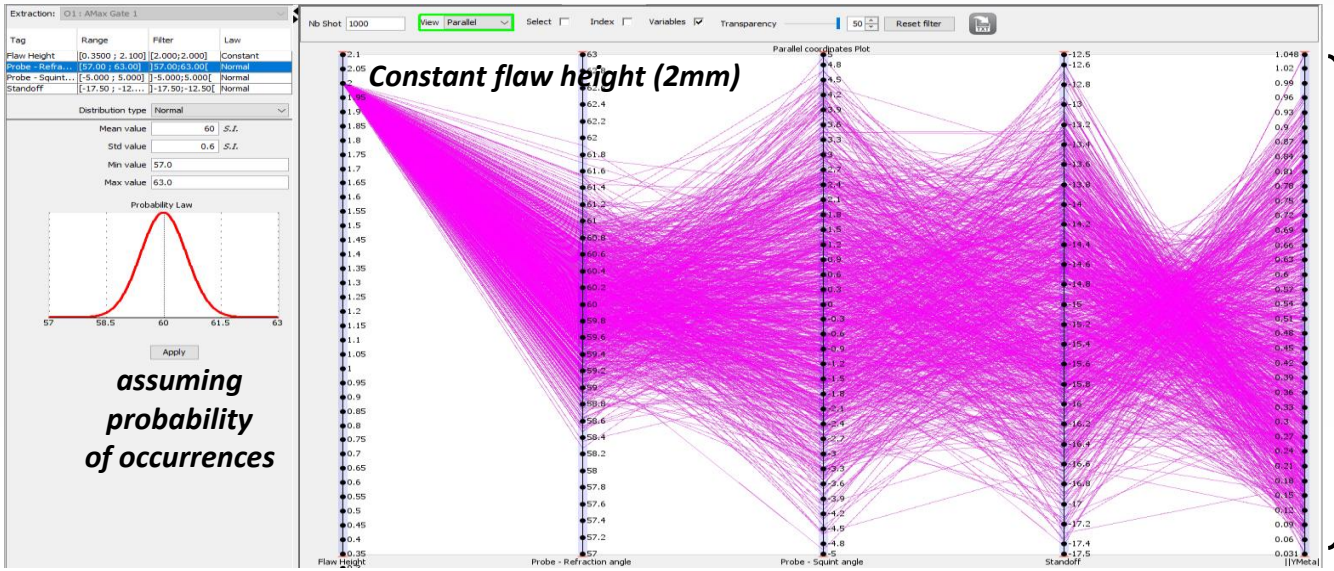


Design/Optimization and reliability studies :

You can explore any combination of parameters' values, i.e., any inspections scenarios:

- **Multidimensional analysis** with parallel plots

Impact of 4 parameters on signal amplitude for N trials (here 1000)

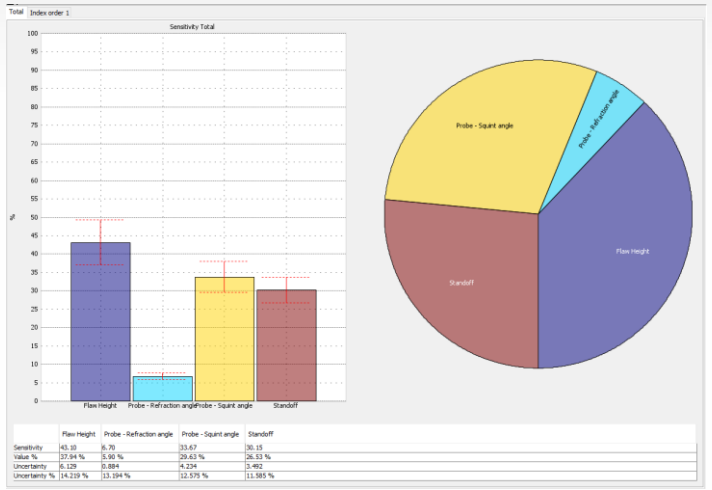


assuming probability of occurrences

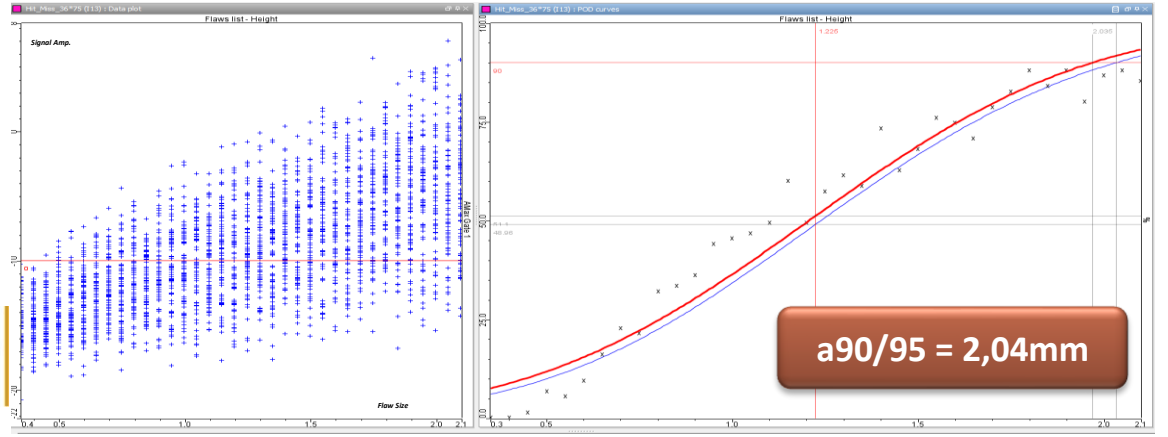
Outcome values

Gaussian laws for 3 other parameters)

- Influential parameters' "ranking" : Sobol Indices:



- **POD Curves**: You can try different hypotheses for parameters



Hybrid Models in UT : SA - FEM

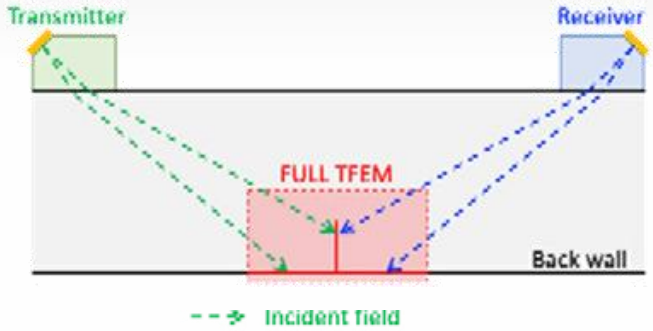
ALREADY IMPLEMENTED IN CIVA PLATFORM

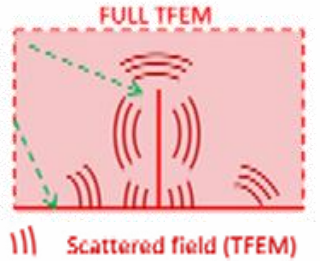
Hybrid models in CIVA UT « FE GRID » :

- Objective: Overcome limitations of semi analytical models for beam/flaw interactions
- Principle : Sound propagation still modelled by pencil models + « local FE » box around discontinuities

ADVANTAGES:

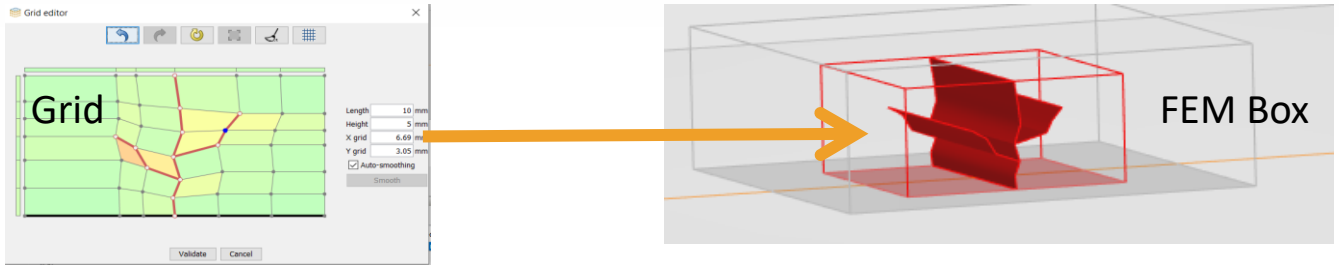
Still quite fast. More accuracy to simulate flaws smaller than wavelength, specific waves phenomena around critical angles, interactions between flaws, etc.





PML boundary conditions at box edges (i.e., no reflections)

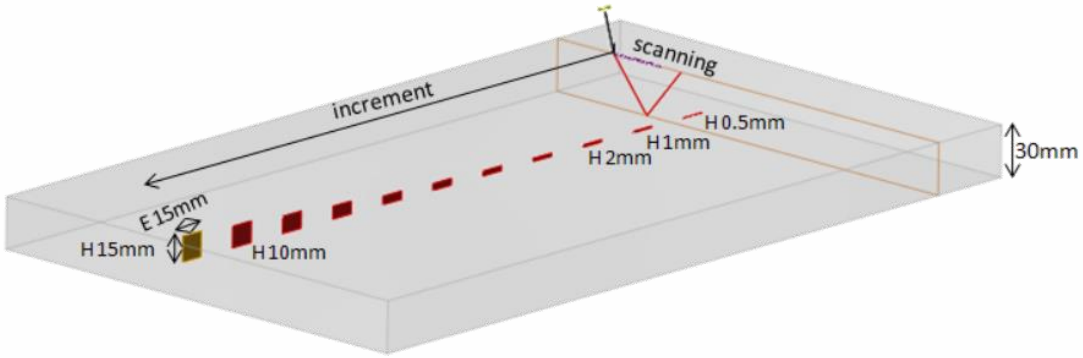
- Finite Element mesh automatically generated from flaw geometry and surrounding grid

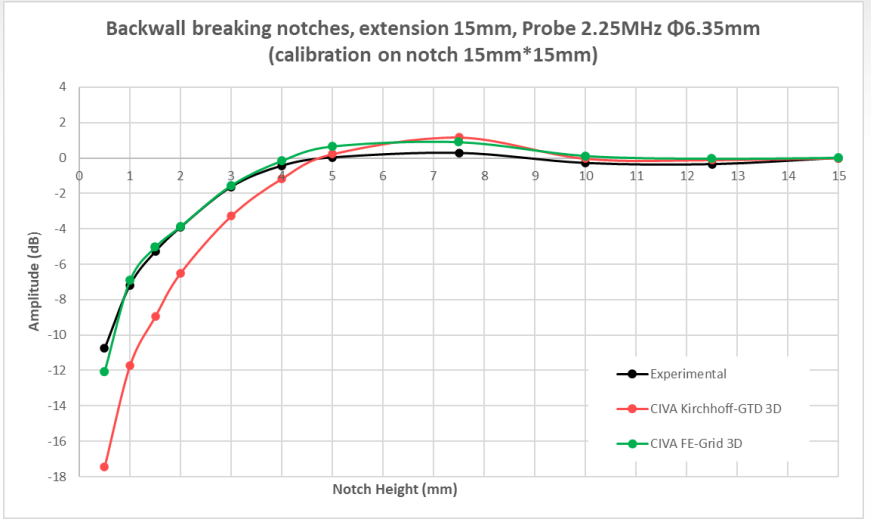


- FEM computations can be made in 2D or 3D

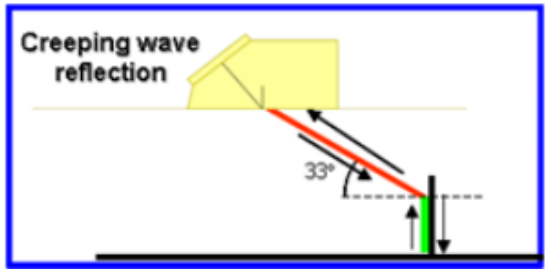
Hybrid Models in UT : SA - FEM

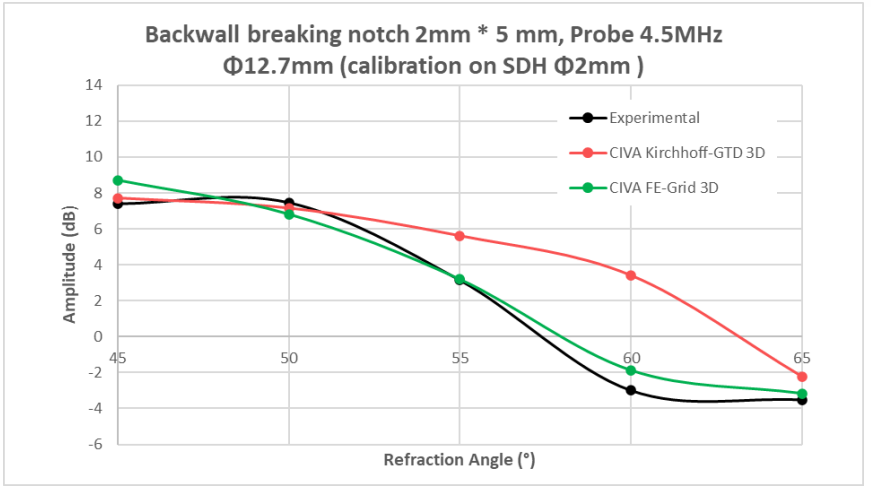
- Hybrid models in CIVA UT:
  - Increased accuracy with Hybrid TFEM CIVA model compared to Kirchoff-GTD one*
    - For small notches with respect to wavelength :





    - For complex waves phenomena around critical angles



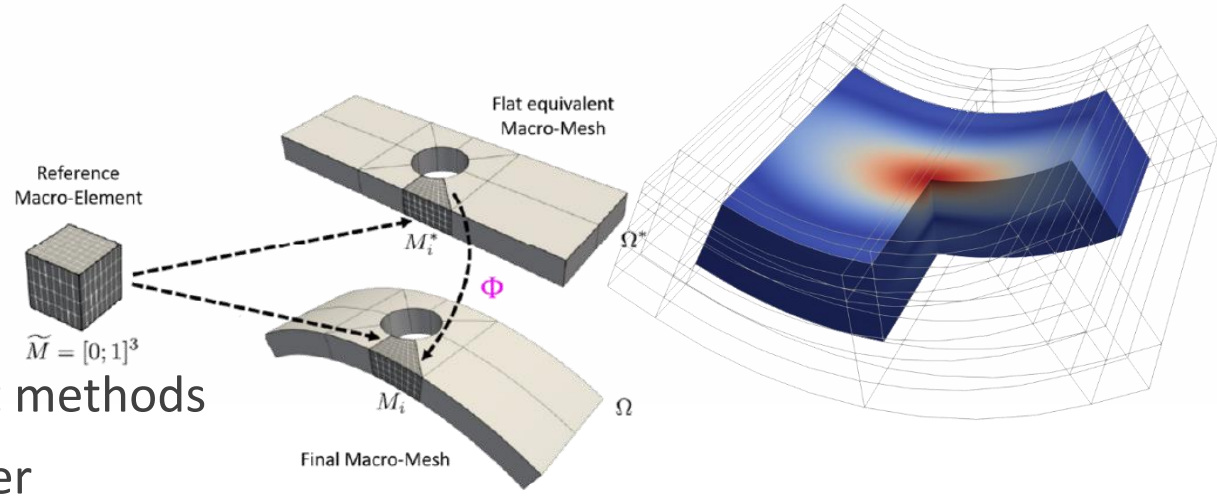


*for more info, refer to CIVAUT
Validation pages on www.extende.com

EXTENDE CIVA

Finite Element Models in UT

- 2D/3D Custom Finite Elements for Ultrasonic Inspection models in CIVA:
  - Which cases ? When the whole sound beam propagation benefits from a Finite Element model
    - Complex propagation media (very heterogeneous structure)
    - Specific configurations (Transmission, creeping waves at entry surfaces, etc.)
  - Which purpose:
    - Qualify “standard” CIVA models
    - Supplement them in critical cases
  - Based on High Order Spectral Finite Element methods
  - Still no need to manage the mesh for the user
  - Compatible with a standard PC, competitive performances for a full FEM solution

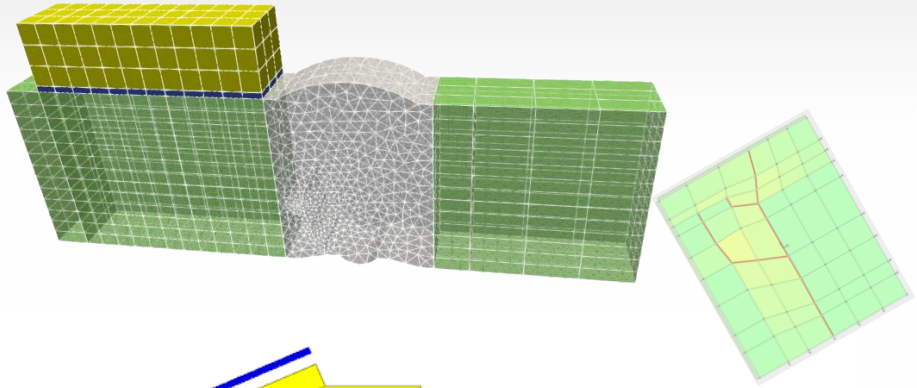


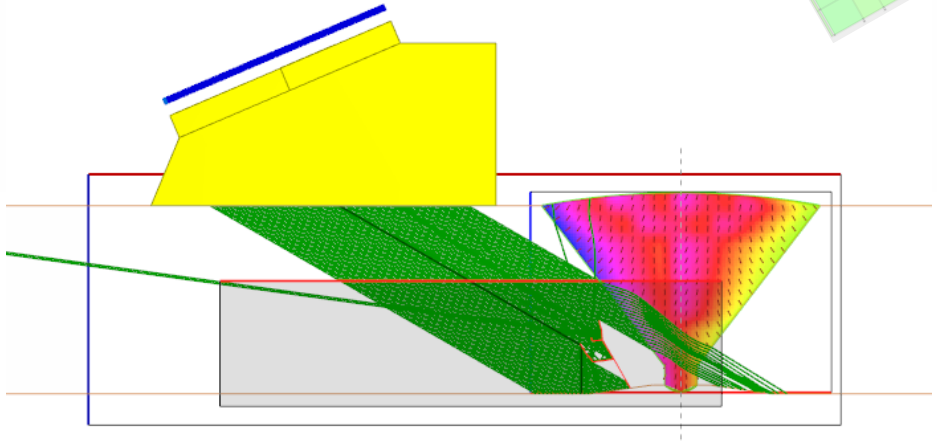
1st version of CIVA UT FEM available in the upcoming release (end of 2024)

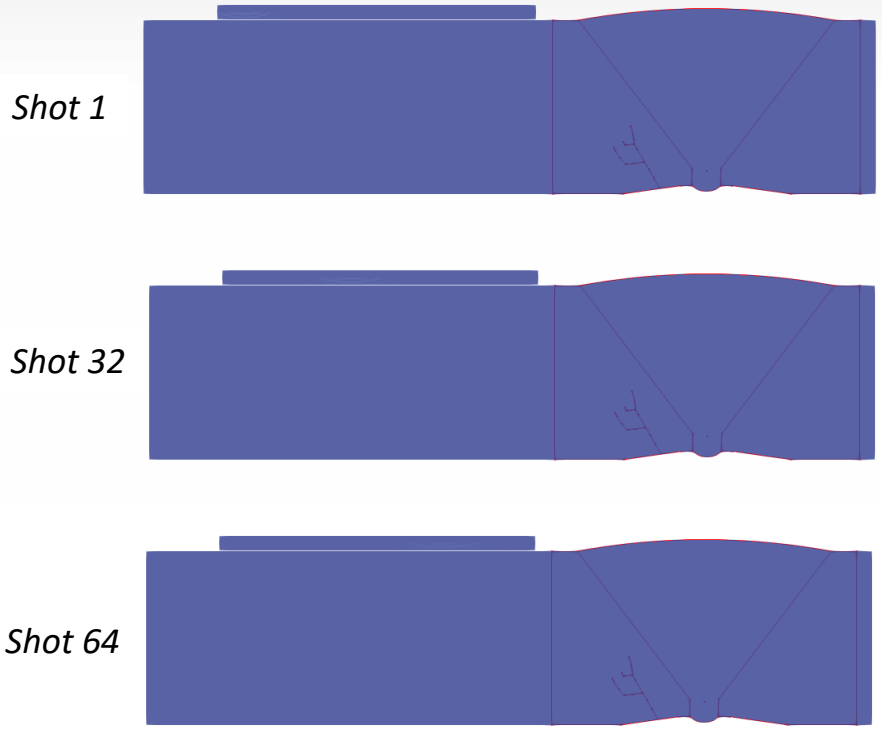
Already implemented for CIVA SHM

Finite Element Models in UT

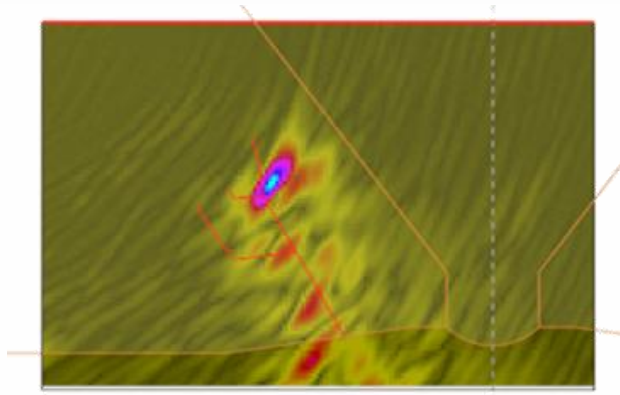
- 2D/3D Custom Finite Elements for Ultrasonic Inspection models in CIVA:
  - Applications: Austenitic Weld Inspection accounting for weld anisotropy and heterogeneities







FMC Simulation

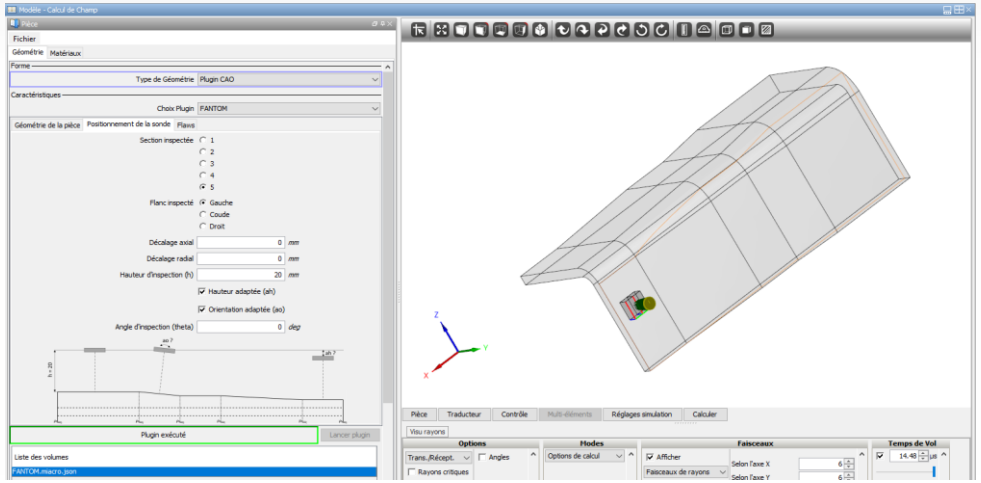


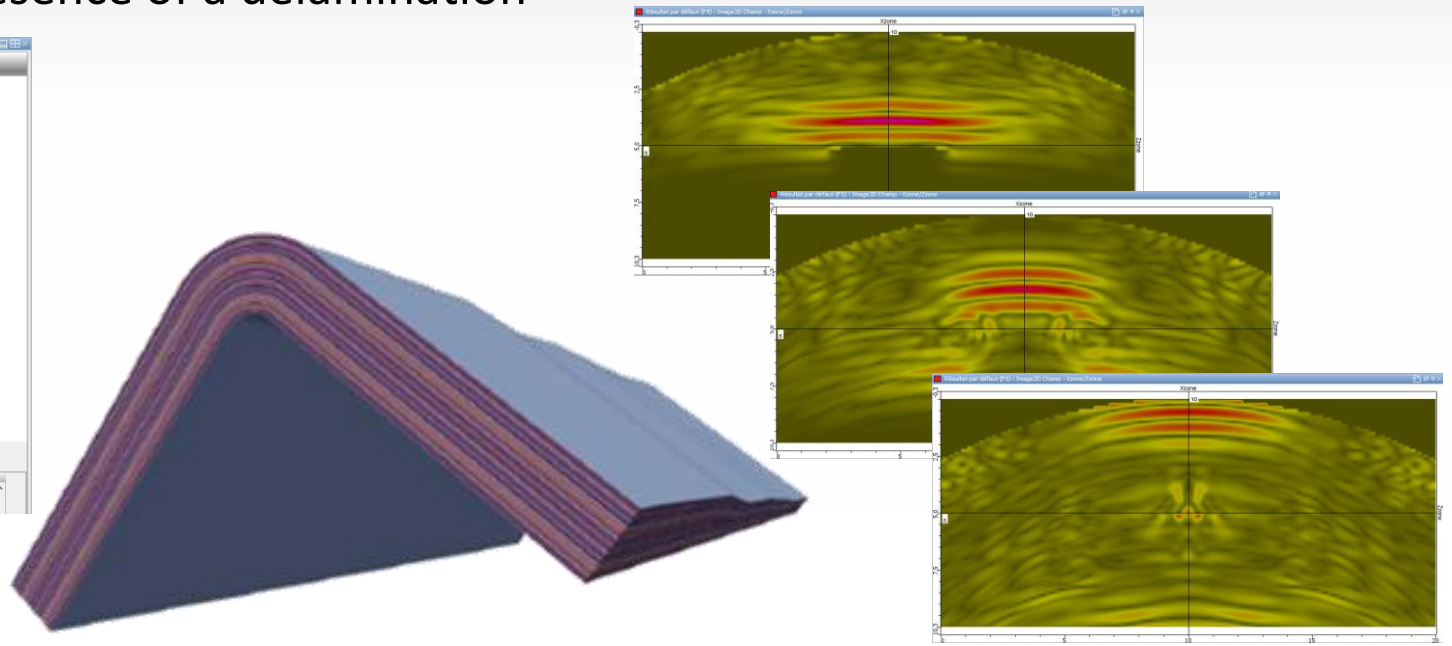
T-Scan (TFM image)
T-wave mode (2MHz)

EXTENDE CIVA

Finite Element Models in UT

- 2D/3D Custom Finite Elements for Ultrasonic Inspection models in CIVA:
  - Applications: L0 inspection of curved, stratified composites
  - Field and signal simulation in presence of a delamination





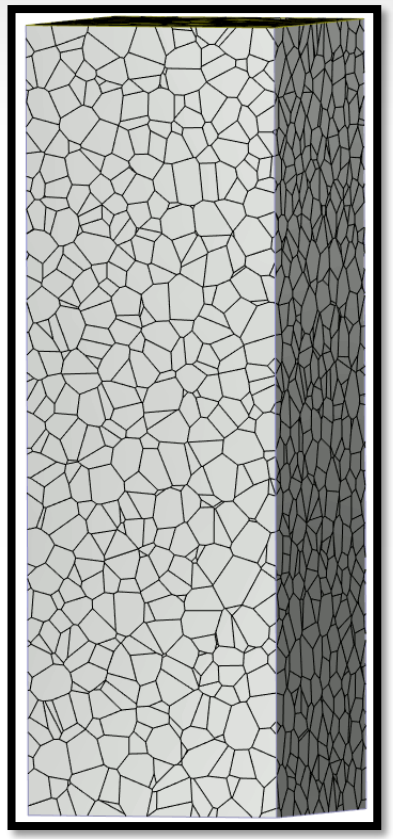
FANTOM
Flexible and Automated NDT plaTform fOr Manufacturing

IRT JULES VERNE

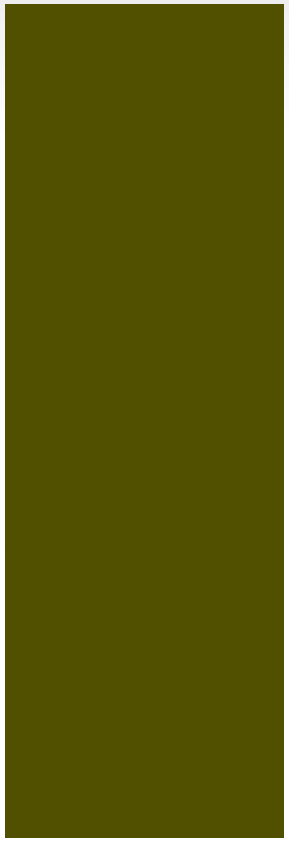
Stratified simulated sample & ultrasonic field snapshots in presence of a delamination

Finite Element Models in UT

- 2D/3D Custom Finite Elements for Ultrasonic Inspection models in CIVA:
  - Applications: Modelling the heterogeneous micro-structure of a concrete block

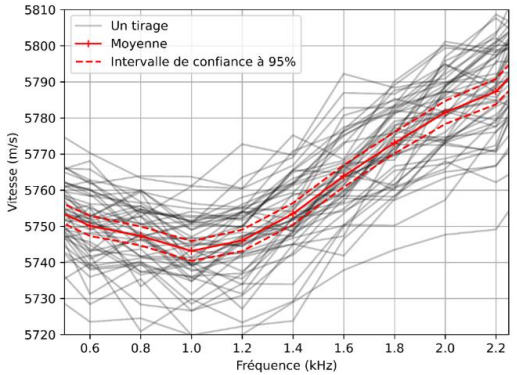


Random generation of parametric microstructures

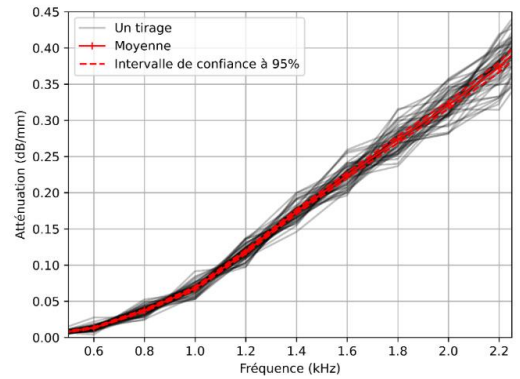


FEM simulation of planar wave propagation

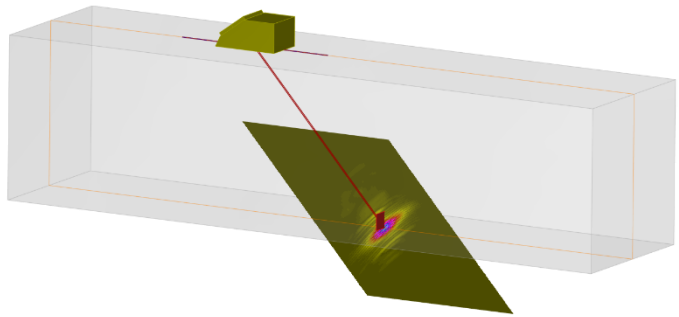
L-wave velocity diagrams



L-wave attenuation diagrams



Automatic post-processing for characterization



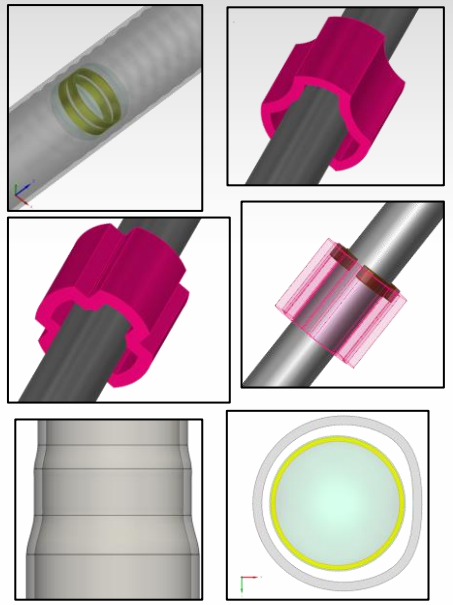
Import of equivalent material properties for fast simulation with SA models

Finite Element Models…and out of CIVA UT ?

- In other CIVA modules, fully numerical models are also available:

ET Within CIVA **ET** :

- **SG Tube module** is based on 3D Boundary Element Method : Dedicated to Steam Generator Tubes Inspection (complex) use cases *(see. Pres. Edouard Demaldent Thursday Session)*



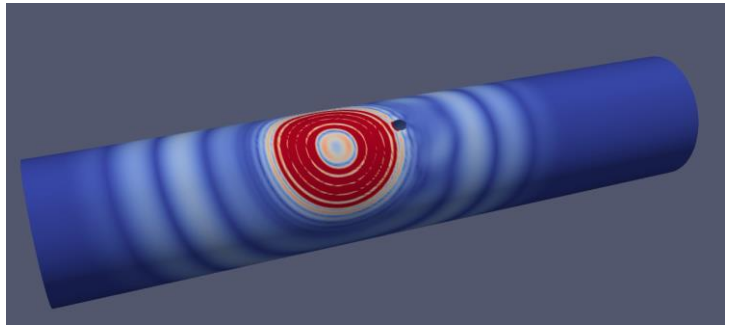
GWT CIVA **GWT**: « SA-FE » hybrid approach

Finite Elements in the guide section and in the beam/discontinuity zone

+

Semi-Analytical Propagation operator in the guiding direction

SHM CIVA **SHM**: Full 3D Spectral Finite Elements method



EXTENDE CIVA

Conclusion

- CIVA :
  - Well established solution for NDT simulation,
  - Recognized for its ability to **simulate efficiently a large scope of NDT applications**,
  - Result of a strategy that priorized semi-analytical models and continuous research efforts that pushes these models to its limits.

- To overcome potential limitations and provide reference results, CIVA now includes more and more tools based on fully numerical models such as **Finite Elements** or **hybrid approaches**

- CIVA also involves **metamodeling** capabilities:
  Physical models are then used to build surrogate models which provide real time simulation capabilities.

A key feature when massive data are necessary → **Data Science** and IA applications