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Application of simulation software for NDT in Civil Engineering

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Abstract

Simulation is a powerful means in the design of inspection methods. It minimizes the number of iterations when building probe prototypes, optimizing inspection techniques and defining the test procedures. It is known to be valuable in supporting performance and reliability demonstrations requiring a lot of data (e.g., POD studies and qualification campaigns), where simulation can reduce the number of necessary mock-ups and experimental trials. Largely used in different industrial sectors, there is still great potential for NDT modelling remaining in the civil engineering field. The aging infrastructures, and the increasing needs for reliable evaluations of structural integrity require deeper investigations and developments, in which modelling can be of great help.

The CIVA platform is a well-established multi technique simulation and analysis software in NDT. Developed by CEA LIST, but also resulting from the contribution of numerous industrial and academic partners within Europe, it implements concepts of numerical efficiency, imaging, and reliability demonstration. The range of NDT methods in CIVA includes UT, GWT, ET, RT, CT, Thermography and is extended to Structural Health Monitoring applications based on guided ultrasonic waves.

In addition to physical models dedicated to metallic inspections largely used in the industry, CIVA offers the capacity to simulate ultrasonic inspections in other media such as concrete. It has recently included the definition of probes polarized to generate shear waves at 0°, thus capturing the current state-of-the art for concrete inspections. This contributes significantly to the potential for studies and inspection planning in the field of concrete inspections, which helps tremendously in ensuring reliable inspections. While such studies would require enormous computational effort for most other simulation techniques, the semi-analytical approach of CIVA makes it highly efficient and application oriented.

This paper illustrates models available in the ultrasonic module of CIVA and best practices for application cases in civil engineering.

Keywords: Simulation, Modelling, UT, Concrete.

1. Introduction

The aging civil-engineering infrastructure requires a large increase of non-destructive inspections to be performed worldwide in order to assess the structural integrity of assets and prioritize replacements and repairs. Therefore, there is a strong need for reliable NDE techniques, which need to be developed or adapted to the specific applications. A sound inspection design needs preliminary tests and investigations to select efficient technologies and methodologies, while reliability studies rely on large data sets to establish valid statistical evaluations. In both situations, the cost of concrete test blocks and the many different damage scenarios that can occur in daily inspection life make it difficult and costly to conduct the NDE development process purely based on experimental tests. Modelling can be of great help in this context by minimizing the number of iterations when designing inspection procedures, assessing inspection feasibility virtually before selecting inspection devices, or reducing the number of necessary mock-ups and experimental trials for performance demonstration purposes. Largely used in different industrial sectors, there is still great potential for NDT modelling and simulation in the civil engineering field. In particular, when modelling tools can offer efficient numerical methods to simulate inspection situations with fast computation times, it can dramatically reduce the time to market and give the possibility to explore greater numbers of testing and damage scenarios than other approaches.

This paper illustrates the use of modelling and simulation for Non-Destructive Evaluations on concrete or metallic civil engineering applications.

2. Modelling techniques and tools available

The CIVA platform is a well-established multi technique simulation and analysis software in NDT [1]. Developed by CEA LIST, but also resulting from the contribution of numerous industrial and academic partners within Europe, the range of NDT methods available in CIVA includes UT, GWT, ET, RT, CT, Thermography and is extended by Structural Health Monitoring applications based on guided ultrasonic waves. All these modules are available in the same environment, bringing to the users a unique NDT oriented Graphical User Interface.

The mathematical formulations used in the different modules often rely on semi-analytical models. This approach allows for solving a large range of applications while offering very competitive calculation times compared with purely numerical methods (FEA, etc.). For instance, most of the modelling configurations available in the UT module will rely on a geometrical ray approach to compute beam propagation (the so-called “pencil method”). The interaction with discontinuities involves several models depending on the context. Some of them rely on semi-analytical or analytical formulations, the “Kirchhoff” or “GTD” (which stands for “Geometrical Theory of Diffraction”) models can be mentioned but other ones have also been implemented to cover several configurations [2]. The current trend is to implement hybrid approaches where semi-analytical methods are used in conjunction with a transient Finite Element Method (FEM). The in-house FEM implemented in CIVA is based on spectral high–order element techniques using mass-lumping which allows to reach very good performances compared to generic FEM solvers [3].

Regarding the UT modelling of concrete structures inspection, a homogenization method is currently available in CIVA and is compatible with semi-analytical models. The concrete medium is defined by a distribution of aggregates of different sizes included in a matrix (cement). Knowing acoustic properties of the cement and individual aggregates, a homogenization algorithm based on the Waterman and Truell [4] model is then used to compute effective velocities and attenuation laws for an equivalent homogeneous medium in terms of sound propagation. Structural noise based on a single scattering computation can be included [5]. This approach gives the possibility to simulate concrete inspections in a few minutes relying on the semi-analytical models available in CIVA. The use of transient elastodynamic FEM solvers for concrete is also being developed and is detailed in another communication presented in this conference [6].

The X-ray and Gamma-ray module uses a "rays" approach associated to the Beer-Lambert straight line attenuation model to compute direct radiation. The scattering radiation is solved thanks to a probabilistic approach (Monte-Carlo method) allowing reproducing photons/matter interaction phenomena (Compton diffusion, Rayleigh diffusion, Photo-electric absorption, pair creations) based on the knowledge of cross-section data, available thanks to an extensive material database. Based on a set of RT projections, CIVA also includes Computed Tomography 3D algorithms such as FdK, PixTV and SART. Finally, models dedicated to films and detectors are used to predict the actual RT image. CIVA RT can be applied for metallic or concrete inspection simulations. For concrete application, let's mention the following papers [7], [8].

3. UT inspection of Concrete Structures: Semi-analytical Modelling

3.1 Homogenized concrete block properties

To implement the homogenized approach described above, it is necessary to define the concrete sample in terms of geometry (planar, cylindrical, CAD), dimensions, and aggregate/cement acoustic properties. A planar block of 300 mm thickness has been defined here including 73% density of aggregates (distributed from groups of 0.125 mm to 16 mm diameters). Acoustic properties are defined by entering the density (2.5 g/cm^3 for aggregates and 1.9 g/cm^3 for cement), and the longitudinal waves (4110 m/s for aggregates and 3500 m/s for cement) and shear waves velocities (2770 m/s for aggregates and 2310 m/s for cement) of the components of the sample. The Waterman and Truell is then enabled to compute effective acoustic properties (density, velocities and attenuation) for an equivalent homogenous medium. As shown on Figure 1, a density of 2.34, and L-waves and S-waves velocities of respectively 4005 m/s and 2642 m/s are obtained here.

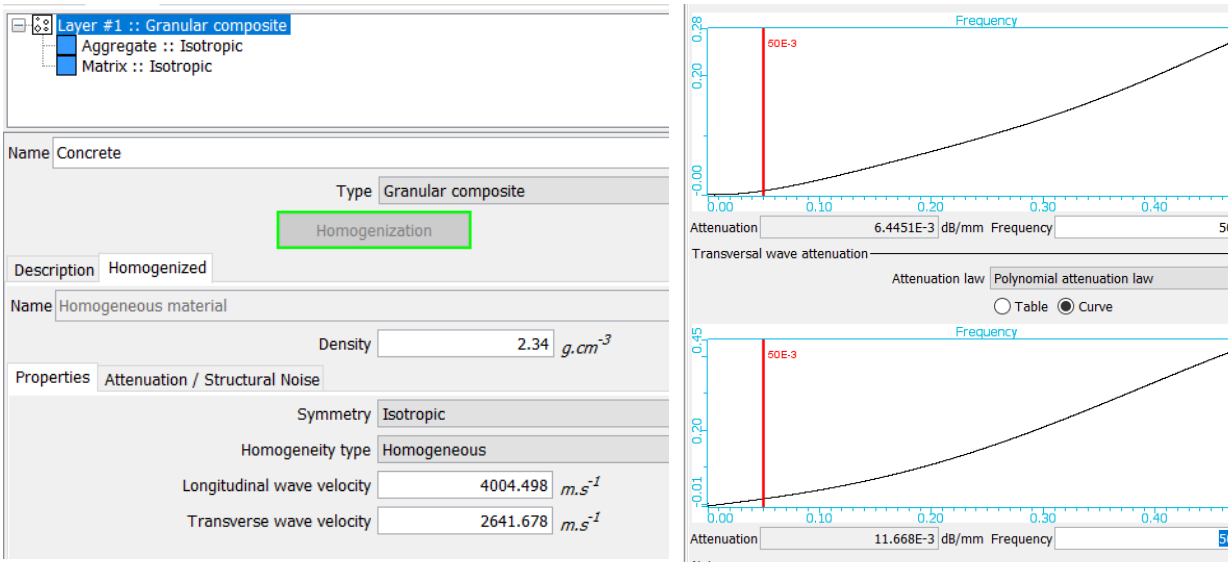

Figure 1: Concrete acoustic properties obtained after homogenizing initial input parameters

3.2 *Probe selection*

Simulation gives the possibility to easily compare various types of UT transducers to estimate the most suitable one for a given inspection. 3 probes have been first tested: a longitudinal wave single element probe made of a 37 mm diameter circular piezoelectric element working at 54 kHz (Proceq 325-40-131 reference); a dry point contact single element probe (2 mm diameter), operating at 50 kHz for which the polarization leads to the generation of shear waves propagating in a normal direction from the front surface (Proceq S1802 reference); and a dry contact 0° shear waves multi elements probe made of 3*6 elements (2 mm diameter each) and separated by 25 mm gap, also operating at 50 kHz (Proceq PL200 reference). Sound beam charts can be computed as illustrated on Figure 2. It shows very divergent shear wave probe beams. Sound beam amplitude versus sound path length can also be plotted.

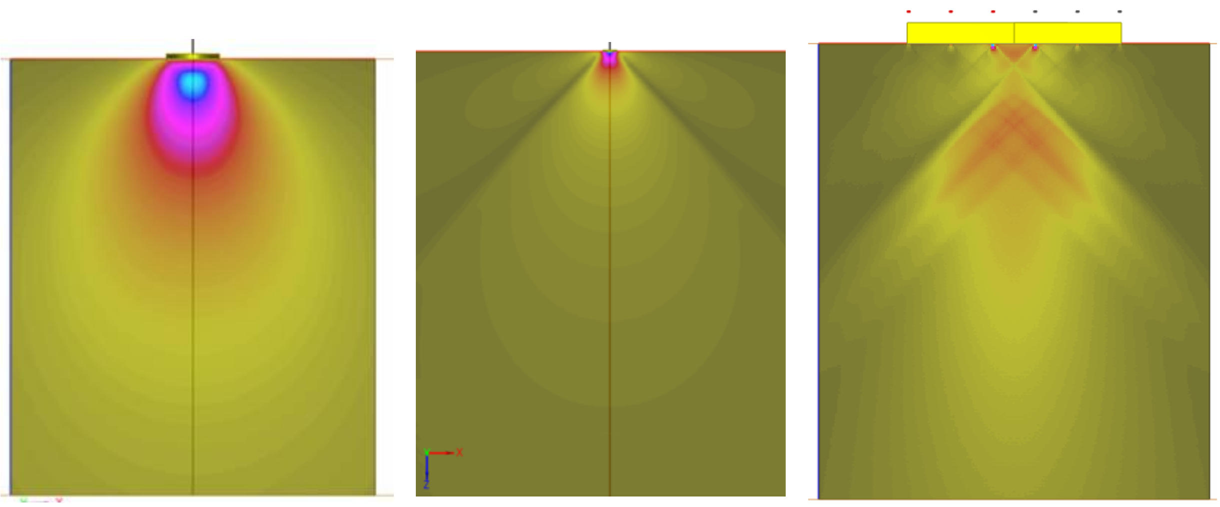

Figure 2: Ultrasound beam mapping for different probes (from left to right: L0° probe then S1802 and PL200 shear waves 0° probes)

The response of different defects can be simulated, such as crack-like defect shapes, delaminations, porosities or inclusions. The response of a 40 mm diameter spherical flaw located at 200 mm depth has been first tested with the 3 probes presented above. Modelling allows predicting the obtained echo and quantifies its amplitude versus a reference one, for instance the backwall echo amplitude. Obtained B-Scans and A-Scans views are represented on Figure 3 showing that the L-wave probe could not detect the flaw in this case (mainly due to a too narrow bandwidth) while dry-contact S waves probes show a clear echo separated from the back wall one (amplitudes around -16dB compared to the backwall echo). The defect can be also identified thanks to the shadowing impact it produces on the backwall echo, causing the amplitude of the back wall echo to be reduced at the location of the flaw.

“Honeycomb” defects in concrete structures can be modelled by simulating the response of a distribution of small spherical flaws [9]. In the following case, a set of seven 12 mm spherical flaws randomly distributed in a given area (still around 200 mm depth) has been defined in the CIVA model. Compared to the previous case, a weaker signal is obtained even if echoes can still be distinguished from the backwall echo with an amplitude of about -23dB versus the backwall echo (see Figure 4).

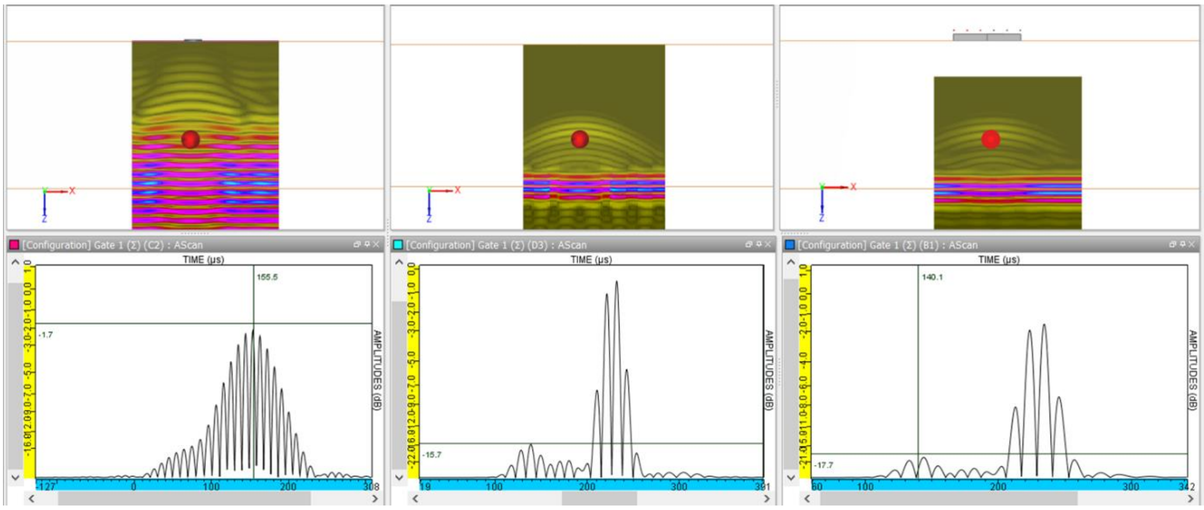

Figure 3: B-Scan images (at the top) and A-Scan signals when probe above defect location (at the bottom) for 3 ultrasonic transducers (from left to right: L0° probe, S1802, PL200 shear waves 0°)

Implementing structural noise in the model is feasible, although it may lead to more computationally intensive models; depending on the specific purpose, it might be more efficient to use experimental data to assess noise level. The detectability of target flaws can be predicted from the model knowing the ratio between the noise level and a reference echo, for instance obtained on a calibration reflector or the backwall echo, which can be directly included in the model. It is also possible to mix simulated data generated for different flaw response scenarios with an experimental scan obtained on a free flaw component or with a synthetic noise generator to efficiently produce a set of realistic hybrid images inside a UT analysis environment. You can refer to the following paper that illustrates the use of this concept in the CIVA analysis environment [10]. CIVA simulation data can be also exported in another analysis tool such as the Echolyst software [11, 12], which is commonly used for concrete inspection applications, as seen on Figure 5. This compatibility allows for data analysis in the same environment as used for practical applications, providing a realistic inspection scenario and allowing to apply all the familiar analysis features.

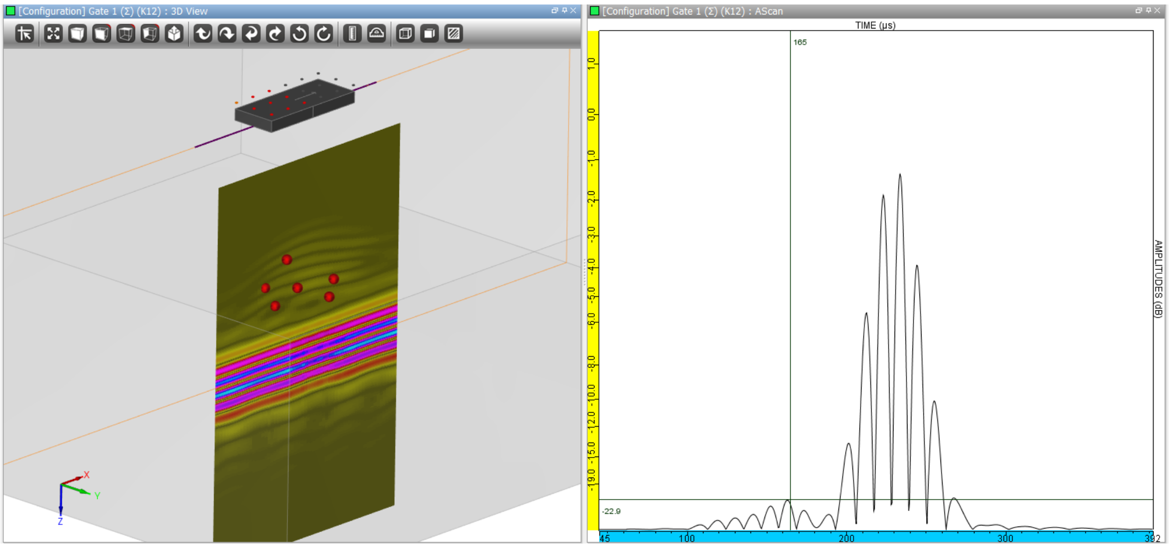

Figure 4: Model of a honeycomb defined by a set of 7 spherical flaws of 12 mm diameter each. Simulated B-scan (at the left) and A-Scan at the location of the max defect signal (at the right).

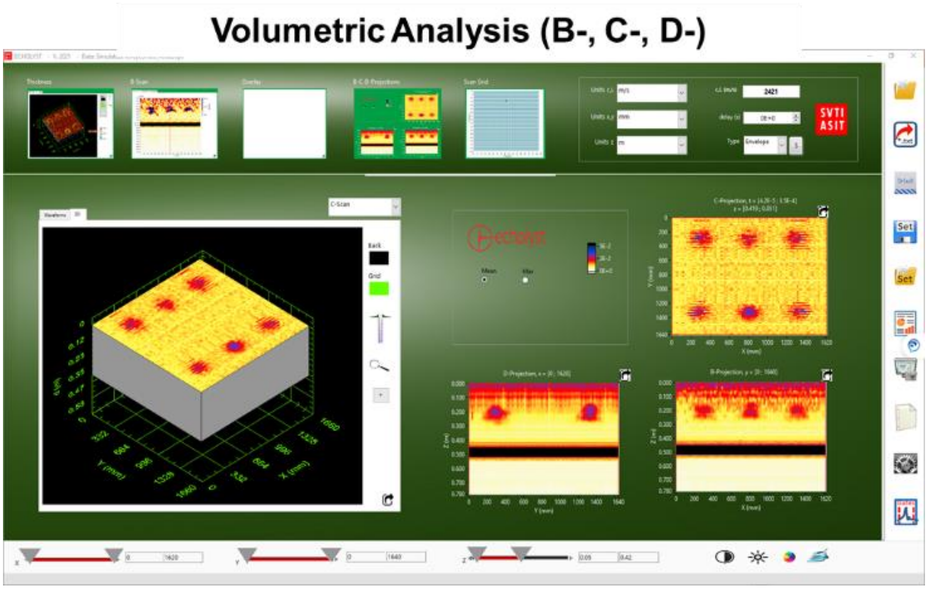

Figure 5: CIVA simulation data exported in Echolyst analysis software.

3.3 *Impact of steel reinforcement*

The presence of metallic reinforcement bars in a concrete structure can decrease the detectability of potential flaws for NDE inspections. Modelling and simulation are highly valuable especially in planning structural inspection tasks to assess the case-specific detectability and potentially adapt the inspection technique accordingly. The following maps show results obtained by simulating the same honeycomb defect in 3 situations: no rebars, defect located between rebars, defect located directly under rebars. As seen on Figure 6, the rebars clearly affect the signal amplitudes and might hide the defect depending on the flaw locations.

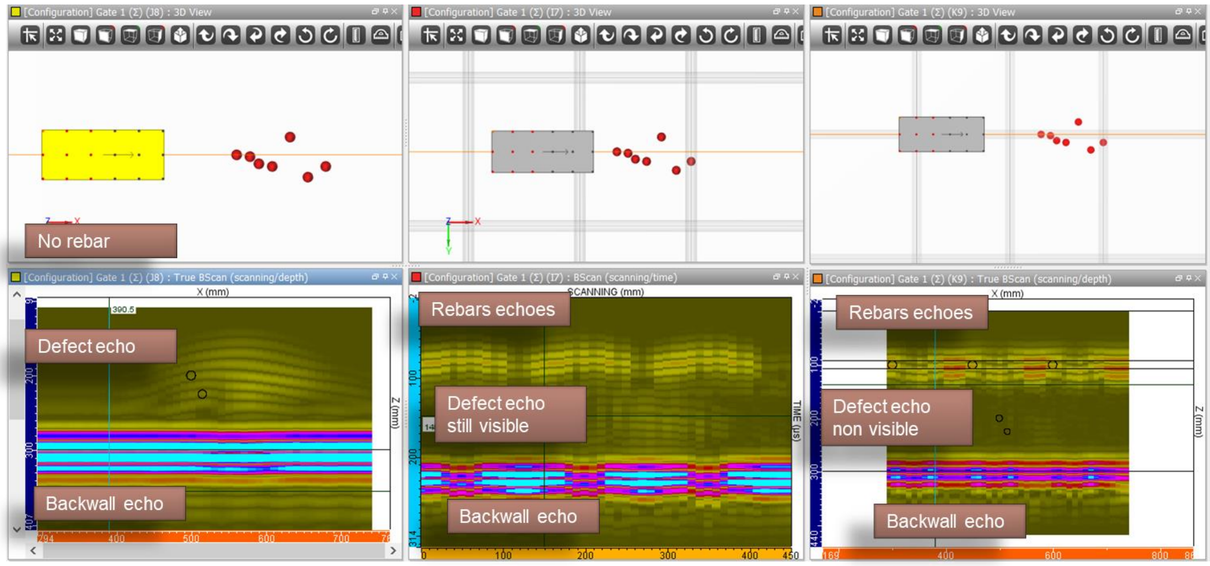

Figure 6: Simulations of defect responses without/with reinforcement steel bars.

3.4 Modelling for extensive parametric studies

Simulation tools become particularly valuable economically when several scenarios have to be investigated because the costs of experimental trials and physical mock-ups become prohibitive. Varying parameters can allow to find the ones that impacts the most the inspection results and it can be tried to optimize flaw detection or characterization techniques for different specimen/defect scenarios. Such variation studies can also help to track worst case situations and evaluate the reliability and efficiency of an inspection process. CIVA implements tools to easily monitor variation studies. As several parameters are often involved and can have combined influences, so called “interactions”, it can be interesting and necessary to perform multiparametric designs of experiments. Such studies could lead to a prohibitive computational cost for models relying on heavy numerical approaches. Semi-analytical models available in CIVA as well as metamodeling techniques allow to overcome this issue in many situations. A design of experiment grouping 3 parameters has been performed on the example introduced above with the PL200 probe and the honeycomb flaw mode1: Variation of defects depth (“Z” parameter, from 100 mm to 200 mm), flaw size (“radius”, from 2 to 10 mm) and flaws density (“K” parameter) for the spherical flaws constituting the honeycomb. 200 simulations have been performed which took just about 4 hours and a metamodel have been generated from this database. Figure 7 shows the impact of spherical flaw sizes on the amplitude response. As a multiparametric study has been performed and a metamodel obtained, it can be analysed for any other values of defect depth and density (illustrated here for instance at 100 mm where a flaw size increase between 2 mm and 10 mm leads to a +15dB amplitude, while at 200 mm depth the same variation leads only to +11dB increase).

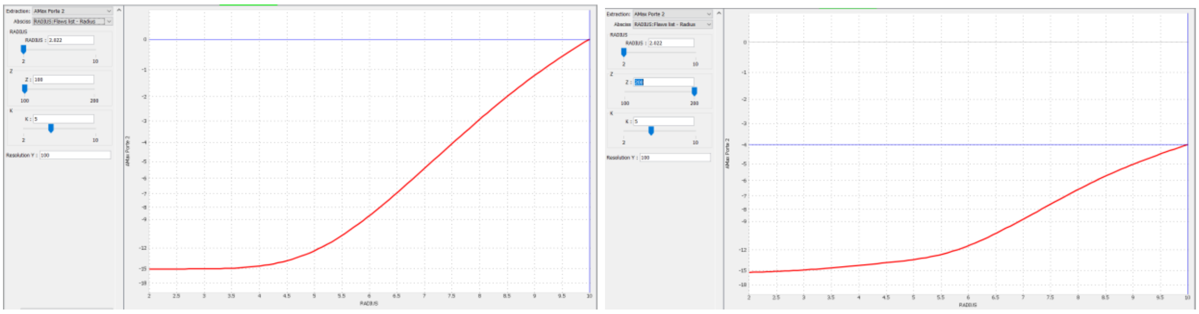

Figure 7: Impact of spherical individual flaws size increase on the honeycomb amplitude response.

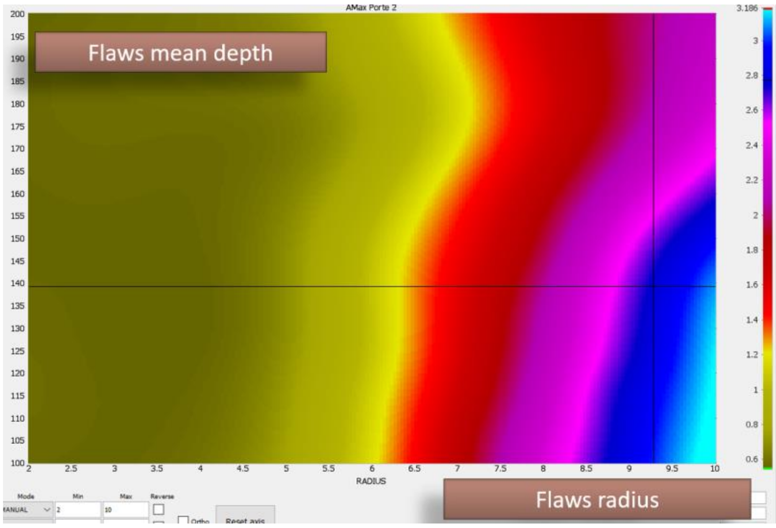

Figure 8: Joint influence of flaw size and depths variation on the signal amplitude observed on a 2D-plot obtained by metamodeling

2D plots can also be displayed, the joint influence of 2 parameters (for instance depth and size in Figure 8, the colour representing the signal amplitude) can then be observed at a glance. Parallel plots can be also extracted to track worst case or best-case scenarios assuming a certain statistical variability on the input parameters. To track the most influential parameters, Sobol indices diagrams are also available. In this case, the impact of these 3 parameters have been evaluated for both dry contact probes: PL200 and S1802, see Figure 9. While the defect size (blue area) is the most influential parameters for both cases, the S1802 sensitivity seems to be notably more impacted by the flaw depth (green area) than PL200, probably due to a stronger beam divergence.

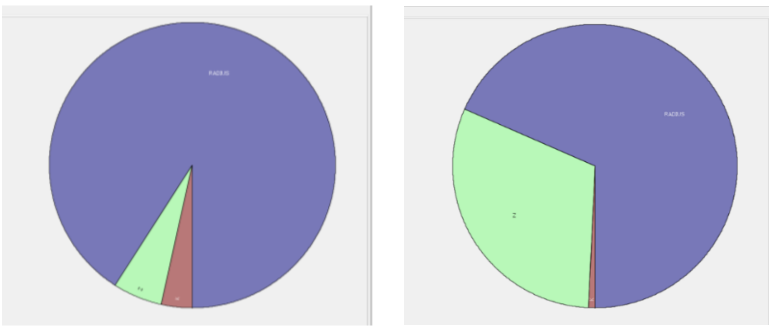

Figure 9: Sobol indices diagrams showing the shared influence of defect radius (in purple), depth (in green) and distributions (brown) on the signal amplitude for PL200 (left) and S1802 probes (right).

One indicator to assess the reliability of an NDT inspection is the so-called Probability Of Detection curve that plots the probability to defect a flaw versus its size accounting for the variability of influential parameters. To be statistically valid, this type of indicators needs large datasets, and it actually often suffers from a lack of data if a pure experimental approach is used. Modelling allows overcoming this sampling problem. Such a data set has been generated in our example and assuming a certain decision threshold (here 24dB below the back wall echo amplitude), a POD curve could be easily derived showing that the defect size for which a 90% probability of detection with 95% confidence level is obtained when the spherical flaws that constitutes our honeycomb defect are about 6 mm radius.

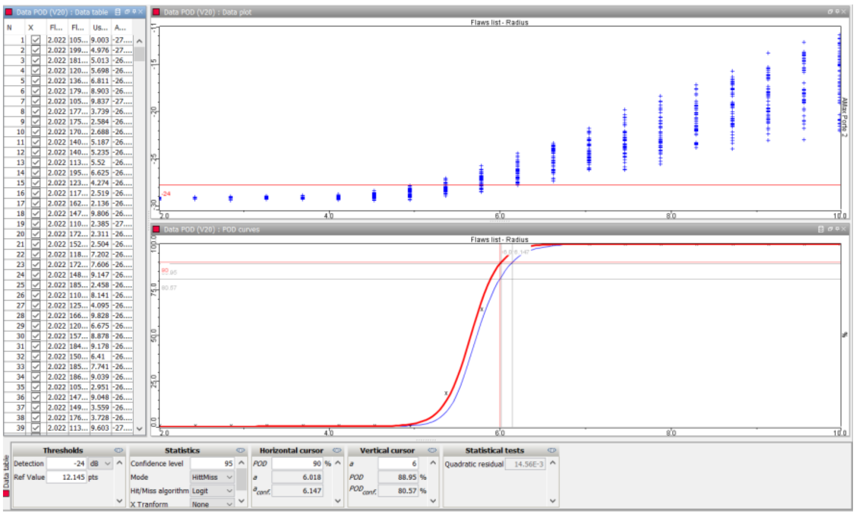

Figure 10: POD curve obtained from simulation.

4. Application case: CIVA UT for metallic inspections

CIVA UT is a well-established modelling tool for metallic parts inspection. Regarding applications in Civil Engineering, CIVA UT was involved in a benchmark proposed by the KINT society in 2016-2017 and dealing with the inspection plan for the RWS bridge deck welds (Trog-Rijdek Las Scheuren). The targeted flaws in this carbon steel structure and weld were a Lack of Penetrations at the weld root and surface breaking cracks located as per shown in Figure 11. The inspection technique proposed was a Phased-Array UT sector scanning using a 5MHz linear array probe mode of 16 elements (pitch is 0.6 mm).

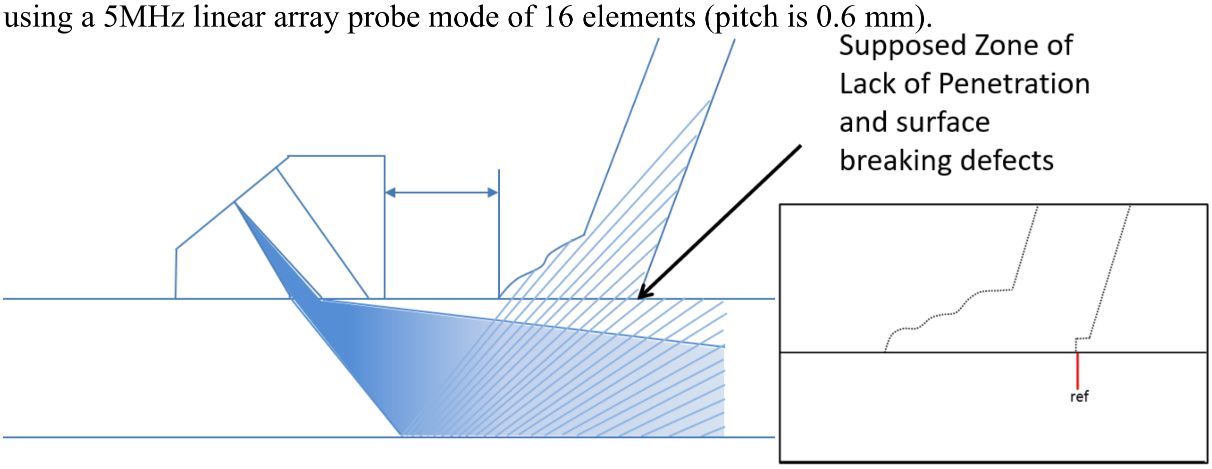

Figure 11: Inspection plan for RWS bridge deck

The scanning covered an angular sector of 30° to 85° to reach the targeted zone with a full skip inspection mode. Beam coverage could be predicted by simulation. The cumulated field for the full angle range in the inspection plane as well as the 45° spot in the incidence and perpendicular plane are displayed on Figure 12**,** showing a large zone coverage and a beam spot of 4 mm*5.5 mm at -6dB in the weld area. Three defect scenarios were simulated (2 mm and 4 mm flaw height with a tilt angle of 73° and another 4 mm flaw located at the other side of the weld, resp. "A", "B" and "C"). All results have been normalized versus the tip diffraction echo obtained on a 2 mm surface breaking flaw in a planar block.

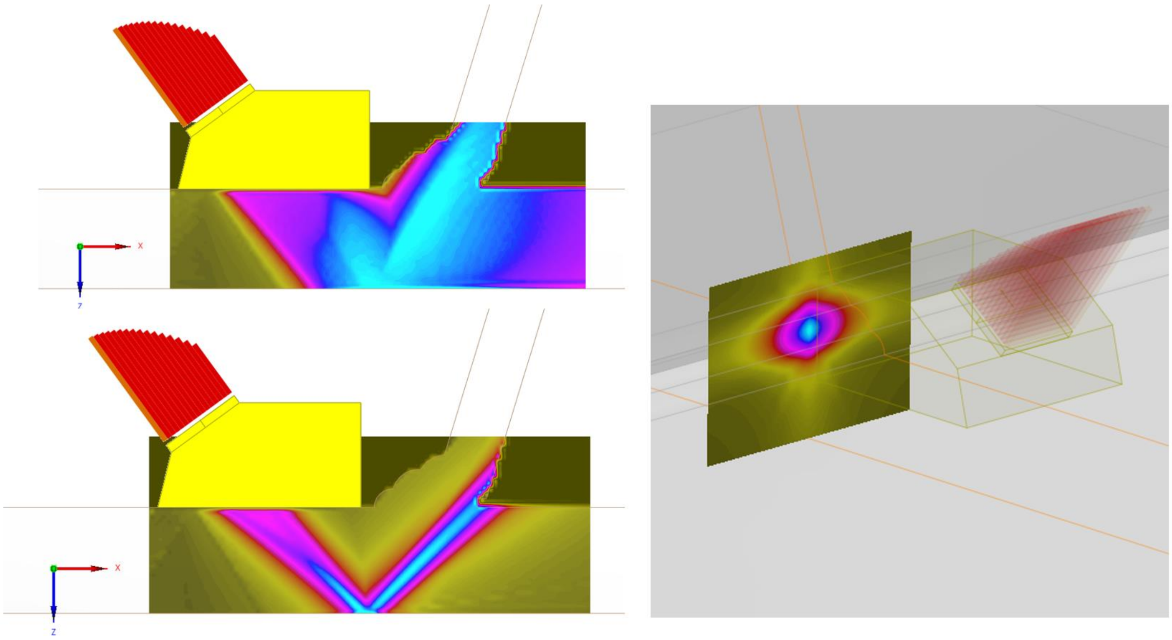

Figure 12: Beam coverage and beam spot characteristics

As shown on Figure 13, the obtained S-Scan images show different types of echoes: Echoes generated at the lack of penetration, echoes from the lower tip of the cracks and other indirect echoes due to additional skips in the weld. Maximum amplitudes obtained in each case were mainly in the range of 80% to 120% compared to the reference echo which allows to predict detectability of such flaws, provided that signal to noise ratio could be evaluated compared to the reference echo. Such modelling results generally needs less than one hour to be computed in 3D, leading the possibilities to explore a large scope of scenarios to optimize inspections set-ups or predict worst case situations.

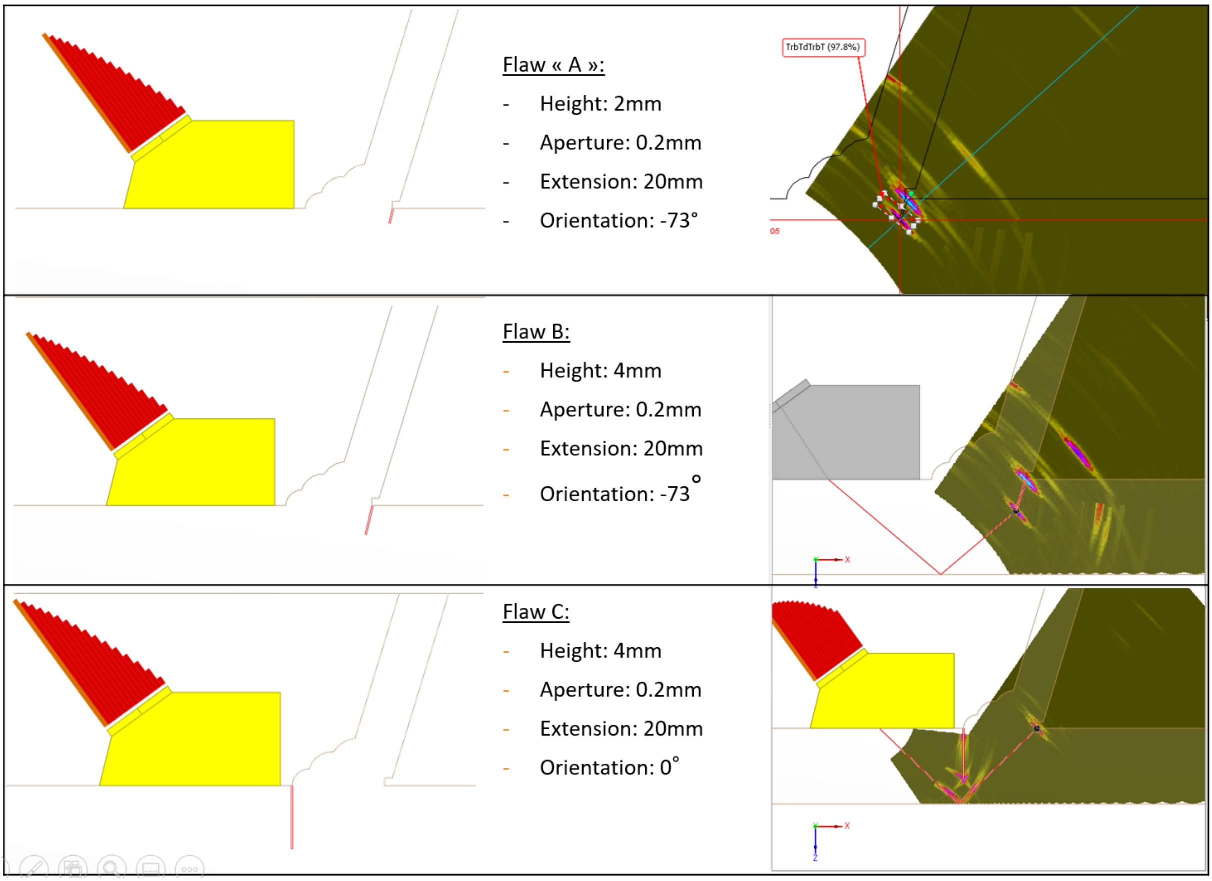

Figure 13: Simulated Defect scenarios and obtained sector scans

6. Conclusions

Modeling and simulation are known to be a powerful methodology, especially in the field of NDT. In this paper, the capabilities of CIVA, as they have been proven in other fields of NDT for a long time, have been demonstrated for applications of NDT in civil engineering and for concrete structures, specifically. In particular, the newly developed feature in CIVA of modelling horizontally polarized Zero-degree shear wave probes, means a significant achievement for concrete applications, as it reflects the state-of-the-art inspection techniques. This provides an important basis for the application of modelling and simulation for the validation of NDT techniques, inspection planning and feasibility studies.

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