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Results of the 2013 UT Modeling Benchmark Obtained with Models Implemented in CIVA

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Abstract. The 2013 Ultrasonic Testing (UT) modeling benchmark concerns direct echoes from side drilled holes (SDH), flat bottom holes (FBH) and corner echoes from backwall breaking artificial notches inspected with a matrix phased array probe. This communication presents the results obtained with the models implemented in the CIVA software: the pencil-model is used to compute the field radiated by the probe, the Kirchhoff approximation is applied to predict the response of FBH and notches and the SOV (Separation Of Variables) model is used for the SDH responses. The comparison between simulated and experimental results are presented and discussed.

Keywords: Ultrasonic Benchmark, Phased Array Probe, UT Simulation, Kirchhoff, SOV

PACS: 43.35.Yb

INTRODUCTION

This work is part of a campaign of systematic experimental characterization of the ultrasonic module of CIVA [1] allowing the simulation of a whole ultrasonic inspection. This validation campaign is carried out at CEA LIST in collaboration with Extende and all the results are published on the EXTENDE site [2].

For several years, the World Federation of NDE center, WFNDEC, at Iowa State University, proposes an annual benchmark study in which simulated results (in either ultrasonic or eddy current NDT configurations) obtained with various models are compared to experiments. This year, the UT configurations, are specifically dedicated to matrix phased array probes. The validations, involving 3D computations, concern both the delay laws computations and the simulation of the inspection of reference defects (FBH, SDH and notches) in pulse echo-mode. Experimental measurements were carried out at CEA LIST. The computations presented in this paper were performed using the version CIVA 10.1.

DESCRIPTION OF THE 2013 ULTRASONIC BENCHMARK

For a complete description of the studied configurations, see [3]. The measurements were performed on 3 steel planar mock-ups: one with $\varnothing 2$ mm side drilled holes embedded at different depths, one with $\varnothing 3$ mm flat bottom holes at different depths and one with vertical backwall breaking notches of various heights (Figure 1).

A 64 elements contact matrix phased-array probe with a wedge dedicated to generate 45° longitudinal waves was used (Figure 2). A 2D scanning of the probe was performed over each reflector. At each probe position, different focusing laws were applied: null delay law, several depths focusing with $L45^\circ$ deviation, 30mm depth focusing with a direction scanning from $L20^\circ$ to $L60^\circ$ (Figure 3). The delay laws, computed with CIVA10.1, were used both in measurements and simulations.

The wave forms received at each position of the probe have been stored (experimental Cscans) and the maximum amplitude of the rectified echo of each reflector is extracted. To check the experimental reproducibility, the experimental measurements were carried out several times (minimum 2 times for all the flaws); a maximum difference of less than 1dB was obtained.

As we have to compare experimental and simulated amplitudes, a reference amplitude A_{REF} , has to be defined for both. It corresponds to the maximum amplitude of the specular $L45^\circ$ direct echo obtained on a 2mm diameter SDH at 72mm depth. The measured relative amplitude A of a given echo, expressed in dB, is given by: $20 \log (A / A_{REF}) - (G - G_{REF})$, where G and G_{REF} are the gains in dB used during the measurement carried out respectively on the current reflector and on the reference reflector.

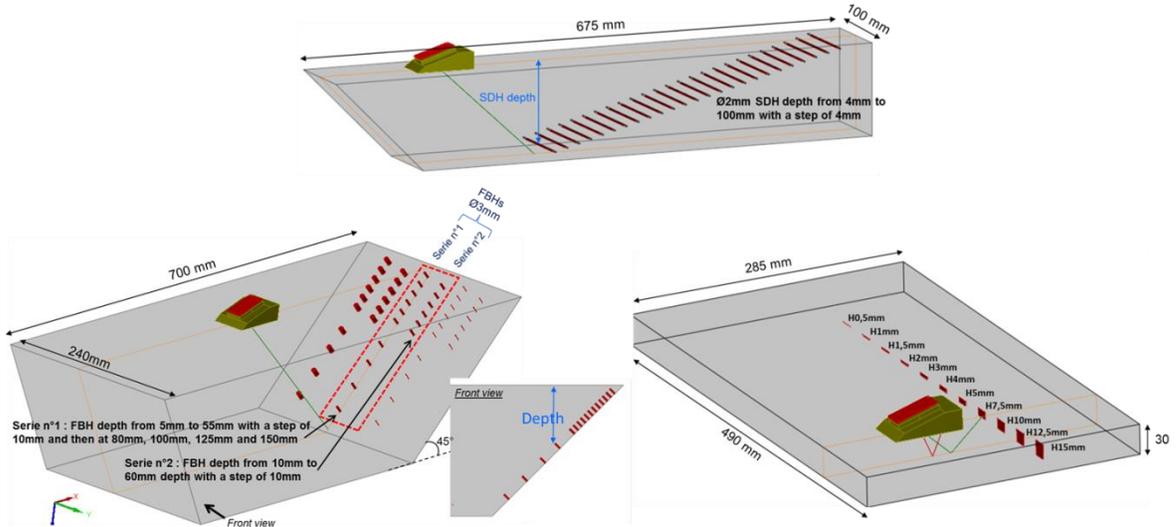


FIGURE 1. Mock-ups and defects implemented inside.

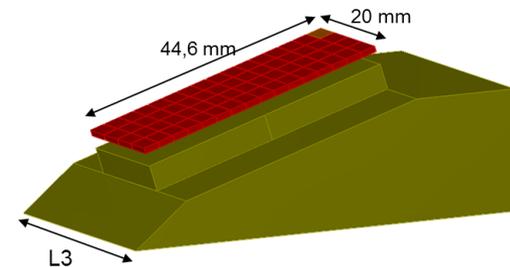
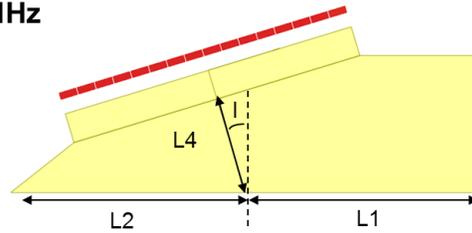
Matrix phased-array probe 16x4elts 2,25MHz

Transducer

- Aperture : 44,6mm (incident plan) x 20mm (perpendicular plan)
- Dimension of each element : 2,6mm x 4,85mm
- Gap between element : 0,2mm in the 2 planes

L45° Wedge

- Incident angle θ : 16,86°
- Wedge dimension :
 - L1 : 35mm
 - L2 : 35mm
 - L3 : 42mm
 - L4 : 14,52mm
- Wedge material :
 - Density : 1,05 g.cm⁻³
 - C_L : 2320 m.s⁻¹
 - C_T : 1160 m.s⁻¹



When computing the delay laws

- The 64 elements are active
- The probe was positioned over a ferritic steel block

FIGURE 2. Description of the matrix phased-array probe.

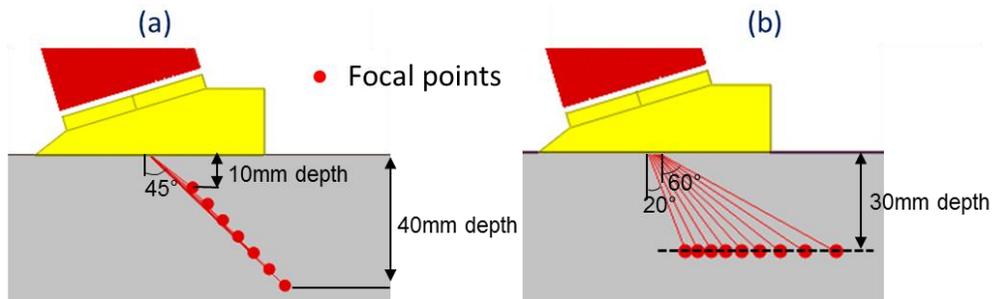


FIGURE 3. Delay laws: (a) Several focusing depths from 10 to 40mm with a L45° deviation; (b) Direction and depth scanning: deviation between L20° and L60° and focusing at 30mm depth.

A description of the models implemented in Civa for field and echo computations can be found in the literature [4] [5] [6] as well as the recent modeling advances performed in CIVA [7].

Amplitudes of the side drilled holes were calculated with the SOV model of echo-defect interaction while the Kirchhoff model was used for the calculation of the flat bottom holes and notches echoes. All the echoes computations were performed with Civa release 10.1.

EXPERIMENTAL VALIDATION PROCEDURE

The experimental validation process has been done following the recommendations of ref [8]. To describe the realistic configurations in CIVA, experimental measurements of some parameters were performed.

Regarding the specimen, the longitudinal (L) and transverse (T) waves velocities (V_L and V_T) have been estimated by measuring the time between successive backwall echoes. The velocities used for the computation in Civa are $V_L=5900\text{m/s}$ and $V_T=3230\text{m/s}$. The material homogeneity has also been checked by comparing the maximum of amplitude of the backwall echo measured at several positions of the probe. A 0.5dB maximal dispersion over all probe positions has been obtained.

Concerning the probe, the sensitivity measurement has confirmed that there was no dead element and the dispersion over the 64 elements was less than 3dB (Figure 5). The L and T wave velocity in the wedge has been obtained by measuring the time between successive geometrical echoes from parallel sides of the wedge. These values have been obtained: $V_L=2320\text{m/s}$, $V_T=1160\text{m/s}$. Then, to determine the incident angle α_i and the wedge height H_s , the wedge backwall echo has been measured for an electronic scanning using one active element (Figure 6). By measuring t_1 , t_2 and t_{moy} , these values have been obtained: $\alpha_i=16.86^\circ$ and $H_s=14.52\text{mm}$.

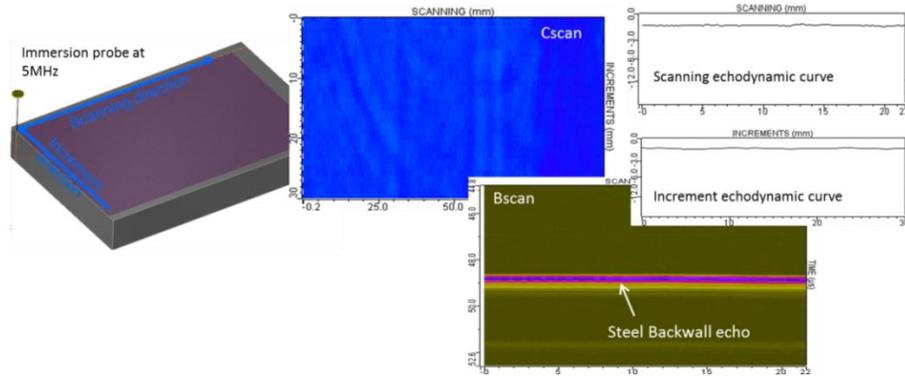


FIGURE 4. Example of experimental material homogeneity check. Cscan with a backwall echo storage.

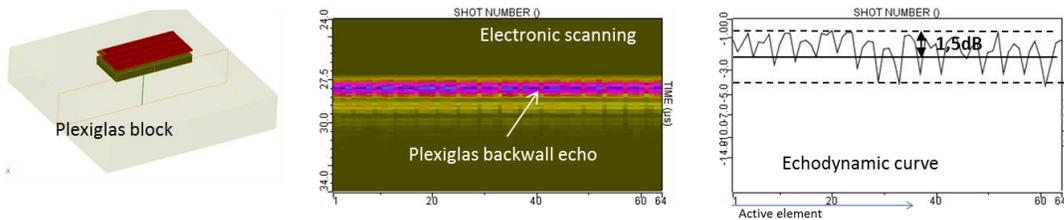


FIGURE 5. Sensitivity of the 64 elements probe.

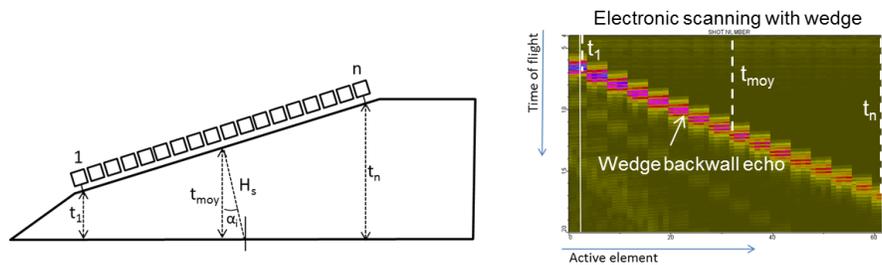


FIGURE 6. Wedge parameters measurements.

FOR SIDE DRILLED HOLES L DIRECT ECHOES

Only a part of the Benchmark results obtained with CIVA is presented in this paper, for all the results, see [2].

The graph (Figure 7) represents the maximum amplitudes (in dB) of direct echoes from side drilled holes (see mock-up Figure 1) obtained for a L20° to L60° sectorial scanning with a focusing at 30mm depth. The predictions are in good agreement with the experimental measurements with a difference of less than 2dB. The CIVA simulated echodynamic curves are also in good agreement with experimental ones (Figure 8).

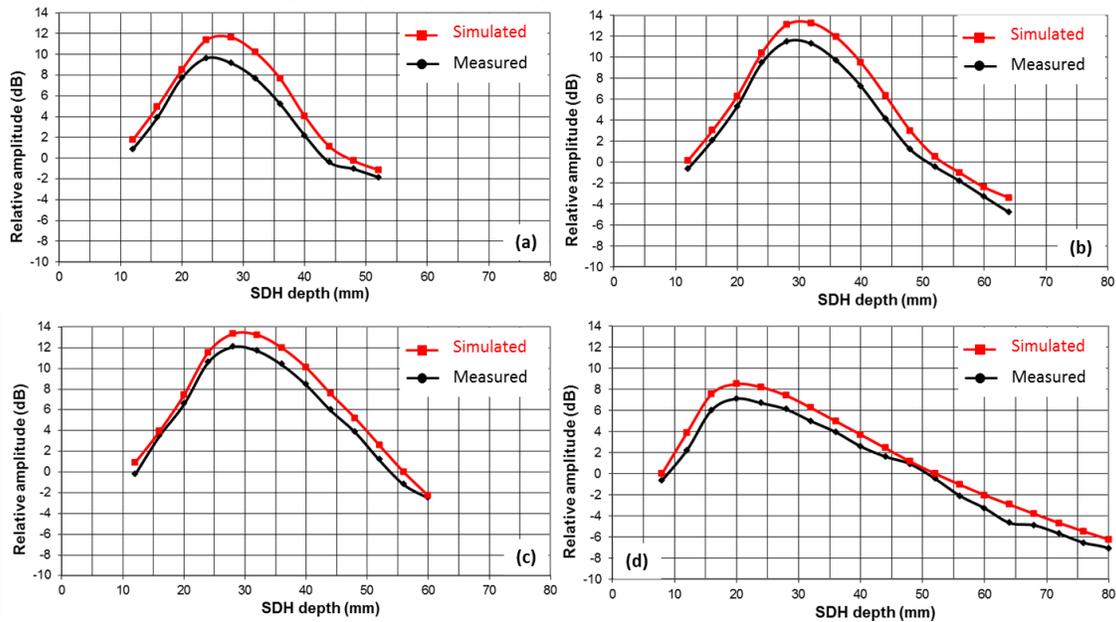


FIGURE 7. Comparison of measured and CIVA simulated amplitudes of L direct echoes of $\varnothing 2\text{mm}$ side drilled holes from 4mm to 80mm depth in the specimen. Delay laws: Sectorial scanning from L20° to L60°, focusing at 30mm depth: (a) L20°; (b) L30°; (c) L40°; (d) L60°. Reference: L45° echo from the $\varnothing 2\text{mm}$ SDH at 72mm depth obtained with a null delay law.

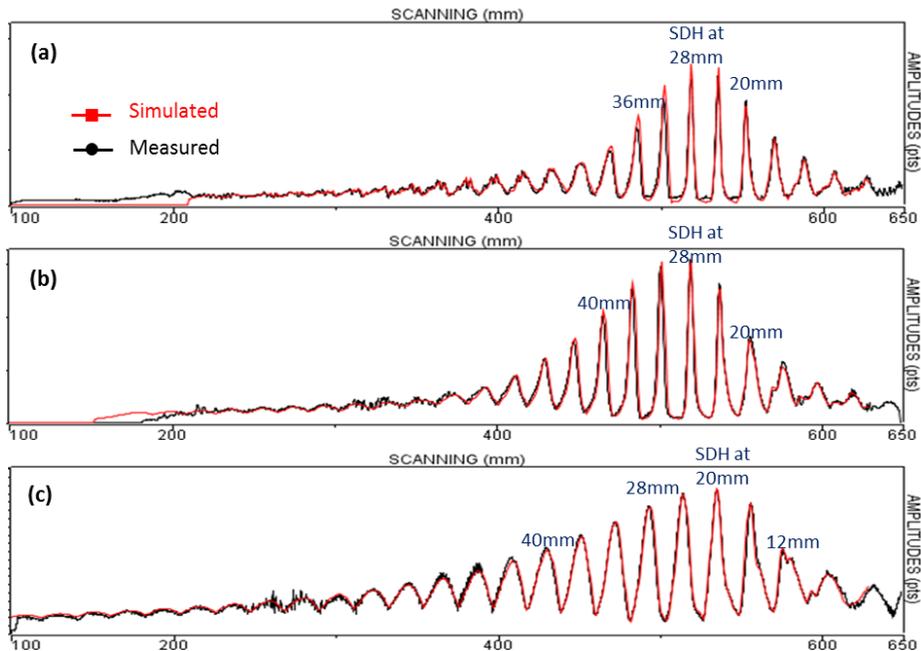


FIGURE 8. Comparison of measured and CIVA scanning echodynamic curves of L direct echoes of SDHs $\varnothing 2\text{mm}$. Delay laws: Sectorial scanning from L20° to L60°, focusing at 30mm depth: (a) L20°; (b) L40°; (c) L60°. Normalized amplitudes.

The graph (Figure 9) shows an example of simulated and experimental measurements of refraction angle. The beam deviation in the specimen is obtained from the slope of the curve representing the SDH detection depth, measured at the maximum amplitude of the L direct echo, as a function of the probe position. Results show the ability of the delay laws computed by CIVA to generate a given beam angle (38° and 58° measured when 40° and 60° were expected, respectively). These results show also that, for a given delay law, the beam deviations obtained from experimental and simulated data are in excellent agreement.

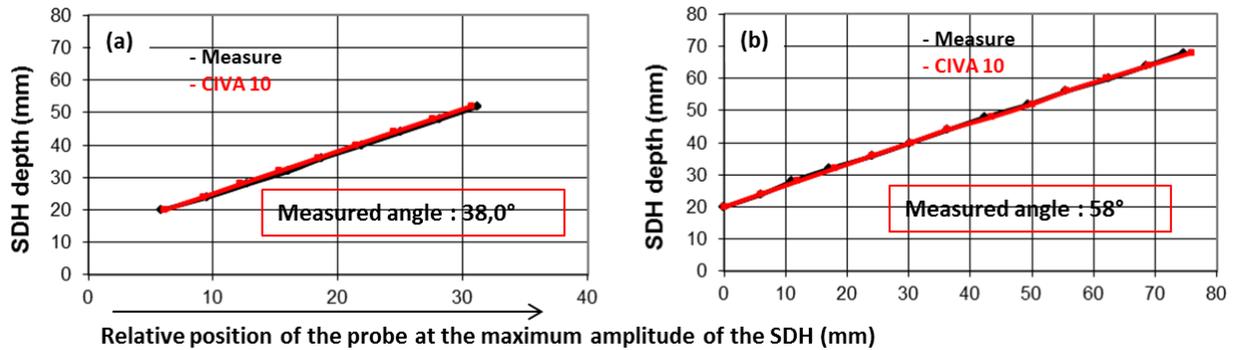


FIGURE 9. Comparison of experimental and simulated beam angle measurement for a focusing at 30mm depth and beam deviations of: (a) L40°; (b) L60°.

FOR FLAT BOTTOM HOLES L DIRECT ECHOES

Figure 10 presents the experimental and simulated C-scans obtained over the Ø3mm flat bottom holes (see mock-up Figure 1) for a L45° deviation and focusing at 20mm depth. The Cscan is very well predicted by CIVA.

The graph (Figure 11) represents the maximum amplitudes (in dB) of flat bottom holes obtained for a L45° deviation with several focusing depths between 15mm and 40mm. Simulated and experimental results are in good agreement with 2dB maximum discrepancy.

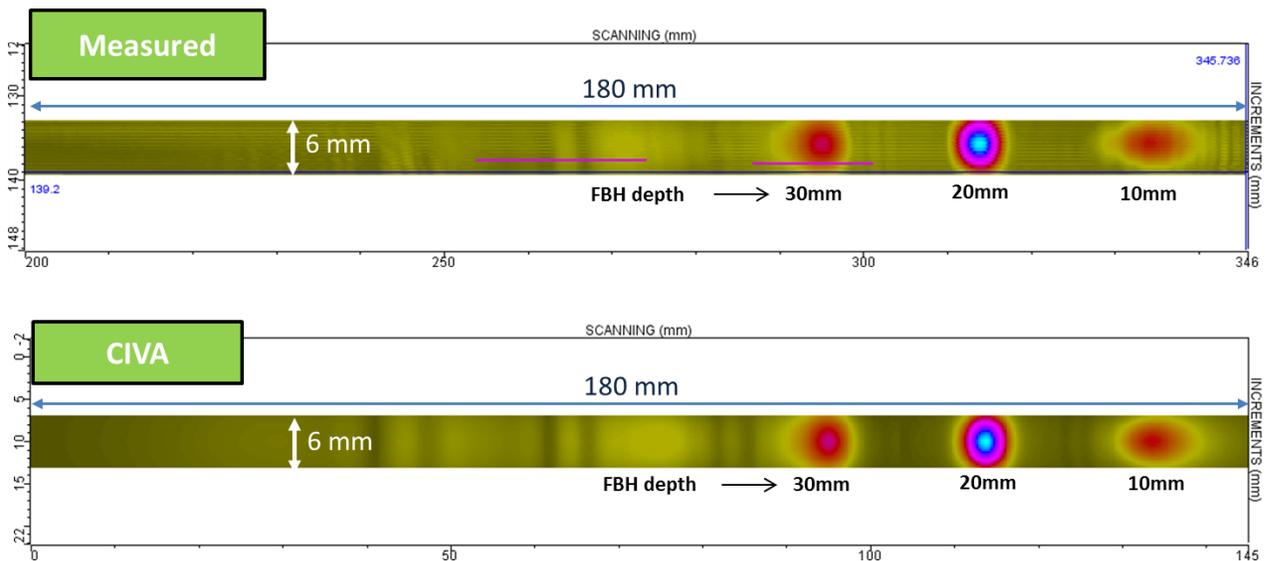


FIGURE 10. Comparison of measured and CIVA simulated C-scans.

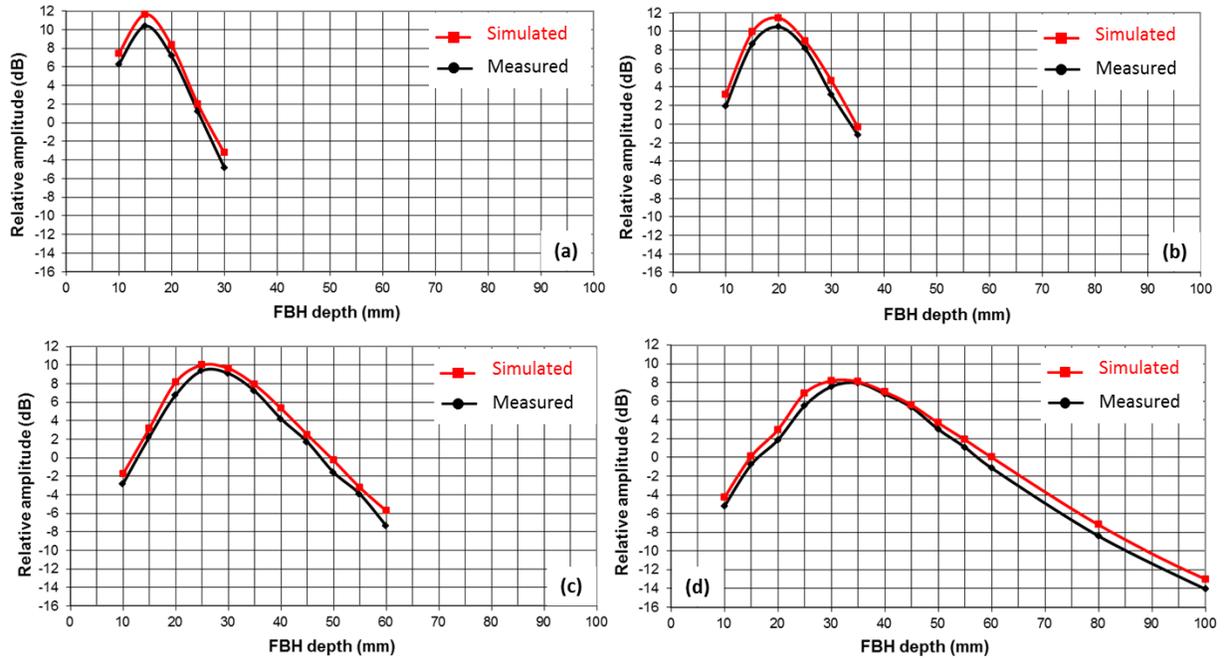


FIGURE 11. Comparison of measured and CIVA simulated amplitudes of L direct echoes of $\text{Ø}3\text{mm}$ flat bottom holes from 5 through 100mm depth in the specimen. Delay laws: $L45^\circ$ deviation with several focusing depths: (a) 15mm; (b) 20mm; (c) 30mm; (d) 40mm. Reference: $L45^\circ$ direct echo from the $\text{Ø}2\text{mm}$ SDH at 72mm depth obtained with a null delay law. The echodynamic curve shapes of the echoes are also very well predicted by CIVA (Figure 12).

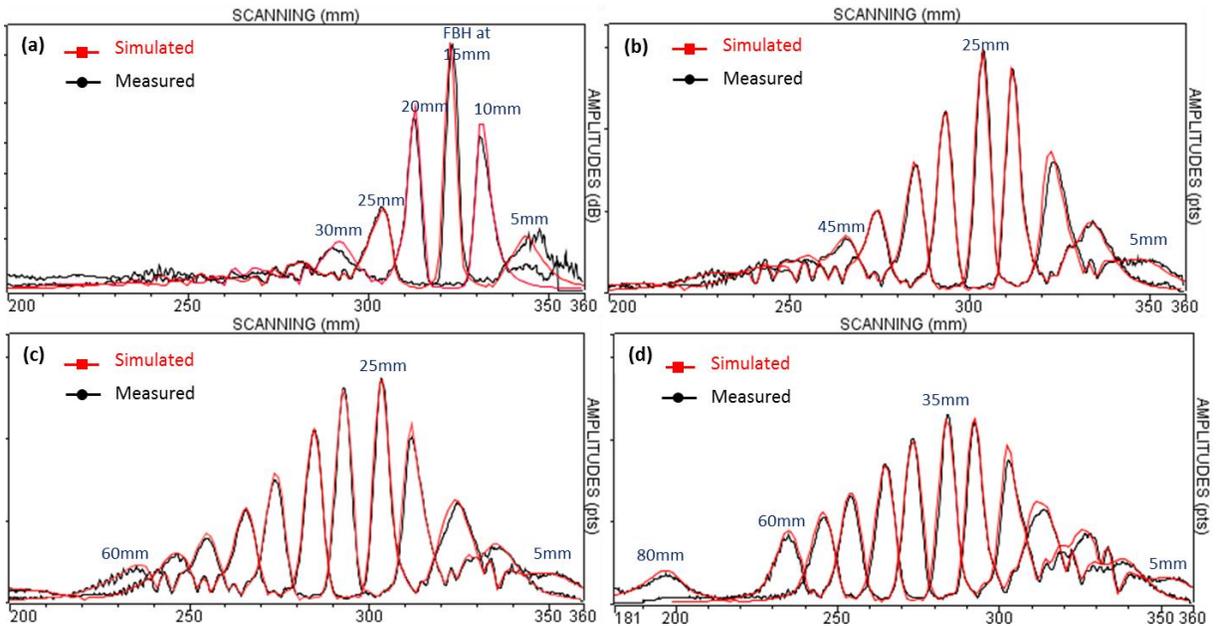


FIGURE 12. Comparison of measured and CIVA simulated scanning echodynamic curves of L direct echoes of FBHs $\text{Ø}3\text{mm}$. Delay laws: $L45^\circ$ deviation with several focusing depths: (a) 15mm; (b) 20mm; (c) 30mm; (d) 40mm. Normalized amplitudes.

BACKWALL BREAKING NOTCHES L CORNER ECHOES

Figure 13 presents experimental and simulated reconstructed B-scans obtained over the 15mm height backwall breaking notch (see mock-up Figure 1) obtained for a $L45^\circ$ deviation with focusing at 15mm and 30mm depth. A very good agreement between experimental and simulated Bscan is obtained.

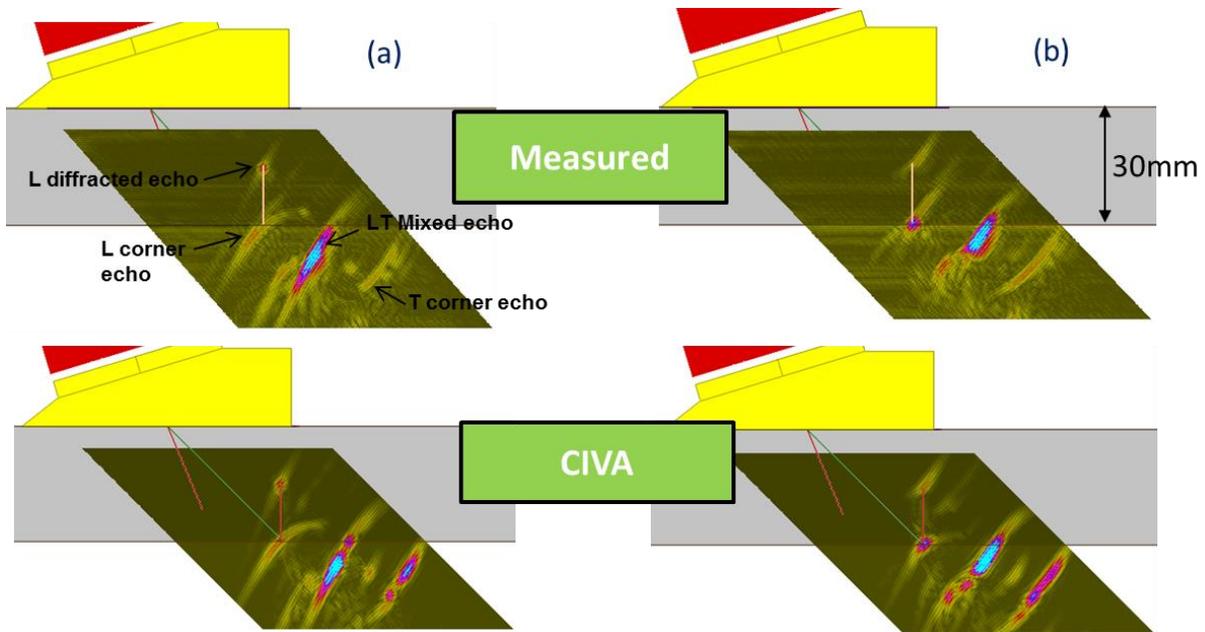


FIGURE 13. Comparison of measured and CIVA simulated reconstructed B-scans over the 15mm height backwall breaking notch. Delay laws: L45° deviation with focusing at 15mm (a) and 30mm (b).

The graph Figure 14 represents the maximum amplitudes of the L corner echo of the notches versus their height for three focusing depths. As expected, the amplitude increases with the notch height, with an amplitude fluctuation between the 2 and 3mm height notches, due to the coupling of the crack tip diffraction with the corner echo, which is fairly well predicted by CIVA. Simulated and experimental amplitude results are in good agreement with 2dB maximum discrepancy.

The shapes of the L corner echoes are also well predicted (Figure 15).

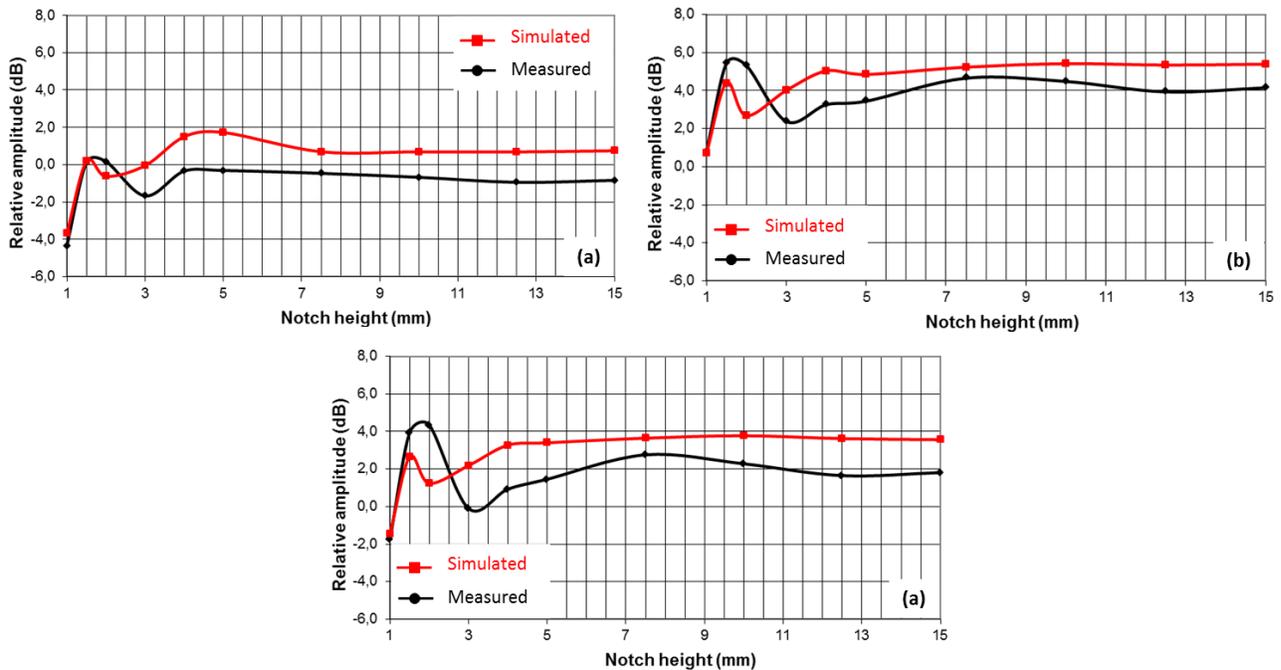


FIGURE 14. Comparison of measured and CIVA simulated amplitudes of vertical backwall breaking notches in the 30mm high specimen. Delay laws: L45° deviation with several focusing depths: (a) 20mm; (b) 30mm; (c) 40mm. Reference: L45° direct echo from the Ø2mm SDH at 72mm depth obtained when a null delay law is applied.

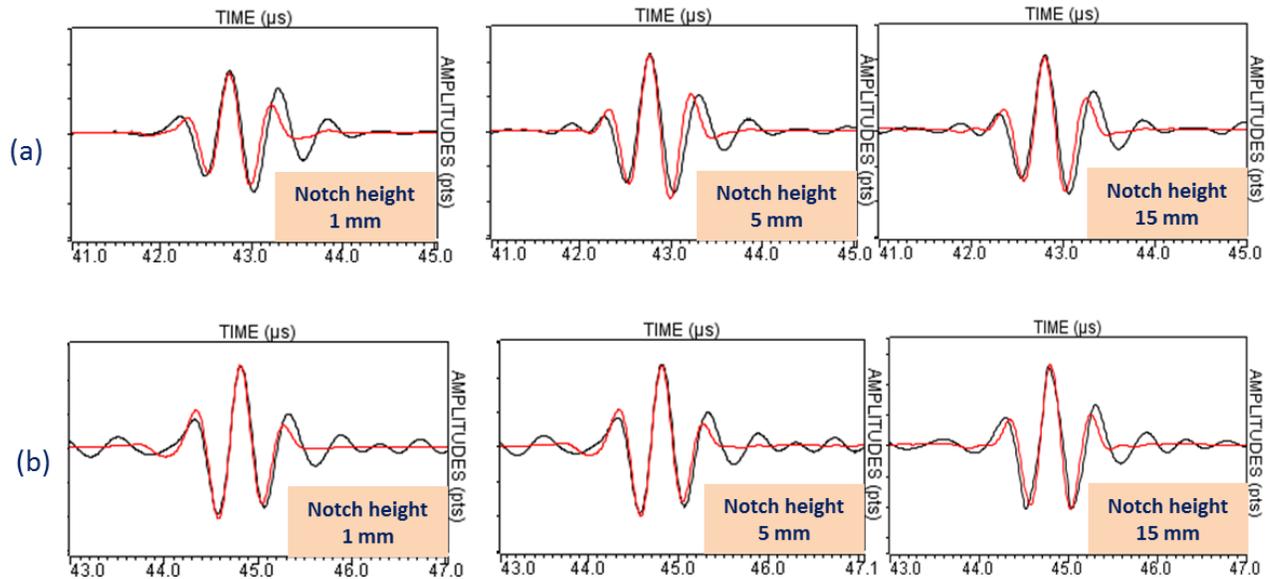


FIGURE 15. Comparison of measured and CIVA simulated Ascans of three backwall breaking notches in the 30mm high specimen. Delay laws: L45° deviation with several focusing depths: (a) 20mm; (b) 40mm. Normalized amplitudes.

CONCLUSION

The WFNDEC UT benchmark was specifically dedicated to matrix phased array probes. The validations, involving 3D computations, concern both the delay computations and the simulation of the inspection over several defects. The experimental validation process has been done following the recommendations of ref [8]. The measurements were performed at CEA LIST on 3 steel planar mock-ups containing respectively $\varnothing 2$ mm side drilled holes at different depths, $\varnothing 3$ mm flat bottom holes at different depths and vertical backwall breaking notches of various heights. The simulations have been performed using the CIVA 10.1 release.

The experimental and simulated results have been compared in terms of amplitudes and waveform on the direct L echoes for the SDH and FBH, and on the corner echo for the notches. Over all the configurations, the difference between measured and simulated amplitudes is less than 2 dB. The experimental and simulated echodynamic curves and Ascans are in very good agreement over all the configurations in L45°.

Note that through automatic non regression testing of the successive releases of CIVA, these benchmark results were revalidated with the latest version CIVA 11.0.

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