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Experimental study for the validation of CIVA predictions in TOFD inspections

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Abstract

Numerical modelling is nowadays currently used in inspection qualification process. The simulation enables to investigate a much wider range of complex cases than that obtained using only measurements. In this context the validation of the models and codes is of great importance.

A long-term validation work is being done at CEA-LIST in collaboration with EXTENDE in order to quantify the level of reliability of the predictions provided by the code and determine its range of capabilities and limitations. The validation process is based on comparisons with accurate experiments.

After first studies performed on pulse-echo techniques and previously reported for instance at ICNDE 2012 [8], we present here a validation study dedicated to TOFD techniques. Experiments have been achieved using blocks containing artificial notches. Results concerning diffraction echoes from the top edges of the notches are reported. The experimental validations are completed by considerations about hypotheses and approximations of the models, allowing to draw conclusions on their validity.

Keywords: Ultrasounds; simulation; experimental validation; CIVA, TOFD.

1. INTRODUCTION

The CIVA modules allow calculating the echoes from defects during a postulated NDT inspection [1]. The calculations are based on several semi-analytical models depending on the physical phenomena involved in the inspection [2, 3]. It is important to evaluate the level of reliability of their predictions and this can be done by considering the models (physical basis, domain of applicability and approximations made for their implementation), the list of code inputs and their values (it helps to check if the influence of the essential parameters of the inspection are taken into account by the code) and also data used to the validation of the code in similar inspection configurations (data from literature, data from other codes, experimental validation data…)

To collect experimental validation data, a long term validation work is being done at CEA-LIST for 3 years. It consists in performing comparisons between experiments and predictions of the CIVA-UT models in series of chosen inspection cases dealing with various items (responses of calibration reflectors, corner echoes of notches, echoes of the specimen geometry, obtained in pulse echo mode with mono-element or phased array probes…).

This paper comes within this validation work and presents quantitative comparisons, performed following the recommendations of ref [4], which aim at investigating the CIVA's capabilities to predict notch edge responses in TOFD mode. For brevity, only a part of the study results are presented in this paper, the whole results being available on the EXTENDE web site [5].

2. EXPERIMENTAL AND SIMULATION PROCEDURES

Specimen

The reference block, of 30mm thickness, is composed of steel and incorporates 11 artificial notches of extension 15mm and heights varying from 0.5mm to 15mm (Figure 1)

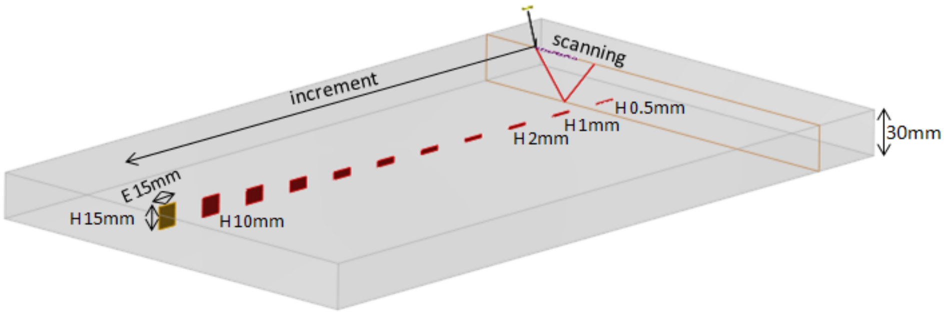

Figure 1: Steel specimen, 30 mm thickness, with back-wall breaking artificial notches of height 0.5mm, 1mm, 1.5mm, 2mm, 3mm, 4mm, 5mm, 7.5mm, 10mm, 12.5mm and 15mm (15 mm extension).

The material homogeneity was experimentally checked and the specimen material (steel) was modelled as isotropic, homogeneous and the attenuation was ignored. The longitudinal (L) and transversal (T) velocities were estimated using successive backwall echoes (V_L = 5900m.s^{-1} and V_T = 3230m.s^{-1}), the density was 7.8g.cm^{-3}.

Probes displacement

The two probes arranged in TOFD mode were moved in two directions over the notches with a scanning step of 0.2 mm and an increment step of 1mm.

Probes

Shape and wedge: the probes used were single element conventional round probes with a centre frequency of 5MHz and a diameter of 6.35mm.

Probe arrangement: two couples "transmitter-receiver" were used: one with probes mounted on wedges designed to generate longitudinal waves at 45° and another one with probes generating L waves at 60° in the specimen. Concerning the material properties of the wedges the longitudinal and transversal velocities are respectively $V_L = 2730 m.s^{-1}$ and $V_T = 1340 m.s^{-1}$ and the density is $1.18 g.cm^{-3}$. For each couple, the TOFD inspection of the back-wall breaking notches was performed for probe centre space "PCS" varying from 35mm to 100mm, allowing various incidence angles of the L waves on the top edge and various positions of the "L axis crossing point" (point where the L axis of the transmitter and receiver intersect) relative to that of the top edge (Figure 2).

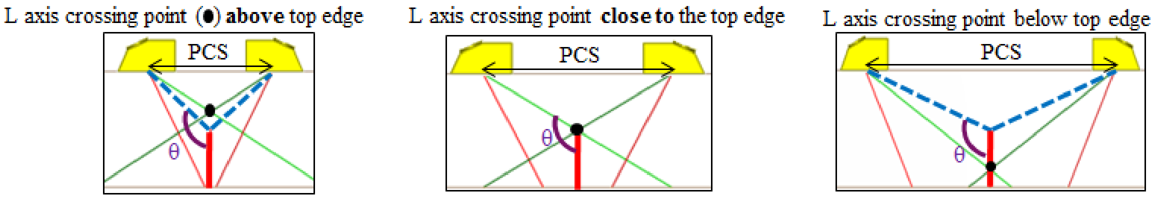

Figure 2: CIVA schematics of TOFD configurations with different PCSs, showing the variation of the L waves incident angle on the top edge of the notch (θ) and of the L axis crossing point position relative to that of the top edge with the PCS.

Calibration in pulse echo mode: the transmitter and receiver of each TOFD arrangement were used separately in a pulse echo mode to perform a calibration inspection over SDHs Ø2mm at different depths. The two experimental scanning echodynamic curves thus obtained were superimposed to check the probe resemblance in terms of sensitivity and L refraction angle. A good agreement was obtained. The refraction angle of the longitudinal waves in the specimen was estimated from this calibration: we obtained 44.5° with the wedge designed to generate L waves at 45° in the specimen and 59° with the L60° wedge. Another calibration block was used to measure the index point and the wedge height.

CIVA input signal: finally, the probe input signal was a synthetic signal generated by CIVA whose parameters (centre frequency, bandwidth and phase) were precisely adjusted so as to ensure a good matching of the experimental and simulated wave forms of a SDH Ø2mm L direct echo obtained in pulse echo mode (figure 3, case of a L60° probe).

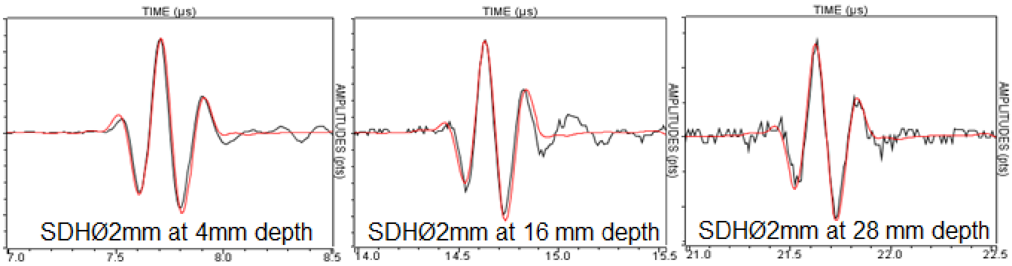

Figure 3: Superposition of measured and simulated L direct echoes of a SDH Ø2mm obtained in pulse echo mode with the L60° probe.

Artificial notches

Shape: the profile of an artificial notch provided by the manufacturer is represented in the left of Figure4.

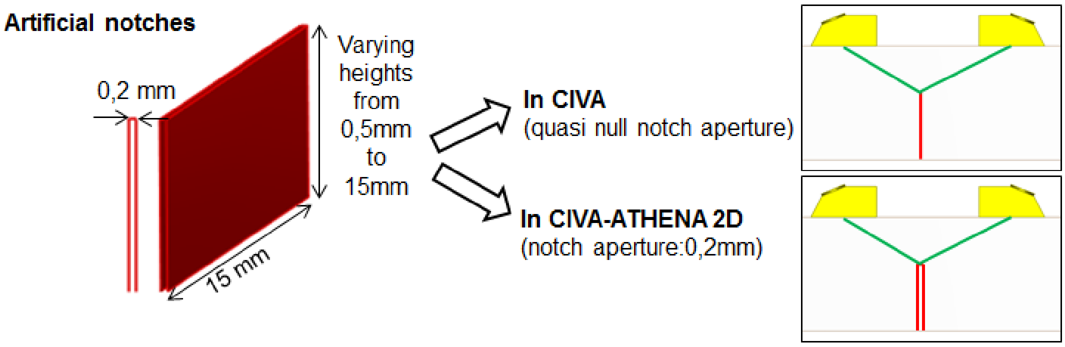

Figure 4: Shape of the artificial notches and description of the notch in CIVA and CIVA-ATHENA-2D.

Echoes studied: during the TOFD inspection the amplitude of the longitudinal top edge echo of the back-wall breaking notches were measured.

Model used to compute the L top edge echoes (TOFD mode): the appropriate model in CIVA to compute the top edge diffraction echoes is based on the GTD (Geometrical Theory of Diffraction) [6]. In this model, a quasi null aperture of the defect is assumed. This null aperture assumption is particularly well-suited for the description of a real fatigue crack but is not consistent to deal with the aperture shape of artificial notches.

Account of the notch aperture: previous studies carried out at the CEA-LIST had shown that, in the case of artificial notches, the notch aperture is an important parameter that may affect the amplitude of the top edge echo. As such, to take this parameter into account, we have also computed the top edge echo with the module CIVA-ATHENA-2D, a hybrid module using both conventional semi-analytical methods of CIVA and the FEM (Finite Element method) code ATHENA from EDF. The connection with Finite Elements allows taking into account more complex flaw scattering phenomena that can occur during the echo formation (and not only the diffraction phenomena as the GTD does).

To illustrate the influence of the notch aperture on the longitudinal top edge echo amplitude, we have simulated in CIVA a symmetrical TOFD configuration studied by Ravenscroft [7] and using circular contact probes of 10mm diameter and 5MHz centre frequency. The amplitude of the top edge echo were compared for three configurations:

- with CIVA-2D: GTD model and notch modeled by a rectangular defect of quasi null notch aperture
- with CIVA-ATHENA 2D and notch modeled by a rectangular defect of quasi null notch aperture
- with CIVA-ATHENA 2D and notch modeled by a multi-faceted defect composed by 3 facets, two vertical and one horizontal of 0.2mm length simulating the notch aperture.

NB: In all cases, the field and the flaw interaction are computed in 2D.

The Ravenscroft configuration and the results of the 3 cases are presented Figure 4. They show that, at incident angles θ greater than 130°, the amplitude of the top edge echo is much more important in the case of the notch with the aperture of 0.2mm than in the case of that with a quasi null aperture. This difference is attributed to an additional specular echo coming from the horizontal part of the notch top. The GTD model does not compute this specular echo.

These results show the necessity to take into account the aperture of the artificial notches whose influence on the longitudinal top edge echo amplitude depends on the L waves incident angle.

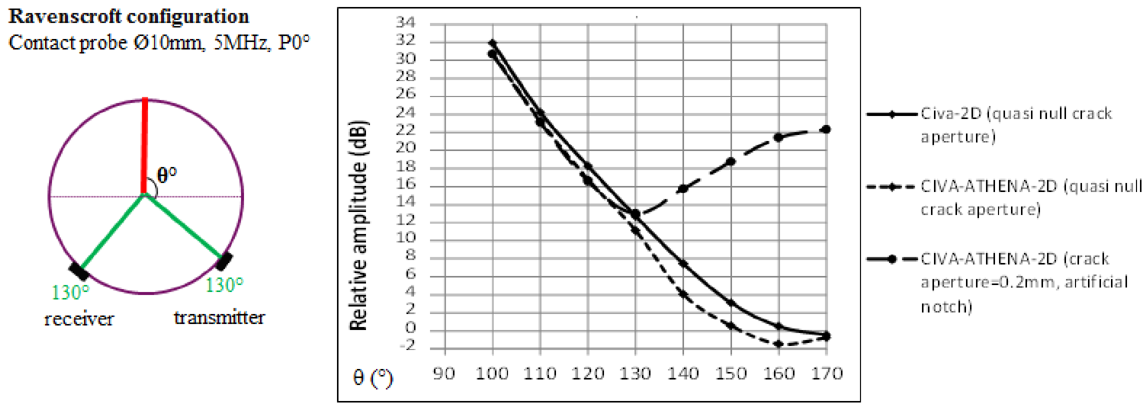

Figure 5: Left) Ravenscroft configuration modeled with CIVA. Right) simulated results.

Reference for the amplitude

The physical quantity considered for the comparisons presented in this paper is the echo amplitude. Previous experimental validation study concerning Side Drilled Holes reflectors of 2mm diameter (SDH Ø2mm) inspected in TOFD mode had showed the reliability of CIVA predictions for L direct echoes of SDHs [8]. So, the amplitude reference for all the results of the current study is the longitudinal echo of a SDH Ø2mm (precise information concerning this reference will be given for each graph).

Experimental results

A rigorous experimental protocol has been followed in order to minimize the sources of inaccuracies. The reproducibility of the results has been checked and the confidence interval of the experimental data presented in this paper has been evaluated to +/-3dB.

3. EXPERIMENTAL VALIDATION, RESULTS AND DISCUSSION

As announced above, the experimental amplitudes of the top edge echo are compared to their corresponding simulated ones obtained with the CIVA GTD model and also with the CIVA-ATHENA-2D coupling code. This last code is a “2D” code (the field and the flaw interaction are computed in 2D) and the comparison between its predictions, experiments or “3D” code predictions (GTD of CIVA) is allowed only if the “3D” aspect of the echo formation can be ignored. To check that point, all the simulated amplitudes obtained with CIVA (GTD) were compared with that obtained with CIVA-2D (“2D” code using the GTD available in CIVA). The results of these comparisons are not shown in this paper, but they demonstrate that it is fair not to consider the “3D” aspect of the echo formation in the case of the studied configurations.

On the graph presented below, we have plotted the L top edge echo amplitudes against the PCS obtained:

- 1) experimentally

- 2) with CIVA: GTD, “3D” model and notch modeled by a rectangular defect of quasi null notch aperture
- 3) with CIVA-ATHENA 2D: “2D” coupling code and notch modeled by a rectangular defect of quasi null notch aperture
- 4) with CIVA-ATHENA 2D: “2D” coupling code and notch modeled by a multi-faceted defect with an horizontal facet mimicking the 0.2mm notch aperture (see above).

On each graph, the vertical line on the left will indicate the PCS for which the “L axis crossing point” is 4mm above the top edge, the dotted line will correspond to the PCS for which the crossing point is very close to the top edge and the vertical line on the right to the PCS for which the “L axis crossing point” is 4mm below the top edge.

3.1 L60° TOFD inspection of the artificial notches

Figure 6 shows the experimental and the three simulated amplitudes of the top edge echo obtained for the TOFD inspection of the 15mm height notch performed with the probes generating longitudinal waves at 60° in the specimen and for various PCS. The reference for the amplitude is the L direct echo of the SDH Ø2mm at 20mm depth obtained in TOFD mode with a PCS of 70mm.

When the PCS increases, the “L axis crossing point”, situated above the top edge for the PCS of 35mm, moves deeper, reaches the top edge for PCS = 50 mm and then drops below it. The amplitude of the top edge echo reaches its maximum when the crossing point is close to the top edge.

We have a good agreement between experiment and CIVA or CIVA-ATHENA-2D predictions whatever the notch aperture. In this case, we observe almost no effect of the notch aperture as expected according to the results obtained in the Ravenscroft configuration. Indeed we can see on the right of Figure 6 that, whatever the PCS, the incident angle θ is less than 130°, and the influence of the notch aperture on the top edge echo amplitude occurs only for θ greater than 130° (Figure 5).

The same agreement between experiments and the three simulations (with CIVA and CIVA-ATHENA-2D with quasi null or 0.2mm aperture) was obtained for the notches of 10mm and 5mm (Figure 7).

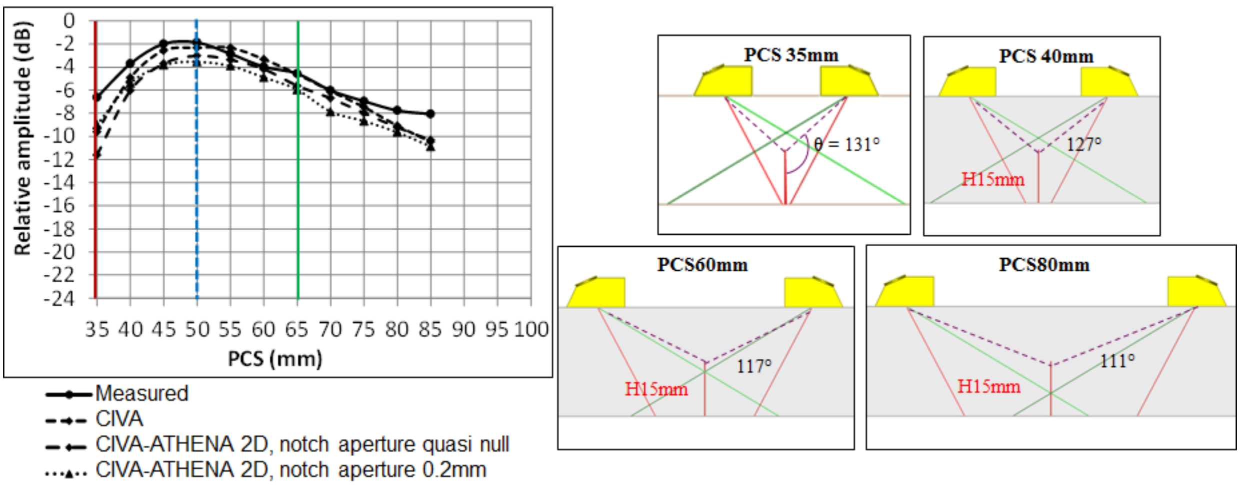

Figure 6: L60° TOFD inspection, notch of 15mm height. Left) Compared experimental and simulated amplitudes of the L top edge echo versus the PCS. Right) CIVA schematics showing the relative positions of the notch and the probes for different PCS.

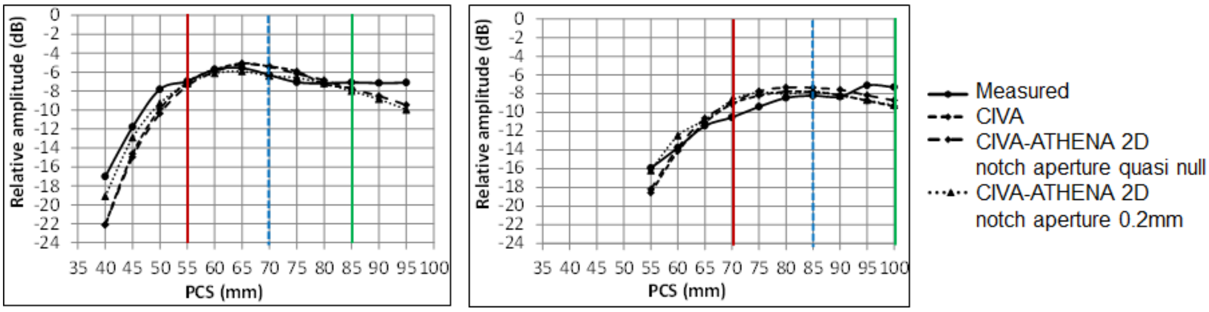

Figure 7: L60° TOFD inspection, notch of 10mm height (left) and of 5mm height (right). Compared experimental and simulated amplitudes of the L top edge echo versus the PCS.

3.2 L45° TOFD inspection of the artificial notches

Figure 8 shows the experimental and simulated longitudinal amplitudes of the top edge echo obtained for the TOFD inspection of the 15mm height notch performed with the probes generating longitudinal waves at 45° in the specimen and for various PCS. The reference for the amplitude is the L direct echo of the SDH Ø2mm at 20mm depth obtained in TOFD mode with a PCS of 40mm.

The “L axis crossing point”, situated above the top edge for the PCS of 25mm, reaches the top edge for PCS = 30mm and then moves below it. The amplitude of the top edge echo reaches its maximum when the crossing point is close to the top edge.

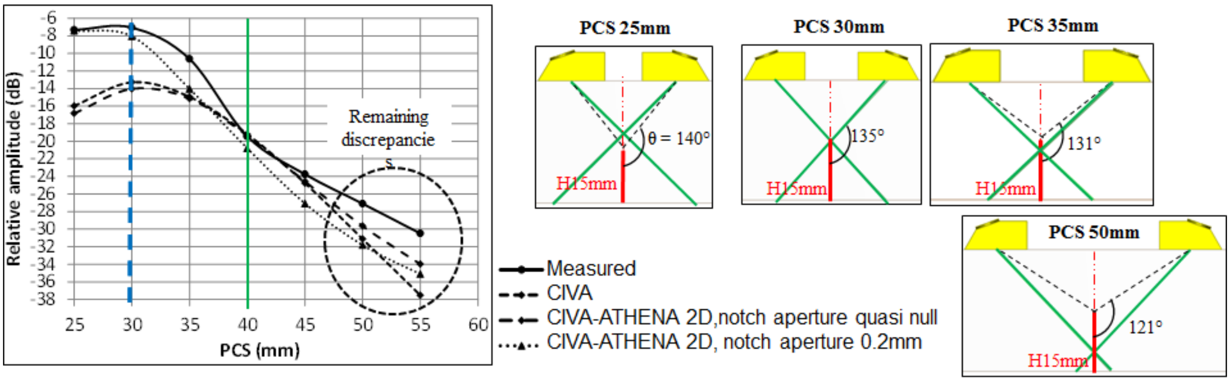

Figure 8: L45° TOFD inspection, notch of 15mm height. Left) Compared experimental and simulated amplitudes of the L top edge echo versus the PCS. Right) CIVA schematics showing the relative positions of the notch and the probes for different PCS.

We can see Figure 8:

- a good agreement between experiment and CIVA or CIVA-ATHENA-2D predictions, whatever the notch aperture, is obtained only for PCS values of about 40mm.
- an effect of the notch aperture: for the small PCSs, only the CIVA-ATHENA-2D amplitudes obtained for the 0.2mm notch aperture match the experimental ones: the real notch aperture has to be taken into account for the top edge echo computation at these PCSs. This need for taking account of the notch aperture can be evaluated by considering the results obtained in the Ravenscroft configuration (see Figure 5). Indeed we can see on the right of Figure 8 that, for the PCS smaller than

35mm, the values of the incident angle θ are greater than 130°, values for which the influence of the notch aperture on the top edge echo amplitudes is significant (see Figure 5).

- discrepancies between experiment and simulations: for the great PCSs, taking into account or not the notch aperture for the echo computation does not modify the L top edge echo amplitude. This is consistent with the predictions from the Ravenscroft configuration because, for the PCS up to 45mm, the incident angle θ is less than 130° (see right of Figure 8 and Figure 5). So, some discrepancies between experiment and simulations remain, and their origin may come from an approximation made in CIVA: hypotheses are assumed in the echo computation to simplify the description of the field. For instance the wave fronts are supposed to be locally plane at the vicinity of a notch edge mesh point and emitted wave-form is supposed to be modified during the propagation in the specimen by nothing but an amplitude factor, a phase shift and a time-delay, which means that distortions of the transient signal will not be taken into account. These hypotheses are less verified when the notch is located far from the probe L axis. It is the case of the top edge of the notch when inspected in TOFD mode with a PCS greater than 50mm.

For the notches of 10mm and 5mm we observed also an influence of the notch aperture for the smallest PCSs corresponding to an incident angle θ greater than 130° (Figure 9).

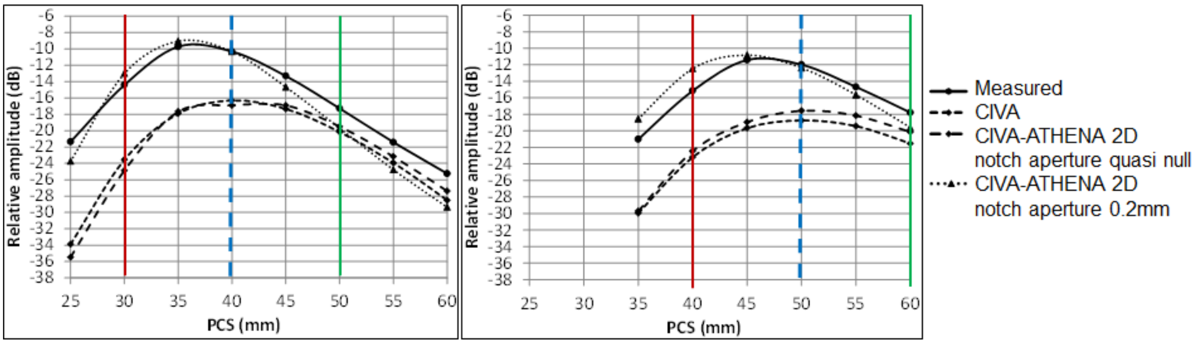

Figure 9: L45° TOFD inspection, notch of 10mm height (left) and of 5mm height (right). Compared experimental and simulated amplitudes of the L top edge echo versus the PCS.

4. CONCLUSION

We have reported results of an experimental validation study aiming at quantifying the reliability of CIVA UT predictions for the amplitude of the longitudinal top edge echo of artificial notches inspected in TOFD mode with conventional probes. The simulations using the GTD code have been performed using the CIVA 11 release and that using the coupling code have been performed using the CIVA 10 release and revalidated with CIVA 11 through automatic non regression testing of the successive releases of CIVA.

The experimental and simulation procedures were described.

In the case of artificial notches (aperture of 0.2mm) and for some values of the L beam incident angle on the top of the notch, the notch aperture is an important parameter that has to be taken into account in the simulation. In CIVA, the GTD model is the appropriate one for diffraction echo computation in the case of realistic cracks of quasi null aperture. Since the GTD model doesn't take into account the real aperture of the artificial notches we compute the top edge echo with the coupling code of CIVA-ATHENA-2D which allows taking into account the real aperture.

The comparisons between experimental and simulated amplitudes showed a good agreement for the studied cases in the zone of interest. Where the notch aperture influence was not expected according to a previous study based on the Ravenscroft configuration [7], the predictions of the GTD model and of the coupling code were in good agreement with experiments. Then, where the notch aperture influence was expected, the coupling code predictions were in good agreement with the experiment unlike the GTD model.

Some discrepancies, not due to the non account of the notch aperture remain, when the top edge is located far from the zone of interest. Hypotheses assumed in the echo computation to simplify the description of the field (plane wave approximation) may explain these discrepancies. To avoid the consequences of this simplification, work is in progress at CEA to take into account a real description of the incident beam for echo response.

REFERENCES

1) CIVA website http://www-civa.cea.fr

2) Darmon M, Chatillon S, “Main Features of a Complete Ultrasonic Measurement Model: Formal Aspects of Modeling of Both Transducers Radiation and Ultrasonic Flaws Responses.” Open Journal of Acoustics, 3A (2013)

3) Darmon M, Leymarie N, Chatillon S, Mahaut S, “Modelling of scattering of ultrasounds by flaws for NDT”, Ultrasonic wave propagation in non homogeneous media ed A Léger and M Deschamps (Springer Proc. Phys. 128) 61 2009 and also Darmon M, Chatillon S. Mahaut S, Calmon P, Fradkin L J and Zernov V, "Recent advances in semi-analytical scattering models for NDT simulation", J. Phys.: Conf. Ser. 269 012013, 2011..

4) Calmon P, Recommendations for the use and validation of NDT simulation, V, IIW Best practice document, IIW 2363-13(2013).

5) EXTENDE website http://www.extende.com

6) Darmon M, Chatillon S, Mahaut S, Fradkin L J and Gautesen A “Simulation of disoriented flaws in a TOFD technique configuration using GTD approach”, Review of Progress in QNDE 27, ed D O Thompson and D E Chimenti (Melville: AIP Conf. Proc. 820) 155 2008

7) Ravenscroft F A, Newton K and Scruby C B, "Diffraction of Ultrasound by Cracks: comparison of Experiment with Theory", *Ultrasonics*, Vol 29, pp 29-37, January 1991.

8) Raillon R, Toullelan G, Darmon M, Chatillon S and Lonne S, “Validation of CIVA ultrasonic simulation in canonical configurations”, 9th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, (2012)