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Experimental Validation of the UTDefect Simulation Software

H. Wirdelius, Chalmers University of Technology, Sweden

ABSTRACT

According to the Swedish Nuclear Power Inspectorate's requirements, in the regulations concerning structural components in nuclear installations, in-service inspection must be performed using inspection methods that have been qualified. Also new demands on production optimization and light weight products require new improved techniques to ensure the product quality. The increased use of fabricated light weight products requires in general higher demands on the reliability of the techniques and the ability for them to detect and characterize smaller defects.

In order to elaborate corresponding procedures, efforts have to be taken towards the development of mathematical models of applied NDT methods. A thorough validated model has the ability to be an alternative and a complement to the experimental work, in order to reduce the extensive cost that often is associated with the conventional qualification procedure.

The UTDefect computer code has been developed during a decade and simulates the entire ultrasonic testing situation. The model is limited to a thick-walled component with a single defect of simple shape. An important issue regarding all models is the validation, and thus a number of benchmarking projects have been initiated by the World Federation of NDE Centers. Experiments have been conducted and made public on some simple but well defined defects.

In this paper UTDefect has been compared with experimental data from this benchmark study. The experimental set-up has been made to measure pulse-echo response of two types of reference reflectors in a stainless steel component using conventional 45° P- and S-wave contact probes. The two reflector types have been a side-drilled hole and a surface breaking rectangular defect with a varying slope of the back-wall. The slope of the backside varied between 0° and 20° in 5° steps and the rectangular defects (all 10mm in height and 20mm in length) were all in the normal direction to the back-wall. The comparison has been made both of the B-scan pictures and of calibrated maximum amplitudes including mode converted contributions.

INTRODUCTION

Demands on reliability of used NDE/NDT procedures and methods have stimulated the development of simulation tools of NDT. The conventional way of qualify a NDT system incorporates extensive experimental work on expensive test blocks. A thorough validated model has the ability to be an alternative and a complement to the experimental work in order to reduce the extensive cost that is associated with the previous procedures.

An infinite number of variables and possibilities have to be reduced into a limited group of statistically relevant NDT situations. The qualification of inspection systems includes the reliability to detect, locate, characterize and accurately determine the size of defects that may occur in the specific type of component. Despite the fact that the proposed qualification procedure with test pieces is very expensive it also tends to introduce a number of possible misalignments between the actual NDT situation that is to be performed and the proposed experimental simulation. Besides the problems of reconstructing the geometry and material, the fabricated defects also has to be introduced with a verified prescription of its size and NDT characteristics.

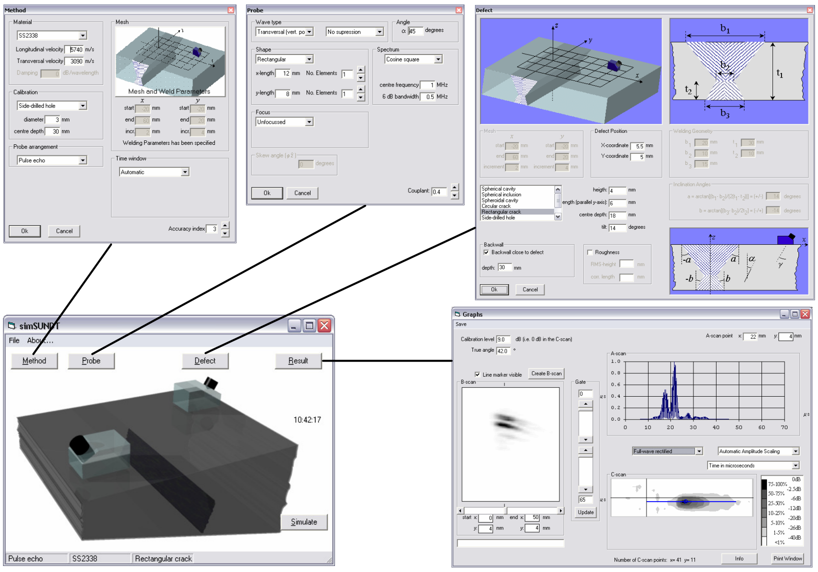

Figure 1 - The environment of the pre- and postprocessor simSUNDT

Up to this date only a couple of models have been developed that cover the whole testing procedure, i.e. they include the modeling of transmitting and receiving probes, the scattering by defects and the calibration. Chapman [1] employs geometrical theory of diffraction for some simple crack shapes and Fellinger et al [2] have developed a type of finite integration technique for a two-dimensional treatment of various types of defects. Lhémery et al [3] employs Kirchhoff's diffraction theory that enables their model to handle more complex geometries in 3D. In the literature, Gray et al [4] and Achenbach [5] presents overviews of ultrasonic NDT models.

The simSUNDT was developed in order to generate synthetic data compatible with a number of off-line analysis software. The simSUNDT program is a Windows®-based preprocessor and postprocessor together with a mathematical kernel (UTDefect, [6-10]) dealing with the actual mathematical modeling. The UTDefect computer code has been developed at the Dept. of Mechanics at Chalmers University of Technology and has been experimentally validated and verified [7-9]. The model employs various integral transforms and integral equation techniques to model probes and the scattering by defects. The software simulates the whole testing procedure with the contact probes (of arbitrary type, angle and size) acting in pulse-echo or tandem inspection situations. In the present paper the UTDefect software has been experimentally validated and different mathematical defect models have been compared.

SIMSUNDT

The simulated test piece is at the present state restricted to be of a homogeneous and isotropic material. The model is completely three dimensional though the component is two dimensional (infinite plate with finite or infinite thickness) bounded by the scanning surface where one or two probes are scanning the object within a rectangular mesh. It is also possible to include a planar back surface, which for the strip-like crack may be tilted, but is otherwise assumed parallel to the scanning surface.

The probe is modeled by an assumed effective area beneath the probe, used as boundary conditions in a half-space elastodynamic wave propagation problem. This enables an adaptation to a variety of realistic parameters related to the probe, e.g. wave type, angle, crystal (i.e. size and shape), focus depth and contact conditions. In addition to the option of specifying the contact conditions it is also possible to suppress the ”wrong” wave component, which enhance the possibility to make an interpretation of the received signal. The receiver is modeled by applying a reciprocity argument by

Auld [11]. The pair of probes can be arranged in pulse-echo (single probe), separate (fix transmitter) or in tandem configuration (TOFD).

Based on information about the scanning mesh and the depth of the defect, the software sets the A-scan range in order to ensure a defect related signal being within the time window. If a certain part of the signal is to be gated out, the A-scan range can be specified.

In order to completely simulate the actual NDT situation, an option of calibration against a reference reflector is included in the software. The calibration procedure with a side-drilled hole is treated exactly, with the use of the cylindrical cavity, while the flat-bottom hole is approximated with an open circular crack.

Four volumetric defects are included: a spherical cavity (pore), a spherical inclusion made of an isotropic material differing from the surrounding medium (slag), a spheroid cavity (pore), and a cylindrical cavity (SDH). Three crack-like defects are included: rectangular crack (lack of fusion), circular crack (lack of fusion) and strip-like crack (fatigue crack). Both the rectangular and the strip-like crack include the possibility to model roughness on the crack surfaces. The circular crack can also be modeled as partly closed, with the degree of closure related to the crack surface conditions (roughness) and the background pressure.

Based on the experiments both the surface-breaking strip-like crack and a rectangular crack placed close to the back-wall were used to simulate the defects in the test-piece. Both defects are planar and perfectly smooth and are prescribed to be open.

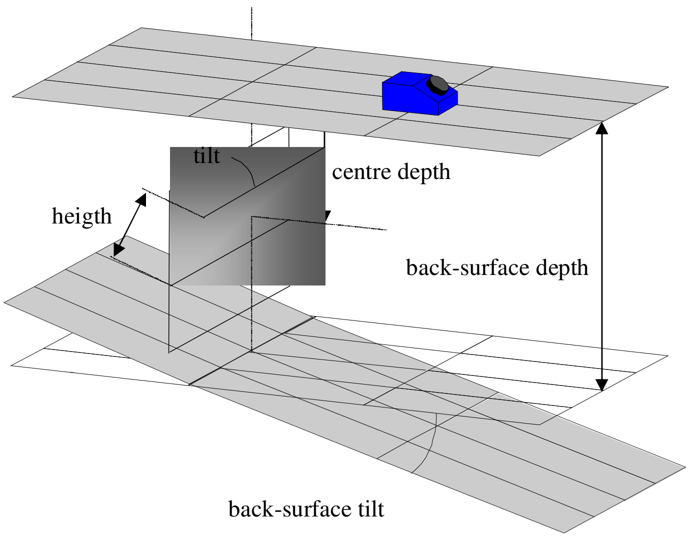

Figure 2 – The defect parameters and the geometry of the simulated pulse-echo situation with a back-surface tilt.

THE EXPERIMENTAL SET-UP

The ultrasonic benchmark study was initiated by the World Federation of NDE Centers and practically conducted by CEA during the year of 2006. The experiments included scanning of rectangular defects on a variable slope bottom specimen (see figure 3). The main interest was to investigate the different corner echoes provided from rectangular surface breaking defects in combination with varying slope of the back-wall specimen (P-wave speed 5748m/s and S-wave speed 3157m/s).

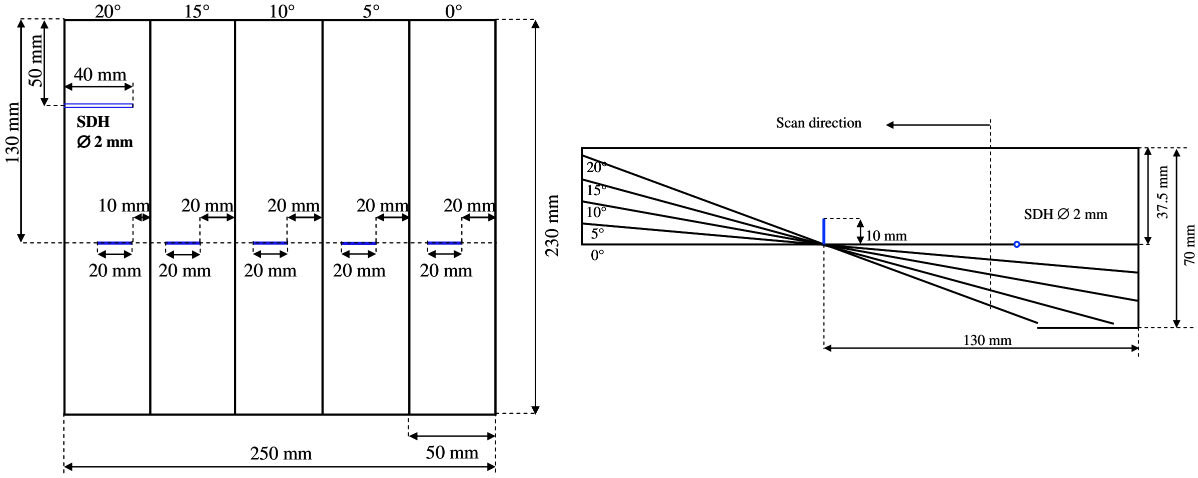

Figure 3 – The geometry of used test piece (to the left from above and to the right is the side view).

The experiments measured pulse-echo response of two different reflectors (a side-drilled hole and a rectangular defect) with conventional contact probes (2.25 MHz 45° P-wave and a 2 MHz 45° S-wave). The test specimen was manufactured in stainless steel with 5 different slopes (0° to 20°) with a rectangular defect produced in each back-wall surface. The defects were slots with a width of 0.3mm slot, 10mm in height and 20mm in length and all perpendicular to scanning surface. A side-drilled hole (2mm in diameter) was used as a reference reflector and for each probe a reference A-scan was obtained. Both pulse-echo B-scan responses and maximum amplitudes were provided as public information.

COMPARISON OF AMPLITUDES IN SIGNAL RESPONSE

In some of the made experiments the reflectors were situated close to the scanning surface and in some cases actually within a near field length of the probe. The mathematical solution to the elastodynamic wave propagation problem is in our case in the form of an integral representation. The integral representation is in most cases numerically solved by utilizing conventional Legendre-Gauss Quadrature but in the case of the defect being a strip-like crack this is numerically evaluated by the method of stationary phase. This method is numerically fast but is only thought to be valid some near field lengths in distance from the transducer and thus the effective boundary that models the probe has therefore been subdivided into smaller regions in order to reduce the near field lengths (for S-probe a reduction from 77 down to 2 mm and in the P-probe case from 25 into 0.5 mm). It should though be noted that the solutions is thus more numerically accurate but the simulation is less relevant since it is not a phased array probe that is acting in the experiments.

From the comparison (see figure 4) it can be concluded that the length of the defect has no larger impact on the maximum amplitude signal response. The actual geometry though becomes essential when the back wall is tilted more than 15 degrees. In all cases the rectangular crack gives a larger signal response than the strip-like surface-breaking crack which may indicate some fundamental errors in the numerical solution for this defect model.

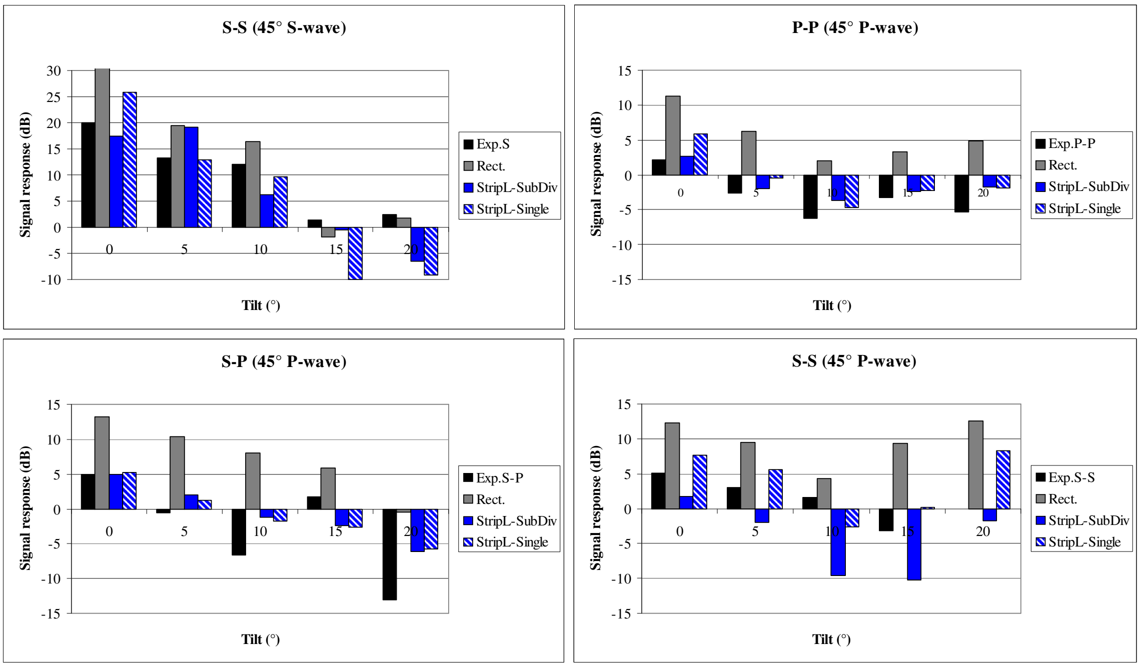

Figure 4 – Calibrated maximum amplitude response compared to the experimental data.

When the deviation between the experiments and the simulations are analyzed (see figure 5) it can be concluded that the surface breaking strip-like crack better simulates the actual synthetic implanted defects, at least when the back-wall is tilted less than 15° (less than 5 dB). Above this tilt angle neither of the models renders a satisfactory compliance with the experimental values. It should though be noted that in the case of the mode converted contributions the values are somewhat more subjective in their nature.

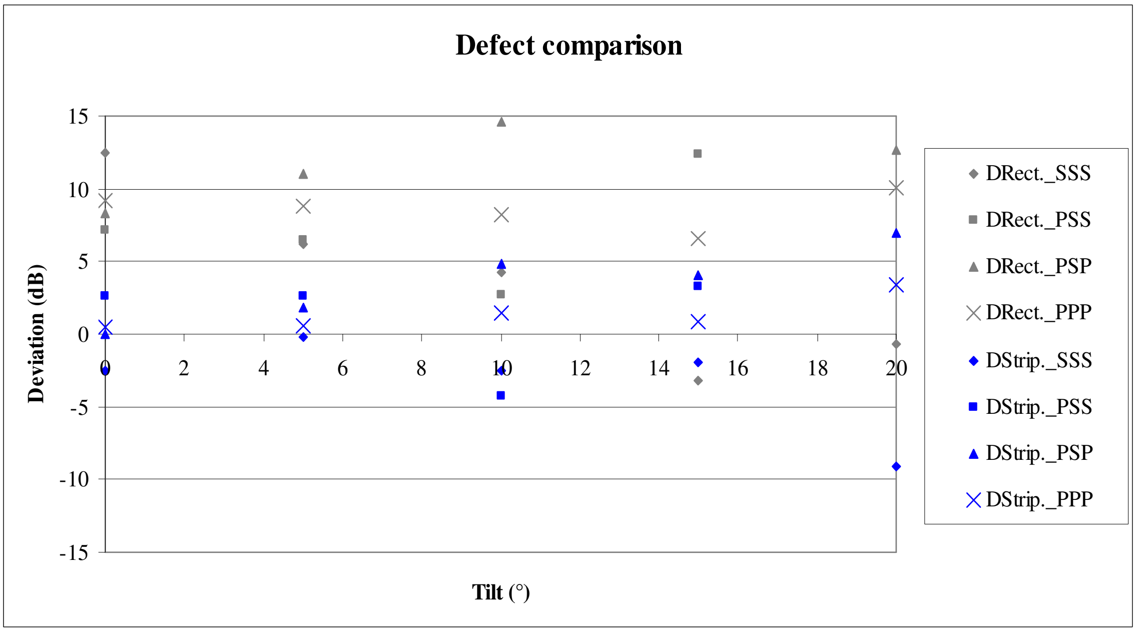

Figure 5 – Deviation (in dB) between experimental values of maximum signal response and corresponding simulations.

COMPARISON OF THE B-SCANS

As can be deduced from figure 6 the simulated B-scans, when the reflector is a side drilled hole, gives a very good resemblance with corresponding experimental results. In general all B-scans that are produced with a rectangular crack or surface-breaking strip-like crack are almost indistinguishable and also give (see figure 7-10) a similar amplitude distribution as the equivalent experimental B-scans. As can be expected from previous discussion of the sub-dived probe model, the B-scans that are produced with this probe tends to somewhat distort the amplitude distribution in the B-scans.

It should also recognized that the notches that has been used in the experiments are without any realistic crack-tips which explains the deviation between simulations and corresponding experiments that can be identified e.g. in figure 9 and 10. The simulations clearly indicate crack-tip diffracted signals that are much vaguer in the experiments.

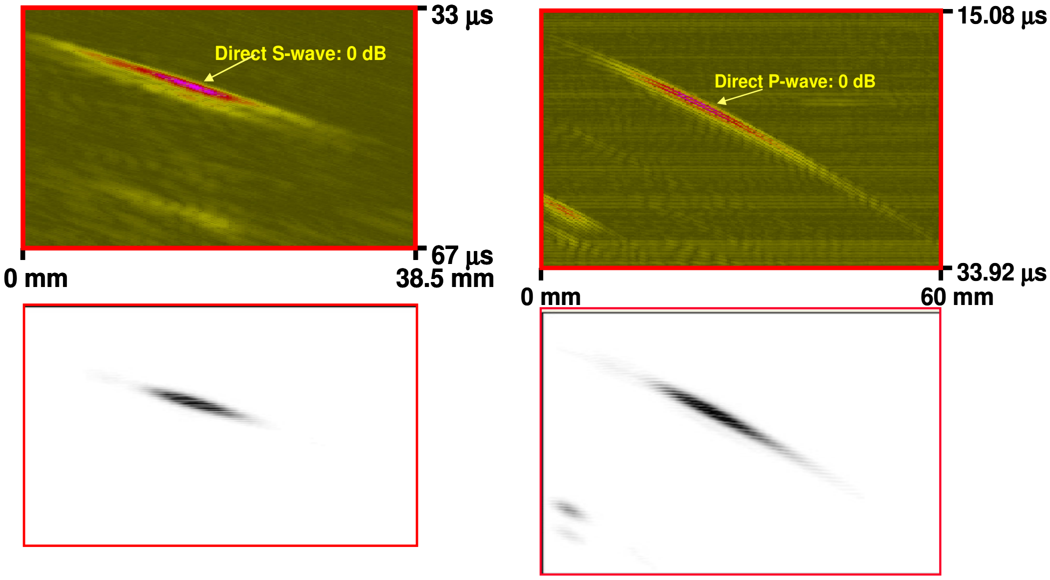

Figure 6 – Calibrated B-scan responses (the simulated are in the bottom pictures) from a side-drilled hole when the S-wave transducer is used (left) and when the P-wave transducer is used (right).

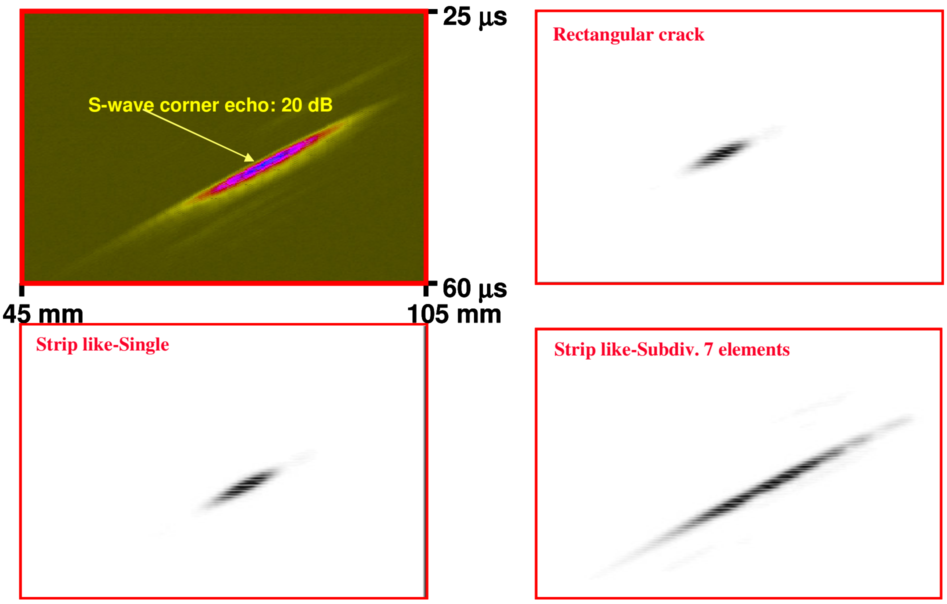

Figure 7 – Calibrated B-scan response from a rectangular crack without any back-wall tilt when the S-wave transducer is used.

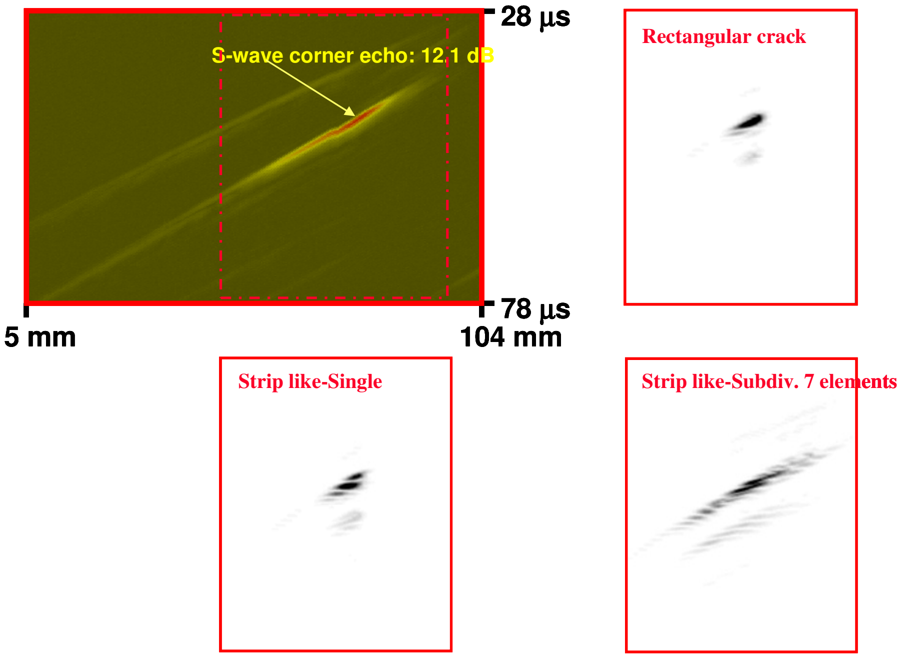

Figure 8 – Calibrated B-scan response from a rectangular crack with a 10° tilt of the back-wall when the S-wave transducer is used.

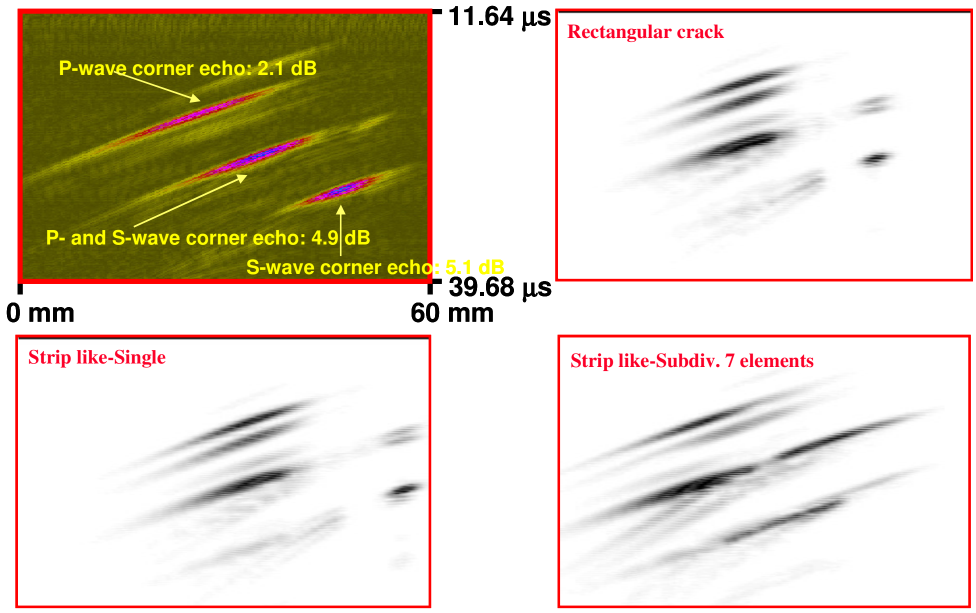

Figure 9 – Calibrated B-scan response from a rectangular crack without any back-wall tilt when the P-wave transducer is used.

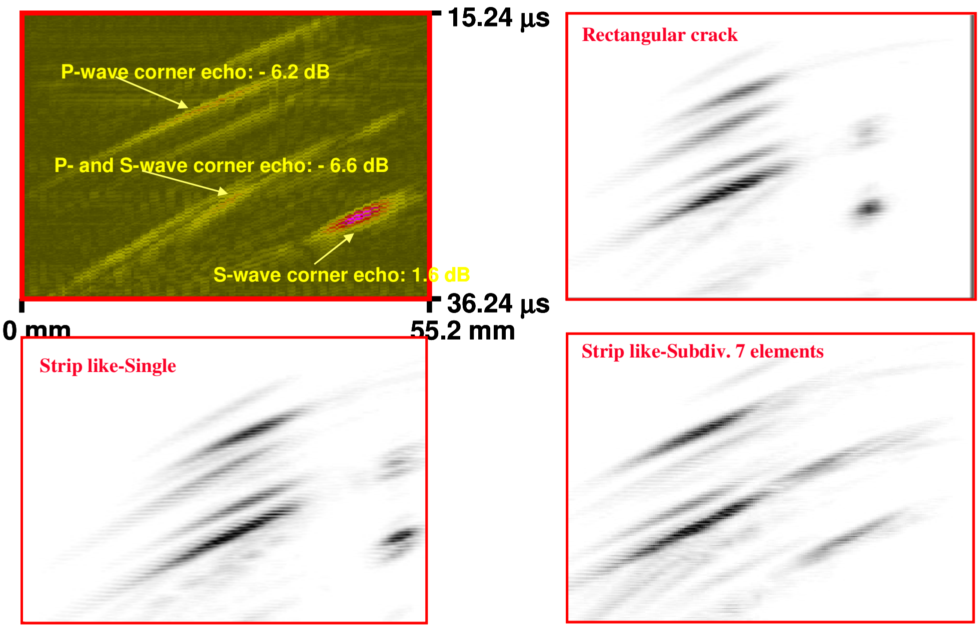

Figure 10 – Calibrated B-scan response from a rectangular crack with a 10° tilt of the back-wall when the P-wave transducer is used.

CONCLUDING REMARKS

In this paper, a simulation tool for ultrasonic nondestructive testing, UTDefect has been compared with experimental data from an international benchmark study. The experiments have been conducted with conventional contact probes. The defects considered was a side-drilled hole (also was used as a reference reflector) and surface-breaking notches perpendicular to the scanning surface and situated in a back wall with different slopes. The notches were simulated as both surface-breaking strip-like and rectangular cracks close to an angled back surface. The results from the experiments are provided both as maximum signal response and as B-scans.

From the comparison it were concluded that the surface breaking strip-like crack better simulated the implanted defects, at least when the back-wall was tilted less than 15°. Above this tilt angle neither of the models gives accurate results. The rectangular crack actually coincides better with the experimental value in these cases. The specific geometry of the reflector (defect and back-wall) becomes an essential parameter when the back-wall is tilted 20°.

The simulated B-scans, when the reflector is a side drilled hole, give a very good resemblance with corresponding experimental results. Also all B-scans that are produced with a rectangular crack or surface-breaking strip-like crack are almost indistinguishable and also give a similar amplitude distribution as the equivalent experimental B-scans.

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