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RESEARCH RESULTS

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CIVA-UT MODEL VALIDATION FOR RAIL FLAW INSPECTION SIMULATION

SUMMARY

In 2022, the Federal Railroad Administration (FRA) contracted with Transportation Technology Center, Inc. (TTCI) to conduct validation studies of CIVA software's rail models for hand-held, angled beam, shear vertical wave (SW) inspections. The research team generated side-drilled holes (SDHs) at different depths in a carbon steel block and in a rail sample to establish a ground truth. They then conducted laboratory-based ultrasonic testing (UT) scans and theoretical simulation studies for both of these test samples. The scans and subsequent simulation demonstrated that, for the most part, the modeling results were in good agreement with the experimental results for the 70 and 45 degree SW inspections. However, the modeling results did not match the experimental results for the 45 degree SW inspections in a steel block with SDHs at depths from 60 mm to 80 mm.

BACKGROUND

Ultrasonic simulation tools continue to gain widespread adoption in various industries as an effective cost-cutting tool to:

- Investigate the performance of and optimize a wide array of UT probes
- Investigate different ultrasonic inspection techniques and procedures
- Support model-assisted probability of detection (MAPOD) activities

One such tool is Extende's CIVA software, which was initially developed by CEA-LIST (French Alternative Energies and Atomic Energy Commission) and its partners. CIVA-UT is a module within the CIVA software and is focused on analyses of UT application. It is based primarily on semi-analytical models, rather than on fully numerical models (e.g., finite elements, finite differences) for faster computation and analysis of ultrasonic beam propagation and interaction with flaws. As a result, the CIVA-UT software allows for accurate and reliable predictions in a variety of situations. The ultrasonic beam modeling in CIVA-UT allows the user to simulate a wide range of transducer configurations, including phased arrays [1].

An inspection simulation in CIVA-UT is done in three steps: (1) computation of the incident beam on the flaw, (2) computation of the ultrasonic beam scattering over the flaw, and (3) computation of the received signal using the reciprocity principle to avoid integration over the probe in reception [2].

OBJECTIVES

All modeling and simulation tools must be validated to ensure accuracy and repeatability in real-world inspection/testing scenarios. Given the complexity and variability associated with the use of UT for nondestructive evaluation of internal rail flaws, a validation of CIVA-UT models is necessary to verify that the models generated will accurately represent trustworthy revenue-service type inspection. The objective of this research was to validate CIVA-UT models generated for hand-held contact type UT inspection of rails for internal fatigue defects.

METHODS

A single-element, flat-focusing, 2.25 MHz, 12.7 mm diameter, ultrasonic transducer (probe) was considered for this study. The probe's bandwidth was 46.07 percent at -6 decibels (dB). Similarly, the research team considered two different wedges for a 12.7 mm probe to generate 45 and 70 degree SW in steel, respectively. Figure 1 shows the wedge geometry considered in CIVA-UT, and Table 1 lists the wedge dimensions used.

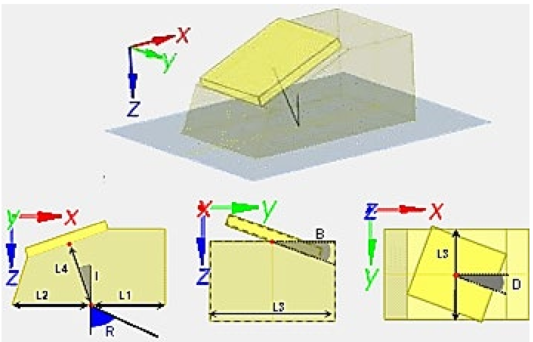

Figure 1. CIVA-UT wedge drawings

Table 1. Modeled wedge dimension in CIVA

Wedge Dimensions	**45°**	**70°**
Front Length [L1] (mm)	9.65	12.70
Back Length [L2] (mm)	16.51	21.34
Width [L3] (mm)	18.54	18.54
Height [L4] (mm)	10.16	14.73

Plexiglass (Perspex) material properties were used for the wedge. Table 2 lists the properties of all the materials used for modeling and simulation. The shear wave attenuation for the wedge was defined as 0.15 dB/mm at 2.5 MHz.

Table 2. Material properties used in CIVA-UT

	Plexiglas	**Steel**
Longitudinal Wave (L-wave) Velocity [m/s]	2680	5900
SW Velocity [m/s]	1320	3251
Density [g/cm^3]	1.18	7.8

The research team used both a 136RE rail and a 1020 carbon steel block for the CIVA-UT validation studies. The 136RE rail consisted of 5 mm diameter SDHs drilled in the railhead at depths of 13 mm, 19 mm, and 25 mm. Similarly, machinists drilled a series of 2 mm diameter SDHs for the 1020 carbon steel block at depths varying from 4 mm to 80 mm in 4 mm increments. Figure 2 shows the engineering drawing of the samples used for the validation studies. During CIVA-UT simulation, the research team employed a direct mode, meaning that CIVA computes contribution from the flaws with no skips on the specimen.

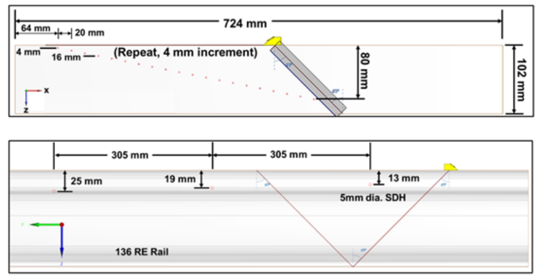

Figure 2. Drawings of samples with SDHs for model validation: (top) steel block, (bottom) 136RE rail

For the experimental studies, the research team used an Olympus Epoch 600 hand-held UT flaw detector (with the exact probe and wedges configuration described previously). The team conducted scans in two directions, from left to right and from right to left, five times each, as shown in Figure 3.

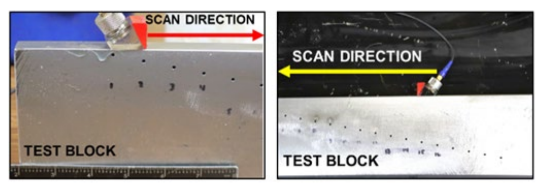

Figure 3. UT scan directions

CIVA-UT Beam Field Computation

A contact (i.e., hand-operated) UT rail model was generated in CIVA-UT to better understand the ultrasonic beam field response of the transducer and wedge that were used. Figure 4 shows an example of ultrasonic beam fields generated in 136RE rail in CIVA-UT for both of the angle beams considered.

Based on the results shown in Figure 4, the 45- and 75-degree probes exhibit around 12 dB loss at depths of 165 mm and 116 mm. The 12 dB loss is equivalent to 25 percent of the max signal (100 percent).

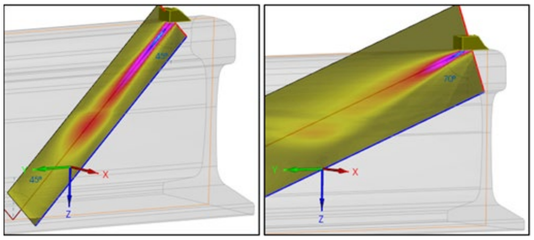

Figure 4. Contact ultrasonic SW beam field response in 136RE rail: (left) 45°, (right) 70°

RESULTS

The research team investigated the carbon steel block with a series of SDHs first using both 45 and 70 degree probes. For the 45 degree SW inspection, they calibrated on the sixth hole (at 24 mm depth) for both the CIVA-UT and experimental hand-held tests. For the 70 degree SW inspection, they calibrated on the first hole (at 4 mm depth) for both the CIVA-UT and experimental hand-held tests. Figure 5 compares the maximum signal amplitudes (by percentage) obtained using both techniques. The hand-held UT experimental results are the averages of 10 total scans (five in each direction).

A Gage Repeatability and Reproducibility (Gage R&R) analysis of the experimental measurements showed the hand-held UT measurement system was only marginal. For the 45 and 70 degree SW inspections, the measurement system contributed 13.0 and 19.5 percent, respectively, of the process variation. For comparison, a measurement system contribution as a percentage of the process variation of 10 percent or less is generally considered acceptable. Measurement systems contributing to 30 percent or more of the process variation are generally considered unacceptable.

While the 70 degree SW inspection results were in good agreement between the CIVA-UT modeling and the experimental UT, the 45 degree SW inspection results were not. In the latter inspections, the experimental UT amplitude increased after a depth of 60 mm, and similar results were observed using different 45 degree probes and flaw detectors. This increased amplitude response for SW in experimental UT after 60 mm depth is an interesting result and will need to be explored further in future research.

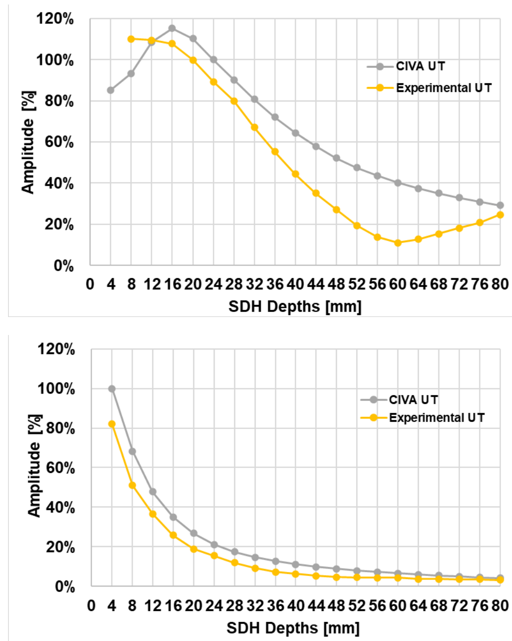

Figure 5. Maximum amplitude comparisons on SDHs in steel block: (top) 45, (bottom) 70°

Next, the research team completed the validation using 70 degree SW inspection in 136RE rail samples with SDHs. They performed the calibration using the 5 mm hole at a 15 mm depth in the International Institute of Welding (IIW) block, which is the calibration standard. Figure 6 compares the direct peak UT amplitude obtained for SDHs using both CIVA and experimental UT in 136RE rail.

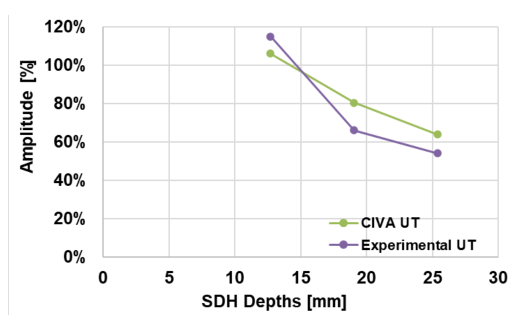

Figure 6. Maximum amplitude comparisons on SDHs in rail using 70° SW

Figure 7 shows the CIVA-UT B-scan results for the simulated SDHs in rail and the experimental UT results for SDH at a 1 inch depth in rail. These findings demonstrate good agreement of 70 degree SW inspections on SDHs in the railhead using both methods.

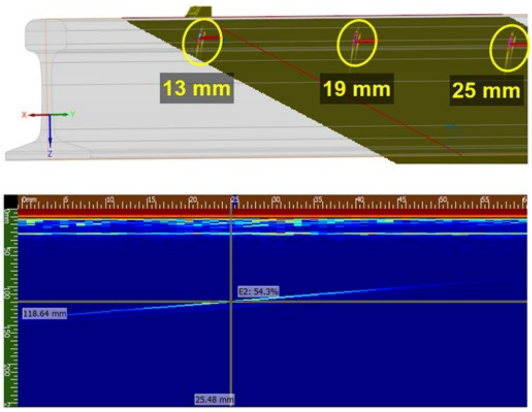

Figure 7. B-scan result for SDHs in rail: (top) CIVA-UT, (bottom) experimental UT

CONCLUSIONS

The main goal of this work was to demonstrate the validity of the CIVA-UT rail models for contact angled-beam SW inspection. While there was, for the most part, good agreement between the CIVA-modeling results and the experimental UT results, the experimental UT amplitudes in 45 degree SW inspection for the SDHs increased after 60 mm depth in the steel block.

FUTURE ACTION

Future work needs to focus on the detailed understanding of increased signal amplitudes for 45 degree SW after 60 mm depth in the steel block for experimental trials.

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KEYWORDS

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