Thick plate demonstration pieces with cracks on demand for PAUT scan to CSA W59-13 requirements

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Abstract

The CSA W59-13 standard permits the use of advanced ultrasonic testing methods such as PAUT on bridge structures, provided there is prior written agreement between the Engineer and the Contractor. Research and development was conducted at the Department of Metallurgy at the CEGEP de Trois Rivières, and Centre Métallurgie du Quebec, Canada to produce thick plate demonstration pieces with known discontinuities for PAUT assessment. The paper describes the findings of this experimental work.

Keywords: CSA W59-13, UT, PAUT, calibration blocks, DAC, TCG

1. Introduction

It is well known that technological advances take time to find their way into national and international standards, since most are developed through consensus between the members of the technical committees representing the stakeholders. At CSA, the technical committees have a balanced matrix between the User, Producer, Engineering Consultant & General Interest categories. It is important to note that members of these committees work benevolently to create these consensus standards sharing their expertise to protect public safety.

In 2013, the CSA W59-13 standard opened the door for the Canadian fabrication community to use advanced inspection techniques such as Phased Array Ultrasonic Testing (PAUT) and Computed Radiography (CR). In the last three years, some progress has been made to use CR inspection techniques for structural work replacing conventional film radiography. On the other hand, adoption of PAUT for mainstream structural work to CSA W59-13 requirements has not materialized due to several technical challenges.

This paper attempts to uncover these technical challenges within the current CSA W59-13 code for PAUT, and discusses experimental work and analyses required for general acceptance of PAUT for structural work in Canada.
2. Acknowledgments

The principal author wishes to thank all the sponsors for this unfunded R&D work. The experimental work completed in 2013 could not have continued without the generous help from Canadian Educational Institutions. Many thanks are due to the Department of Metallurgy and the professors at the CEGEP de Trois Riviers for providing the funding to purchase calibration blocks and contracted precision machining and inspection services. Thanks are also due to many students who participated in the preparation of the test plates for developing the “cracks on demand” methodology. Special thanks are due to Olympus - NDT division and their entire development and application team in Quebec City for providing valuable laboratory space and PAUT hardware and software for evaluating the welds. Leading up to the conference, the tireless and enthusiastic support of all co-authors and Level 3 experts from SGS Inc, Holloway NDT & Engineering Inc., and Torngats NDT was very much appreciated.

3. Background of PAUT

Ultrasonic examination uses the same principles as sonar used for the detection of submarines – a sound wave is emitted from a transmitter, bounces off any objects in its path and is reflected back to a receiver, somewhat similar to shining the beam of a torch at a mirror. Knowing the speed of sound in the material enables the distance of an object to be determined by measuring the time that elapses between the transmission of the sound pulse and detection of the echo. In welded components, the examination is generally performed by moving a small probe acting as both a transmitter and receiver over the reflector and displaying the echo on a screen. The oscillator sends pulses of electricity to a piezo-electric crystal, the pulse generator, embedded in the ultrasonic probe which causes it to vibrate at very high frequencies. Probes used for weld examination have frequencies generally between 2MHz and 5Mhz, the lower frequency probes being used for the examination of coarse grained and thicker materials, while the higher frequency probes are used for thinner materials and improved sensitivity to small defects.

The ultrasonic vibrations are transmitted into the material to be tested using a couplant such as water, oil, glycerine, and high-temperature paste. The better the surface finish the better the coupling – hence there is sometimes a requirement to grind the weld cap and adjacent areas of the welded joint smooth.

Once in the material, the vibrations travel in a predictable path until they encounter an obstruction or interface such as a line of slag, porosity or a crack. Depending on the angle at which the beam strikes the obstruction, some of the beam may be reflected back to the receiver in the probe. Here it vibrates a piezo-electric crystal and is converted back into electrical energy. This resultant signal is then amplified and displayed on a screen.

When the sound beam enters the object, it has a cross section approximately that of the transmitter. But like the beam of a torch, it will diverge. The beam divergence, in combination with beam scatter and absorption effects, effectively weakens the signal and is collectively referred to as attenuation. Attenuation effects need to be taken into account when evaluating signal amplitudes.
To obtain the strongest reflected signal, the beam should strike the feature ideally at 90° – flaws that lie parallel to the beam may be missed. This means that to examine a weld that may contain flaws in any number of orientations, a range of different angle probes and scanning patterns must be used. The CSA W59-13 code recommends shear wave probes with angles of 45°, 60° and 70°.

As with any measurement equipment, ultrasonic examination systems require calibration to confirm proper function and determine operating parameters. Calibration blocks must be made of the same material type as the test piece, and reference features such as side-drilled holes must be carefully controlled to ensure accurate and repeatable inspections. Ideally, a calibration block would be made from the actual test material to ensure the most accurate sound path and attenuation measurements possible. However, the practicality of this limited, so general material properties are assumed for most carbon and low-alloy steels, and thus only one calibration block is used for most cases.

CSA W59 assumes a fixed attenuation factor of 2dB per inch of sound path. This estimate is considered valid only while using a rectangular crystal over a specific range of sizes and at a nominal frequency of 2.25MHz. It is therefore understood that round crystals of different sizes and frequencies may differ from the assumed fixed attenuation factor and are generally not permitted.

The rapid progress of electronics and computing power has enabled complex methods of scanning and data processing to be developed. This has culminated in phased array ultrasonic testing (PAUT) which, as the name suggests, uses a transducer comprised of an array of individual elements. A single PAUT probe typically contains between 16 and 64 elements, although 256-element transducers are used for specialized applications. Each element in a phased array transducer can be pulsed independently in a set sequence or phase; the pulses of sound combining to produce a sound beam of a certain angle. By varying the time and pattern of the pulses, the angle and shape of the beam can be varied so that the beam can be steered electronically creating a sectorial scan or S-scan.

The benefits of this technology compared with conventional single transducer scanning are that the beam can be steered and focused with a single probe. Beam steering enables the beam to be swept through an object without moving the probe, the reflected data being processed to provide a visual image of a cone shaped slice through the object. Moving the probe enables a large number of slices to be assembled to provide a three dimensional image – a good example is the use in medical diagnostics to examine the functioning of the heart in real time.

For the non-destructive examination of welds, this ability to inspect a weld with multiple angle beams from a single probe means that the probability of detecting flaws is greatly increased. It is also possible to focus the beam electronically at multiple depths to improve the ability to accurately determine the size and position of weld flaws.
Methods developed now with PAUT enable flaw sizes to be determined with accuracy of better than ±1mm\(^1\) used in determining fitness for purpose using fracture mechanics.

![Angle beam conventional UT vs Angle Beam PAUT, sectorial scan](image)

**Figure 1**

Figure 1 Standard 2.25 MHz W59-13 code probe versus a small 5 MHz PAUT probe scan plans for detecting a toe crack in 1 inch thick plate. PAUT sectorial scan displays the indication with the associated A Scan.

### 4. Experimental work to create “Cracks on Demand” methodology

In order to produce real cracks on demand, the author with the help of the technical staff at ESAB\(^2\) designed a special FCAW wire such that, under restraint, the wire would produce cracking due to the higher levels of boron added to a base chemistry of a standard CSA E491T-9C or E71T-1C type wire. This was designed to produce a chemistry close to the C-Mn base metal of CSA 300W for the plates.

Earlier experimental work showed that it was difficult to produce cracks on demand in 0.75 inch thick plates using a U groove in the plate. This was directly related to the lack of restraint created on the weld bead due to the geometry of the preparation. Experimental work undertaken in this study was to create cracks on demand that were around 4 inches long and also create very small 3/16 inch long cracks in 0.50 inch thick plates.

a) **Four inch long cracks**

Under the guidance of professors at the CEGEP de Trois Rivieres, students succeeded to create these two categories of cracks while working over three work sessions in 2015 and 2016. Many geometries were tried, however, there was lack of consistency in producing the cracks on demand. Finally a 4 inch long machined groove approximately 0.50 inches deep in 1 inch thick

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\(^1\) TWI reference  
\(^2\) CSA W59 Advanced Inspection Methods, Vaidya et al. Cinde, NDT in Canada 2013, Calgary
plate with a 0.062” root opening produced the desired results. The preparation and presence of crack was confirmed with magnetic particle testing at the root and then by radiography of the finished weld.

b) Creation of 3/16 inch long cracks

There was a need to create very small cracks on demand, and this was achieved after number of trials on deep ground out grooves on 0.50 inch thick plates. The idea was to create a small tack weld that would crack on demand. After many trials with different groove dimensions and FCAW process, this approach was abandoned. Finally using the special Ti-B FCAW wire as filler with a GTAW process produced success. The results were confirmed with a PAUT scan. This technique now could produce cracks as small as 0.125” in test welds.

![Figure 2 Methodology to create 4 inch long and 1/8 inch long cracks on demand](image)

c) 3/4 inch thick plate welds with flaws for PAUT R&D

A large test plate 18” wide x 24” long x 0.75” thick was prepared in 300W material with a double V groove with 60 ° included angle, with 0.125” opening and a root face. Lack of Penetration was planned at 6.25” from side A, a round crater crack was created at 9.75 inches from side A and lack of penetration flaw approximately 4.5 inches was created towards the end of the side B. The plate was completely welded after flaw insertion by Submerged Arc welding at 500 amps, 34 volts at 10.2 inches of welding speed.
5. Results of the experimental work

The test plate was inspected with radiography, computed radiography and with PAUT encoded scan with two different laboratories. All techniques identified the areas and placement of the flaws in the experiment.

a) Radiographic testing

The test plate was inspected with radiography and detected three rejectable indications approximately at the location they were introduced. The report picked up a small 0.200” crack, at the location of the drilled hole to create a crater crack. No borderline indications could be produced acceptable to clause 11 but rejectable to clause 12. More work will be needed to create these in the future. The plate was rejected to both static and cyclic loading clauses.

b) CR testing by the CEGEP experimental

The results of CR testing in presented below. Once again, no code evaluation was performed on the CR radiographs represented below. This technique picked up 8 indications, some between 0.25” to 0.10” one at 5.6 inches length.

c) PAUT testing by lab 1 and 2

The plate was submitted to two PAUT inspectors for blind testing. The first lab produced a report indicating 5 areas of indications and the second lab produced 4 areas of indications. None of the PAUT results could be evaluated to CSA W59-13 requirements due to lack of suitable acceptable criteria for grading the indications, equivalent to, Table 11.3 and Table 12.5.

![Figure 3 Encoded PAUT scan of the test plate identifying 5 indications](image-url)
6. Discussion on CSA W59-13 – for application of PAUT

The authors reviewed the code\textsuperscript{3} with the intent of applying manual, non-encoded PAUT for ultrasonic examination. The following paragraphs outline just some of the areas that would require revision to bring the code inline with modern practices; critical if PAUT phased array is to be accepted as a general inspection technique. These revisions would entail significant changes to the Clause 8.2 because the current procedures are based on outdated analog technology and methods.

a) Limitations based on analog equipment

The existing requirement for frequent 2-month or 40-hr periodic calibrations stems from the inherent electrical variances of older analog equipment. Digital equipment has long-since replaced analog equipment, yet the code still prescribes the same calibration and setup procedures in use since 1970\textsuperscript{4}. The recommendation is to revise the code to accept only digital instruments, and to change the calibration procedures and intervals inline with modern standards.

b) Limitations of the 2.25 MHz large probe

The present practice involves using large, low frequency probes and a fixed attenuation estimate of 2 dB per inch. This process is an estimate and is not based on scientific study or physical laws of sound propagation. It was originally released as Appendix C in AWS D1.0 and D2.0 in 1969. The intent was to limit variability and attain consistent results by placing tight controls on equipment and processes, and to allow calibration using just the IIW-type block. The estimate is a poor representation of actual sound attenuation, requires the use of awkward large transducers, and requires adding high fixed scanning gains.

The following lists some of the drawbacks of the current 2.25 MHz transducer:

- Inconsistent coupling is common with large wedges
- Physical size limits access (especially in angled joints) and frequently prohibits evaluations on the 1\textsuperscript{st} leg
- 2 dB per inch attenuation estimate is inaccurate given variations due to transducer bandwidths and sizes
- Fixed high scanning gains can produce excessive signal to noise ratios at long sound path distances
- Indication rating calculation is cumbersome to perform manually, or requires purchasing software options

The 2dB per inch assumption was based on a probe similar to a 20x22mm Krautkramer WB-series probe and is not typical of all probes within the allowable range.

\textsuperscript{3} CSA W59-13 Welded Steel Construction (Metal Arc Welding)
\textsuperscript{4} AWS D1.0 (1969) Appendix C – Ultrasonic Testing of Groove Welds
The mindset is “don’t fix what ain’t broke”. Although W59 and D1.1 can be awkward to perform, the fact of the matter is that they are both extremely conservative and thus have a good track record for weld quality (consistent with most workmanship-based criteria). However, the system is indeed “broke” as it pertains to practicality and repeatability, resulting in numerous shortcuts taken in the field and a general lack of understanding of the limitations.

c) Other size probes and DAC/TCG calibration

It is time that the code be modified to allow use of more traditional, round probes of different sizes, and frequencies other than 2.25 MHz. When using these probes, a Distance Amplitude Correction (DAC) or Time Corrected Gain (TCG) calibration will be needed and the fixed 2dB/inch attenuation approach abandoned.

All of the following standards prescribe the use of a DAC for sensitivity calibration:

- API RP2X – Offshore Structural Fabrication
- ASME Sec. V
- ASTM E587 – Standard Practice for Ultrasonic Angle-Beam Contact Testing
- CSA Z662 – Pipelines (follows ASME guidelines)
- DNV Class Guideline 0051 – Non-destructive Testing
- EN 583-2 - Non-destructive testing, Ultrasonic examination, Part 2: Sensitivity and range setting
- ISO 17640 – UT of Welded Joints

Keep in mind that a CGSB Level 2 inspector performing inspections to W59 requires no code-specific training, and many inspectors shy away from structural work due in large part to the fixed attenuation estimates requiring the “d=a-b-c” calculation. And although the practical examination for CGSB Level 2 certification includes a W59 component, the transducer supplied for the examination is quite frequently the same ½” round transducer used for the ASME component, not the big red brick or snail wedge that the code requires. Thus, the misunderstanding and misapplication of the techniques is inherited “from birth”.

d) Zero degree scan from Face C for fusion defects and lamellar tearing

Referring to Table 8.3, the code is directive in restricting the examination from Face A of all joints. Currently there is no mandatory instruction for inspection of the flat, unbeveled fusion faces opposite Face C on T-joints and corner welds.

This area is difficult to inspect with angle beams from Face A or Face B, especially for fusion and lamellar tearing type defects. It should be mandatory, if accessible, to scan T-joints with a zero-degree probe from Face C. There is an Annex Q regarding lamellar tearing, but currently the code prescribes no corresponding inspection technique.
e) **Limitations of angle specific procedure tables**

W59-13 code describes specific procedures and probe angles in Table 8.3. However, there is no best angle for any general joint type and weld thickness. A joint beveled at 45° is best inspected with a 45° beam, if accessible, regardless of thickness. Yet the inspector is bound to use a single angle of 70° for most of the welds they are likely to see in the field. The probe angle should be selected based on the bevel angle and the sound path, amongst other considerations. This generally will be dictated by work at hand and actual joint specifics.

As the acceptance tables are also tied to specific angles, they would need to be addressed accordingly.

f) **Transfer correction for scanning surface**

Calibration for sensitivity is performed on reference blocks which are typically shiny and clean, and usually nickel plated to resist corrosion. They do not accurately represent the condition of the test surface, which is usually ground, scraped, or somewhat irregular due to chipping and the typical surface roughness found in rolled plate or other product forms. The code should at least put the onus on the responsible Level 2 to evaluate the differences between the calibration and test surfaces to determine if a transfer correction should be carried out. This is common practice in ASME.

g) **Permission to use manual PAUT in substitution of conventional UT**

In 2013 when W59 was revised, the use of PAUT was included in the Clause 8.2.12, with an additional condition that phased array be considered an "alternative ultrasonic system" and may only be used if agreed to in writing by the Owner’s Engineer and the Contractor. No differentiation was made in regards to manual versus encoded systems.
A clarification is needed for the word “Phased Array Systems”. PAUT inspection can be performed manually or in an automated phased array system with an encoder. The encoded scan can then be read much like a radiographic film, in addition to indicating the length and depth of the flaws along the length of the weld. This clarification could open the door to use PAUT interchangeably with conventional UT.

Manual PAUT is in fact, exactly the same as traditional UT. Both techniques use electronic pulse generating equipment but different type of probes. PAUT is performed with many angles instead of just one. Portable PAUT equipment has been commercialized over the last two decades and is currently used on fabrications inspected to ASME, API, and other codes.

Additionally the following items need to be addressed in an Appendix to the current code, provided revised procedures and acceptance criteria, usable for alternate probes, frequencies, and manual PAUT, are demonstrated to be equivalent.

1. Define PAUT flaw detector requirements
2. Define calibration block requirements
3. Define transducer size limits
4. Define focal law requirements
5. Define jobsite calibration procedure (velocity, sensitivity, wedge delay, DAC/TCG)
6. Define scanning procedures for various joints
7. Define and demonstrate, acceptance criteria to be equivalent to static and cyclic requirements (Tables 11.3 and 12.5)

7. Conclusions

a) Experimental work undertaken during this work shows that small and long cracks on demand can be created using the specially designed Ti-B FCAW wire. Such demonstration pieces will be needed to establish equivalence for acceptance between PAUT and UT in the near future.

b) The paper identifies many areas of the current W59-13 code that need improvements in keeping with practicality and good science. Use of smaller transducers with higher frequencies will need the inclusion of DAC/TCG testing for sensitivity requiring significant revisions to the current Clause 8.2 in W59-13.

c) Cohabitation of PAUT in an appendix to the code may be one way to move forward.

8. References

1. TWI reference : http://www.twi-global.com/technical-knowledge/job-knowledge/ultrasonics-examination-part-3-129/


3. CSA W59-13 Welded Steel Construction (Metal Arc Welding)