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Advanced Ultrasonic Testing Technologies with Applications to Evaluation of Steel Bridge Welding - an Overview

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Abstract Non-destructive evaluation (NDE) methods are widely accepted for quality control of welding in steel bridges. Recent development of advanced ultrasonic testing technologies enriched the categories of NDE methods used for steel bridges and more importantly these enhanced techniques provided more effective flaw detection and characterization. No guidelines, however, is available in existing bridge welding code for their more widespread applications to bridges. In this study, we overview the state-of-the-art advanced ultrasonic testing technologies in welding inspection. Benefits of the enhanced ultrasonic testing technologies are summarized, aiming to pave the way for deciding methods need for various steel bridge welding inspections.

Introduction

It is known that all welded bridge joints contain flaws. These flaws may initiate cracks when bridges are in service. Such premature cracks dramatically shorten the service life of bridges. Bridges initially designed for service life of 100 years may require repair or replacement within shorter period of time. Repair, retrofit or even structural replacement for bridges can be very costly in terms of construction, and traffic closures.

The development of NDE methods, such as ultrasonic testing (UT), radiographic testing (RT) and magnetic particle inspection (MT), allows quality control of steel bridge welding either at early stage (during the steel fabrication, and construction process) or later in-service stage. Existing NDE methods and procedures have been stipulated in current AASHTO/AWS D1.5 - Bridge Welding Code [1]. In recent years, various enhanced ultrasonic testing techniques, including phased-array ultrasonic technology (PA-UT) [2-4], automated ultrasonic testing (AUT) [5], and phase-array automated ultrasonic technology (PA-AUT) [6,7], allow for more efficient detection and characterization of flaws. Studies [2-6] have demonstrated that these enhanced ultrasonic testing techniques can more accurately locate and size the flaws, and even provide more unique functions over conventional RT or UT. For example, remote ultrasonic testing [8] allows sharing data and images from bridge on site seamlessly with bridge owners and practitioners to immediately evaluate, diagnose and treat weld defects in remote locations. These advanced UT technologies have been gaining increasing attention as new NDE methods for potential replacement of conventional UT or RT. Existing D 1.5 steel bridge welding specifications, however, does not include any guideline for these advanced UT methods, which hinders widespread application of these advanced methods in evaluation of bridge life performance.

The objective of this study is to provide an overview of advanced UT technologies over conventional NDE methods for steel bridge welding. An understanding of the benefits and drawbacks of each form of advanced UT technologies can help steel bridge fabricators, construction welding inspectors or bridge owners to select appropriate method for effective welding evaluation.

Conventional NDE Methods Used in the D 1.5 Specifications

Conventional NDE methods codified in the D 1.5 steel bridge welding specifications mainly include UT, RT and MT. UT technology is widely used for evaluation of complete-joint-penetration (CJP) welding. The UT method is based on interpretation of reflection and diffraction under material discontinuity of interest during ultrasonic wave propagating through metal, and are thus used for detection and sizing of defects in welds. RT is a method of locating the discontinuities and inclusions in terms of variation in radiant energy absorption when X-rays and gamma rays pass through material discontinuity. MT technology is used to locate discontinuities based on magnetic behavior of material, which is particularly effective for detecting surface defects in steel welds. Detailed summary of these three methods can be found in the literature [9]. As clearly demonstrated in Table. 1, application of each method is limited at different conditions. In general, interpretation of data/images generated from these conventional methods is a difficult task. The ability of detecting a flaw depends on the welding types, geometry and locations. Some defects depending on their shape and orientation might be undetectable by conventional UT or RT [2,5], which may overlook the severity of the welding defects, and in turn lead to premature cracks.

Table 1. Major methods for the NDE of Welds (revised after [9])

NDE	Capability	Advantages	Limitations
UT	- small surface and subsurface flaws that are too smaller to other methods - subsurface delamination.	-very sensitive -joints inaccessible to radiography	-skill in operating equipment -high degree of skill in interpreting -weak signal for certain orientation of defects -manual operation without permanent records for future use -low signal to noise ratio in field
RT	- interior macroscopic flaws.	-low cost -permanent record	-skill in operating equipment -high degree of skill in interpreting -impossible to analyze fillet welds -exaggerated results for porosity or inclusions -weak signal for delamination or certain orientation of defects -high power consumption -low signal to noise ratio in field -safety precautions
MT	- surface discontinuities.	-simple method -low cost	-ferromagnetic materials only -selecting the angle of exposure -high degree of skill in interpreting -difficult to use on rough surfaces

Advanced UT Technologies

Conventional UT method is based on interpreting amplitude of reflected signal, while the amplitude may is strongly dependent on the orientation of the defects, thus leading to relatively less reliablility for sizing defects. Also, the signal collected from conventional UT system may be contaminated by noise ratio. To overcome drawbacks in conventional NDE methods, several studies have been conducted to enhance its functionality and capability. The advanced UT technologies, such as PA-UT, PA-AUT, Time of Flight Diffraction (ToFD), Inverse Wave field Extrapolation (IWEX), and RUT, have been developed [2-8,10] for enriching the capacity of NDE. General information for each form of advanced UT technologies is briefly summarized below and is also listed in Table 2.

Time of Flight Diffraction (ToFD). ToFD [10] is one of advanced methods of ultrasonic inspection. ToFD ultrasonic test method measures the size and locates discontinuity of interest in terms of the time of flight of an ultrasonic pulse. In general, ToFD ultrasonic test system consists of a pair of probes (transmitter and receiver) placed on each side of a weld. The size of the discontinuity is calculated by measuring time of flight of the ultrasonic pulse times its velocity. Although ToFD can provide accurate information regarding size of a defect, this method has relatively poor capability of positioning of the defect in the weld cross-section [4,10]. Requirement of placing both transmitter and receiver on a weld may hinder its applications to those welding joints with restricted access and complex geometry. Also, ToFD ultrasonic testing instruments and probes are more complex and relatively more expensive as compared to conventional UT. In addition, since the ToFD ultrasonic test method is based on the diffraction signal, relatively wider defects may produce very weak signal which is hard to detect [4].

Table 2. Major advanced UT technologies for the NDE of Welds

NDE	Capability	Advantages	Limitations
ToFD	-accurate sizing of defects	-very sensitive - permanent record	-skill in operating equipment -inaccuracy for certain orientation of defects -data interpretation is not straight forward -low signal to noise ratio in field
PA-UT (Tandem)	-accurate sizing of defects	-very sensitive -accurate -permanent record	-skill in operating equipment -inaccuracy for certain orientation of defects -data interpretation is not straight forward -low signal to noise ratio in field
PA-UT (Sectorial)	-accurate sizing, orientation and location of defects	-very sensitive -accurate -permanent record	-skill in operating equipment -data interpretation is not straight forward -low signal to noise ratio in field
AUT	-accurate sizing of defects	-provide efficient and repeatable inspections of standard weld	-skill in operating equipment -inaccuracy for certain orientation of defects -data interpretation is not straight forward -low signal to noise ratio in field
PA-AUT	-accurate sizing, orientation and location of defects	-significantly improve signal quality -high-speed -automatic -easier to interpret, especially in areas with complex geometries. - permanent record	-skill in operating equipment
IWEX	-better imaging -accurate sizing, orientation and location of defects	-high-speed -easier to interpret, especially in areas with complex geometries. - permanent record	-skill in operating equipment

Phased Array Ultrasonic Testing (PA-UT). PA-UT [2-4] is another advanced method of ultrasonic inspection. The main feature of phased array probe is an array of small ultrasonic transducers while each of them can be pulsed individually. Compared to monocrystal probe used in conventional UT method, the ultrasonic beam from each individual transducer can scan/sweep through the welding cross section of interest, and the data from those beams are analyzed together to size and position defects. As a result, phased array ultrasonic method can more accurately and effectively detect welding defects that cannot be easily revealed by conventional RT or UT method. Use of phased array technology significantly minimizes frequency of placing probes, and thus dramatically simplifies scanning and accelerates the inspection.

Considering different scanning patterns, PA-UT can also be categorized into: a) **PA-UT Tandem** scan and b) **PA-UT Sectorial Scan**. The PA-UT Tandem system sizes and locates defects through amplitude of reflected signals in the weld. On some occasions, therefore, when reflection amplitude from the defect has a different orientation to that of ultrasonic beams, size measurement of defects in this method are inaccurate [4]. PA-UT Sectorial scan system is performed by steering the angle of ultrasonic beams. Amplitudes in a sectorial scan mainly rely on defects orientated in favor of the ultrasonic beams and diffraction signals. The defect sizing and characterization should be based on relation of signal amplitude with respect to defect orientation.

Automated Ultrasonic Testing (AUT). Implementation of automation technology in ultrasonic testing system is an important step. Use of automation in UT system offers relatively much faster data interpreting through combining computerized data acquisition and processing with conventional ultrasonic testing methods. Compared to conventional UT system, AUT system [5] generate images that will be relatively easier to interpret. The permanent record provided by AUT can use for confirmation of completeness of the inspection and future use over conventional manual UT system. AUT technologies can be alternative over conventional RT and UT during routine inspections of welding in bridge applications from fabrication, construction to in-service stages.

Phase Array Automatic Ultrasonic Testing (PA-AUT). PA-AUT system [6,7] is an cutting-edge high-speed automatic ultrasonic inspection of welds. This system can be mostly combining various functional units, including phased array, ToFD and other conventional pulse echo techniques [7]. Use of automatic technology in several ToFD and conventional probes simultaneously with PA probes, provides much better signal quality, significantly improving signal to noise ratio, thus leading to complete coverage of the weld volume through welding cross section. Specifically, PA probes Tandem and Sectorial techniques perform for the detection of various compact and longitudinal defects, transverse defects, or detection of lamination in the heat affected zone, while ToFD probes implement complimentary technology allowing detection of compact and longitudinal defects [7]. Field experience with PA-AUT system [7] demonstrated consistent performance without any reduction in signal to noise ratio, even with increasing weld thickness, bringing implementation to more practical convenience level.

Inverse Wave Field Extrapolation (IWEX). IWEX [4] is an imaging technology and currently has been implemented in PA ultrasonic testing system. Utilization of IWEX imaging approach offers better perspective for the interpretation of the image as compared to ToFD or PA-UT Tandem/Sectorial scan. ToFD and other advanced technologies provide data or images for sizing of defects. However, as mentioned earlier, actual size or orientation of defects cannot be measured directly from those obtained data and some interpretation of data is required.. In particular, the interpretation process requires known reflectors that are used as a benchmark to be compared. This may lead to inaccurate sizing if the defect's orientation is different to that of reflectors. Large deviation between different methods is observed in certain situations [4]. Thus, compared to these imaging techniques, IWEX system provides more effective defect characterization through more straight forward interpretation of sizing and orientation of defects.

Limited studies can be found in the literature for comparison of different advanced ultrasonic testing methods in flaw detection. One of studies was reported by Deleye et al. [4] on their experimental studies of defect inspection using four types of advanced UT systems, including PA-UT Tandem and Sectorial, ToFD, and IWEX systems. Total number of 17 cases for each method was conducted to account for flaws with different orientation and location (Fig. 2a). The frequency histograms of measuring error based on different methods are re-plotted based on the data [4]. The results show that ToFD, PA-UT Sectorial and IWEX have high consistence and relatively high accuracy. Note that ToFD was unable to detect cases A, E1, E2 and F due to certain orientation, which confirms the statement associated with drawbacks of ToFD system in Table 2.

Benefits of Advanced UT Technologies for Steel Bridge Welding Applications

Advanced UT technologies offer promising solutions and benefits to NDE of welding quality control in steel bridges. All advanced UT technologies offer high-speed inspection as compared to conventional ultrasonic testing methods. Permanent record generated through these advanced methods confirms the completeness of the process and can be archived for future record. In addition, the enhanced features of advanced UT technologies allow high signal to noise ratio, which offers more practical implementation to bridge welding inspection in field. Most importantly, a couple of advanced UT technologies, including PA-UT and PA-AUT, significantly improve signal quality, thus leading to higher detection capability. Thus, use of these advanced UT technologies pave the way for more fit-for-purpose concept in steel bride welding applications. With the aid of enhanced functionality in advanced UT technologies, defect size, location, and orientation can be more accurately detected against convention ultrasonic testing. In this way, more accurate decision-making in terms of acceptance criteria could be achieved through using these advanced UT technologies. By combining fatigue performance of welding, the further evaluation could be reached on whether the defect is severe enough to impair the serviceability of the welded bridge.

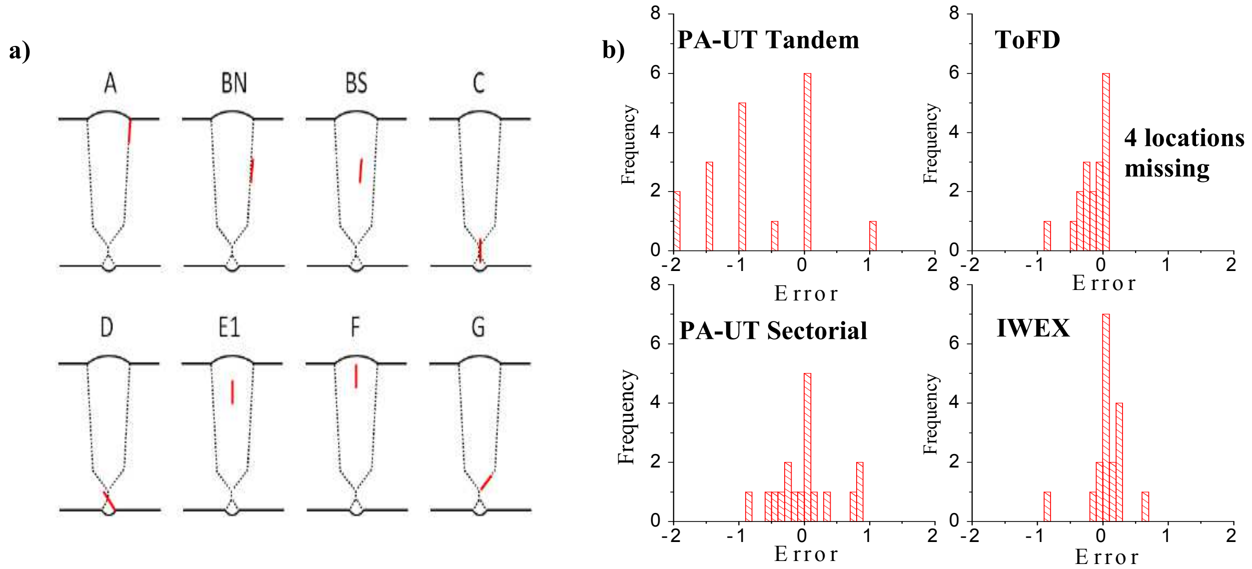

Fig. 2. Comparison of different advanced UT systems for flaw detection: a) artifical flaws [4], and b) frequency histograms of measuring error by different methods.

Conclusions

The following main observations and conclusions can be drawn from this study:

1. Advanced UT technologies show exceptional capacity over conventional NDE methods codified in bridge welding specifications.
2. Advanced UT technologies offer more clear interpretation of the accept/reject criteria over convention methods, providing the potential alternative in existing bridge welding specifications.
3. Future studies are directed to characterize the welding flaws using the advanced UT technologies through both laboratory and field tests, and specify the detailed guidelines for more widespread applications in bridges.

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