PHASED ARRAY ULTRASONIC TESTING ON THE UPPER DECK REPLACEMENT PROJECT AT THE VERRAZANO-NARROWS BRIDGE

BIOGRAPHY

Rami Boundouki is a Professional Engineer with 10 years of experience in the construction, fabrication, and design of major structures including the San Francisco-Oakland Bay Bridge and the World Trade Center Towers in New York. Currently, Mr. Boundouki is Alta Vista’s Project Manager for Quality Assurance on the Verrazano-Narrows Bridge VN-80B upper deck replacement project.

Mike Foerder has 25 years of experience in construction inspection, Quality Assurance, safety compliance, and material testing on numerous large-scale infrastructure and building projects. He is a seasoned Certified Welding Inspector and Alta Vista’s Corporate American Society for Non-Destructive Testing Level III. Mr. Foerder helped develop the PAUT procedure used on the Verrazano-Narrows Bridge VN-80B upper deck replacement project.

Brendan Scahill is a Professional Engineer with 30 years of experience in the construction and fabrication of bridge structures. Mr. Scahill has worked extensively on all the East River Bridge Crossings in New York City. Brendan is the Resident Engineer for Greenman-Pedersen, Inc. on the Verrazano-Narrows Bridge VN-80B project overseeing the Quality Assurance during the steel fabrication in China and the field installation on the bridge site.

SUMMARY

Phased array ultrasonic testing (PAUT) was performed on the closed U-rib to deck welds of the new orthotropic deck panels at the Verrazano-Narrows Bridge upper deck replacement project. The orthotropic deck is a more durable, lighter, and stiffer deck system, improving seismic and wind performance of the bridge. Closed U-ribs serve as the primary stiffening elements for the orthotropic deck panels. Due to long-term fatigue issues that can occur, consistent quality in the U-rib to deck weld is essential to the orthotropic deck’s ability to meet the specified performance and lifespan requirements. PAUT was used extensively in order to determine the consistency of the depth of penetration and identify discontinuities in the critical U-rib to deck weld.

The PAUT procedure was developed using an iterative process that required detailed scan plans, calibration blocks, and verification on test samples. Hundreds of macroetch coupons extracted from mock-up and test panels provided the necessary information for designing, calibrating, and tailoring the PAUT equipment and procedures to the current project. Utilizing this iterative process, the depth of penetration was determined within an accuracy of ± 3 % on average.

On the Verrazano-Narrows upper deck replacement project, PAUT provided the ability to quickly perform complex inspections on the shop floor in order to verify the quality of the U-rib to deck weld that is a critical component of steel orthotropic decks.
Phased Array Ultrasonic Testing on the Upper Deck Replacement Project at the Verrazano-Narrows Bridge

1. Introduction

The Verrazano-Narrows Bridge is a double deck suspension bridge that connects the boroughs of Brooklyn and Staten Island in New York City. It is currently the longest bridge in the Americas with a center span of 4,260 ft. and a total length of 13,700 ft. The bridge is shown in Figure 1.

Figure 1: View of the Verrazano-Narrows Bridge from Brooklyn looking west towards Staten Island.

The Verrazano-Narrows Bridge is owned and operated by the Triborough Bridge and Tunnel Authority (TBTA). The upper deck of the bridge, which entered service in 1964, was built using a grid reinforced concrete deck. After more than 50 years of service the existing upper level roadway has reached the end of its useful life and the TBTA is replacing the aging upper concrete deck with a steel orthotropic deck which provides a more durable, lighter, and stiffer deck system, improving the seismic and wind performance of the bridge (1).

On November 29, 2012 the TBTA awarded Tutor Perini a $236 million dollar prime construction contract to rehabilitate the upper level suspended span which includes fabrication and installation of the steel orthotropic deck panels. Greenman-Pedersen Inc. (GPI) is performing the Construction Management for the TBTA and Alta Vista Solutions (Alta Vista) is providing quality oversight of the steel fabrication. Construction began in 2013 and is expected to be completed by the end of 2017.

This paper will provide details of orthotropic deck panel fabrication, the U-rib to deck weld joint, and the Phased Array Ultrasonic Testing (PAUT) that was performed to validate the U-rib to deck welds. The details of the PAUT equipment and the comprehensive procedure development will be discussed. Furthermore, the PAUT results will be summarized and explained. A comparison of the non-destructive testing results to the large number of macroetch coupons that were removed from mock-ups and test panels will be summarized. Finally, this paper will address the advantages and limitations of PAUT.

2. Orthotropic Deck Panel Fabrication

The fabricated steel orthotropic deck panels are approximately 50 ft. (15 m) in length and vary between 6 and 11 ft. (2 – 3 m) in width depending on their location on the bridge. The deck panels consist of a \( \frac{3}{8} \) in. (16 mm) thick steel deck plate with three, five, or six \( \frac{5}{16} \) in. (8 mm) thick trapezoidal U-ribs, with internal bulkhead plates, welded to the bottom of the deck plate. These closed U-ribs serve as the primary stiffening element for the orthotropic deck panels. The new upper deck of the Verrazano-Narrows Bridge is comprised of a total of 938 deck panels. A deck panel with three U-ribs is shown in Figure 2.

Figure 2: Steel orthotropic deck panel during fabrication.

The U-rib to deck weld is a partial joint penetration (PJP) groove weld connecting the U-rib to the deck plate. Design drawings of the U-rib to deck weld are shown in Figure 3.
The PJP U-rib to deck joint is welded using a robotically controlled flux-cored arc welding (FCAW) process. Due to long-term fatigue issues that can occur, consistent quality in the U-rib to deck weld is essential to the orthotropic deck’s ability to meet the specified performance and lifespan requirements.

Figure 3: Detailed drawings showing the U-rib to deck PJP weld dimensions and weld requirements.

Per the contract specifications, the PJP U-rib to deck weld shall have a minimum depth of penetration (DOP) of 80%, minimal undercut, no overlap, and complete fusion in the weld nugget with no weld discontinuities. Figure 4 shows a cross-section of a U-rib to deck weld that meets contract specifications.

Figure 4: Example of a U-rib to deck PJP weld.

The unique geometry of the U-rib to deck PJP weld required the use of Phased Array Ultrasonic Testing (PAUT), an advanced ultrasonic testing method. PAUT is used to verify the PJP weld’s DOP and detect any unacceptable weld discontinuities.

3. PAUT Operation

Unlike conventional ultrasonic testing (UT) probes that contain a single transducer element, phased array ultrasonic testing (PAUT) probes contain multiple small individual transducer elements (probes typically contain arrays with 16 to 256 elements) that can be pulsed individually using computer-calculated timing (“phased or delay laws”). The beam from a phased array unit can be electronically swept through multiple angles (usually in the range of 45 - 75°) at the same time in order to scan a volume of weld without moving the probe toward and away from the weld joint as done in conventional UT. This is accomplished by pulsing each individual transducer element at slightly different times and thus the sound from each element pulse interacts with one another creating a single wave-front at a given distance based on parameters set by the technician and PAUT focal laws. Figure 5 shows a general overview of how multiple transducer elements can be used to create a wide ultrasonic beam capable of identifying a defect in a volume of welded material.
Figure 5: Example of PAUT weld examination. A series of beams from the PAUT transducer identify a defect in a volume of welded material.

Scan plans are developed to visualize and tune the setback distance (fixed point from a specific location), sound wave path, depth of focus, and interactions with geometries within the sound path. Figure 6 shows how different scan plans can be used to map different areas in the weld while the probe remains fixed.

PAUT scanning on this project uses an Olympus OmniScan MX2 flaw detector combined with a manual mini wheel encoder. The mini wheel encoder (or string encoder) allows the PAUT data to be collected, stored, and correlated to a known location along the deck panel. The fixed set back is obtained by either a straight edge mounted to the panel or a scanning apparatus which holds the probe in a fixed position from the weld toe as it traverses along the weld. The PAUT information is encoded and saved by the OmniScan MX2 flaw detector and then exported to a computer for further post-processing analysis and interpretation.

Post-processing analysis of the acquired PAUT data is done using OmniPC software or TomoView software. OmniPC and TomoView are PC-based software for the visualization and analysis of PAUT signals. The software allows the PAUT technician to generate detailed reports summarizing the results of the PAUT examination and allows the weld profile to be visualized from multiple orientations to accurately visualize any weld indications.

Figure 7 shows quality oversight inspection personnel operating the PAUT equipment to scan a U-rib to deck weld. Due to the difficult joint geometry and configuration, this PAUT procedure requires a high degree of precision and an advanced understanding of PAUT and UT theory and principals.

Figure 7: NDT personnel scanning a U-rib to deck PJP weld with PAUT.
4. Developing PAUT Inspection Procedures for Orthotropic Deck Panels

The PAUT procedure development is an iterative process. The first step in developing the PAUT procedure is to identify the equipment to be used, the geometry of the weld joint, the initial scan plans, and the initial scanning and analysis parameters. The scan plans were developed by an ASNT NDT Level III technician and provided maximum coverage of the weld area and heat affected zones. The PJP joint geometry was idealized and plotted using ES Beam Tool, a computer generated scan plan software program.

Secondly, calibration of the PAUT equipment is performed on a standard IIW block, a Side Drill Hole Block, and a job specific calibration block. The job specific calibration block is manufactured using Electric Discharge Machining (EDM) or another similar method to introduce an unfused feature of known dimensions. The third step is a verification of the PAUT results by removing and verifying macroetch samples from various test specimens.

Based on a comparison of the PAUT results with the macroetch results, the scan plans, scanning parameters, and analysis parameters were updated and the remainder of the process was repeated. This iterative process was used until the PAUT results and the macroetch results for depth of penetration were on average within ± 3 %.

4.1. PAUT Equipment

The PAUT equipment used to validate PJP U-rib to deck joints consisted of an Olympus OmniScan MX2 16:64 (16 pulsars and 64 channels) displayed in A, B, C, S, linear scans, or a combination thereof (2). The aperture was fitted to a 55° shear wave wedge with elements oscillating at 5.0 MHz. A linear digital encoder recorded data for post processing using TomoView and/or OmniPC software.

4.2. PAUT Calibration

Ultrasonic equipment used to identify weld flaw detection and weld sizing must be calibrated prior to inspection. The PAUT equipment was first calibrated using a Standard IIW (International Institute of Welding) block to calibrate the wave velocity, wedge delay, and angle corrected gain (ACG or “sensitivity”). The time corrected gain (TCG) was established on a standard 1.5 mm diameter side drilled hole block. Furthermore, the digital encoder was calibrated to ensure the measured distance was within ± 1% of the actual distance the probe traveled along the weld (3).

Job-specific calibration blocks were manufactured using EDM to include unfused notches with known dimensions as shown in Figure 8. The unfused depth of penetration notches ranged from 50% to 85%. Multiple notches provided a wide range for PAUT equipment and procedure validation that were then applied to deck panel production.

![Figure 8: Job-specific calibration blocks with known EDM notches for verification of PAUT procedure.](image)

4.3. PAUT Procedure Verification

Before PAUT was used to validate production deck panels, several pre-production mock-up panels were fabricated. These panels were also used to validate and improve the PAUT procedure’s accuracy in measuring the DOP and ability to identify planar weld discontinuities in the U-rib to deck PJP weld joint.

Hundreds of macroetch coupons were removed from the U-rib to deck welds at locations with different signal types and characteristics, in order to investigate the wide spectrum of ultrasonic...
signals present in the complex U-rib to deck PJP weld joint. During the mock-ups, Non-destructive Testing (NDT) was performed including Visual Examination (VT), Magnetic Particle Testing (MT), Ultrasonic Testing (UT), and Phased-Array Ultrasonic Testing (PAUT).

Following visual inspection of the macroetch coupons, the DOP and weld discontinuity were documented. Furthermore, MT was performed on the ends of samples and the results were photographed. The MT results highlighted the DOP in some samples and provided evidence of linear and planar type indications in other samples. In order to further investigate the weld within the macroetch sample between the two ends, PAUT was performed on each macroetch sample and the magnitude of the least depth of penetration and the location and extent of the planar-type indications, if any, were recorded. In some cases, the macroetch coupons were further sectioned in order to inspect the specific location pinpointed by the PAUT results.

**Figure 9:** Mock-up panels with macroetch coupons removed from the U-rib to deck.

The mock-up panel was scanned using the updated PAUT procedure and a thorough post-processing analysis was performed to determine the DOP along the length of the weld in addition to any indications of weld discontinuity. Following this analysis, macroetch coupons were removed to validate the DOP and weld discontinuities at known locations.

Figure 9 shows a mock-up panel with multiple macroetch coupons removed for analysis. The bottom image in Figure 9 is a representative image of the macroetch coupons that were removed from test panels. All macroetch samples were photographed and catalogued and each macroetch was identified with a unique marking. The macroetch samples varied in length from 20 to 60 mm.

**Figure 10:** Weld indications visible at the ends of macroetch specimens using MT. These indications were also detected using PAUT.

When conducting the inspection of the macroetch coupons, MT performed on the ends of the samples resulted in the observation of planar-type indications and/or lack of fusion at the bevel face on the inside of the U-rib. Some of these
indications started at the root of the weld and extended into the weld or propagated along the bevel face. Other indications were within the weld nugget. Figure 10 demonstrates the two types of weld indications that were visible on the ends of macroetch samples with MT.

The investigation of hundreds of macroetch coupons with PAUT and other NDT methods demonstrated PAUTs ability to more accurately measure the depth of weld penetration and identify weld indications that existed beyond the face of the macroetch samples. After a detailed analysis of the PAUT results and the iterative approach to PAUT development, the PAUT procedure to be used on the deck panels was verified to accurately identify the DOP on average within ± 3 % of the measured DOP on the macroetch coupons.

5. PAUT Inspection During Panel Fabrication

5.1. Quality Program
The comprehensive quality program on this project is comprised of three levels of oversight. The Fabricator is responsible for quality control (QC) operations and the Contractor is responsible for quality assurance (QA) operations. The TBTA, through Alta Vista, is performing an independent verification of the quality of the steel fabrication as the prerogative of the Engineer. The verification oversight that the TBTA and Alta Vista are performing does not relieve the Contractor of their responsibility to comply with all contract specifications.

As part of the project specifications, verification PAUT by the contractor/fabricator is required on at least 20% of the U-rib to deck PJP welds for each panel. If defects are found when inspecting 20% of the welds, 100% of the U-rib to deck PJP weld must be inspected using PAUT. The fabricator performs PAUT of the U-rib to deck PJP weld and data is shared with the quality oversight team. At the direction of the Engineer, the quality oversight team reviews the fabricator’s PAUT data and performs additional independent testing.

5.2. Destructive Test Panels
The project specifications also require randomly selected production panels to be set aside for destructive testing. These “destructive test panels” (DTPs) are sectioned and macroetches are removed from the U-rib to deck PJP weld (along with other macroetches removed from other welds). The macroetches are inspected for weld quality and compliance with contract specification. Furthermore, the macroetches from the DTPs serve as verification that the PAUT and other NDT inspection methods are being performed during production and can be relied upon for acceptance.

As seen by visual examination, and confirmed in the 100% PAUT scan, macroetch sample in Figure 11 met all requirements for depth of penetration and weld quality as determined by the Engineer.

Figure 11: Macroetch coupon removed from DTP #5.

5.3. Job Control and Verification Samples
As required by the project specifications and in order to determine the depth of penetration and consistency of the robotic FCAW process, job control samples and verification weld tests were performed. A job control sample is performed at the beginning of the day’s U-rib to deck robotic welding operations in order to confirm the correct operation of the robotic welding process. Verification weld tests are performed for every panel following the completion of U-rib to deck welding.

The image in Figure 12 shows a finished job control specimen prior to extraction, macroetch removal, and investigation.
5.4. PAUT of Fabricated Panels

The fabricator is performing 20% (30 m) PAUT on the U-rib to deck welds on all 938 fabricated deck panels. The data is encoded in 1 m sections and analyzed for weld penetration and weld soundness such as planar indications. PAUT scanning a typical deck panel’s U-rib to deck weld joints takes approximately 8 hours per panel with a two-person PAUT Inspection team.

The detailed post-processing analysis includes a review of the A-scan, B-scan, and S-scan utilizing OmniPC software or TomoView software as shown in Figure 13. Post-processing analysis of the PAUT data typically takes the PAUT Inspector 8 hours and varies depending on the number of indications detected in the weld. Utilizing the signal characteristics and verified calibration, the depth of penetration can be determined for each location along the length of the weld. Furthermore, any indications that could be due to slag, porosity, lack of fusion, or cracks are further evaluated using PAUT and provided to the Engineer for acceptance or repair.

Throughout the entire fabrication process, more than 15 miles (24 km) of weld have been scanned by PAUT and the data was encoded at 1 mm increments for post-processing. During post-processing, the weld DOP was determined at 25 mm increments. Based on this extensive PAUT methodology, it was determined that the fabricator is providing a consistent PJP weld with minimal repairs required.

Figure 14 shows a summary of the depth of penetration results for Panel 3E-097. PAUT was performed on the entire length of the U-rib to deck weld of this panel and it was selected for sectioning as DTP #5.

Panel 3E-097 (DTP #5) was a deck panel with 6 U-ribs (12 PJP welds), with a total U-rib to deck weld length of 590 ft. (180 m). The depth of penetration results in Figure 14 show the majority of the weld penetration exceeded 75% and more than three quarters of the weld length that was analyzed exceeded 80% penetration. These PAUT results were confirmed by the extracted macroetches coupons.
6. PAUT Feasibility and Limitations

Phased array ultrasonic testing is not designed to replace more traditional UT methods; however it is another tool in the NDT tool box that has some unique advantages.

- **Speed** – Automatic/semi-automatic scanning allows for a faster scan rate over a larger volume of material facilitating an increased shop production rate.
- **Flexibility** – A single probe can be used to scan small areas or larger volumes by adjusting the scan plan.
- **Complex inspection** – Multiple scan plans can be created to investigate complex geometries and/or large volumes of materials that may be otherwise inaccessible.
- **Increased probability of detection** – The ability to test welds with multiple angles from a single probe greatly increases the probability of detection of anomalies.

Electronic focusing permits optimizing the beam shape and size at the expected defect location, as well as further optimizing probability of detection.

- **Encoding** – Digital encoders allow the full spectrum of UT data to be saved for post-processing and shared with others for independent analysis.
- **Unique imaging** – S-scans permit easier interpretation of an indication’s size and location in the sample.

The advantages of PAUT do not come without some challenges.

- **Non-standard procedures** – AWS D1.5 welding committees are working to incorporate PAUT in the upcoming edition.
- **Expensive equipment** – Compared to conventional, single-element ultrasonic testing systems, phased array instruments and probes are more complex and expensive (approximate 2x to 5x the cost of conventional UT).
- **Skilled operator** – Phased array technicians require more experience and training than conventional UT technicians.
- **Time-intensive** – Data analysis and post-processing time increases with the large amount of data collected by PAUT.

Nevertheless, as PAUT requirements become more common in construction and inspection standards, many of the challenges facing PAUT today will likely be overcome.

7. Conclusions

The new orthotropic deck panels for the upper deck replacement of the Verrazano-Narrows Bridge will greatly extend the structure’s lifespan, improve its seismic and wind performance, and lower roadway maintenance costs. All of these achievements are in part due to the advanced and detailed engineering of the orthotropic deck panels and in particular the critical U-rib to deck PJP weld. Consistent quality in the U-rib to deck weld is essential to the orthotropic deck’s ability to meet the specified performance and lifespan requirements.

PAUT was used extensively in order to determine the consistency of the depth of penetration and
identify discontinuities in the critical U-rib to deck weld.

The PAUT procedure development is an iterative process that requires detailed scan plans, calibration blocks, and verification on test samples. Utilizing this process, the depth of penetration can be determined within an accuracy of ± 3 % on average compared to macroetch coupons removed from the same locations in the weld.

On the Verrazano-Narrows upper deck replacement project, PAUT provided the ability to quickly perform complex inspections on the shop floor in order to verify the quality of the U-rib to deck weld that is a critical component of steel orthotropic decks.

8. References

