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Testing Program Validates Wrinkle Bend Repair Solution

By **Tim Mally, ClockSpring|NRI**

Wrinkle bends are ubiquitous in the United States, and many exist in lines that have been in service for decades. Continuous service and wear take their toll over time, but on wrinkle bends, which experience high strains resulting from bending and axial forces caused by shifting terrain and suffer in many cases from insufficient pipe support, there is concern about their continuing integrity.

In many cases, repairs will be essential to ensure safe operations, and owners want reliable options to the very costly practice of cutting and replacing the bend areas with new pipe.

Then, Now

Until the mid-1950s, bending pipe was a common way to bring pipelines into alignment. Bending techniques used during pipeline construction typically resulted in circumferential pipe deformation that formed sharp wrinkles on the inside bend radii of the pipe. In looking at these pipes today, it is clear the construction process introduced severe geometry changes in the pipeline that generate areas of stress concentration.

Because corrosion and mechanical damage are more pervasive integrity issues, a great deal of time and attention has gone toward finding solutions related to these issues, and less time has gone into finding methods to address the integrity of wrinkle bends in vintage lines. The sheer number of these wrinkles in the field leads to the conclusion that finding ways to ensure integrity is important.

Composite materials presently are applied to repair a broad range of pipeline damage and have been proven effective over the last 25 years. The versatility and success of this technology make it a likely solution for repairing wrinkle bends, but before industry is willing to accept a different repair methodology, testing and analysis need to validate repair systems based on composite materials.

Wet layup composite repairs are proven to be successful in restoring pipe to its original operational and design strength for more common pipeline anomalies such as corrosion and dents. This approach has not been generally applied to wrinkle bend reinforcement. Several manufacturers have developed composite solutions and applied them with varying levels of success. One of the goals of the investigation discussed here was to find a way to decrease composite installation defects and increase the reliability and speed of each installation.

Setting the Stage

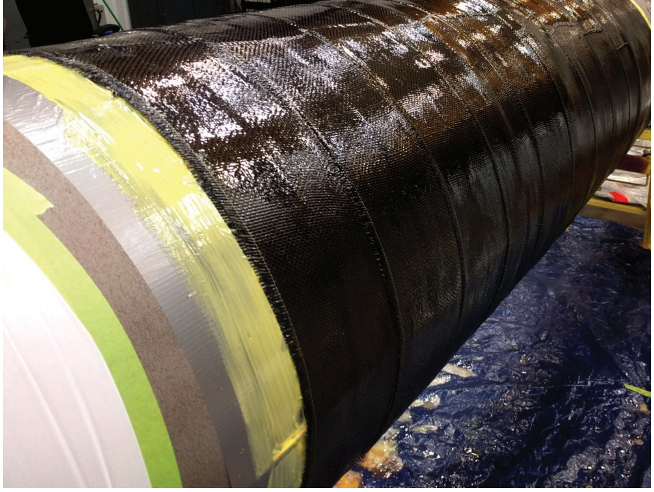
Tests carried out by ClockSpring|NRI were set up to evaluate three composite repair layup configurations for reinforcing wrinkle bends, using finite element analysis (FEA) and full-scale testing to validate the design methodologies. Two of the composite layups were tested to validate a new composite designed to decrease installation defects and increase installation speed and reliability. The other used a conventional layup technology.

The first step of the testing program was to secure a piece of vintage pipe with wrinkle bends to use for the physical tests. A section of Grade X52 steel pipe was removed from service for this purpose. The 26-inch line, with a nominal wall thickness of 0.281-inch, was subjected to elastic-plastic FEA to evaluate the stress-strain response of wrinkled pipe and to optimize the new composite design and layup.

The full-scale test program exposed the pipe section to cyclic-bending under constant internal pressure. The goal was to validate the ability of composite repair materials to improve the cyclic bending fatigue life of the pipe section. Testing included samples with and without composite reinforcement.

The next step was to assess current composite repair installation techniques to identify shortcomings, so the new design would

Composites provide quality repairs that can be installed quickly for reliable results. *(Photos by ClockSpring|NRI)*



A piece of pipe was covered with the new proprietary composite design to undergo laboratory tests to determine its durability.

be an improvement over current installation methods. In addition, the research team examined wrinkle-bend reinforcement work previously performed by the company to help refine finite element analysis (FEA) accuracy and gain an understanding of the current composite repair materials in use.

One of the first limitations identified in many composite repairs is the difficulty in appropriately applying the repair on the underside of the pipe, where gravity hinders adherence. The axial strip is applied to the pipe, but sags, leaving voids that inhibit proper bonding. Without good adherence, the composite cannot provide reinforcement in that area of the pipe.

A better product or application technology would simplify application and deliver an improvement over this inconsistent approach so gaps, voids and sags would not reduce the efficacy of the composite repair.

Running Tests

In an earlier analysis carried out by Stress Engineering, a similar piece of pipe was used to test a composite repair that was 0.35-inches (8.9 mm) thick with the line under 810 psi (5.58 MPa) and a bending moment range of 1,000 kip-ft (1,355.8 kN-m). The unreinforced sample failed at 165 bending cycles, while the reinforced wrinkle failed after 749 bending cycles.

The results were analyzed using FEA to optimize the performance of the applied composite repair under bending and axial fatigue while minimizing the repair thickness.

For the ClockSpring|NRI testing, two types of tests were carried out in four scenarios: 1) Pipe free of all defects, 2) Pipe with wrinkles, 3) Pipe with wrinkles covered with a composite repair as designed for the Stress Engineering study, and 4) Pipe with wrinkles covered with an optimized composite repair.

These cases were subjected to FEA elastic simulation modeling to determine a theoretical stress concentration factor (SCF) and to optimize the new design as well as elastic-plastic simulation to determine the strain range on the wrinkle of each scenario with respect to the bending moment range.

The elastic FEA model was applied to the four scenarios under conditions identical to those used in the original testing. FEA results correlated well with the SCF that was determined based on strain gauge data collected during the previous study.

This validated the theoretical SCF, giving confidence that the FEA model could be used to represent changes in performance in full-scale testing of the new optimized repair, which was designed to lower the theoretical SCF in comparison to that of the unreinforced wrinkled pipe.

The elastic-plastic simulations, carried out on the scenarios under the same conditions as the original testing, revealed the range of elastic and plastic deformation in the pipe and wrinkle under different repair methods. With the wrinkled, unrepaired pipe simulation results, it was possible to compare the performance of the original experimental study design to the optimized composite repair design.

Results from the FEA analysis predicted that the optimized design decreased the maximum strain at the wrinkled section by 69% in tension and 50% in compression. This reduction in maximum strain at the wrinkle extended the fatigue life of the pipe.

FEA analysis was followed by full-scale testing of the pipe samples at a fully equipped test facility under the same conditions used for the FEA model. Strain gages were placed on and around the wrinkle to collect data to quantify the performance of each design, and an unreinforced wrinkled pipe was used as a baseline.

The unreinforced pipe was pressurized and subjected to load cycling between the minimum and maximum bending moments until failure occurred. Within 165 bending cycles, the pipe experienced a through-wall circumferentially oriented crack that developed at the wrinkle.

Based on the results of the unrepaired wrinkle, a 1,000 kip-ft bending moment range was used to test the reinforced pipe specimens, which were subjected to 1,500 bending cycles – corresponding to a factor of safety of approximately 10, relative to the unreinforced sample failure.

In the subsequent test, a piece of pipe was covered with the new proprietary composite design with a thickness of 0.43-inch (10.9 mm) using an installation technique that decreases application defects by addressing application inconsistency.

This specimen was subjected to 1,340 bending cycles before the composite failed. This represents an increase of almost 600 bending cycles over the composite repair designed for the original study. Additionally, the average axial strain range at the wrinkle decreased from 4,997$\mu\varepsilon$ in the original experimental study to approximately 4,000$\mu\varepsilon$. The decrease in axial strain directly reduces the calculated effective SCF from 2.4 to 1.8.

Hypothesizing that a thicker repair would improve performance, the team treated a second specimen with an increased composite repair thickness to 0.65-inch (16.5 mm). This specimen was pressurized to a constant pressure of 810 psi (55.8 bar) and then subjected to the 1,000 kip-ft bending moment range. No limits were set for the number of bending cycles for this test. Instead of stopping at 1,500 cycles, the pipe was tested to failure – which occurred after 2,068 bending cycles.

The axial strain at the wrinkle also showed improvement, decreasing to 3,000$\mu\varepsilon$ and leading to a calculated SCF of 1.2. This axial strain measurement and the resulting SCF are the lowest of all the manufacturer's tested designs and demonstrating significant improvement over the composite design evaluated in the original study. The optimized composite design decreases the axial strain at the wrinkle by 40%.

Based on the full-scale testing results, there is a clear correlation between the strain at the wrinkle, the effective stress concentration factor, and the number of bending cycles to failure. The low-cycle, high-strain fatigue testing in this program shows that installing composite reinforcement increases the fatigue life of unreinforced wrinkle bends by a factor up to 12.5. This proves that the optimized composite repair design is an effective way to improve fatigue resistance of wrinkled pipes subjected to cyclic bending moments under constant internal pressure.

Field Composites

The new, proprietary composite design was used to strengthen four wrinkle bends on an 18-inch natural gas transmission line in the United States. The operator could not afford to shut down the line to cut and replace the bends because of the high transport volume through the pipe. And a welded sleeve could not be used because of the odd configuration of the anomaly.

A team of project engineers designed a repair for the wrinkle-bend defect according to ASME PCC-2 Article 4.1, prescribing a composite repair solution that comprised two layers of a combination of ClockSpring|NRI's proprietary wrinkle bend repair fabric and a carbon fabric.

Trained technicians were able to complete the repair within three hours, which is not only much faster than alternative repair methods but considerably quicker than other composite repairs available.

The pipeline remained in operation during the repair installation and the curing process. The completed repair exhibited no defects, and the repaired line has operated so effectively that this repair method has become the pipeline operator's repair of choice for other pipeline anomalies.

Proven Alternative

The extensive FEA and laboratory testing of this composite solution and its subsequent performance in the field prove the viability of composite technology in effectively addressing wrinkle bend repairs.

Ongoing research and development (R&D) efforts continue to push the boundaries of this technology, and as more repairs are carried out in the field, there is more real-world evidence that composite technology is a reliable alternative to traditional strengthening and repair methods and that it can be applied without negatively impacting operations. ***P&GJ***

ClockSpring|NRI is a Houston-based manufacturer and provider of high-performance critical infrastructure construction and repair products and associated engineering support and training services. ClockSpring|NRI solutions are used to construct, maintain, and rehabilitate pipelines, natural gas distribution lines, high-consequence industrial pipework, and civil structures. ClockSpring|NRI composite pipe repair systems and inline insertion valves are used in more than 75 countries and include industry-leading products such as Clock Spring™, Atlas™, Syntho-Glass® XT, Scar-Guard®, Contour, and DiamondWrap® composite products, as well as the award-winning AVT EZ Valve™ for water and gas lines. All ClockSpring|NRI products are easy to install, cost-effective to deploy, and durable for decades. www.cs-nri.com

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