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Strain Monitoring in Water Pipelines

PICA
Pipeline Inspection and
Condition Analysis Corporation

PICA- PIPELINE INSPECTION & CONDITION ANALYSIS CORPORATION

RTS 125+ Distributed Strain Measurement

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Analysis Report

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Project Overview

In 2020, Pipeline Inspection and Condition Analysis Corporation (PICA) partnered with a water utility in Northern Texas to study failure mechanisms in Prestressed Concrete Cylinder Pipe (PCCP) using Remote Field Technology (RFT). The aim of the study was to discover if compromised pipe could be better classified and ranked according to its remediation requirements. PICA performed an initial study onsite at the water utility's facilities in June and motivated by breakthrough discoveries returned for further research in January 2021.

PCCP is a composite of a concrete liner, steel cylinder, and concrete coating with embedded prestressing wires wound in a helix. Most of the hoop strength (pressure carrying capability) of PCCP is gained through the pretension strength of the helix. The steel cylinder acts simply as a barrier to fluid transfer between the interior and exterior of the pipe. If the helix fails due to corrosion or embrittlement, a catastrophic failure of the pipe may occur. PICA's aim is to leverage non-destructive testing to preempt these failures.

Based on data collected during PICA's initial study in June 2020, a theory developed which stated that the condition of prestressing wires could be inferred by measuring changes in preload on the steel cylinder. RFT is well suited to measuring magnetic permeability changes in ferrous materials which reflect physical stress changes in those materials. A series of tests indicated that an increasing quantity of cuts in the prestressing wire resulted in larger perturbations in RFT measurements. In the two regions of pipe where experiments were carried out, only one region strongly exhibited this effect.

PICA determined that a key component of the research was the ability to map actual strain measurements of the steel cylinder to RFT measurements, in regions affected by cut prestressing wires. Sensuron, a leader in fiber optic sensing technology, was contracted to assist with data collection as PICA carried out further experiments in January 2021. Over the span of a week technicians worked to prepare the pipe surface for sensor installation, installed two strain sensors in two test sites, and collected strain data for over a dozen different experiments.

The following report details constituent components of PCCP, summarizes the installation procedure for Sensuron's fiber optic strain gauges, enumerates the type of pipe modifications made to synthesize failure modes in PCCP, and highlights results of the strain gauge data.

Inspection Details

Pipeline Configuration

The pipe used in this study is “Embedded Cylinder Pipe”, AWWA C-301E.

Embedded cylinder pipe is manufactured by the following sequence:

- A relatively thin steel sheet is wound into a cylinder pipe and spirally welded. Steel joint rings are welded to both ends. The pipe is hydrostatically tested to ensure the quality of welds.
- The pipe is embedded in a concrete form that has a rotating, retractable trough that delivers cement to the inside and outside of the steel pipe. The assembly is cured with steam at elevated temperatures.
- Prestressing wire is attached to one end of the pipe and wound under controlled tension and spacing to the other end of the pipe. The tension and spacing are variables which contribute to the final strength of the pipe.
- The pipe is horizontally revolved as an external layer of cement slurry is applied to protect the wires from corrosion.
- After curing, the pipe is ready for delivery to the customer.

When the wires are wrapped onto the pipe under high tensile load, the effect is to place the steel cylinder into compression. When enough wires break, this compression is changed, resulting in a “Loss of Preload”.

When the steel cylinder changes state due to this Loss of Preload, it essentially expands or relaxes. Because the steel is too thin to carry the design hoop strength of the pipe, if enough adjacent wires break, the pipe will rupture.

It is important to understand that C-301E is substantially different from C-301L which is “Lined Cylinder Pipe”. In this design, the wires are wound directly onto the steel cylinder and there is only one layer of external cement. This pipe is overall thinner than C-301E, and the pre-load characteristic are likely substantially different.

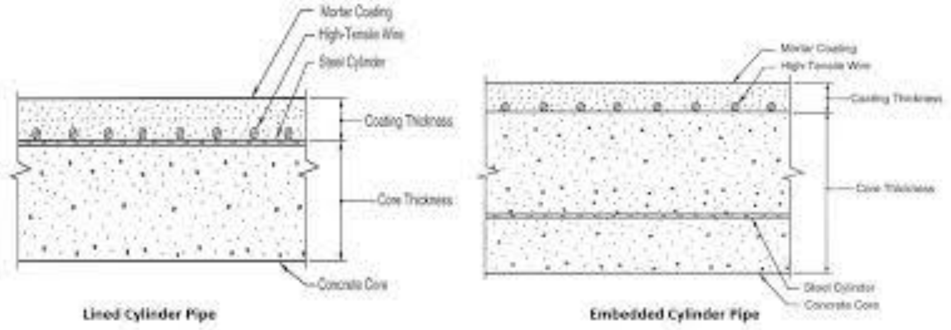

Figure 1. Mechanical construction of C-301 (Type L left, Type E right)

Strain Monitoring Equipment

Strain is a mechanical response to applied stress. It is a unitless ratio of the amount of deformation due to stress over the original length of material. By generating a strain-stress curve, many properties of mechanical bodies can be determined such as strength, elasticity, and yield. These properties are key in the design of any mechanical system as they establish working limits of that system. In the context of pipelines, such strain-stress curves can dictate the makeup and quantity of overburden or maximum operating internal pressure of conveyed product, as two examples.

In this study, a fiber Bragg grating (FBG) was employed for monitoring stress. This is a type of optical fiber which has a spatially modulated index of refraction. This modulation is achieved by periodically changing the mechanical characteristics of the fiber along its length by illuminating with UV light through a mask to generate an interference pattern. This results in a fiber that selectively transmits light of a particular wavelength: the Bragg wavelength.

When the fiber is adhered to a material-under-test, the Bragg wavelength becomes coupled to the stretch or compression of this material. If the test material changes length, the index of refraction is locally altered in the fiber. By energizing the fiber with laser light, and subsequently measuring the wavelength and time of arrival of reflections, strain information may be inferred.

To continuously measure strain along the inner surface of the embedded steel cylinder in PCCP, PICA used the Sensuron RTS125+ interrogator. This is an 8-channel instrument that can simultaneously monitor 16,000+ sensors at a refresh rate up to 100Hz. For purposes of this study, PICA required two fibers installed in two test pipes. Fibers were configured to collect readings every 0.25-inches.

The complete list of equipment required to measure, and log strain data included:

1. RTS125+ Interrogator
2. RTS125+ Power Supply
3. 2 Blackbody Radiators
4. 2 Fiberoptic cables
5. 2 Patch chords
6. Laptop and power-supply

Figure 2. 8-channel Sensuron instrument. (https://www.sensuron.com/rts125/)

Site Preparation

The test specimens selected for this study were the internal steel surfaces of two excavated pipes. These pipes originated from a water conveyance system and exhibited signs of distress. After excavation, the pipes were joined to form a “Test Loop” above ground and mechanically modified in a variety of ways to synthesize natural failure modes. Two strain gauges were installed, one in each pipe, in areas where most stressing modifications were performed. Henceforth the two segments of pipe will be distinguished as Segment A, and Segment B, each having different stressing mechanisms applied to them.

Prior to strain gauge installation, technicians marked out regions of internal concrete liner that required removal. These regions were 3-inches wide and marked around the circumference. Subsequently, a grinder with a 4.5-inch diamond cutting disc was used to score the concrete to a depth of 1.5-inches. A pneumatic chisel then carved a channel out of the concrete liner to expose the bare metal surface of the embedded steel cylinder.

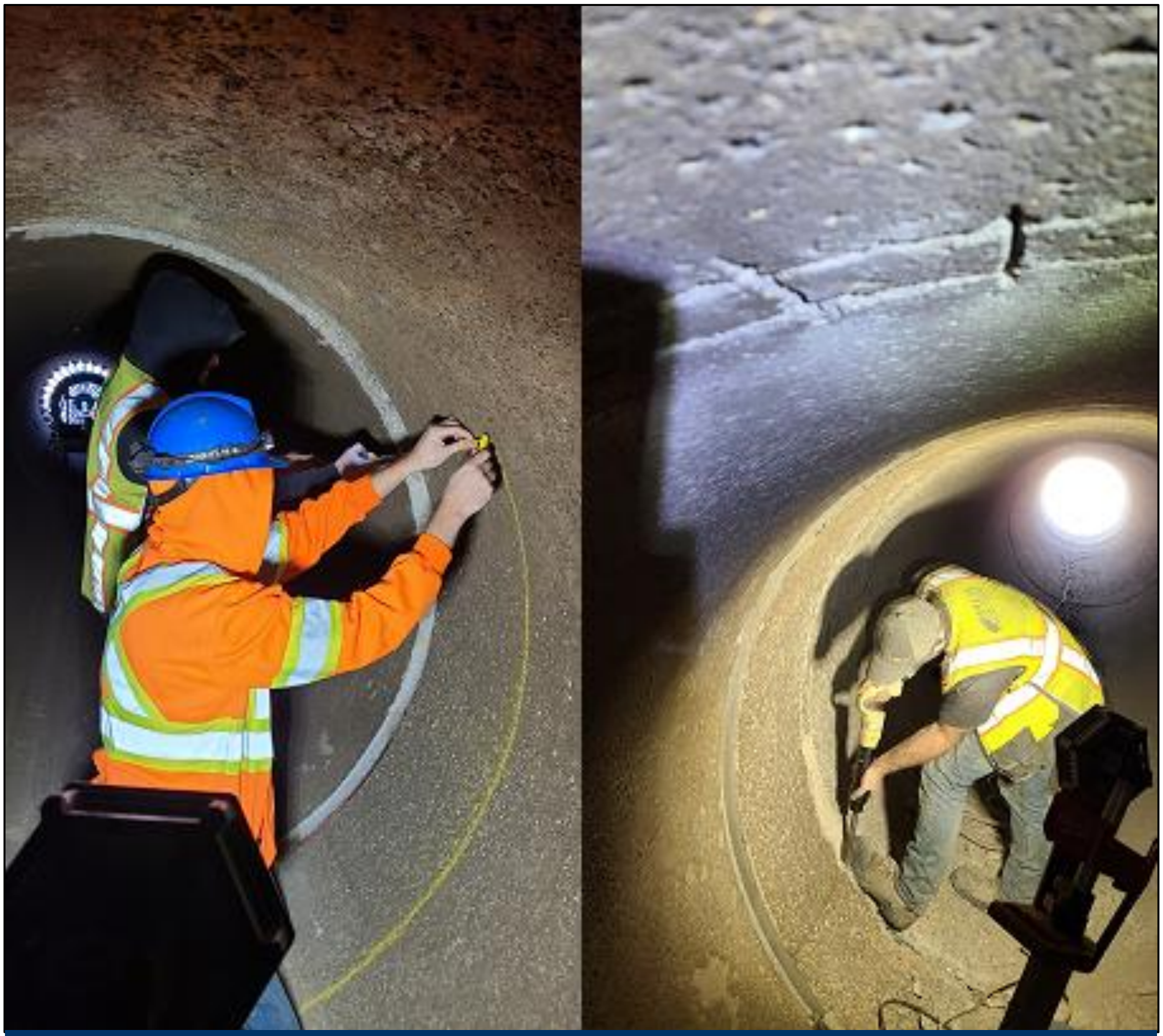

Figure 3. Technicians modifying inside of PCCP in preparation for strain gauge installation.

Significant physical exertion was required to remove the 2-inch-thick ring of concrete, and despite best efforts to leave the steel surface unharmed, several marks and punctures were incurred. This is because the amount of force required to chip away the concrete liner differed around the circumference. In some spots the concrete was well adhered to the steel and a technician was obliged to remove concrete with more vigour, while in other spots the concrete spalled off quite easily. The accidental damage never spanned the length of the exposed gap; thus, a strain gauge fiber could still be snaked around the circumference.

Figure 4. Sample of damage incurred during concrete removal: punctures (left) and scratches (right).

With the bare steel accessible, technicians began to install the fiber optic strain gauge. First, compressed air was used to remove dust and loose particles. Next a rag doused in isopropyl alcohol was wiped along the steel pipe to degrease the metal surface. A short length of test fiber was adhered to the metal using cyanoacrylate to confirm bond strength which proved sufficient. Next, a technician proceeded to apply fiber and bonding agent along the circumference, working with 6-inches of fiber at a time. Care was taken to avoid the existing punctures and scratches on the steel. In one area, a 1.5-inch hole from an earlier pipe modification prevented fiber installation, thus the fiber was hung over the hole but not adhered to the pipe. Finally, the fiber was protected with a thin layer of RTV silicone.

Figure 5. Gluing strain gauge fiber to steel (left) and protecting with red and blue RTV silicone (right)

For best strain gauging results, a temperature compensation standard is used to exclude material changes due to fluctuating temperatures throughout the workday. Technicians cut out a 10-inch by 2-inch-wide steel coupon from scrap pipe and adhered the calibration fiber to it. This coupon represented the same mechanical properties as the embedded steel cylinder. It was placed in the same environment as the test pipe and acted to offset the common temperature effects.

Once fiber installation was complete, the RTS125+ Interrogator energized the system and began to collect readings. A baseline measurement was established which represented the pipe state prior to any external modifications. This is the state against which all subsequent measurements would be compared.

Analysis Results

Data Visualization

The strain gauge data was visualized by plotting strain along the vertical axis, in units of micro-strain, and location along fiber on the horizontal axis, in inches from 6:00 datum. The 6:00 datum was selected because that is the location where the sensor was first adhered to the steel pipe, continuing along the circumference in a counter-clockwise (looking West) fashion, then returning to the starting clock position. The visualization scale was limited to 1000 micro-strain and 240-inches as these represented the extents of the meaningful data.

The sensing fiber was longer in length than the circumference of the pipe-under-test, thus extraneous data was recorded to each log file. This additional data did not encode information that was interesting for this study and required cropping. A Python script was written to extract just the pertinent sections, apply a filter, and export plots to a Portable Network Graphics (PNG) file. A 51-point moving window median filter was selected as the optimal choice for conditioning the data. This represents a filter that smooths data over a 12-inch span. Because PICA was interested in general strain effects, this 12-inch smoothing window was deemed acceptable.

Figure 6 represents raw data extracted form the Sensuron RTS125+ Interrogator (left), and processed data (right).

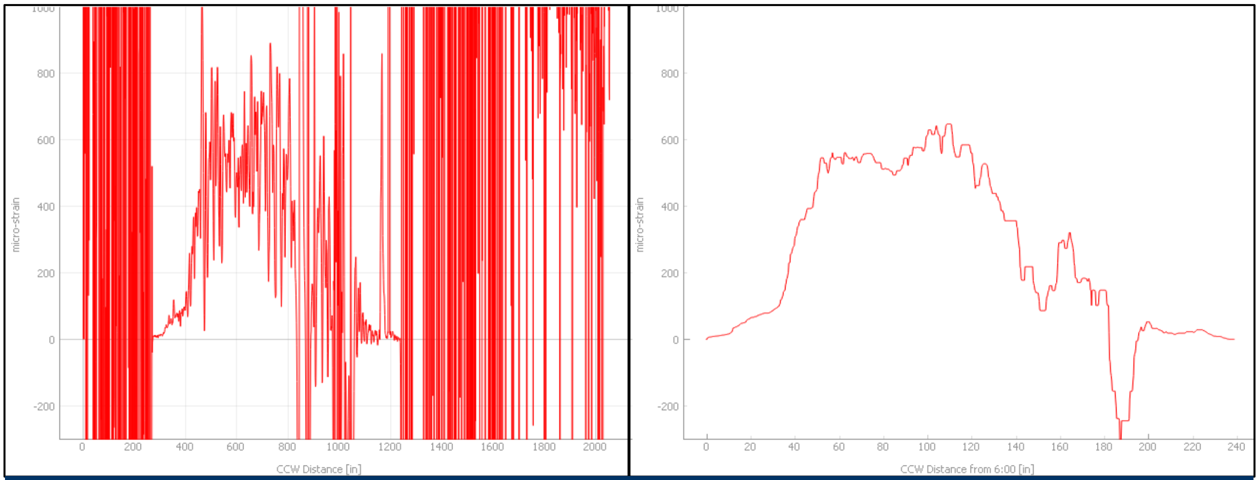

Figure 6. Raw strain gauge data (left), filtered and cropped strain gauge data (right)

Outer Concrete Removal in Segment A

Based on previous studies on PCCP, PICA posited that when a wire in the concrete coating breaks, the preload exerted on the embedded steel cylinder may not perturb uniformly around the circumference. If the concrete is well bonded to the wire, then even if wire breaks are present, the concrete may prevent the wire from contracting and recoiling in its channel. This would result in wire that still carries pretension for a portion of its length, and still exerts a force on the steel cylinder.

In prior experiments on Segment A, PICA cut several dozen wires in a localized position around the circumference and did not observe wire recoil. Data from subsequent electromagnetic scans did not reveal a change in steel cylinder properties that would indicate loss of preload. For this round of testing, PICA experimented with exposing more wires and diminishing the strength of concrete-wire bond by removing concrete windows at an increasing amount of clock positions.

The baseline state was a 2-foot wide by 1-foot-tall window with outer concrete removed and all wires cut using a grinder. This represented conditions at the end of PICA's previous studies on this testbed. For the subsequent study, PICA made the following pipe modifications in sequence:

1. Removed 2-foot wide by 1.5-foot-tall window in outer concrete at 9:00 on the circumference. No additional wires were cut.
2. Removed 2-foot wide by 1.5-foot-tall window in outer concrete at 12:00 on the circumference. No additional wires were cut.
3. Removed 2-foot wide by 1.5-foot-tall window in outer concrete at 1:30 and 10:30 on the circumference. No additional wires were cut.
4. Removed all concrete from 9:00 to 3:00 clockwise around the circumference. No additional wires were purposefully cut, but several broke due to existing compromised wire condition.

Figure 7. PICA technicians removing an outer concrete window in Segment A at 3:00 (left), at 12:00 and 1:30 (center), and from 3:00 to 9:00 (right)

Figure 8 depicts changes to the preload on the embedded steel cylinder resulting from the increased concrete removal.

The green trace represents the baseline scan prior to any new modifications and is depicted as a flat line.

The red trace represents the removal of concrete at 3:00 which is depicted by a perturbation at around 70-inches measured counter clockwise from the invert.

The blue trace represents missing outer concrete at 12:00 and 3:00, depicted as two perturbations centered around 70-inches and 110-inches.

The brown trace represents missing outer concrete at 10:30, 12:00, 1:30, and 3:00 and is depicted as a wide-spread perturbation between 40-inches and 170-inches.

Finally, the purple trace represents the complete removal of outer concrete between 9:00 and 3:00. The strain perturbation grew in amplitude but was still confined to between 40-inches and 170-inches around the circumference.

A surprising outcome of these experiments is that the strain data did not perturb in the vicinity of cut wires as concrete coating was removed around the circumference. If indeed it was the strong bond between wire and concrete which helped retain preload on the embedded steel cylinder, then as concrete was removed the wire should release tension. This release in tension would then lessen the amount of force exerted on the steel cylinder. One interpretation of these observations is that the wire had lost all pretension prior to PICA's pipe modifications – the pipe had been already compromised in this region when it was excavated. Any additional modifications would thus not induce strain changes. The small perturbations observed in the regions where concrete was removed may indicate that the outer concrete also induces some amount of preload, but not as much as the pretensioning wires.

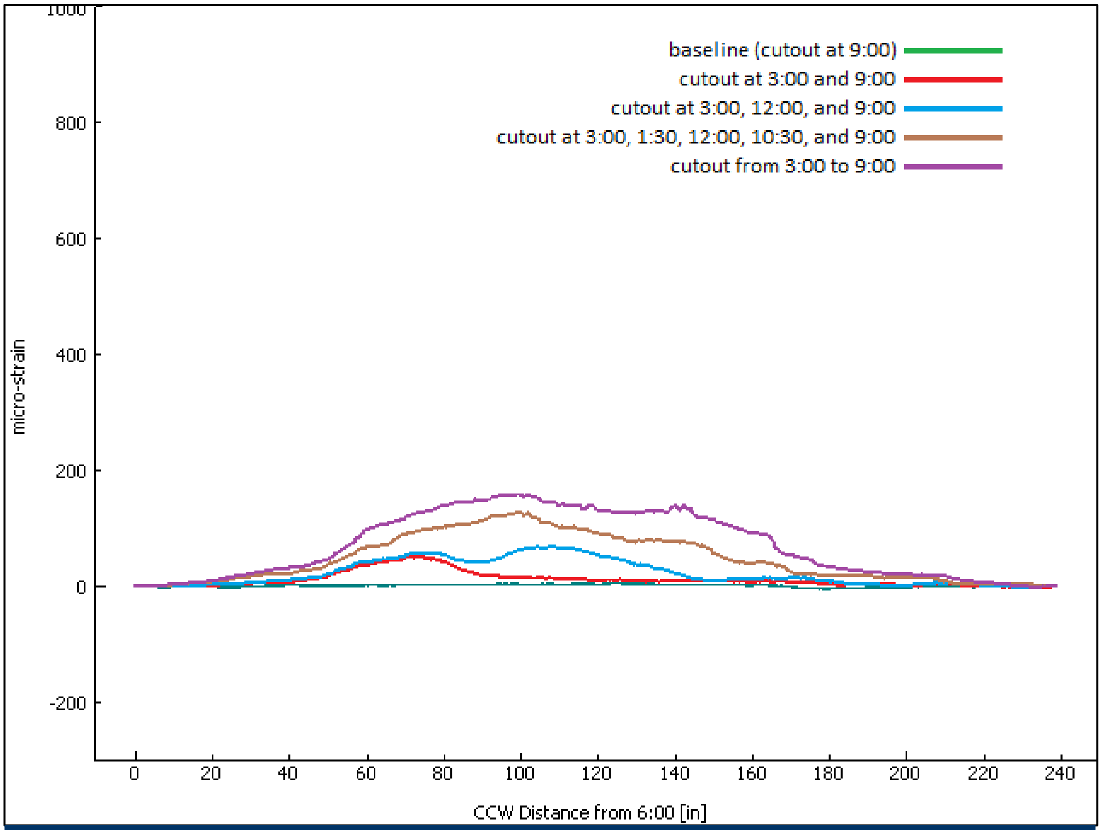

Figure 8. Strain data for outer concrete removal in Segment A. Different colors represent different stages of concrete removal.

Concrete and Wire Removal in Segment B

It is well understood that compromising the external wire or concrete coating on the outside of PCCP works to reduce its pressure carrying capability. This is because the pretensioning wires exert a normal force from the outside, on the embedded steel cylinder, which counteracts the normal force from the inside, exerted by the conveyed product. With the two forces balanced, the steel cylinder does not observe a net force acting to yield its material.

The aim of the study on Segment B was to determine whether preload could be restored after the wires and concrete coating had been removed altogether. By using a handheld grinder with a 4.5-inch concrete cutting disc, PICA technicians worked to remove the top layer of concrete coating down to the pretensioning wires. This concrete was removed between 7:00 and 12:00 circumferential positions. The wires were cut at both ends and also removed. The handheld grinder proved to be an inadequate tool to remove more concrete, thus a concrete cutting saw with a 14-inch cutting disc was used for all remaining work. The saw scored the remaining concrete coating down to the bare steel cylinder between 7:00 and 5:00 circumferential positions. Finally, a pneumatic chisel was used to dislodge the concrete.

Figure 9. PICA technicians removing concrete and wires in Segment B at 9:00 (left), at 3:00 (center). Bare steel pipe between 7:00 and 5:00 (right).

As technicians worked to modify the pipe, the strain gauge continuously recorded changes in pipe characteristics. Figure 10 depicts changes to the preload on the embedded steel cylinder resulting from pipe modifications in Segment B.

The dark green trace represents the baseline scan prior to any new modifications and is depicted as a flat line.

The red trace represents the removal of top layer of concrete, down to the pretensioning wires, between 7:00 and 12:00 circumferential positions.

All remaining traces represent a strain reading recorded every 30 minutes as technicians used the concrete cutting saw to remove move concrete.

Interestingly, the red trace representing the removal of just the top layer of concrete and wires closely resembles results from the same action performed in Segment A. All other traces predictably grow in amplitude and circumferential extent representing a larger loss of preload. The downward perturbation at 180-inches from the invert represents the location of a thru-hole that was fabricated in the steel cylinder during PICA's first study. The strain sensing fiber was not adhered to the pipe at this location and simply draped over the hole. The large purple excursion presents a mystery but may be the result of technicians standing on the pipe to make modifications at the crown. This action may have initiated localized strain changes.

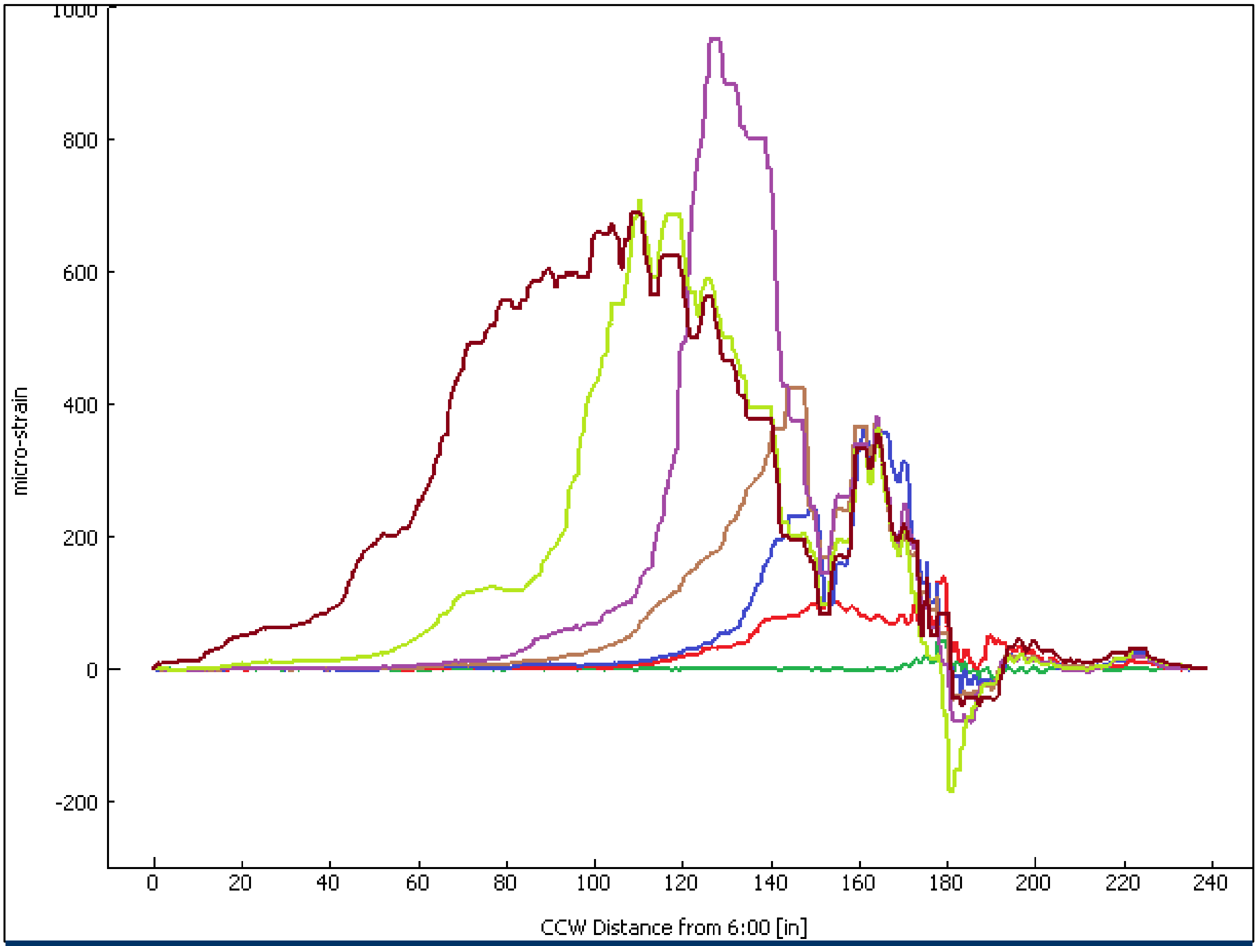

Figure 10. Strain data for concrete and wire removal in Segment B. Different colors represent different stages of material removal beginning at 7:00 (220-inches) and continuing in a clockwise fashion to 5:00 (20-inches).

Strain Restoration in Segment B

Once bare steel was exposed in Segment B, PICA technicians installed pipe tensioning devices. These took the form of three hydraulic utility cylinders, each with a 1-inch diameter piston, driven by a hydraulic pump. The pistons pulled on three 2-inch-wide cargo straps that were looped around the pipe and positioned on rollers every 6-inches. The rollers acted to minimize capstan effect by reducing friction effects between strap and steel cylinder. The working limit of the hydraulic pump was 3,000 PSI which meant that each piston could tension the straps with a maximum of 3,000 lbs of force.

Figure 11. Strain restoration tool installed in Segment B.

Figure 12 summarizes strain data from four different states in Segment B.

The green trace represents the baseline scan prior to any new modifications and is depicted as a flat line.

The red trace represents the strain observed after concrete and wire were removed between 7:00 to 5:00 circumferential positions. The concrete between 5:00 and 7:00 could not be removed due to difficulty of physically accessing that arclength of pipe.

The blue trace represents the application of 1,500 PSI to the three hydraulic utility cylinders. This translates to a force of 1,500 lbs along the tensioning straps.

The purple trace represents the application of 3,100 PSI to the three hydraulic utility cylinders. This translates to a force of 3,100 lbs along the tensioning straps. Although this was beyond the advertised limits of the hydraulic pump, the pressure was successfully maintained at this figure for the duration of the experiment.

The sensor data indicates that preload could be restored to near baseline conditions given sufficient tension applied to external straps. The restoration does not appear uniform around the circumference, however. This could be the result of the tensioning strap not lining up directly over the sensing fiber which is bonded on the inside of the steel cylinder – the two do not track parallel around the pipe. Additionally, preload does not appear to have restored on the side of the tensioning mechanism. This may be because the strap loses contact with the steel cylinder as it enters the tensioning device, which is resting on the remaining concrete coating. The preload force does not transfer into the cylinder because it is counteracted by the compressive force of the concrete.

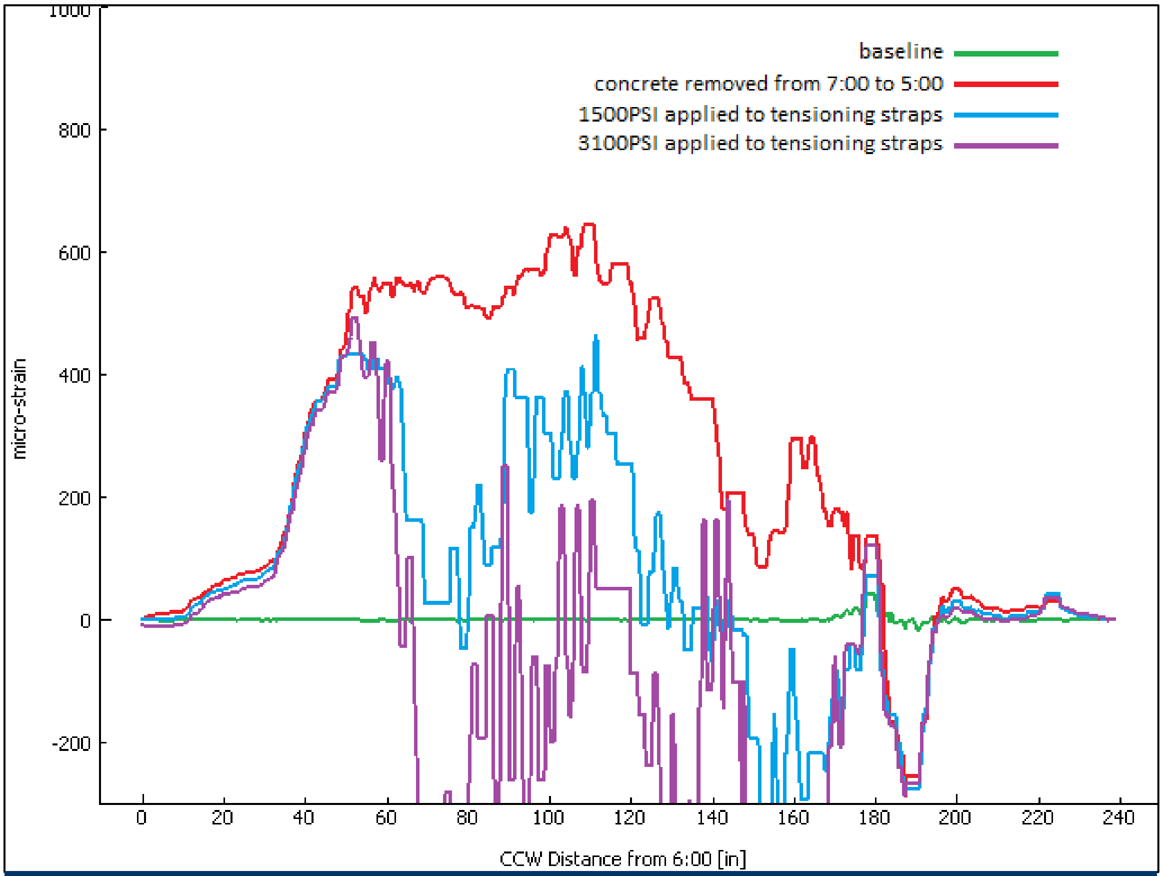

Figure 12. Strain data for different stages of strain restoration on Segment B.

Conclusions

Fiber optic strain gauging technology is a useful tool for comprehensively tracking changes in a material subjected to stress. In the context of pipelines, such a tool can help determine areas susceptible to catastrophic failure due to external damage or aging components. This is key information for pipeline asset owners as it impacts health, environmental, and financial costs.

PICA, a leader in non-destructive testing of pipelines, continues to seek out new ways to advance its technology and help industry pre-empt pipeline failure. As part of a sponsored study, PICA performed experiments on a test loop with the aim of better assessing the health of Pre-stressed Concrete Cylinder Pipe (PCCP). PCCP is used for potable water conveyance throughout the world and is a critical component of a healthy society.

A common failure mode in PCCP is broken pretensioning wires. These wires act to reinforce the hoop strength of the pipe and, when compromised, they reduce the pressure carrying capability of the pipeline. In a common failure scenario, a leak develops, and in the most catastrophic scenario a burst, which can wash away roadways or property.

Through a series of tests PICA determined the impact of different types of damage on the exterior of PCCP, to the steel cylinder that is embedded in the concrete. PICA’s Remote Field Testing (RFT) technology is sensitive to magnetic permeability and thickness variations in steel pipes. A theory has emerged that relates a quantity of broken pretensioning wires to physical changes in the steel cylinder. By employing Sensuron’s strain gauging technology, the theory was further refined.

Through strain measurements PICA proved that compromising either the concrete, or the pretensioning wires impacts the preload exerted on the steel cylinder. Sections of external concrete were removed from the pipe, in increasing coverage around the circumference, and strain changes were continuously recorded. Subsequently, different quantities of pretensioning wires were cut, and impact was measured. Concrete and wire was then removed completely until just the bare steel cylinder remained. Finally, re-tensioning devices were installed on the bare pipe and pulled taught. In all cases where material was removed, the strain on the steel cylinder increased. This is interpreted as an expansion of the pipeline and a diminished ability to contain internal pressure.

Armed with strain data provided by Sensuron’s instrument, PICA now aims to refine its failure models. Given the reliability of the strain measurements and the quality of the data, a technological advancement is guaranteed.