installation stations. The access point is clearly visible on the lower left portion of the figure. Figure 7c shows the transition between the top and bottom half installation. Notice that there is no epoxy paste used in the lower half. Since gravity effects in this area tend to hold the FRP fabric in place, only a seal coat of epoxy resin was used to prevent excessive absorption from the saturated fabric. Figure 7d illustrates overlap and fabric edge detailing. Detailing is done with epoxy paste and/or epoxy resin to feather down edge fibers, and to secure in place the overlaps in the lining.

Specially designed construction joints (Figure 8) were prepared at the starting point of each installation run, which also became the end points of the installation front that started at a downstream access point. The joint was later sealed with an epoxy paste. Nowhere in the 5,742 ft. length of the pipeline were FRP lining edges left exposed to peeling from water

Figure 8: Construction joint of FRP lining

flow, maximizing the water tightness of the installation.

The average rate of production of each of the four installation stations was 2,500 ft² (232 m²) of FRP lining installed in an average 8 hour work day. The operation continued seven days per week, allowing the complete installation of approximately 150,000 ft² (14000 m²) of the FRP lining system in 15 calendar days. This also included the application of the epoxy top coat, which, as stated pre-

Figure 9: Application of epoxy top coat

viously, was used to provide abrasion protection for the FRP, as well as to seal any remaining pores in the installed FRP laminate. Figure 9 shows the application of the top coat. The application took place before the lining was fully cured (surface was still tacky on contact) to ensure maximum bond.

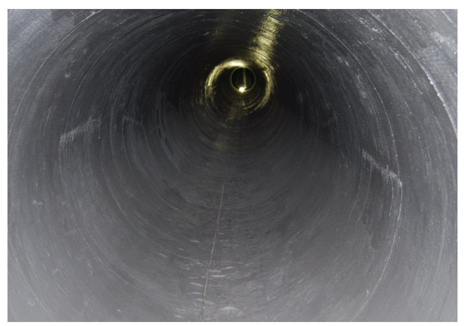

Figure 10: Completed segment of the FRP installation

The FRP lining installation was completed on July 8th, 2009, and pressurized test runs were successfully completed. Figure 10 shows a completed lining installation prior to testing.

More than one mile of a 7-ft diameter pipeline was successfully retrofitted to its original condition in three weeks (one week of prep work and two weeks of FRP lining installation). The FRP lining is expected to require no maintenance and to have a useful life that will match the pipeline's operational lifetime.

CONCLUSION

The FRP retrofit of the 5,742 ft. (1750 m) long and 7 ft. (2130 mm) interior diameter, cast in place concrete pipeline at "El Encanto" Hydropower plant in Costa Rica is the largest reported FRP pipeline retrofit job completed to date in the world.

The features unique to the project, such as the extent of the prep work required to assure a smooth surface free of the irregularities caused by the cast in place procedure; the significant changes in the vertical and horizontal alignment of the pipeline due to the mountainous topography and that required solutions to challenging engineering issues relative to the layout of the FRP lining; the training of local installation crews and the urgent need to minimize downtime of the power plant, made the successful completion of the project an outstanding engineering achievement.

The fact that over one mile of a large diameter pipeline can be retrofitted to its original condition with minimum downtime and no excavation required, even under the unique challenges mentioned above, is a testament to the versatility and effectiveness of this FRP technology and the experience of the project team.

Mo Ehsani, Ph.D., P.E., S.E. is President and CEO of QuakeWrap, Inc. and Professor of Civil Engineering at the University of Arizona. He pioneered the application of Carbon FRP in repair and retrofit of structures in the late 1980s, and he is internationally recognized as an expert on this subject.

Carlos Peña, M.S., P.E. is President and CEO of QuakeWrap México and Professor of Civil Engineering at the University of Sonora. He has more than 25 years of experience as a structural consultant in México and the U.S.

This project has received Honorable Mention for the 2009 Trenchless Technology Project of the Year Awards.

WORLD'S LARGEST PROJECT ON PIPE RENOVATION WITH FRP COMPLETED AHEAD OF SCHEDULE

Mo Ehsani, Ph.D., P.E., S.E. & Carlos Peña, M.S., P.E.

INTRODUCTION

The use of FRP structural linings to strengthen and/or rehabilitate existing pipelines is increasingly gaining widespread acceptance among power plant and utility facility managers. The versatility of the linings to conform to a wide range of diameters and lengths, their high strength properties, light weight, impermeability, thinness and fast rate of application/installation are some of the reasons why managers prefer FRP linings to other retrofit alternatives.

FRP linings typically consist of fabrics made with high strength fibers that are soaked in an adhesive resin, and are applied like wall paper to the interior or exterior of the pipe surface. Once the resin cures, the fabric turns into a very thin (about 0.05") composite laminate. The density and orientation of the high-strength fibers, as well as the fiber type (usually comprised of bundles of very small diameter strands of materials such as glass, carbon, or Aramid) are parameters that the engineer can vary in order to create customized FRP linings that meet specific project criteria. A recent innovation in FRP lining technology is the PipeMedic™ product, which is a very thin plant-manufactured laminate that adheres to the pipe surface using only an epoxy paste. The greatest advantage of PipeMedic™ is that it eliminates the need for in-situ saturation of the fabric, thereby significantly increasing the speed and quality of the installation.

When applied to the inner surface of a pipeline, the FRP lining becomes a trenchless alternative; all labor, equipment and materials are introduced into the pipeline through service access points, thus avoiding the need for excavation. Since many major pipelines lie under freeways and urban or industrial developments, excavation is not possible without major disruptions to traffic, production, or other normal operations. The economic impact of the disruptions, coupled with the significant investment required to replace deteriorated pipelines, increase the relevance of trenchless retrofit options.

Although the use of FRP linings has focused on the rehabilitation of deteriorated pipelines that have been in service for decades, they can also be used to correct design and/or construction errors of new pipelines. Such was the case of the low-pressure pipeline at the "El Encanto" power plant outside San José, Costa Rica. This project included the installation of about 150,000 ft² of FRP lining, and is the largest reported FRP pipeline retrofit project to date. The design problems, and the FRP lining solution implemented to address them, are discussed herein.

PROBLEM DESCRIPTION

The low-pressure pipeline at the "El Encanto" power plant (Figure 1) conveys river water from an upstream dam to the turbine com-

Figure 1: Above ground segment of the "El Encanto" pipeline

plex downstream. The pipeline is built of cast in place reinforced concrete, has an inner diameter of 7 ft. (2130 mm), and a total length of 5,742 ft. (1750 m) The water flows by gravity, but because of the elevation difference between the dam and turbine complex, as well as the continuous changes in the vertical alignment of the pipeline required to conform to the mountainous topography, the water flow is pressurized.

Although the structural design properly addressed the strength requirements of the pipeline and accounts for the design pressure and hydrodynamic loads, the pipeline's serviceability requirements were overlooked in the structural design.

The pipeline was drained and all visible cracks were sealed using typical repair materials available locally. When the pipeline was pressurized again, the repaired cracks again leaked. The leaking at the repaired cracks was most likely due to the increase in the crack width due to the deformations of the pipeline caused by the increase in internal pressure. Given the rigidity of most crack sealing materials, full deformation compatibility between the repair material and concrete could not be achieved,

Figure 2: Leaking after conventional crack sealing

degrading the seal and allowing leaks to reoccur. Figure 2 illustrates typical leaks occurring at two locations along the length of the pipeline during tests conducted at maximum operational pressure.

Moreover, the cracks generated multiple paths for humidity intrusion that reached the steel reinforcement of the pipeline, allowing for corrosion problems that, if not properly addressed, could compromise the structural integrity of the pipeline in the future. Complicating the problem even further was the combination of mountainous topography and the constant tropical rains. Since most of the pipeline is buried underground, water draining down the mountains keeps the surrounding soil constantly saturated and generates seepage pressures. In fact, with the pipeline empty, seepage

Figure 3: Seepage water draining into pipeline

water was observed draining through some of the longitudinal cracks (Figure 3). It was at this point that QuakeWrap's Mexico (QWM) office was contacted for engineering consultation to repair the longitudinal cracks. A site visit was quickly arranged for one of QWM's structural engineers. The engineer inspected the cracks, reviewed structural plans and available local engineering reports pertinent to the leak issues, and identified the main cause of the problem.

In order to arrive at an optimal engineering solution, all the problems mentioned above needed to be properly and simultaneously addressed. An additional consideration was the urgency of minimizing the time required to implement the repair, since – obviously – the power plant could not produce electricity while the pipeline was shut down. The solution that QWM implemented is discussed in some depth, as follows.

SOLUTIONS TO THE PROBLEM

The application of FRP linings requires a certain amount of preliminary work to the pipe surface in order to maximize contact and bond strength between the substrate and the FRP. Therefore, pressure washing, as well as some patching and/or grinding must take place in the areas targeted for lining with FRP. In the case of the El Encanto pipeline, the amount of preliminary work was atypically large, since the cast in place construction process caused significantly more surface irregularities than those associated with the more traditional precast pipes, such as Prestressed Concrete Cylinder Pipe (PCCP). Figure 4 shows the typical condition of the interior surface of the pipeline prior to initiating prep work activities. Evidence of cast in place procedures can be observed, such as construction joints, formwork fins, etc. The pipeline was pressure washed with 7,000 psi (482 bar) machines to remove any scour, sediment, and curing compounds, or

Figure 4: Initial interior surface conditions of the pipeline

Figure 5: Prep work activities prior to installing FRP lining

any other substance that could hinder the bond between the FRP and the pipe surface. Figure 5 shows grinding of protrusions on the interior surface of the pipeline.

An FRP lining consisting of one layer of bidirectional glass fabric was designed to provide a humidity barrier, to provide an effective crack control mechanism, and to provide additional hoop strength to account for a significant loss of hoop steel due to corrosion. Since in all likelihood the corrosion process at the reinforcing steel had already started due to the two-way humidity paths occasioned by the existing cracks, the additional

hoop strength provided by the FRP effectively increased the useful life of the pipeline. It should be noted that the humidity barrier is effective against water leaking into and out of the pipe, due to seepage or internal pressure effects, respectively; however, the corrosion of the steel reinforcement will not be slowed significantly as a result of the humidity barrier, since seepage water will continue to provide the means for this process to continue. While nonstructural linings can also provide two way humidity barriers, nonstructural linings cannot account for the loss of structural integrity caused by the ongoing corrosion due to the presence of seepage water.

Moreover, the adhered FRP laminate was designed to achieve full deformation compatibility with the pipe as the pipe expands due to pressurization, and the bidirectional orientation of the high strength glass fibers in the fabric guarantees that existing and/or future cracks are intercepted in orthogonal directions providing superior crack control. Nonstructural linings, on the other hand, cannot serve as an effective crack control mechanism.

Finally, an epoxy top coat was applied as a cover for all the installed FRP. This coat provides resistance to the abrasion caused by sediment carried by the river water, and additional leak proofing by covering any pin holes remaining in the FRP lining. The coating has a concrete gray color, which facilitates quality control by providing a visual means of verifying that the entire light green-colored FRP lining is fully covered, and that any uncovered spots can be easily detected.

The time urgency associated with the power plant's imminent start of operations cannot be overstated, and required the development of the entirety of the engineering design, specifications, installation shop drawings, as well as securing very large quantities of FRP fabrics and epoxy resins, pastes and top coats, on a very short schedule. QuakeWrap's manufacturing plants were placed on accelerated production runs to meet rather tight deadlines, and part of the production was prepared for air cargo transport.

A technical team of two structural engineers and three field supervisors traveled from QWM to Costa Rica to oversee the project and train the local installation crews. A technical team fluent in Spanish was a must in order for the job to run smoothly.

INSTALLATION PROCEDURE

The 5,742 ft. long pipeline had four lateral access points at the locations of relief valves, with spacing ranging from 1,000 ft. to 1,500 ft. These 24" x 24" access points (Figure 6) were

Figure 6: Typical 2 ft. x 2 ft. access point

used to supply FRP materials, tools and equipment to four installation stations inside the pipeline.

The installation direction was opposite to the flow direction to prevent the joints in the FRP lining from being lifted and detached by the water flow. Each installation station consisted of

Figure 7(a): Epoxy paste installation on top half of pipeline

Figure 7(b): Installation of FRP lining

Figure 7(c) Transitions between top and bottom half installation

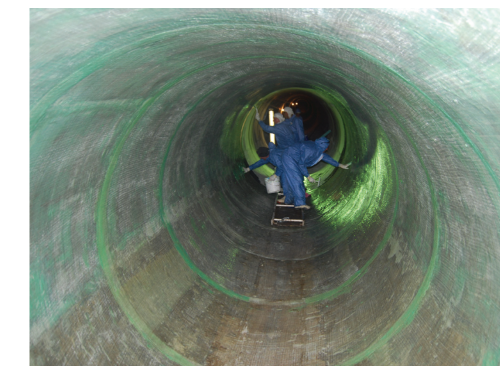

Figure 7(d): Detailing of FRP lining

a 5-man crew inside the pipe applying the FRP lining to the pipeline's interior walls, and another 5-man crew performing support activities such as transporting the rolls of lining material from the access point to the installation point, cutting and preparing the FRP rolls, etc.

Figure 7a illustrates the application of an epoxy paste to the top half of the pipeline; the main purpose of the paste is to prevent peeling due to the weight of the saturated FRP fabric, and to seal the surface to prevent excessive absorption by the dry concrete surface of the epoxy resin from the saturated FRP fabric. Figure 7b shows the installation of the first roll of FRP lining material at one of the