Repair of Riveted Steel Penstock in Mormon Flat Dam with Carbon FRP

M. Ehsani[1], C. Hurley[2], and J. Ahumada[3]

[1]Mo Ehsani, PhD, PE, PipeMedic by QuakeWrap, 2055 E. 17th Street, Tucson, AZ 85719; PH (520) 791-7000; email: Mo@QuakeWrap.com
[2]Craig Hurley, PE, Salt River Project, Mail Station PAB357, PO Box 52025, Phoenix, AZ 85072; PH (602) 236-3690; email: Craig.Hurley@srpnet.com
[3]Joshua Ahumada, FRP Construction, LLC, 2055 E. 17th Street, Tucson, AZ 85719; PH (520) 861-3331; email: Josh@FRPConstruction.com

ABSTRACT

Mormon Flat Dam is one of four hydroelectric projects on Salt River, Arizona. The smaller hydroelectric generating unit on this dam utilizes a 120-in. (3048 mm) diameter 5/8-inch (16 mm) thick riveted steel penstock. Ultrasonic testing results indicated that the penstock had lost as much as 50% of its thickness in certain areas. After considering various alternatives, SRP's engineers chose to repair the pipe with carbon FRP.

The repair area included two 96-inch (2440 mm) pipes about 15 feet long (4.57 m) that merged into a single 120-inch (3048 mm) 45-ft long (13.72 m) segment. The geometry of the Y-connection complicated the repair. A drop in elevation of nearly 20 feet (6.1 m) halfway through the repair section provided additional challenges to the project. The pipe surface was prepared by removal of nearly ½-inch (13 mm) thick coal tar before blasting the surface to a near-white condition. The rivets proved to be longer than anticipated, adding further difficulty in smoothing those regions for a gradual transmission in profile.

The strengthening of the pipe included application of 5 layers of FRP based on the design-build contract. A total of 11,000 ft^2 (1022 m^2) of carbon FRP was installed within the allotted 3-week time frame. A final abrasive resistant coating was then sprayed over the FRP for additional protection against any small debris that may enter the penstock. The repair is expected to provide a long-lasting maintenance-free penstock for the dam.

INRODUCTION

For a primarily desert state, Arizona has a significantly large number of hydroelectric facilities. The larger of these are four dams along the mighty Colorado River and include the famous Hoover Dam near Las Vegas. These vary in electricity production capacity from 2.1 million to 120,000 kW. There are also four smaller dams along the

Salt River. The Salt River is about 200 miles (322 km) long and includes the Roosevelt Lake that was created in 1911 and was once the largest man-made lake in the world. From that lake, the Salt River flows towards Phoenix in a generally southwesterly direction.

Mormon Flat dam is one of four smaller dams along the Salt River. The Salt River Project (SRP) is the oldest multipurpose federal reclamation project in the United States. SRP has been serving central Arizona since 1903, nearly 10 years before Arizona became the 48th state. Today the SRP power district is one of the nation's largest public power utilities, providing electricity to nearly a million retail customers in a 2,900-mi^2 (7511 km^2) service area that spans three Arizona counties, including most of the metropolitan Phoenix area (known as the Valley).

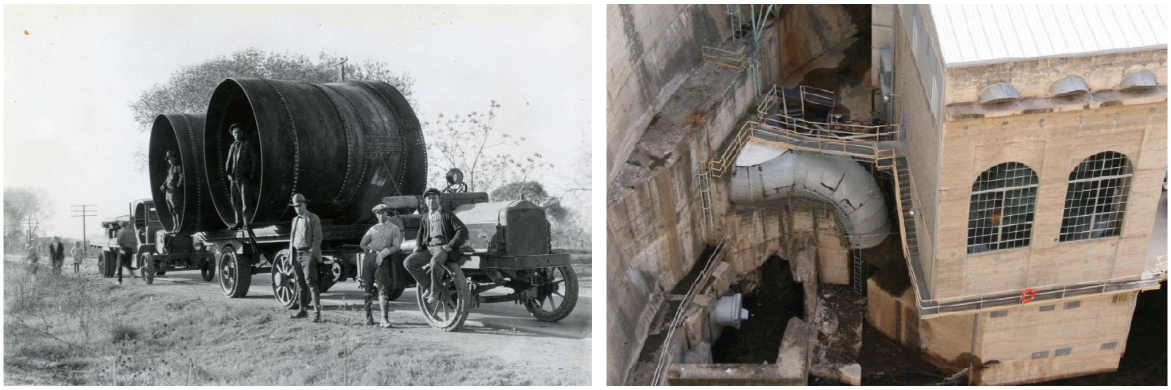
Along with power generation, SRP's water business is one of the largest raw-water suppliers in Arizona. It delivers about 800,000 acre-feet (987,000,000 m^3) of water annually to a 375-mi^2 (971 km^2) service area and manages a 13,000 mi^2 (33670 km^2) watershed that includes an extensive system of reservoirs, wells, canals and irrigation laterals.

Mormon Flat Dam, the site of this project, is on the Salt River about 50 miles north east of Phoenix and was named after nearby Mormon Flat, a place where pioneers from Utah stopped to camp en route to the Valley. The dam, built between 1923-25, is 224 feet high and 380 feet long. Two hydroelectric generating units are at the dam; one is a conventional unit rated at 10,000 kW; the other is a pumped storage unit built in 1971 and rated at 50,000 kW. The pumped storage unit permits recycling of water for hydroelectric production and keeps lake levels relatively constant. Mormon Flat Dam forms Canyon Reservoir.

ORIGINAL CONSTRUCTION

The construction of the dam started in 1923. The dam was designed as an arch dam. Although the development of arch dams had been around beginning with the Romans, over the centuries its application faded. Beginning in the late nineteenth century it developed growing popularity in the American West. The demand for low cost irrigation, flood control and hydroelectric works provided the impetus for the design’s resurgence. An arch dam is curved upstream in plan, the dam uses the compressive strength of the structure’s construction material to deflect or transmit water load by arch action or thrust to the dam’s abutment walls and foundation.

The two 96-inch (2440 mm) diameter riveted steel penstocks were assembled off site and shipped to the job site Fig. 1(a). As shown in Fig. 1(b), these two pipes deliver the water from the dam to a single 120-inch (3048 mm) diameter riveted pipe through a complex geometry. At the Y-connection, the 120-inch (3048 mm) pipe drops in elevation by 20 ft (6.1 m) before turning into a 90-degree elbow. This complicated geometry not only made the original construction difficult, it would also limit the options available for repair of the penstock as mentioned later in the paper.



(a) (b)

Fig. 1. The riveted penstock: (a) being transported to the dam c. 1925 and (b) in service.

CORROSION OF PENSTOCK

The penstock exterior has always been well maintained with appropriate coatings (Fig. 2). The interior of the penstock is lined with a coal tar coating for protection.

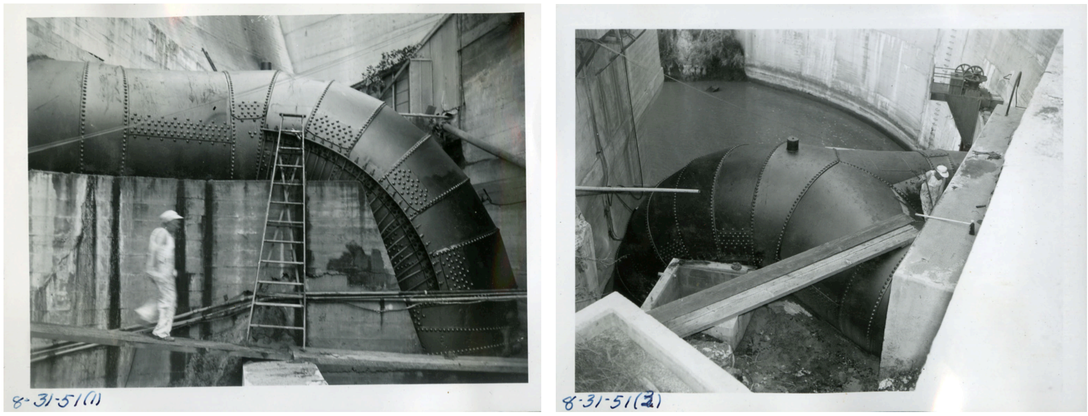


Fig. 2. Periodic inspection and maintenance of the exterior of the penstock – circa 1951.

The overall condition of the interior coating was unknown and routine inspections several years ago by SRP raised concerns of possible thinning of the penstock material. More recent inspection showed that the coating had come off in certain points (Fig. 3) and this had accelerated the corrosion rate. A consultant was retained to provide a structural evaluation and recommendations for the penstock. Using ultrasonic testing, the pipe thickness was obtained and a report was prepared indicating that there was material wall thinning percentage of close to 50% of the original thickness in some areas. Their analysis also showed that many of the riveted sections in the exposed

Fig. 3. Damaged tar coating and internal corrosion of pipe

portion of the penstock did not meet the acceptance criteria of ASCE Manuals and Reports on Engineering Practice No 79, Steel Penstocks.

Four options were considered for the repair of the penstock. Replacement with a smaller penstock inside the original was considered but discarded due to the increase in head loss. Encasement of the penstock was also considered and discarded due to uncertainty of the condition of the existing concrete beneath the penstock. The final two options were replacement of the current penstock with a welded penstock and carbon fiber lining of the penstock. The consultant recommended replacement with a welded penstock due to uncertainty of the use of carbon fiber lining. A life cycle cost analysis was performed on the two feasible options. Budgetary costs and schedules were developed for the complete replacement and FRP lining. One item that was identified early was the outage time required for the welded penstock replacement. The CFRP coating schedule was well within a routine maintenance outage schedule. The ongoing costs of coatings and maintenance of each option was also considered in the analysis. The results of the analysis show that even if the penstock CFRP coating needed to be replaced at the end of its 20-year warranty, lifecycle costs would still favor choosing the CFRP solution. The engineer's estimate for the replacement cost was about \$3 million excluding the loss of revenue from the long downtime. The lowest CFRP repair bid was approximately \$350,000.

DESIGN-BUILD CONTRACT

The project followed a relatively tight schedule from initial announcement to completion. One of the requirements of the Request for Proposal (RFP) issued by SRP was that the contractor had to "*furnish all engineering plans, drawings, labor, tools, materials, and equipment for the design, fabrication, testing, delivery and installation of the work in accordance with the terms and conditions set forth in the RFP*." A further requirement of the contract was that "*the contractor's field staff must include an onsite engineer for inspection/supervision*."

Such design-build contracts are ideal when the project has to be completed in a short time frame and significantly reduces delays due to potential changes in the project. A pre-bid conference was scheduled to ensure that all bidders had a good understanding of the site access restrictions that included being in an area 45 minutes from town with no cellular access. Figure 4 shows the narrow and winding access road along a steep canyon to the dam and the small parking/staging area at the end of the road.


Fig. 4. Limited access to the dam through a winding road and a small parking area.

The bids were due the following week and the contract was awarded within 5 weeks of the RFP. The team consisting of FRP Construction, LLC as the contractor, and

QuakeWrap Inc. as the materials supplier and design engineer was selected as the successful bidder based on price and schedule. The two companies had teamed up on numerous projects in the past and have established an excellent working relationship over the past 10 years. The contract was issued in late January 2015. Construction was to begin in March 2015 during a scheduled three-week shutdown at the plant.

CARBON FRP DESIGN

Fiber Reinforced Polymer (FRP) has been successfully used in various repair and retrofit projects since it was introduced by the author in the late 1980s (Saadatmanesh and Ehsani 1988). As the name implies, FRP is comprised of a polymer (such as epoxy, vinyl ester or polyester) that is reinforced with fibers (such as carbon or glass). Carbon FRP (CFRP) has been effectively used in a number of repair and strengthening of steel pipes where the resin-saturated fabric can be applied externally or internally to the deteriorated pipe (Ehsani 2015).

Carbon fabrics are typically supplied in 24-inch (610 mm) wide rolls that are several hundred feet long. The thickness of the fabric is approximately 0.02-0.03 inches (0.5-0.8 mm) depending on the weave pattern and the aerial weight of the fabric. Among the advantages of FRP products is that they are anisotropic, meaning that the strength of FRP is different in x- and y- direction and it depends on the amount of the reinforcing fiber that is present in each direction. As an example, one of the carbon fabrics used on this project was unidirectional and had an aerial weight of 27 oz/yd^2 (915 g/m^2). When this fabric is saturated with resin in the field and allowed to cure, it becomes a laminate with a thickness of approximately 0.05 inches (1.3 mm). If this laminate is tested in tension, it will require a breaking force of 6700 pounds per inch (1173 N/mm) width of the fabric to cause tension failure of the sample.

To illustrate the design process, assume that a single layer of this fabric with a thickness of 0.05 inch (1.3 mm) is internally applied to the surface of the 120-inch (3408 mm) diameter pipe. For hoop stresses, this band will be applied as a continuous ring inside the pipe with adequate overlap for continuity to develop the full capacity of the carbon fabric. The contribution of CFRP to resisting the hoop tension in the pipe can be calculated by considering a unit (1 inch long) length of the pipe. The internal pressure will be (6700+6700)/120 = 111 psi (765 kPa). Adding an additional layer of CFRP will increase the pressure rating of this pipe to 222 psi (1530 kPa). Note that by doing so, the thickness of the line has been reduced by an insignificant amount of 0.05 inch (1.3 mm) per layer. In fact in most FRP repair projects, the smooth surface and the reduced friction that will result from the repair will cause an increase (rather than a reduction) in the flow capacity of the pipe. In the foregoing simplified example, factors of safety and other reduction factors for environmental conditions, expected life of the repair, etc. have been ignored.

In locations where excessive longitudinal stresses require strengthening of the pipe, layers of the same unidirectional carbon fabric can be applied along the axis of the pipe. In repair of steel structures with CFRP, care must be taken to avoid direct contact between the steel and carbon fibers which acting as dissimilar metals could result in galvanic corrosion. While the epoxy may provide adequate protection, a more conservative approach is to apply a layer of glass fabric as a dielectric barrier to the steel surface. This fabric will serve as a physical barrier to prevent direct contact between the carbon and steel. For this project, a layer of glass fabric was applied to all steel surfaces. Figure 5 shows various layers of reinforcement and coating applied to the penstock.

Details of how individual layers are applied and terminated are shown in Figs. 6 and 7. Once the surface of the pipe has been cleaned, the glass fabric that serves as the dielectric barrier is applied first. The CFRP layers in the longitudinal direction are applied next. As shown in Detail 2 in Fig. 7, a small overlap of 2 inches (50 mm) is sufficient for these layers in the hoop direction. Because these layers are serving as longitudinal reinforcement along the length of the pipe, sufficient overlap must be provided in that direction (Detail 3 in Fig. 7).

In application of FRP attention must be paid to apply the fabric under a slight tension to avoid any kinks. Otherwise, when subjected to tension, the fabric will want to rid itself of the kinks first before resisting any tension. Similarly, sharp changes in curvature must be avoided. For this reason the areas around the rivets had to be filled with a mix of thickened epoxy. Such epoxy is very thixothropic and can be applied like a viscous paste. Figure 8 shows the detail for repair of riveted areas. The gentle slope produced by application of thickened epoxy ensures proper transfer of force.

FIELD INSTALLATION

As shown in Fig. 3, access to the site was through a narrow, winding 1.25 mile (2 km) long road along a steep canyon with sharp turns. There was also limited space available for staging of equipment and materials and setting up a workstation.

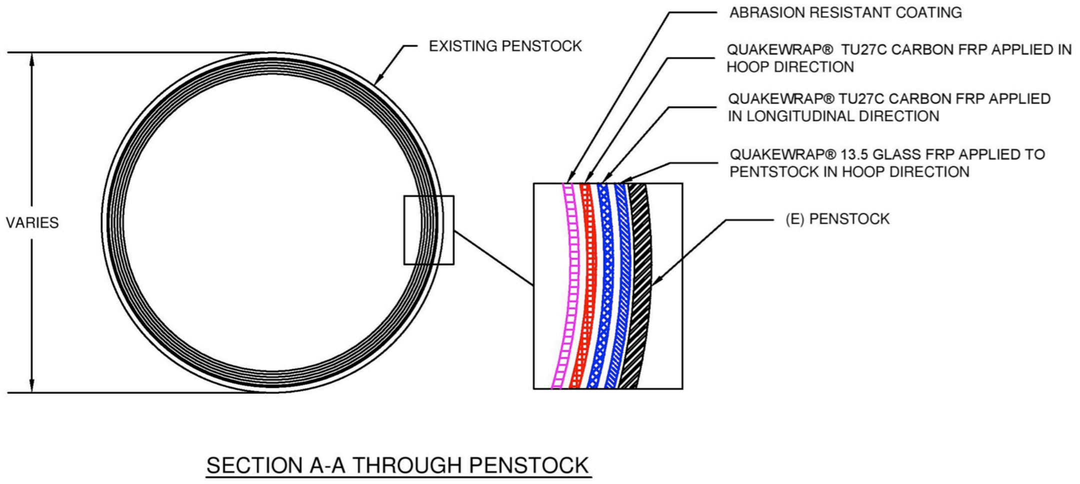


Fig. 5. Various layers of FRP and coatings applied to the penstock

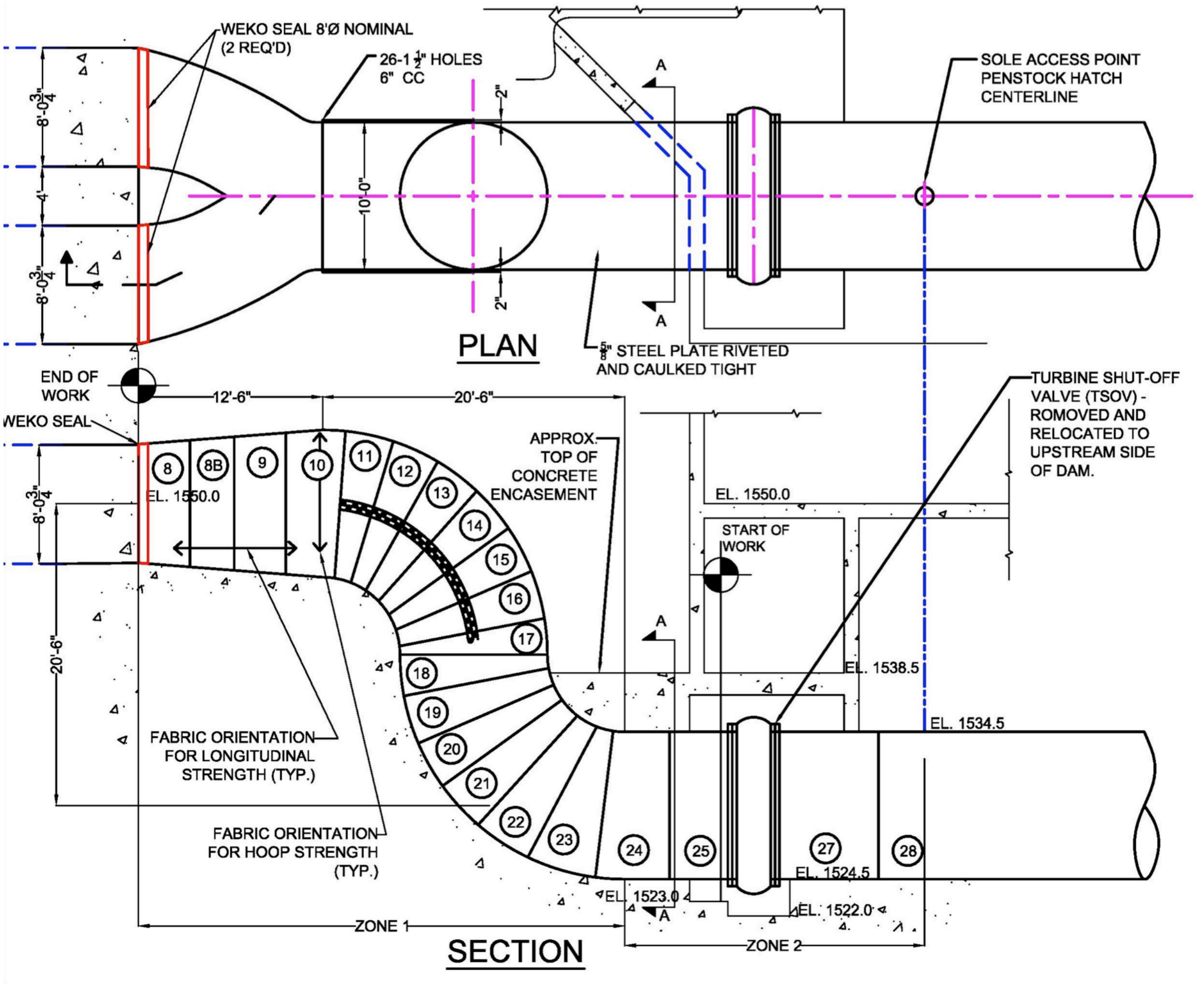


Fig. 6. Overall repair area

Like all such projects, safety of the crew and construction site is the outmost concern. The repairs had to be conducted following OSHA confined space guidelines. Access to the penstock was available through a 24-inch opening, down a flight of stairs approximately 20 feet (6.1 m) below ground. This made the repair a truly trenchless operation. A winch was set up to lower all materials and tools into the penstock, eliminating foot travel and repeat trips up and down the stairs carrying heavy items.

To ensure proper ventilation, air quality was continuously monitored by a technician positioned at the entry to the pipe using a 5-gas meter. In addition, the crew was equipped with air-monitoring devices that they would carry inside the pipe. Ring scaffolding was used so that individual pieces could be lowered into the penstock and assembled into a custom unit. The penstock itself had significant change in elevation. Scaffolding was set up in the lower pipe that would reach the entire circumference of the penstock by hand (Fig. 9).

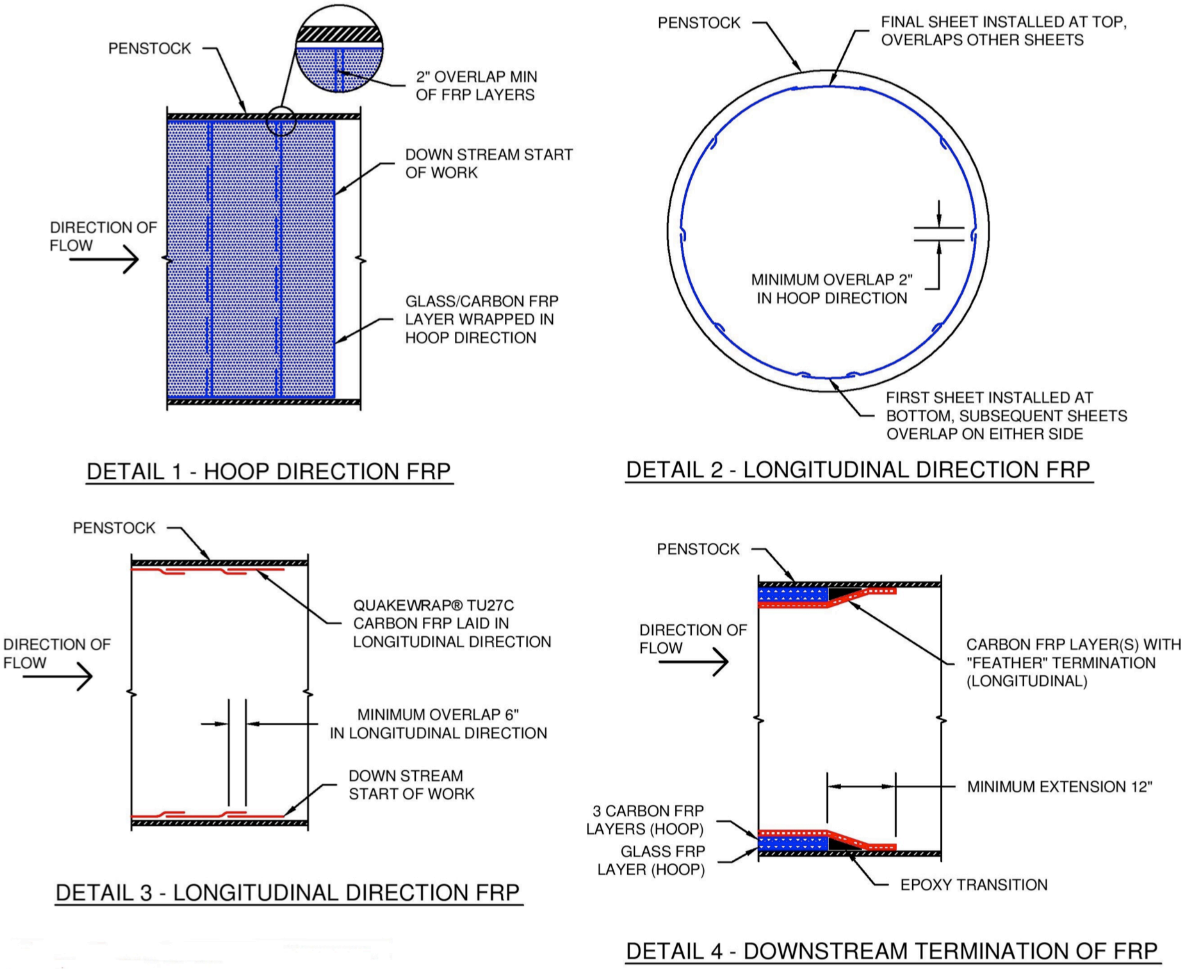


Fig. 7. Various details of the CFRP liner

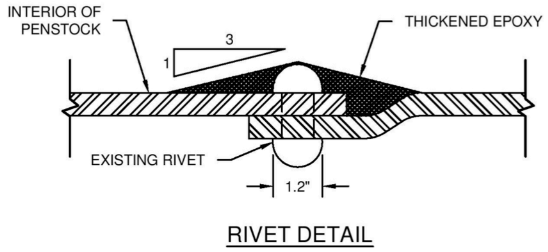


Fig. 8. Preparation of the area around rivets prior to the application of CFRP.

Fig. 9. Scaffolding set up inside the penstock.

Surface preparation required a near-white SSPC-SP10/NACE10 condition. The interior surface of the penstock was coated with coal tar for corrosion protection. This coating was as much as 2 inches thick in many locations. There were some areas where the coating was damaged (Fig. 3). Most of the coating was removed by mechanical chipping. This was followed by blasting using a special media to obtain a near white surface that would be acceptable for installation of the FRP liner.

A significant effort was spent to cover the thousands of rivets in the penstock. These rivets protruded from the pipe surface longer than previously assumed. A mix of thickened epoxy was troweled over the rivets to provide a gradual transition to the pipe interior surface. In some cases, chopped glass fibers was also blended with the thickened epoxy prior to application. Figure 10 shows some of the rivets and the crew applying thickened epoxy in the area. Once the surface was completely prepared, the first layer of glass fabric was saturated with resin and applied to the cover the entire interior surface of the penstock.


(a) (b)

Fig. 10. (a) close-up of the rivets inside the pipe and (b) coating the rivets with

The CFRP layers were applied in the longitudinal and hoop directions according to the details shown in Fig. 7. The saturation of the fabric utilized a saturating machine and an epoxy metering and mixing pump. This ensured uniform production of the materials in the field and higher quality of the installation. The complex geometry and the large size of this penstock shown in Fig. 10b clearly demonstrates the challenging nature of the repair and why the use of CFRP liners that can accommodate such geometries is an ideal solution for this project. The site engineer representing the materials manufacturer and the design team recorded all batch numbers for fabric, resins and their location of installation.

As the layers of fabric are installed, it may be necessary to apply an additional layer of thickened epoxy between the fabric layers. This is necessary especially in overhead applications to prevent the saturated fabric from sliding before the epoxy cures. The overlapping joints and edge of the fabric must also be trimmed and coated with epoxy (Fig. 11a). Once all fabric layers were installed, the leading edge in each of the 96-inch pipes was protected by applying a Weko seal. As discussed earlier, this seal presses the fabric firmly against the host pipe, eliminating the possibility of water reaching behind the CFRP liner (Fig. 11b).


(a) (b)

Fig. 11. (a) Repaired penstock prior to application of topcoat and (b) at termination point showing Weko Seal

As the last step of construction, the entire installation was coated with a 40-mil thick top coat for abrasion resistance. This coating was applied using a pneumatic pump. The repairs required a total of 11,000 ft^2 (1020 m^2) of FRP fabrics to be installed over the 60-ft (18.3 m) long section of the penstock. The work was completed with a single 8-man crew within the allotted 3-week time frame.

The repairs provided have been designed to restore the loss of strength in the penstock considering the stresses in both longitudinal and hoop direction. The CFRP liner will serve as a moisture barrier that will protect the penstock from internal corrosion for decades with minimal maintenance.

LESSONS LEARNED

Before the project the SRP Hydro department had lost quite a bit of the tribal knowledge on past repairs to the penstock. No one who remained seemed to know exactly what the coating on the pipe was. It was estimated to be coal tar. The actual coating turned out to be up to ½” (13 mm) of coal tar which was extremely time and material consuming to sand blast off. A decision was quickly made to chip the majority of the material out and sand blast to do the final prep. Another unknown was the exact dimensions of the heads of the rivets inside the penstock. The dimension of the rivet head was substantially larger then estimated. The original design to coat with epoxy was still determined to be valid but it is possible another option of having prefabricated molds to cover the rivets to ensure a uniform coating/feathering over the rivets may have saved some repair time. It would have been beneficial to have had an inspection of the penstock performed by the personnel who were involved with the project before the actual installation outage to make sure the most cost effective installation procedure was identified.

SUMMARY AND CONCLUSION

The 90-year old riveted steel penstock had corroded and lost some of its capacity. The challenging geometry of the pipe, limited access and short window of time available for repairs were among the key factors for the owner to select CFRP as the method of strengthening this penstock. The design-build contract resulted in a well-coordinated effort among the materials supplier, designer and the contractor that ensured in timely completion of the project within the limited available time frame. The CFRP repair not only restored the strength of the pipe, it will also provide an impervious liner that will protect the penstock from internal corrosion for decades with virtually no required maintenance.

REFERENCES

Ehsani, M. (2015). "Chapter: 3- Repair of corroded/damaged metallic pipelines using fiber-reinforced polymer composites, " in Rehabilitation of Pipelines Using Fiber-Reinforced Polymer (FRP) Composites, edited by V. Karbhari, Elsevier, 1st ed. (ISBN: 9780857096845), pp 39-59.

Saadatmanesh, H. and Ehsani, M.R. (1988). "Strengthening of Concrete Girders with Epoxy-Bonded Fiber-Composite Overlays," *Proc.*, NSF-Sponsored Symposium on Bridge Research in Progress, Des Moines, Iowa, September 1988, pp. 117-120.