Retrofit of CFRP Installation to Meet Current Design Standards

Michael McReynolds, S.E, P.E.[1], Bill Sleeper, PE[2], and Mehdi S. Zarghamee, PhD P.E.[3] , Anna Pridmore, PhD[4]

[1]Team Manager VII, Pipelines and Facilities Team, Metropolitan Water District of Southern California, 700 North Alameda Street, Los Angeles, CA 90012; PH (213) 217-6694; email: mmcreynolds@mwdh2o.com
[2]Senior Engineer, Metropolitan Water District of Southern California, 700 North Alameda Street, Los Angeles, CA 90012; PH (909-392-5163); email: wsleeper@mwdh2o.com
[3]Senior Principal, Simpson Gumpertz & Heger Inc., 41 Seyon Street
Building 1, Suite 500, Waltham, MA 02453; PH (781) 907-9000; email: mszarghamee@sgh.com
4 Vice President- Pipe Solutions, STRUCTURAL TECHNOLOGIES, 1332 North Miller Street, Anaheim, CA 92806; email: apridmore@structural.net

ABSTRACT

Metropolitan Water District of Southern California (MWD)[1] was one of the first agencies to adopt the use of Carbon Fiber Reinforced Polymer (CFRP) as a method to repair distressed Prestressed Concrete Cylinder Pipe (PCCP) starting in the middle of the 1990's. At that time MWD performed tests to determine the best method to bond the CFRP to the inner core of the PCCP and tested distressed PCCP repaired with CFRP to validate its ability to resist external ground load. MWD studied the other tests conducted by the industry to insure the distressed PCCP reinforced with CFRP could resist the internal pressure[3]. MWD was one of the first agencies to adapt the use of CFRP as a method to repair distressed PCCP. However, at the time the need for the CFRP to terminate on the steel cylinder was not recognized. Over the last ten years the need for the CFRP to be terminated by attaching it to the steel cylinder has become the industry standard[4]. Another advancement in CFRP design methodology was the need for and the quantity of longitudinal CFRP reinforcement applied in these repairs.

IMWD recently upgraded all of its CFRP installations to bring them up to the requirements of the new draft code which is currently in development through AWWA. This was accomplished by removing the CFRP lining in the region adjacent to the joints, exposing the bell and spigot, which was followed by attaching new CFRP to the cylinder and overlapping the new CFRP onto the existing CFRP. In addition, more longitudinal layers were installed to resist the longitudinal stresses in the CFRP.

This paper will discuss the reasons MWD decided to retrofit their existing installations, the construction challenges of installing the CFRP over the PWC, and the effect that the changes in the recent draft code had on the existing number of

longitudinal and hoop layers of CFRP layers. PWC stands for potable water coating and is the final coating covering the CFRP.

During construction, MWD performed adhesion pull tests to insure that the new CFRP would bond properly with the existing CFRP. Several different pull tests were performed to determine how much PWC had to be removed to insure the CFRP would bond together properly. Construction has now been completed on these projects.

INTRODUCTION

Metropolitan Water District of Southern California (MWD) was one of the first utilities to use CFRP to repair distressed Prestressed Concrete Cylinder Pipe (PCCP). MWD's original design focused on resisting the internal pressure and external load only and used a composite design concept to resist the external load. The design did not consider several factors which have been addressed by the current draft code[4]. This paper will discuss the original design; how the original design compares to the new draft code requirements, the original design deficiencies and the installation of the new CFRP modifications.

ORIGINAL DESIGN CRITERIA

MWD began installing CFRP in the 1990's to repair distressed PCCP sections. There were several reasons it was used. First, it represented a method of construction which is significantly less disruptive to the local community than the traditional methods, which requires excavating, removing and replacing of the pipe. Second, the cost of the CFRP repair is significantly less than the traditional methods. MWD often used CFRP in areas where the traditional excavation was impractical.

In preparation for these initial installations, MWD performed a significant amount of testing to determine the level of surface preparation required to achieve a sufficient bond between the CFRP and the surface of concrete inner core of PCCP. MWD completed several full scale mock up assemblies and load tested them to determine if the CFRP would remain bonded to the surface of inner concrete core. MWD determined that high pressure water blasting provided an adequate profile to insure an acceptable bond. By water blasting the surface of the PCCP inner concrete core, the failure plane was found to be cohesive, i.e., within the concrete and not at the interface between the concrete and the CFRP.

MWD relied upon testing performed by University of California at San Diego to validate the CFRP's ability to resist the internal pressure and used this research as the starting point for the design of the CFRP in the hoop direction. Ultimately, MWD designed the CRFP so that it did not allow a strain higher than 95% of the cylinder's ultimate strength. This insured that the cylinder would remain intact and act as a water barrier. This typically meant many more layers of CFRP were needed to resist the internal pressure compared to one or two layers often used by other agencies at that time. In Table 1, the number of hoop layers is shown for several pipes using the original design criteria.

MWD used a composite design to assess the ability of the pipeline to resist external load. At the springline the concrete and CFRP would resist the compressive forces and the cylinder would take the tension forces. At the invert the inner concrete core would take the compressive forces and the CFRP would take the tension forces. The number of hoop layers required was almost always governed by the internal pressure.

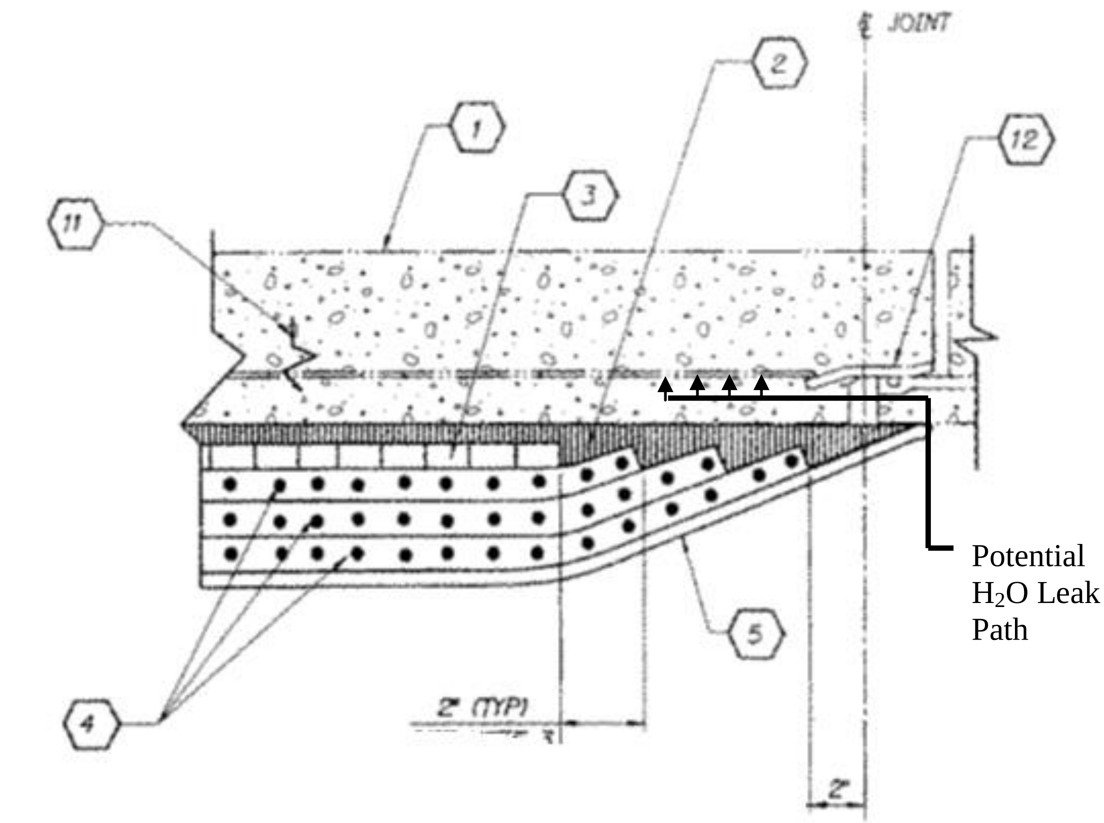
Pipeline Name	Diameter inches	Pressure psi	Cover ft	CFRP material	# of Hoop Layers	# of Longitudinal Layers
Foothill Feeder (Sta. 362+99)	201	110	20	TYFO SCH-41-2X	9	0
San Diego #5 (Sta. 1260+17)	96	65	10	TYFO SCH-41S-1	4	0
Sepulveda Feeder (Sta. 244+75)	96	175	16	Sika Hex 103C	17	0
AMP (Sta. 16+50)	78	195	15	TYFO SCH-41S-1	9	0

Pipe Properties and Original CFRP Repair Data: Table 1

DEFICIENCIES IN THE ORIGINAL DESIGN

During the original design, a hydrotest was not performed due to the cost of such a test. At the time of installation, the need to terminate the CFRP on the steel cylinder was not recognized. The CFRP was terminated on the surface of the PCCP. Subsequent testing performed by other agencies has shown that failure to attach the CFRP to the cylinder allows water to get behind the CFRP and can result in catastrophic failure of the PCCP. See Figure 1. This failure mechanism has been confirmed by Water Research Foundation (WRF) tests which show that the cylinder can fail due to water intrusion behind the CFRP lining at the joint. Over the last ten years the need for the CFRP to be terminated by attaching it to the steel cylinder has become the industry standard[4].

MWD's original design also did not provide longitudinal CFRP to account for Poisson Ratio effect in the longitudinal direction. The only longitudinal reinforcing provided was from the Kevlar fill fibers used to hold the weave together. The Kevlar fill fibers have negligible reinforcement provided in comparison with the amount of reinforcement in the primary fiber direction and don't provide adequate longitudinal reinforcement. The current draft code[4] requires that longitudinal CFRP be provided to account for Poisson's Ratio, and temperature effects.



1 Existing PCCP

2 Tack Coat, Primer and Epoxy

3 CFRP in Longitudinal Direction

4 CFRP in the Hoop Direction

5 PWC Coating

11 Bell and Spigot

12 Existing PCCP

Termination Detail in Original Design: Figure 1

NEW DESIGN

In 2009, MWD reviewed its existing CFRP installations. There were two factors driving this decision. First there was the testing that showed the need for the CFRP to be attached to the cylinder in order to prevent water from getting behind the CFRP. MWD wanted to insure that the pipe integrity would not be in jeopardy even if the pipe degraded significantly.

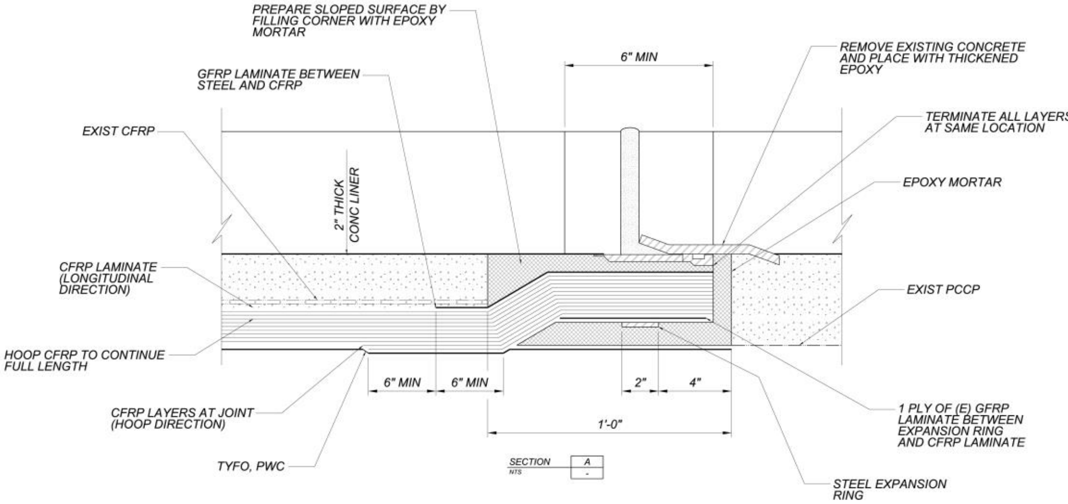
The second factor was the formation by AWWA of a subcommittee to the Prestressed Concrete Cylinder Pipe Committee C304 for the design of CFRP in degraded PCCP. AWWA established the new subcommittee in 2010 to develop a new draft code[4] to govern the installation of CFRP repairs. The new draft code required the CFRP to be terminated at the cylinder. After reviewing the draft code requirements MWD decided to modify its design to meet all of the new requirements. This meant that the CFRP had to be able to resist buckling and internal pressure in the hoop direction, Poisson's effect and temperature strain in the longitudinal direction, and the CFRP had to be terminated at the cylinder at the joints.

MWD evaluated the existing CFRP in the hoop direction. That evaluation found that the original design criteria (which required that the strain in the CFRP be lower than the cylinder strain) provided enough hoop layers to resist the new buckling requirements in most of the cases. A minimum of one additional hoop layer was always required to insure that if one layer was damaged during the removal of the PWC covering the existing CFRP, there would be no loss in the number of layers in the hoop direction. See Table 2 below, for a comparison between the existing design and the new draft code[4] requirements.

Pipeline Name	**# of Hoop Layers Original Design**	**# of Hoop Layers Required for Buckling**	**Hoop Layers Required for Internal Pressure**
Foothill Feeder	18	18	5
San Diego #5	2	12	2
Sepulveda Feeder	17	16	9
AMP	9	9	9

Calculated CFRP Repair Data: Table 2

MWD then evaluated the longitudinal strain and determined that the number of longitudinal layers required was at least 30% greater than the previously installed number of longitudinal layers. These new longitudinal layers were designed to resist temperature and Poisson's Ratio. MWD developed a new design detail to remove existing CFRP at the joint and install new longitudinal and hoop layers of CFRP attached to the cylinder at the bell or spigot. The detail is shown in Figure 2.

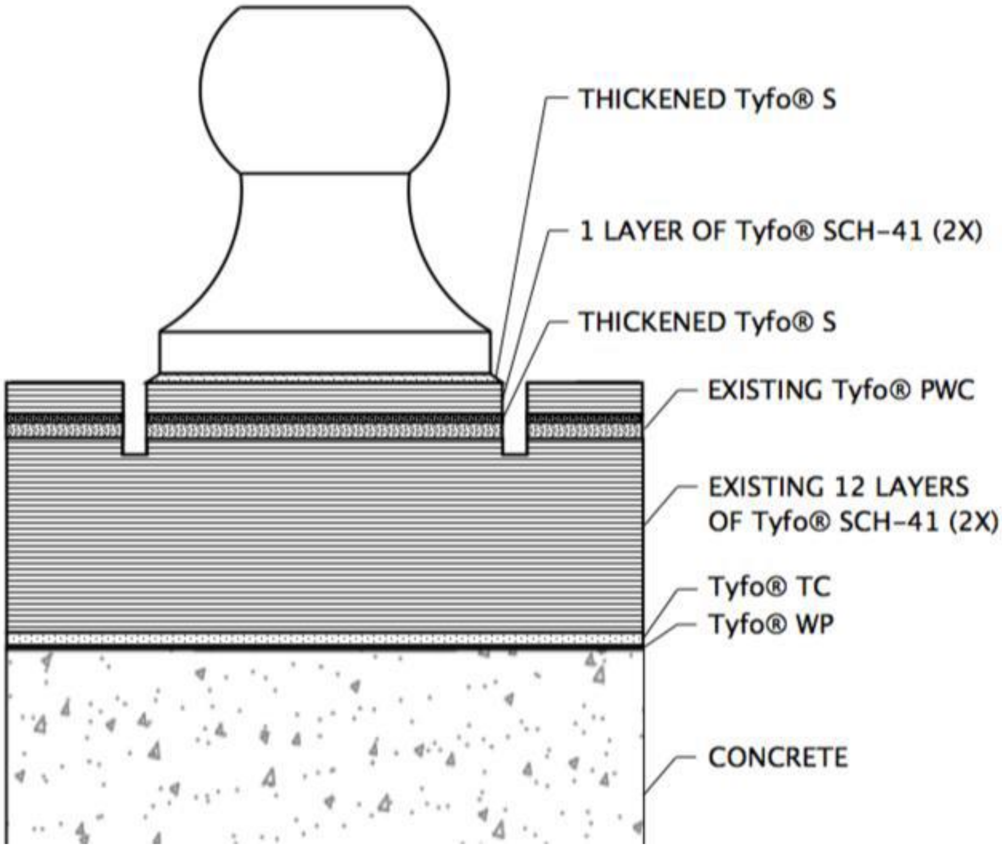


Termination Detail in New Design: Figure 2

INSTALLATION

As MWD developed its construction package, the most significant issue was to determine the best method for attaching the new CFRP to the existing CFRP. The primary issue was how to deal with the existing top coating (PWC). It was necessary to determine whether or not the existing Tyfo PWC needed to be completely removed to achieve sufficient bond between the new CFRP and existing CFRP or if the top coat could be just partially removed to gain an adequate bond. The bond was required to insure the CFRP layers would act as a composite section. This was a critical decision because the amount of time required to completely remove the Tyfo PWC would result in extending the pipeline shutdown. Tyfo PWC is very hard and grinding by hand methods is required to remove it. Sandblasting was found to be ineffective and would be very time consuming. The time required to remove the PWC was especially important on the Foothill Feeder portion of the project (which is PCCP that measures 201 inches (16.08 feet) in diameter) because the size of the pipe would mean that removal of the PWC would take a very long time.

In order to determine if the Tyfo PWC had to be removed entirely, several Direct Tension Pull-off tests were conducted in accordance with *ASTM D4541 Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Tester*[5]. The bond strength as well as the failure modes were recorded. These failure modes are described in Figure 3.



Pull Test Assembly Detail: Figure 3

The pull tests were used to determine the amount of surface preparation required. In one study some of the samples had only the surface of the Tyfo PWC roughened with sandblasting (from 1% to 5% of the PWC coating removed). Other samples were sandblasted until 5% to 25% of the PWC was removed. One set of samples received aggressive grinding and this resulted in 30% to 80% of the PWC being removed. The pull test results can be seen in Table 3. The test results indicated that there was no significant difference between the various levels of surface preparation and the resulting bond strength.

Surface Preparation	**% PWC Removed**	**Bond Strength**
PWC Roughened by Sand Blasting	1% to 5% removed	1227 psi
PWC Removed by Sand Blasting	5% to 25% removed	1527 psi
PWC Removed by Aggressive Grinding	30% to 80% removed	1208 psi

Bond Strength using Various Methods of Surface Preparation: Table 3

Similarly, a second study using previously immersed and conditioned samples indicated that the proper amount of surface preparation could be obtained using either hand preparation or mechanical means. Both methods provided bond strengths exceeding the minimum design requirements for adhesion. These results are displayed in Table 4.

Hand Sand		Power Tool	
Method	**Average Bond Strength (psi)**	**Method**	**Average Bond Strength (psi)**
Green Scotchgard	963	Brown 7” Grinding Pad, Light Abrasion	833
Brown Scotchgard	932	Brown 7” Grinding Pad, Heavy Abrasion	853
60 grit Light Sanding	1063	39 grit, 4.5” Grinder Light Sanding	760
60 grit Heavy Sanding	683	39 grit, 4.5 Grinder Heavy Sanding	592

Bond Strength using Hand or Mechanical Means: Table 4

Based upon these test results the Contractor was allowed to just roughen the surface. However, during construction the Contractor actually removed between 50% and 90% of the Tyfo PWC.

The next issue to address was the surface preparation required at the cylinder to insure that no water can get behind the CFRP laminate at the joint. Testing recently conducted by the WRF found that this connection is a potential leak source. Since the purpose of this repair was to prevent the pipe from leaking at this location, MWD decided to provide the maximum protection from potential leakage at the joint. To insure that CFRP laminate was well bonded to the steel cylinder, the joint was prepared by grinding the cylinder, spigot and bell to a white metal. CFRP was terminated at both ends on the steel substrate (i.e., the bell or spigot and the steel cylinder). A stainless steel expansion ring was expanded to achieve a 100 psi radial pressure and further insure that the water will not migrate behind the CFRP laminate at the joint.

The repair consisted of cutting the CFRP and removing the mortar lining at the joint. The removal of the existing mortar and CFRP was performed using power-tooled equipment with a diamond blade. The material was easily removed and the cylinder exposed. The Contractor then brought the steel cylinder surface to white metal. Only light grinding was permitted; sand blasting was prohibited because of the risk of puncturing the cylinder. The PWC was roughened or removed. Then an epoxy mortar was installed to transition from the cylinder to the top of the existing CFRP. CFRP was then attached to the cylinder for 6 to 8 inches depending upon the development length required. The CFRP prevents a corrosion cell between the CFRP and the steel cylinder. Next the longitudinal layers of CFRP were installed over the entire length of the pipe including the portion with the CFRP. Following this, a minimum of one layer of CFRP was installed over the whole length of the pipe. This final layer insured that if any of the existing CFRP damaged during the removal of the PWC by grinding was replaced with a new layer of CFRP. At the joint, multiple layers of CFRP were installed. The number of layers at the joint was based upon the buckling requirements. Finally the Tyfo PWC was installed over the top of the new CFRP. See Figure 2.

Another issue which arose during construction was the concern that the cylinder might buckle if too much of the inner core was removed. The concern was that the loss of support from the inner core would make the cylinder vulnerable to buckling. To address this concern the amount of mortar lining removed was minimized to the extent possible. In addition, calculations were performed to determine if the cylinder could buckle without the inner mortar support. The calculations showed that the cylinder was not in danger of buckling. Considering the bell or spigot is immediately adjacent to the cylinder, unless large areas of the cylinder are exposed it seems unlikely that the cylinder can buckle. Finally it was believed that if the cylinder did buckle it would not have an impact on the repair. The buckle would have a minimal deflection and the CFRP could be placed over the buckled steel cylinder without any adverse effect on the repair. The cylinder did not buckle when the mortar was removed.

The last issue that arose during construction was the discovery of a large void under the original CFRP lining. The void was determined when the PWC was being removed by grinding. The size of the void was approximately one foot wide and 6 feet long. The void was located at approximately 10 o’clock on the pipe. This void was not observed during the original CFRP construction and was only found by the Contractor during grinding off the PWC. Several options for repair were considered including filling the void with epoxy and doing nothing. The biggest concern with filling the void with epoxy was the possibility of increasing the size of the void through the epoxy injection process. After considering the options it was decided that attempting to fill the void was more risky than leaving the void empty. The void had already been subjected to hydrostatic pressure for several years without a problem so it was decided the “do nothing” option was less risky.

The CFRP was successfully installed over a period of several days. The CFRP was cured and the repair placed into service. The pipeline was successfully placed into service. The new installation now meets the requirements of the new draft code[4] and is expected to last for the design life of the pipe.

CONCLUDING REMARKS

There are many times when the use of CFRP has advantages over replacement or other rehabilitation methods. MWD typically only uses CFRP in locations where more conventional repairs are not feasible. In order to insure that our existing pipeline repairs meet current standards and do not have any deficiencies, it was imperative that MWD fix the termination details of the existing CFRP repairs, and to check to insure the CFRP was able to resist buckling and longitudinal strain.

MWD's initial design typically had enough layers to prevent buckling because the design required that the stress in the cylinder not exceed the yield strength of the steel. In some cases where the head was low, extra hoop layers had to be installed to insure the CFRP could take the buckling.

As a result of this project the following lessons can be learned:

- New CFRP layers can be placed over the existing top coating (PWC) as long as the coating is properly prepared. Testing showed that there was no need to completely remove the PWC coating to achieve adequate bond strength.
- Based on the testing by WRF, The surface of the cylinder must be prepared to white metal before applying the CFRP as indicated by WRF testing. This connection is very important, and if the surface is not adequately prepared a leak path under the CFRP at the connection to the cylinder may occur.
- The amount of lining removed at the joint should be minimized to prevent the risk of the cylinder buckling under the existing prestressing.
- The owner should consider adding enough layers of CFRP in the hoop direction to prevent the stress in the cylinder from exceeding yield. This will help insure the cylinder will not rupture and provide a better long term fix.

REFERENCES

[1] Metropolitan Water District is a consortium of 26 cities and water districts that provides drinking water to nearly 19 million people in parts of Los Angeles, Orange, San Diego Riverside, San Bernardino and Ventura counties. The mission of MWD is to provide its service area with adequate and reliable supplies of high-quality water to meet present and future needs in an environmentally and economically responsible way. MWD currently delivers an average of 1.7 billion gallons of water per day to a 5,200 square mile service area.

[2] Water Research Foundation 2012, *CFRP Renewal of Prestressed Concrete Cylinder Pipe* (Mehdi S. Zarghamee, Murat Engindeniz, and NaiyuWang).

[3] University of California San Diego, Report SSRP-2002/03, *Rehabilitation of Large Diameter PCCP with Composites* (David Lee, Vistasp Karbhari).

[4] American Water Works Association, *Draft AWWA Standard for CFRP Renewal and Strengthening of PCCP*, May 1, 2012.

[5] *Draft 2012 Carbon Fiber Lining Repair Testing, ASTM D4541 Adhesion Test, MWD, R. Witowski.*