How to Fund Pipeline Renewal:
Transitioning from O & M funds to Capital Improvement Budgets

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Abstract

Municipalities have challenges funding both emergency and planned infrastructure repairs. Challenges come from time and value requirements predetermined for use of O&M funding, and time requirements needed to secure capital funding. O&M budgets are a great source of ready to go funds. Should an operations manager's organizational costs not be impacted by use of these funds for an emergency repair, then O&M funding may make sense for smaller projects. However, O&M funding value limitations will likely not support the higher costs associated with renewal projects. Although every agency differs, each agency has limitations for use of O&M dollars. For example, O&M funding may be limited to projects having a useful life of less than 5 years and project costs below $50,000. From this, it becomes obvious why O&M funding is a better fit to support maintenance operations rather than infrastructure renewals. The vast majority of infrastructure renewals exceed the time and value requirements set for use of O&M funding.

As a result, Municipalities must obtain Capital funding to address both emergency and planned renewals. This paper discusses the ways in which municipal agencies have been able to successfully utilize capital improvement allocations for carbon-fiber-reinforced-polymer (CFRP) renewal of pipelines by recognizing this technology as a long term method for asset management for renewal of both buried and above ground infrastructure. The methods discussed are prequalification of materials and installers, award of on-call contracts, and methods for projecting the costs of future renewals for long term budget allocations.

1. Introduction

Water agencies are faced with the challenges of replacing and renewing aging infrastructure, meeting regulatory requirements, and providing infrastructure for growth, all with limited funds. A recent report by the United States Environmental Protection Agency estimates a shortfall of $334.8 billion over next 20 years in funds for renewing the nation's water infrastructure (EPA, 2009). Of the required funding, 60% of the necessary funds, or approximately $200.8 billion, would be needed for rehabilitation of water transmission and distributions systems (See Figure 1), which mainly consists of buried pipelines. Large diameter pipelines are of particular interest in terms of agency concern due to the higher consequence of failure associated with a potential break in a large diameter pipeline as compared to a small diameter pipeline.

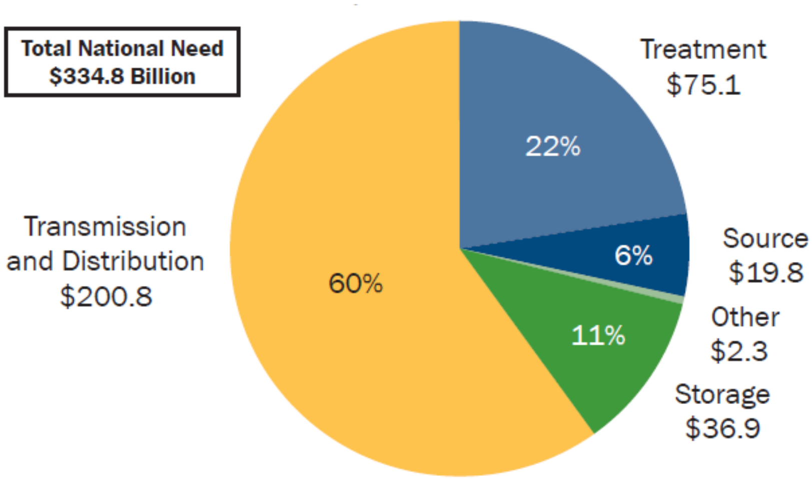

Figure 1. Total Project Need by Project Type (in Billions of January 2007 Dollars)

Given the nation's substantial challenges with funding shortfalls, the nation's water agencies are increasingly seeking improved asset management strategies to allow for best utilization of limited funds. One effective strategy adopted by water agencies is the use of proactive inspection and strategic rehabilitation of buried pipelines. By using technologies which provide direct insight into the structural condition of individual segments of pipeline, selective repair or replacement of only the sections with structural deterioration provides a more cost effective alternative to the more tradition strategy of replacing a specified number of miles of pipeline every year regardless of the condition of the pipelines.

A technology that is able to facilitate this improved asset management philosophy is carbon fiber wrap strengthening of pipelines. The use of carbon fiber wrap for structural strengthening has been well documented as a durable means of structural strengthening and renewal of civil structures for over 25 years and for use in pipeline rehabilitation for over a decade. The carbon fiber wrap system for large diameter pipeline strengthening involves a proprietary process of applying the carbon fiber wrap to the inside of the pipeline to create a durable structural liner which can serve support the internal and external loads that were previously supported by the host pipe. This process is trenchless and can be applied with precision to individual pipeline segments, allowing for direct collaboration with the targeted structural data provided by accurate pipeline inspections.

The streamlined asset management approach which couples pipeline condition assessment with precision carbon fiber wrap repairs has provided numerous water agencies nationwide with a cost effective solution. Different methods for funding this approach will now be addressed.

2. Maintenance versus Renewal

Two major sources of funding for water agencies are operation and maintenance funds, known as O&M funds, and capital improvement funds. O&M budgets typically are used for expenditures that are required to maintain the water agencies system in good operating condition, such as repairs and minor replacements. In contrast, capital improvement budges are typically used for larger scale expenses such as system rehabilitation, major equipment replacements, improvements, and expansions (Brandt and Davis, 2006). Funds available for distribution maintenance through the O&M budget are typically limited, whereas funds for pipeline renewal through the capital improvement budgets are substantially greater. A comparison of O&M budgets to capital improvement budgets for selected water agencies is provided in Table 1 to illustrate the relative difference between in available funds.

Table 1. Comparison of O&M Budget versus Capital Improvement Budget Potentially Available for Distribution Repair or Renewal

Sample US Water Municipalities	O& M budget allocation for Outside Services Including Distribution Maintenance	Capital Improvement Budget
Water Agency #1	$7.4 million	$70 million
Water Agency #2	$37.7 million	$250.9 million
Water Agency #3	$23.2 million	$152.9 million
Water Agency #4	$2.9 million	$17.4 million

Some of the key differentiators between O&M categorized projects and capital projects are the dollar values associated with the projects and the intended life of the project. For example, O&M funding may be limited to projects having a useful life of less than 5 years and project costs below $50,000. From this, it becomes obvious why O&M funding is a better fit to support maintenance operations rather than infrastructure renewals. The vast majority of infrastructure renewals exceed the time and value requirements set for use of O&M funding.

The use of the carbon fiber wrap technology for pipeline strengthening and renewal has been established as durable solution that is typically designed with a 50-75 year design life. The long term useful life of the carbon fiber wrap liner pipeline renewals lends itself to funding through the capital improvement funds. However, agencies must feel confident with the long term durability of the carbon fiber wrap system in order to justify its inclusion in capital improvement budget. A discussion on the technical vetting of the carbon fiber wrap system to feel confident with a 50-year design life is discussed in the following section.

3. Durability for a Carbon Fiber Wrap Pipeline Renewal System

The use of the composite materials was well established in the aerospace, boating and automotive industries by the time that composites were first applied to strengthen civil structures in the mid 1980's. Since the initial applications of fiber reinforced polymer composite materials (fiber wrap) for seismic retrofit of bridge structures, extensive research and testing has allowed for composite materials to be used for a variety of civil structure rehabilitation applications including internal strengthening and repair of large diameter pipelines. For typical civil rehabilitation applications such as rehabilitation of a bridge or building, the fiber wrap serves as supplementary reinforcement for the primary structural member requiring strengthening. In contrast, pipelines requiring rehabilitation can be designed to rely on the fiberwrap as the primary reinforcement for the system such that the existing pipe is used solely as a formwork for the new stand-alone system. This reliance on the fiber wrap as the stand-alone structural member makes proper design, material selection, quality control, and implementation of the selected composite system especially important for pipeline applications. This paper will highlight the important factors which impact the lifecycle of the CFRP liner system and address impacts on lifecycle for pipeline rehabilitation designs which are stand-alone designs or rely on designs which work compositely with the host pipe to provide structural integrity.

3.1. Material Selection

A fiber reinforced polymer composite system is comprised of two main components. The reinforcing fiber is typically woven into a unidirectional cloth and which is saturated by the resin system and then allowed to cure to form the hardened composite. The reinforcing fiber provides the structural properties for the system in the direction of the reinforcing fibers, whereas the saturating resin provides nominal structural properties for the system in the direction perpendicular to the reinforcing fibers and also controls the durability of the composite system.

The most common reinforcing fibers for civil applications are glass and carbon fibers, and both have been used widely for civil infrastructure rehabilitation for over 20 years. For pipeline strengthening applications, carbon fibers are typically preferred because the superior structural properties of the carbon fibers over glass fibers allow for labor savings that substantially outweigh their higher material costs. Also, extensive durability testing has shown that carbon fibers have superior durability to glass fibers, particularly when exposed to alkaline environments such as a concrete substrate, such as the inside of a prestressed concrete cylinder pipe (PCCP).

A wide variety of resins which originated in the aerospace and boating industry have been tested for potential application to civil structures. Based on multiple accelerated durability tests as well as field studies of different resin systems, two part epoxy systems have been found to be the most suitable resin system for use in the fiber wrap strengthening of pipelines. Unlike traditional construction materials like concrete and steel, there are not standards which composite material manufacturers are forced to comply with regarding chemical and structural properties. Instead, the responsibility of selecting an appropriately durable and structurally adequate fiber wrap system is placed on the owner or engineer through the requirements that they place in a performance based specification. For inexperience owners and owner representatives, this can cause substantial challenges, and may run the risk of having unsuitable FRP materials installed, resulting in drastically reduced service life for the repair system.

To aid the owner in specifying high quality fiber wrap systems, the International Code Council (ICC) developed a set of minimum durability and performance criteria which must be adhered to in order to receive ICC approval and a valid ICC report. The minimum acceptable durability criteria, structural performance, and inspection criteria for any fiber wrap system to be considered suitable for structural rehabilitation applications is outlined in ICC AC125 and ICC AC178, with pipeline specific criteria addressed in ICC PMG. These ICC reports include criteria for minimum retention of structural properties after 1,000 hour, 3,000 hour, and 10,000 hour exposure to various aggressive environments including water at different temperatures, saltwater, alkali solutions, and dry heat (ICC 125, 2010 and ICC 178, 2010). Compliance with the NSF 61, the listing by the National Sanitation Foundation which governs safety of the nation's drinking water supply, is also listed as a requirement which must be achieved in order to receive valid ICC reports (ICC PMG, 2010). In order to ensure durability of any fiber wrap repair, requirement of valid ICC reports to be provided with bid by any potential fiber wrap material supplier is an important component of any well written specification for pipeline rehabilitation using CFRP.

3.2. Durability Testing

More extensive durability testing beyond the 10,000 hour exposure tests required by ICC AC 125 are available for selected fiber wrap materials. For a carbon fiber/epoxy composite system which is widely used for pipeline repair applications, the Tyfo SCH System, a recent study was released which highlights an 8-year durability study that was recently completed by the Metropolitan Water District of Southern California (Sleeper et al, 2010). In this study, an inspection on segments of fiber wrapped PCCP was performed approximately eight years after the initial installation of the CFRP composite repair. As shown in Figure 1, the visual and sounding inspection indicated no damage in the form for delaminations, bubbles, cracks or edge lifting. Observations from the same inspectors who originally observed the CFRP liner during its original installation, noted that the CFRP liner was observed to be in the comparable condition to the when it was installed eight years ago (Sleeper et al, 2010).

Figure 1. MWD inspector observing condition of the Tyfo Fibrwrap system after 8-year in service history

In addition the field results from the in-service application of the CFRP system, coupons made from the same Tyfo SCH system installed in MWD's pipeline where tensile tested after eight years of exposure to tap water in environmental chambers. The tensile test results shown in Table 1 indicate minimal change in the structural performance of the Tyfo SCH system, as measured through tensile strength, tensile modulus and breakage strain, after being continuously immersed in tap water for a period of over eight years. The results of this durability study indicate strong potential for the examined fiber wrap to serve as a long term solution for the intended application in pipeline repair.

Table 1. ASTM D3039 Tensile Testing Results of Tyfo SCH System Samples (Sleeper et al, 2010)

Properties	Un-aged Sample	8-year Water Immersed Sample	Datasheet Values [Fyfe Co, LLC]
	Average ± STD	Average ± STD	Typical Test Value
Tensile Strength (ksi)	128.7 ± 15.6	139.5 ± 18.5	127.0
Tensile Modulus (10^6 psi)	12.7 ± 0.14	10.6 ± 1.23	10.5
Breakage Strain (%)	1.16 ± 0.17	1.3 ± 0.1	1.2

3.3. Design Considerations

While there does not currently exist national standards which govern the design of CFRP liners, there are industry accepted design approaches which are consistent with methodologies used by modern pipeline engineer and relevant AWWA standards for pipelines made of traditional construction materials. These design approaches were developed through research and development performed by the Metropolitan Water District of Southern California, the University of California, San Diego, and material manufacturers (Loera, 2006). The research performed included materials testing as well as full scale internal pressure and external loading tests to validate design concepts (Loera, 2010). These design methodologies take into account the different structural demands acting on the pipeline, which typically include internal water pressure and surge pressure as well as external loading from soil or vehicular traffic.

A critical component of the design of the CFRP liner is the residual strain at which the fiber wrap system is exposed to under operating conditions and surge conditions for the pipeline. In order to achieve the desired design life for the system, the maximum sustained strain induced in the CFRP must be limited. Reasons for limiting the strain in the system are provided in the following two sections that describe material specific reasons and design methodology specific reasons, respectively.

3.3.1. **Strain Limitations- Material Property Specific Justification**

Durability studies of FRP material have documented that inducing sustained strains in the composite above certain thresholds can cause premature failure of the composite system, known as creep rupture, due to continued plastic deformation of the polymer matrix. As shown in Table 2, ACI 440.2R, the code which governs design of FRP strengthened concrete structures, places a strain limitation on CFRP material under sustained strain of 50% of the ultimate strain in the CFRP system. Note that fiber wrap is linear elastic to failure, so a limitation on ultimate tensile stress is equivalent to a limitation on the strain of the system. This sustained strain limitation provides an upper threshold for material defined strain limitations, however does not take into account other knockdown factors imposed on the material or the desired design life for the CFRP system.

Table 2. Strain limitations imposed by ACI 440.2R (ACI 440.2R, 2008)

	Fiber Type		
Stress Type	GFRP	AFRP	CFRP
Sustained Plus Cyclic Stress Limit	$0.2^{*}f_{fu}$	$0.3^{*}f_{fu}$	$0.5^{*}f_{fu}$

Where
GFRP= Glass fiber reinforced polymer composite
AFRP= Aramid fiber reinforced polymer composite
CFRP = Carbon fiber reinforced polymer composite
f_{fu} = ultimate strength of the FRP

Further research into the impact of sustained strain on the design life recommends sustained strain limitations based on analytical modeling which has been correlated to durability data from material tests. (Guixian et al, 2009). Figure 2 shows a logarithmic plot of strain as a fraction of the ultimate breakage strain versus the service life of the CFRP system indicates that the service life of the fiber wrap exceeds 75 years for sustain strains which are approximately 30-40% of the ultimate strain for the system. Based on this research, it is recommended that the sustained strains for a CFRP system be limited to below 30% of ultimate to achieve the highest service life.

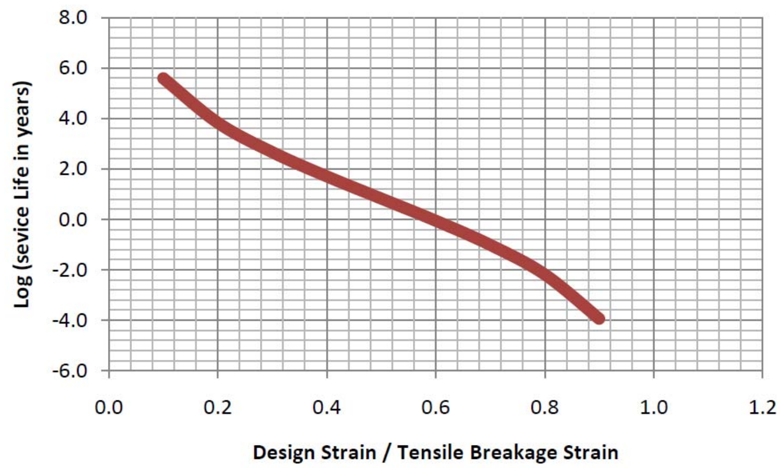

Figure 2. Service life as a function of sustained strain for a CFRP composite system (FTC – 15, 2010)

3.3.2. **Strain Limitations- Material Property Specific Justification**

Depending on the condition of the host pipe, the soil conditions, and the level of conservatism taken by the pipeline owner, the CFRP liner can be designed as a stand-alone design in which the fiber wrap provides the structural integrity for resisting all internal and external loads, or as a composite design in which part of the host structure is relied on for part of the structural strength. In the case of prestressed concrete cylinder pipe (PCCP), the embedded steel cylinder and the inner concrete core are considered in conjunction with the carbon fiber as a transformed PCCP section for the composite CFRP liner designs. In order to avoid plastic deformations of the host pipe it is recommended that strains be limited to 75% of steel yield for operating condition and 95% of steel yield for surge conditions. By limiting the strain to below steel yield for stand-alone designs as well as composite designs, the the integrity of the host pipe will be maintained, which helps to keep the core water tight and save the integrity of the host bell and spigot joints. For composite designs, the bond between the carbon fiber and the concrete substrate is critical for load transfer, and the imposed strain limitation protects this bond as well as provides crack mitigation for the concrete. This strain limitation provides a factor of safety on the ultimate tensile strength of the CFRP of over 10, which ensures its longevity and avoids any concerts regarding creep rupture of the CFRP system. The continuous refinement in design methodologies for CFRP liners over the past decade as well as the current state-of-the art design concepts are described in detail by a recent paper (Loera, 2010), so this paper should be referenced for a more in depth look at design methodology and the importance of strain limitation for ensuring the desired design life.

3.4. **Installation of CFRP Liner**

While a good design with appropriately selected materials and proper strain limitation is necessary to ensure the desired design life for a CFRP liner, proper installation of the system is just as critical. The application of fiber wrap for pipeline renewal is a highly specialized construction process which is controlled by stringent safety standards and there are few contractors nationwide who are qualified to perform this work. Recent failures of CFRP liners installed by unqualified contractors emphasize the importance of specifying minimum experience requirements for contractors as well as the key personnel planning to perform the work in terms of both minimum number of projects, as well as minimum number of years of experience in the industry of pipeline rehabilitation using fiber wrap materials. Particularly important steps in the installation process are the surface preparation of the host pipe, saturation of the fiber wrap material, dehumidification and proper temperature control of the pipe, careful installation of the fiber, and an appropriately followed QA/QC procedure.

For pipelines with a concrete substrate, it is important to remove the laitance layer of the concrete surface and expose the underlying aggregate, as shown in Figure 3, such that the CFRP system is able to achieve a chemical and mechanical bond with the host structure. Once the surface has been prepared through mechanical means, the substrate surface should be cleaned, dehumidified and kept at a temperature which allows for proper cure of the selected resin system. A test piece of CFRP is then typically bonded the host structure such that a bond test in accordance with ASTM D4541 (ASTM International, 2002) can be performed, as shown in Figure 4, to ensure that the surface preparation procedure was performed correctly.

Once the surface is fully prepared, batches of the selected two part epoxy system are mixed and the spools of carbon fiber fabric are saturated. Use of a mechanical saturator ensures even application of the resin system and is typically specified on all fiber wrap projects to avoid inconsistencies in terms of over and under saturation of the fabric that arise when attempting to hand saturate the spools for carbon fiber fabric. The spools for carbon fiber fabric are ran through the mechanical saturator as shown in Figure 5 and then the spools are carefully lowered through the manhole into the pipeline so the saturated fabric can be applied on site. The fabric is then carefully laid up in accordance with the specified design, as shown in Figure 6, and the system is cured in place. A QA/QC procedure which is mandated in the specification, provides direction for methods of repair of any bubbles, voids, or delaminations which were introduced into the CFRP liner system during installation. Full details regarding appropriate specification requirements are too extensive to be addressed adequately here. For further information please contact the author.

4. Conclusion

An effective asset management plan which proactively performs condition assessment on critical buried pipelines, thereby allowing for improved planning for the capital costs associated with segmental pipeline renewal for the sections found to be structurally deficient, plays an important role in a capital improvement budget. By using direct structural condition of the pipelines to plan future capital expenditures, improved budgeting processes can by implemented, avoiding costly failures and best allocating limited resources. The concept of proactive inspection and pipeline renewal as part of a capital improvement budget allows for stretching limited resources, helping to solve the challenges with the nation's aging water infrastructure.

5. References

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