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Composite versus Stand-Alone Design Methodologies for Carbon Fiber Lining Systems

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Abstract

Fiber Reinforced Polymer (FRP) composite lining systems are used by major municipalities throughout the United States to structurally rehabilitate and upgrade large diameter pipelines. For internal Carbon Fiber Reinforced Polymer (CFRP) lining systems addressing prestressed concrete cylinder pipes (PCCP), there are two design approaches utilized relative to interaction with the host pipe structure. These approaches are referred to as stand-alone and composite. For a stand-alone design, the carbon fiber takes 100% of the loads acting on the pipeline system with no reliance on the host pipe for structural integrity. Composite designs rely on the carbon fiber lining system and inner concrete core of the PCCP to interactively provide a structural system to resist the loads. A composite design approach relies on the inner core to resist bending and buckling due to external loads such as soil cover, water table, vehicular loads and vacuum pressure. When applicable, this type of design can be more cost-effective because the amount of carbon fiber materials utilized can be less than stand-alone design. This paper presents design limit states and includes information from recent research, development, and testing. It discusses factors to be considered, potential challenges and best practices for determining stand-alone versus composite designs for carbon fiber lining systems.

BACKGROUND

Over the past more than 15 years, Fiber Reinforced Polymer (FRP) composite materials have been utilized with increasing frequency for internal structural rehabilitation and upgrade of pipelines. The overall process involves surface preparation of the internal pipe substrate followed by manual application of layers of unidirectional carbon fiber fabrics (Figure 1) which have been saturated with a two part epoxy directly prior to installation using a calibrated mechanical saturator.

Figure 1. Typical process for Installation of CFRP inside a pipeline

The layers of carbon fiber fabric are oriented in the longitudinal and the circumferential directions and are designed to resist the structural demands acting on the pipeline. Depending on the design approach, the CFRP liner can be designed as a stand-alone system or a composite system which relies on the host pipe for partial structural strength.

CFRP liners are commonly used to structurally rehabilitate prestressed concrete cylinder pipeline (PCCP) segments which have been identified as distressed. An embedded-cylinder type (ECP-type) PCCP, the type of PCCP used for larger diameters pipelines, is composed of an inner concrete core, a steel cylinder, an outer core, prestressing wires over the outer core, and a protective mortar coating (Figure 2). A common failure mode of PCCP is breakage of the prestressing wires within individual PCCP sections.

Once enough prestressing wires break, the concrete core in the region near the broken wires is no longer in compression and can crack, exposing the steel cylinder to ground water and thus, causing corrosion. The condition of the host pipe is critical in determining what extent of the host pipe, if any can be taken into account in the CFRP lining design. Since the steel cylinder, outer core, and prestressing wires are debonded from the inner core, only the inner core can be relied on in composite CFRP design for addressing distressed PCCP segments.

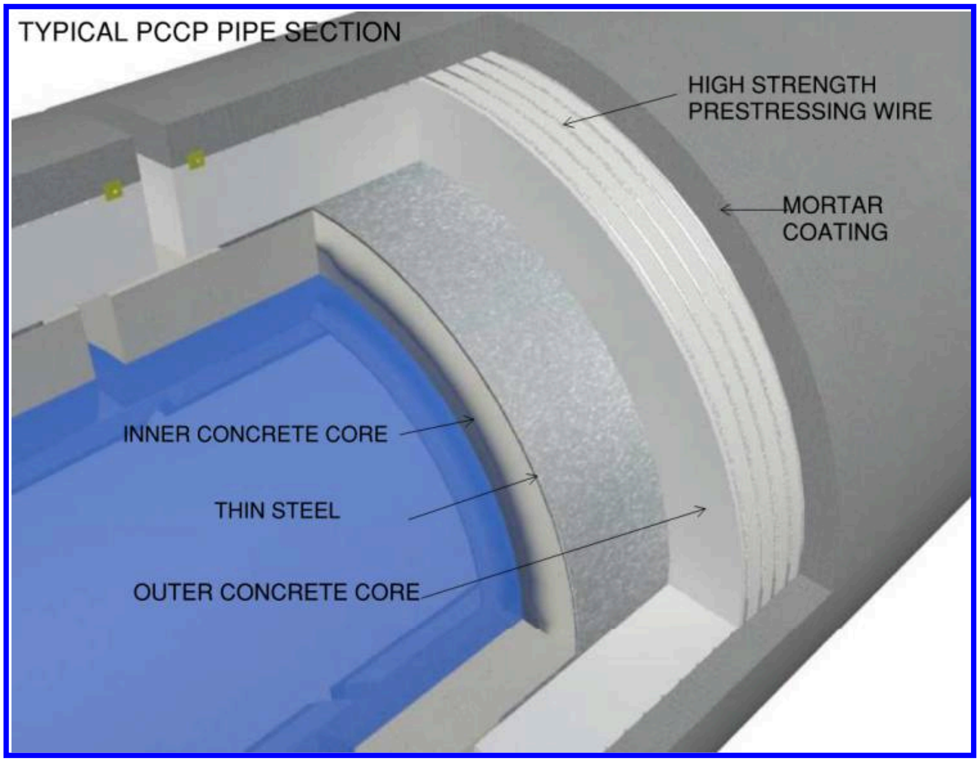

Figure 2. Components of an ECP-type Prestressed Concrete Cylinder Pipe Section

DISTRESS LEVEL OF THE HOST PIPE

As part of the CFRP lining design process, the overall distress level within the host pipe is considered. These levels of degradation are defined in a draft AWWA standard for CFRP rehabilitation and strengthening of PCCP as Non-Degraded Pipe, Degraded Pipe, and Severely Degraded Pipe.

a) A non-degraded host pipe is taken into account in the design when there is no known damage to the PCCP segment and the CFRP liner is added due to load increases acting on the pipeline (live load, earth load, pressure, etc.). Based on the good condition of the pipe, the CFRP system can be designed as composite action with the entire pipe wall thickness.

b) A host pipe is defined as a degraded pipe when the PCCP has some broken wires and the outer concrete core may be also cracked and softened, but any minor cracking of the inner core can be repaired and the inner core is still circular. The host pipe is expected to continue to degrade with time after the CFRP repair is in place. Since additional wire breakage, outer core cracking, and corrosion of steel cylinder are anticipated over time, the CFRP repair of degraded pipe can be based on either composite action of the host pipe inner core reinforced with CFRP laminate or stand-alone CFRP liner.

c) A severely degraded host pipe consists of PCCP with a non-circular inner concrete core showing multiple wide cracks as well as an uneven internal surface with ovality or waviness. Pipes with this level of severe distress require special design consideration and additional attention should be given to determining applicability of CFRP lining for these applications.

DESIGN PROCESS FOR FRP REHABILITATION OF PCCP SEGMENT

Design process used for FRP Rehabilitation of PCCP at WSSC consists of several steps depicted in below the diagram (Figure 3).

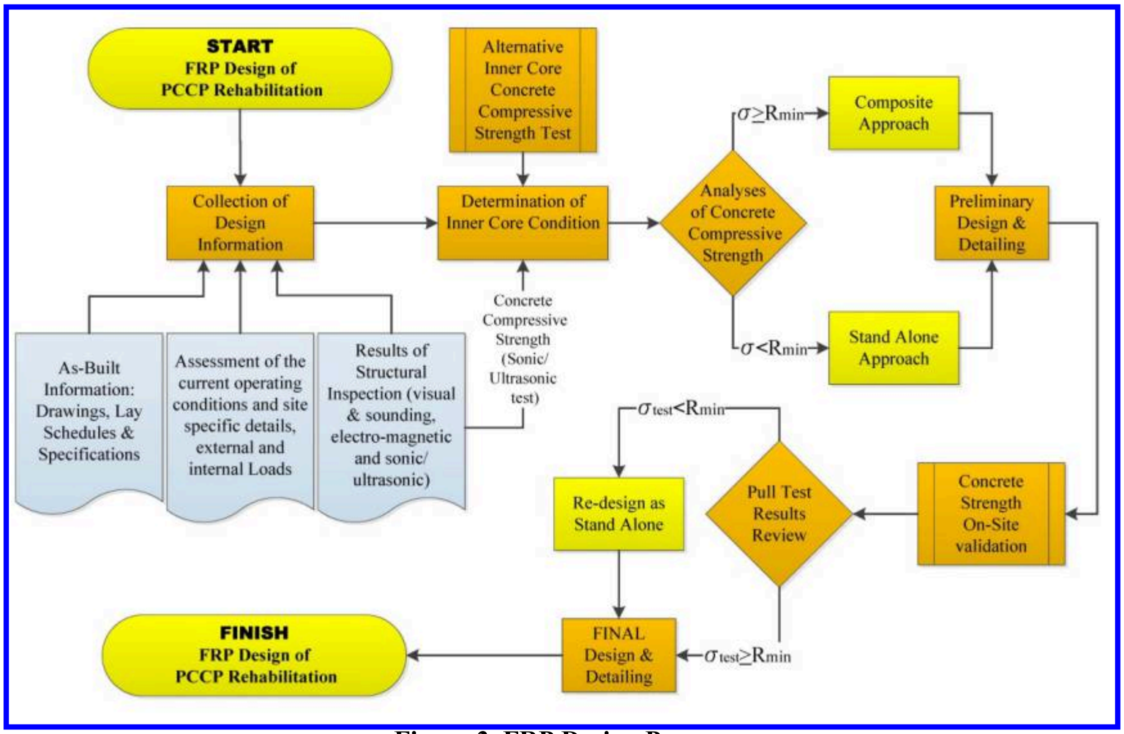

Figure 3. FRP Design Process

The design process involves collection of the design information, including as-built drawings, lay schedules and pipe specifications, results of structural pipe inspection (visual and sounding, electro-magnetic, sonic/ultrasonic, etc.) and assessment. Since stand-alone design for the large diameter PCCP most likely will utilize more layers of the FRP material than the composite design method, the design process may start with validation of the less expensive composite method which relies on the existing condition of the substrate, i.e. inner core concrete. Determination of the concrete condition is one of the most critical components needed for the "composite versus stand-alone" decision since inner core concrete compressive strength is used for the estimate of the FRP-to-substrate bond. Should adhesion bond, σ, be less than the minimum allowed bond value (R_{min}) per AWWA [5] such that $\sigma < R_{min}$, a stand-alone design approach may be used. In order to confirm the adhesion bond and therefore determine applicability of a composite design approach, on site pull-off testing must be performed.

Determine Condition of Inner Core

In order to determine whether the inner core is capable of being used in a composite CFRP design, a condition assessment is performed to evaluate the level of deterioration that has taken place. Several methods are used at WSSC for determining condition of the inner concrete core include visual and sounding, adhesion testing, sonic/ultrasonic, and rebound hammer testing.

Visual and sounding inspection of a pipe involves a trained inspector looking for signs of distress within the pipe which include cracks within the inner core, damaged joints, areas with severe pipe ovality, and concrete spalling. One sign of severe distress in a PCCP section involves longitudinal cracks within the inner core, which could indicate loss of prestress due to broken wires.

Tests to estimate the compressive strength of concrete include sonic/ultrasonic inspection which can be performed as a part of the structural assessment [8], and the rebound hammer test (i.e. Schmidt hammer test) per ASTM C805 [4] which involves a spring loaded hammer hitting a steel plunger, which is in contact with the concrete as shown in Figure 4. Once the concrete is impacted by the defined energy, the hammer's rebound distance is measured. This rebound hammer can be used to determine the concrete's compressive strength using the manufacturer's conversion chart [9].

Figure 4. Evaluation of Inner Concrete Core via Rebound Hammer Test

In order to validate design based of the estimated inner core concrete values, adhesion tests must be performed in accordance with ASTM D4541 [3]. Adhesion tests are a part of the typical QA/QC process for the CFRP lining process. A common failure mode observed in the adhesion tests is tensile failure within the inner concrete core substrate so the results from adhesion testing provide a measure of the tensile strength of the concrete core (Figure 5). Since the tensile strength of concrete is approximately 10% of concrete's compressive strength, the compressive strength of the concrete can be approximated through use of adhesion tests on the inner core substrate. The calculated compressive strength for the inner core concrete can be checked against the minimum required values used in the design ($\sigma < R_{min}$).

Figure 5. Pull Test per ASTM D4541

DESIGN APPROACH

CFRP systems are designed using a Load and Resistance Factor Design (LFRD) approach (AWWA draft standard), where factors are applied to applied loads and material properties to account for uncertainties within the design assumptions.

As part of this design approach, design limit states are analyzed separately and the CFRP lining design is governed by the limit state that has the lowest demand to capacity ratio for the particular design scenario. Various limit states are accounted for in the design depending on whether a composite or stand-alone system is being considered.

Stand-Alone Design

For stand-alone design, the following limit states must be considered:

- Rupture of CFRP laminate in the circumferential direction due to internal pressure.

- Rupture of CFRP laminate in the circumferential direction due to bending of empty pipe.

- Rupture of CFRP laminate in the circumferential direction due to combined pressure and bending due to gravity loads.

- Buckling of CFRP laminate in the circumferential direction due to external loads and pressures and internal negative pressure

- Rupture of CFRP laminate in the longitudinal direction due to pressure induced thrust, Poisson's effect of internal pressure, and temperature changes in the pipe.

- Shear bond failure of the CFRP at pipe ends.

- Rupture of CFRP laminate in the longitudinal direction due to radial expansion of pipe in broken wire zones.

- Compressive failure of CFRP laminate in the longitudinal direction due to radial expansion of pipe in broken wire zones.

- Buckling of CFRP liner in the longitudinal direction due to temperature increase.

Composite Design

Composite design can be applied in situations where the host pipe is classified as non-degraded or degraded.

When a PCCP section is considered degraded and only the inner concrete core is taken into account in the CFRP design, the following additional limit states are addressed:

- Debonding of CFRP from the concrete inner core under one of the following circumstances:

    - Shear between the CFRP and the concrete inner core.

    - Excessive radial tension.

    - Concrete core crushing from gravity loads, in absence of internal pressure.

In situations where the host pipe is considered non-degraded and the CFRP lining is utilized to upgrade or strengthen the existing pipe, the entire wall thickness may be considered in composite action.

In the design process, it is initially assumed that the CFRP lining is acting compositely with the concrete inner core. Since stand-alone designs typically require higher layer counts than composite designs, in order to not unreasonably increase an amount of CFRP layers and consequently the cost of the repair, the design may start as composite. The bond between the CFRP liner and the inner core is checked and if any of the limit states are not satisfied, then the system must be designed as a stand-alone.

*Recent Testing Affecting CFRP Lining Design*s

Over the past several years, significant research and development efforts have taken place impacting best practices regarding designs of CFRP linings. One of the major testing programs was completed in conjunction with the Water Research Foundation (Zarghamee et al.) [10]. The testing included full scale external load tests and internal pressure tests.

External load testing, such as that recently completed (as shown in Figure 6), assists in better understanding of the CFRP and inner core composite action mechanism and ultimately helped validating the design approach which relies on the inner core for composite CFRP design.

Figure 6. Water Research Foundation Testing Setup (Zarghamee et al, 2013)

One of the most significant findings in recent testing is that watertightness of the CFRP lining is critical to long term performance, whether in a stand-alone or composite design approach. The termination details must be effective in preventing pressure build-up behind the CFRP liner. It was determined that preparation of the steel substrate at the pipe ends (for PCCP) is to be completed in a manner which ensures that material bonding is not compromised.

Along with its importance at the terminations, watertightness of the entire CFRP liner is a recent point of focus with regard to permeability. Best practice for CFRP liner materials now includes validation of watertightness for different laminate designs through testing and inclusion of watertightness provisions within each CFRP design.

CONCLUSION

The composite design process is considered a typical design concept for CFRP lining of PCCP. In order to establish feasibility of a composite design, the pipe must be verified through inspection to determine the condition of the inner core substrate within the host pipe. When composite designs are feasible, they have the potential to help reduce the overall layer count for the CFRP lining system, thereby helping pipeline owners further extend rehabilitation dollars. When composite designs are not feasible, the CFRP lining system can be designed as a stand-alone system to take all loads without reliance on the host pipe for structural integrity.

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