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Performance of spray-applied epoxy lining system subject to infiltration

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ABSTRACT

This study focuses on a bonded repair technique for deteriorated concrete infrastructure located below the water table. A spray-applied lining system is a monolithic system applied to the inside of a concrete structure, such as a pipe, culvert or tank, sealing the structure and mitigating limit states associated with structural deterioration, corrosion and/or infiltration. The resulting lining is a thin, durable, chemical resistant product that is intimately and permanently bonded to the host structure. An experimental program utilising hydrostatic pressure, intended to mimic hydrostatic forces driving infiltration into a cracked concrete pipe, was conducted. Parameters considered in the study include concrete flaw size, epoxy thickness and concrete surface preparation. Results indicate that the performance of the spray-applied epoxy system is governed primarily by host concrete tensile strength and epoxy shear capacity. The proposed system represents a feasible alternative for the repair of concrete infrastructure, including large diameter pipe, subject to large hydrostatic infiltration forces.

Introduction

This study focuses on a bonded repair technique for deteriorated concrete infrastructure located below the water table. Although the motivation for the study lies in the repair of large diameter gravity pipe systems, the application is appropriate for concrete infrastructure subject to infiltration such as culverts, buried tanks and reservoirs, risers, etc. The paper presents a study of the behaviour of a bond-critical method of repair for such infrastructure and introduces a relatively simple test method suitable for qualifying materials and/or comparing the performance of candidate systems. This latter aspect will be described at the end of the paper.

In order to place the work in context, the motivating example of the repair of deteriorated large diameter concrete gravity pipe is considered. Often, a cured-in-place pipe (CIPP) liner is used for such installations. Assuming that the original pipe remains able to support the soil and surcharge loads – the so-called 'partially deteriorated' condition, the CIPP liner is only required to support hydrostatic loads associated with groundwater infiltration (ASTM F1216-09). This limit state is premised on the fact that the CIPP is not intimately bonded to the host pipe and infiltration will result in pressure building between the CIPP and host pipe. Inward buckling or collapse of the CIPP is the limit state of interest in this case. ASTM F1216 requires that the thickness of the CIPP be sufficient to resist the hydrostatic load associated with groundwater infiltration. The required thickness of CIPP increases rapidly with depth below the water table and with pipe diameter. This study was initiated when considering the case of a 3.67 m diameter gravity sewer interceptor located 33 m below the water table. In this case, using typical material properties, the required thickness of CIPP was found to be 130 mm. Clearly this is impractical. For a 'fully deteriorated' pipe (ASTM F1216-09), which must support hydrostatic, soil and surcharge loads, the required CIPP thickness would be significantly greater.

The objective of this study is to introduce an alternative to CIPP systems suitable for cases subject to high hydrostatic pressure and/or large host pipe diameter: a spray-applied epoxy pipe lining system. Such a system is also appropriate for rehabilitation of any concrete system subject to infiltration, as will be shown.

Spray-applied epoxy pipe lining systems

A spray-applied lining system is a monolithic system applied to the inside of a concrete component, sealing the component and mitigating limit states associated with continued structural deterioration, corrosion and/or infiltration (or exfiltration). The resulting lining is a thin, durable, chemical resistant product that is intimately and permanently bonded to the host structure; thus the collapse limit state, represented by inward buckling of CIPP for instance, does not need to be considered.

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The lining serves to provide *continuity* to the inner surface of the concrete structure; it bridges existing and anticipated cracks, preventing infiltration products from completely penetrating the structure wall. Additionally, the lining system may be designed to enhance structural capacity in small and medium diameter pipes (Harries et al. 2004, 2014) or the flexural capacity of concrete tank wall (Harries and Young 2003). Generally, the epoxy thickness is a function of the amplitude of the concrete substrate to which it is applied. The epoxy serves to 'fill' the small amplitude variation present on the prepared substrate and may be built out beyond this to provide a smooth interior finish. Considerations of impact and/or abrasion resistance may also inform the design thickness of the epoxy lining.

The liner is intimately bonded to the concrete substrate and relies on this bond to provide the required performance. Large regions of debonding are unlikely and may be immediately addressed upon initial inspection following installation. Small regions of infiltration pressure reaching the depth of the liner through existing or anticipated cracks in the host structure are likely. These are resisted by the bridging action of the epoxy layer. This is a design consideration unique to such systems and is described in the following section.

Because the lining offers little structural enhancement in large diameter pipes or in long span walls (Harries et al. 2014), the host structure must be able to resist all mechanical and hydrostatic loads; a pipe, for instance, must satisfy the 'partially deteriorated' requirements of ASTM F1216. If the host structure is shown to be structurally adequate, the epoxy lining is required only to address the infiltration limit state.

Local hydrostatic pressure

In systems having adequate structural capacity, the lining system is only required to address the infiltration limit state. For this, intimate bond between the epoxy and substrate concrete is required. Quality control can ensure the integrity of this bond at the time of, and shortly following, installation.

Nonetheless, future cracking of the host concrete structure must be anticipated. Such cracking will permit ground water to infiltrate the structure wall and should be expected to result in *local* spikes in hydrostatic pressure at the locations of the cracks. Elongation properties of the epoxy (rupture strains of 0.048 are reported for the epoxy considered in this study) are at least two orders of magnitude greater than the concrete cracking strain, thus the epoxy should bridge the cracks with relative ease.

Conceptually, the epoxy bond must be sufficiently robust to resist the 'wedging' or 'prying' action of the hydrostatic pressure, p at the concrete-epoxy interface. A simple analogue is shown in Fig. 1, representing a section through a crack having a crack width of w_i. At each side of the crack, the hydrostatic pressure results in: (a) a tensile force, σ_{II}, generated in the epoxy which is transferred to the concrete through Mode II shear stresses, τ; and; (b) a Mode I tensile peeling force acting at the epoxy–concrete interface at the edge of the crack resisting the hydrostatic force σ_I. These forces result in a complex 'mixed mode' stress condition at the epoxy–concrete interface as shown in Fig. 1b. Two failure paths may result: **A**: adhesive failure along the interface (Fig. 1b). This failure path is associated with the *in situ* bond strength of the epoxy; and, **B**: cohesive failure in the concrete adjacent the epoxy interface (Fig. 1c). This failure path is associated with the concrete tensile properties. Because the hydrostatic pressure results from the crack behind the epoxy, cohesive failure of the epoxy is not possible.

Experience with epoxy adhesives bonded to concrete indicates that the adhesive bond strength far exceeds the concrete tensile strength; therefore path **B** is more likely. The mixed mode nature of loading, the *in situ* stresses in the host structure, the anticipated tortuous failure path, and additional uncertainties make calculation and/or prediction of this failure mode virtually impossible. For this reason, an experimental study is undertaken to establish empirical behaviour parameters.

A third failure mode: **C**: punching shear of the epoxy layer, is addressed by ensuring that the shear capacity of the epoxy layer is sufficient to resist the punching shear force resulting from the hydrostatic pressure in the concrete crack.

Assuming that hydrostatic pressure exceeds the concrete tensile strength, debonding failure will initiate and propagate along path **B**, extending essentially radially from the concrete crack, resulting in a 'delamination bubble' shown schematically in Fig. 1d. As the delaminated bubble grows radially from its source, the force causing delamination (a function of the area of delamination; i.e.: $\pi w^2/4$) increases faster than the circumference of the delamination (πw) were resistance to failure is mobilised at failure path **C**′ (Fig. 1d). For a circular delamination, the shear stress, f_{ev}, carried by the epoxy around the circumference of the delaminated bubble is:

$$f_{ev} = pw/4t \quad (1)$$

Failure may also occur as mode **D**: flexure, governed by the modulus of rupture of the epoxy. In this case the failure will be affected by the stiffness of the epoxy layer (primarily a function of thickness, t). Assuming a flexible epoxy yields the largest flexural stress, f_{er}, and therefore the critical case (Young 1989, Table 24, Case 10a):

$$f_{er} = 6pw^2(3 + \nu)/64t^2 \quad (2)$$

These equations are based on an ideal circular flaw of diameter w shown in Fig. 1d. ν is Poisson's ratio of the epoxy, often assumed to be 0.3.

Experimental program

An experimental program intended to replicate the behaviour of spray-applied epoxy material under hydrostatic pressure represented in Fig. 1 was developed. Concrete slab specimens are used; these may represent walls of rectilinear concrete structures or, the authors contend, the walls of large diameter concrete pipe.

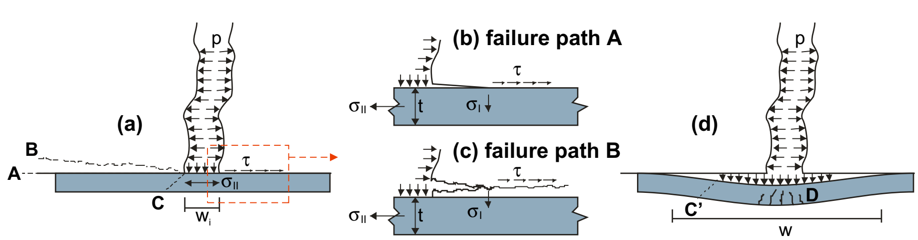

Fig. 1. *Conceptual* representation of debonding phenomena.