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Experimental and numerical evaluation of the impact of folds on the pressure rating of CIPP liners

A. Jaganathan [a,1], E. Allouche [a,*], M. Baumert [b,2]

[a] Trenchless Technology Center, Ruston, LA, USA
[b] Department of Civil Engineering, Louisiana Tech University, USA

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Abstract

A cast-iron water main rehabilitated with a thermoplastic structural liner can be viewed as a hybrid pipe. Depending on the degree of corrosion of the host pipe, stress levels carried by the liner may vary significantly. Several limit states can be developed for a liner-pipe structural system. One such state is related to the presence of a longitudinal fold in a cured-in-place-pipe (CIPP) liner that coincides with gaps in the host pipe's wall. This paper reports the results of an experimental testing and numerical modeling study undertaken to evaluate the impact of a longitudinal fold on the ability of a CIPP liner to resist internal pressures when there are significant gaps present in the host pipe's wall. Two 3-D numerical models were constructed and validated using physical testing and the analytical solutions provided in ASTM F 2207-02. The results of a parametric study performed to estimate the stress concentration in the fold as a function of the fold's geometry and level of applied internal pressure are also reported. An empirical approach is proposed as a basis for a guideline regarding the maximum allowable oversizing of CIPP liners in pressure pipes.

Keywords: Water pipes; Longitudinal fold; CIPP liner; Geometric imperfection; QC criteria

1. Introduction

Grey cast iron is the most common material used in North American water distribution systems, representing about 50% of the total length of installed water mains (Kirmeyer et al., 1994). These pipes are prone to frequent breaks with larger water main utilities experiencing 300 or more breaks per year (Makar et al., 2001). Water main breaks occur in several modes of failure, namely, circumferential breaks, bell splits, corrosion pits, spiral breaks, longitudinal cracks and wedge splitting (Rajani et al., 1996). Makar et al. (2001) discusses failure mechanisms in grey cast iron pipes including the presence of long corrosion pits. Rehabilitation of these water mains by cured-in-place liners to extend their service life and improve water quality is a practice that has been gaining market acceptance in recent years in Canada and the USA.

A CIPP liner set inside a partially deteriorated cast-iron water main life might be subjected to several types of loading, broadly classified as: external loads and internal loads. External loads include: (a) overburden soil loads; (b) traffic loads; (c) bending of the pipe due to poor bedding, frost action, swelling of soil surrounding the pipeline and/or poor compaction; (d) point loads induced by irregularities in the inner wall of the existing pipeline caused by internal corrosion; and, (e) thermal loads in places where there is a wide variation in seasonal soil temperature. Internal loads include: (a) design/operating loads; (b) loads due to pressure surges ('water hammer'); and, (c) thermal loads due to temperature changes in the transported fluids. The serviceability of a liner subjected to some of the abovementioned loads could be constrained by several potential limit states including: (a) local bending of the liner as it crosses a corrosion pit or a longitudinal crack in the host

* Corresponding author. Tel.: +1 318 257 2852; fax: +1 318 257 2777.
E-mail addresses: aja004@LaTech.edu (A. Jaganathan), allouche@LaTech.edu (E. Allouche), baumert@LaTech.edu (M. Baumert).
[1] Tel.: +1 318 257 4072.
[2] Tel.: +1 318 257 2940.

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pipe which along with internal pressure causes a hoop tension in the liner (ASTM, 2002, F 2207-02; EN 13689, 2002); (b) geometrical imperfection in the liner including longitudinal folds; (c) bending of liner wall at a clamped section; (d) local bending in the wall of liner caused by ring breaks or differential settlement across a bell and spigot joint (Rajani et al., 1996); and, (e) combinations of two or more of these limit states.

To date, little published material regarding the effect of longitudinal folds on the pressure rating of structural liners is available in the open literature. This work is focused on providing insights into the effect played by longitudinal folds in combination with corrosion pits on the pressure rating of CIPP liners. The study undertaken here is based on finite element modeling of the limit state in concern, which is compared with experimental and analytical results for validation purposes. Following validation, the numerical model was used to perform an extensive parametric study to evaluate the stress concentration in the fold as a function of the fold's geometry and applied internal pressure. Based on the results, an empirical approach was developed for calculating the maximum allowable oversizing of CIPP liners as a function of host pipe nominal diameter.

1.1. Longitudinal folds and their formation

The Canadian Institute for Research in Construction (IRC) has identified a number of common manufacturing defects that occur in grey cast-iron pipes including internal diametrical variations throughout their length (IRC, 2005). A liner used for rehabilitation of these pipes has to accommodate these diametrical variations. A common practice is to oversize the circumference of the liner to avoid introduction of gaps between the host pipe and the liner that may be caused as a result of an insufficient diameter of the liner material. By avoiding the formation of gaps through oversizing, the likelihood of buckling due to external pressure is minimized. However, a new problem of the potential creation of longitudinal folds arises, representing a form of geometrical imperfection in the liner. Much of the research in the area of geometrical imperfections in liners so far focused on buckling caused by external loading conditions. However, limited published information is available regarding the impact of geometrical imperfection on liner performance due to internal loading conditions, as it is the case for pressurized water mains.

1.2. Analytical model

ASTM F 2207-02 ASTM (2002) provides a mathematical model for determining the pressure rating of a fiber reinforced CIPP liner exposed by a hole in the host pipe. The model was developed exclusively for metallic gas pipes lined with CIPP liners exhibiting a bilinear constitutive behavior. It predicts the short-term burst pressure of the exposed liner and its service life based on uniaxial tensile test results of the liner material and hole (corrosion pit) diameter. Pressure rating in the model is obtained by solving a set of equilibrium equations, strain displacement equations, constitutive equations, and compatibility equations in conjunction with a failure criterion.

1.3. Collection of pipe samples

Samples used in this study were collected from a trial relining project in the City of Hamilton, Ont., Canada. A 1000 m long section of a 70 year old 152 mm (6 in.) internal diameter and 12 mm (0.43 in.) thick grey cast-iron water main (Fig. 1), which exhibited approximately two breaks per winter over a five year period, was lined with a fiber-reinforced CIPP liner. The operational water pressure in this part of the city is 340–410 kPa (50–60 psi) with periodical surges to 550–750 kPa (80–110 psi), which are believed to last 10–12 s. Following installation, excavations were performed at a number of locations along the alignment, and short sections (1.2 m each) of the lined cast-iron water main were exhumed for testing and evaluation purposes. It was noticed that many of the samples collected had continuous 'folds' running along the pipe's longitudinal axis (Fig. 2). The folds were continuous, running along the entire length of the samples. In many cases, the void created by the fold had little or no resin in it. The CIPP liner used in this water main was a three component system consisting of an elastomer skin, a jacket and an adhesive. The jacket was a woven textile fabric (polyester) reinforced with glass fibers. Fig. 3 shows a section of an uncured liner (jacket with an elastomer skin). Coupons (dog-bone shaped specimens) were cut from the samples and subjected to uniaxial tensile tests on an MTS multi-purpose testing machine. The tests were done in accordance with ASTM 638 (ASTM, 2000). Data from the tensile test was plotted to derive material parameters. Curves plotted using engineering stress–strain values as well as true stress–strain values are shown in Fig. 4. As suggested in ASTM F 2207-02,

Fig. 1. A typical corroded water main from the City of Hamilton.