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LABORATORY EXAMINATION OF A CURED IN PLACE PRESSURE PIPE LINER FOR POTABLE WATER DISTRIBUTION SYSTEM

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ABSTRACT

A new pressure pipe liner system has been examined with a field trial, sample exhumation, laboratory test program and computer analyses. Constitutive tests revealed that the short term behavior of the material is characterized by a bi-linear response, with modulus of 2000MPa active up to axial tensions of 1.3%, and a subsequent modulus of 180MPa. Internal pressure tests suggested that in the case of perfect geometry, the liner was able to resist internal pressures higher than 3.8MPa over significant time periods in the presence of large gaps in the host pipe. The liner pressure rating declined significantly when geometrical imperfections in the form of longitudinal folds coincided with the gap in the host pipe. The integrity of an internally reconnected tap connection subjected to high, prolonged, monotonic internal pressure was found to be sound. However, the lateral reconnection method used appeared to result in a measurable reduction in the cross-sectional area of the connection at the tap-main.

1. INTRODUCTION

While many lining systems are available for repair of damaged gravity flow sewers and the use of these systems is widespread, the problems associated with re-opening laterals have slowed the development and use of liner systems for smaller diameter water supply pipes. Furthermore, the dearth of suitable liner systems has meant that there is currently no known design standard or published design procedure for cast-in-place polymer liners inserted within pressure pipes. Like many municipal agencies, the Infrastructure Management group at Hamilton City are actively employing liner systems as part of their buried infrastructure rehabilitation work. The effectiveness of liner systems and the savings in direct and indirect costs mean that liners are now an established part of their management strategy for gravity flow pipes. Sanexen of Montréal have recently developed a liner system whereby laterals can be reopened from within the small diameter water pipe. This has prompted considerable interest in Ontario where there are many kilometers of cast iron water pipes servicing older sections of a number of cities. In the absence of established design methodologies for pressure pipe liner systems, and in keeping with their past practices with respect to research and development in liner technologies (i.e. Research into the external load characteristics of Cured In Place Pipe Spot Repairs – No Dig 1999, Orlando), the City of Hamilton conducted a field trial of the new system, and funded an assessment exercise to examine the performance of the new system. Reported here are a brief literature review, the field trial, and program of testing and analysis for the new liner system.

European Norm 13689(2002) characterizes various aspects of the pipe liner system, both for gravity flow and pressure pipes. The standard commences by classifying renovation techniques as i. Lining with continuous pipes; ii. Lining with close-fit pipes; iii. Lining with cured-in-place pipes; iv. Lining with discrete pipes; v. Lining with inserted hoses; vi. Lining with spirally-wound pipes. It then discusses design for each of these liner systems. The Norm suggests that pressure pipe liners are either designed as an *"independent pressure pipe liner" or "interactive pressure pipe liner".* The former "*is capable on its own of resisting without failure all applicable internal loads throughout its design life, without relying on the existing pipeline for radial support. It also has ring stiffness and the capability to resist external loads".* The latter "*is not capable on its own of resisting without failure all applicable internal loads throughout its design life, and therefore relies on the existing pipeline for some measure of radial support. Specifically, it transfers all or part of the internal pressure stress by radial contact to the existing pipe wall, but retains a long-term capability to span any corrosion holes or joint gaps in the existing pipeline. An interactive pressure pipe liner may or may not, depending on its ring stiffness, be able to resist internal vacuum pressure and/or external groundwater loads".*

The Sanexen Cast In Place Liner System would be classified as a close-fitting independent liner system. For this case, the loadings that are potentially of significance include internal water pressure (considering long term operating pressures, test pressures and pressure transients, positive and negative caused by water hammer, pressure cycling, or vacuum), as well as ground movements such as the differential settlements resulting from frost action.

Work has been conducted in the U.K. examining use of HDPE liners within gas and water pressure pipes. The work conducted by Boot and his colleagues (Boot et al. 1996, 1999a,b) identified that sections where the liner spans across voids or gaps in the host pipe can be critical sources of polymer wall stress. That work focused on a different installation process and a different liner material, so design recommendations are not directly applicable.

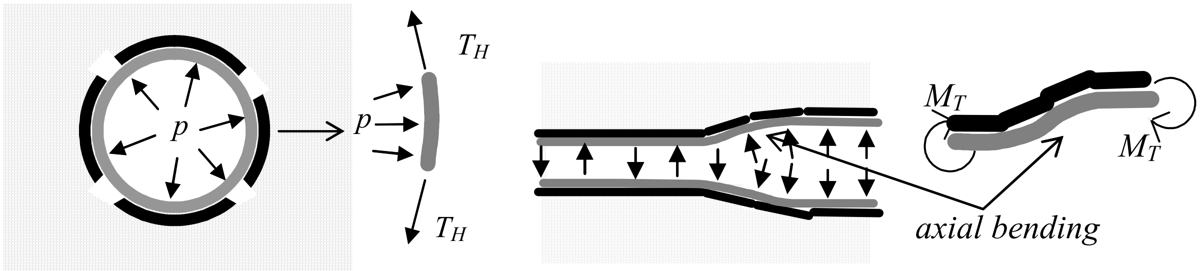
Day (1995) conducted a review of testing and field demonstrations of CIPP internal liners for a gas utility. Specifics of the design criteria and the liner selection process were not presented.

Hamilton City's assessment exercise involved the following steps:
1. Identification of limit states that could result in failure of the liner during its service life; 2. A field trial featuring repair of a cast iron watermain currently in service, and subsequent exhumation of samples of the lined pipes; 3. laboratory testing to examiner liner performance under internal pressure, and constitutive tests to establish other polymer characteristics; 4. analysis to examine the liner performance relative to the limit states. Each of these phases of the project is reported here in turn.

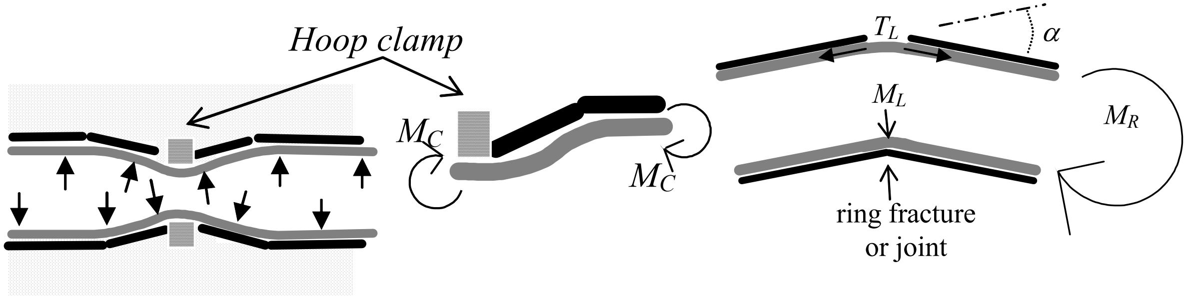
2. POTENTIAL LIMIT STATES

The project commenced with efforts to identify the different limit states that could cause liner instability as a result of internal water pressure and nonuniform ground movements. Figure 1 illustrates six different limit states that could potentially affecting liners used to repair water supply pipes (denoted LS1 to LS6 respectively):

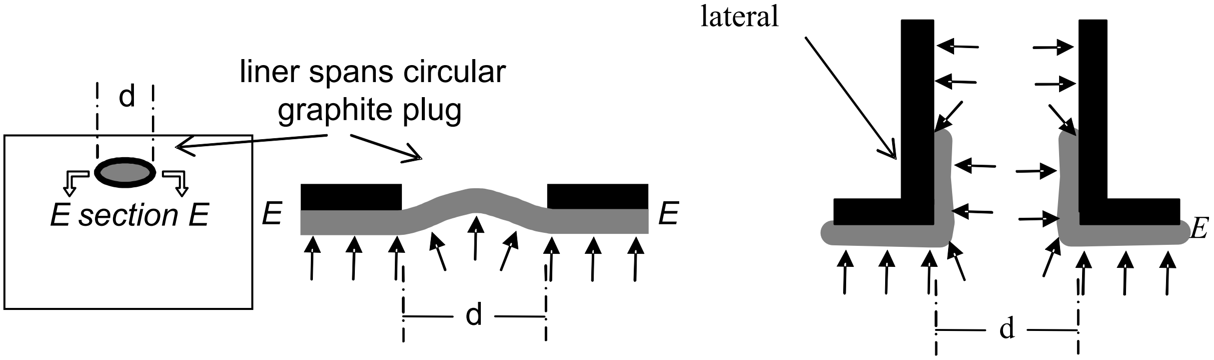
- LS1: Simple hoop tension in the liner induced by internal fluid pressure in sections where the metal 'host' pipe has fractured longitudinally, Figure 1a
- LS2: Axial bending in the wall of the liner where the liner spans from a section of host pipe that has split, to one that is maintaining its integrity, Figure 1b
- LS3: Axial bending in the liner where it passes through a pipe section fitted with a ring clamp, Figure 1c
- LS4: Overall bending moment for the liner M_G or local bending moment M_L and stretching force T_L in the liner wall can occur across ring fractures or joints, Figure 1d; rotation α of one pipe segment relative to the next results from differential ground movement due to frost or moisture changes in 'reactive' clays.; Rajani et al. (1996) examined this using elastic springs to characterise the soil response; Trickey and Moore (2005) are working to evaluate the rotation angles α that develop;
- LS5: Local bending where the liner spans across circular plugs formed by graphitization of cast iron, Figure 1e; liner design for cast iron gas mains has considered this in the past, EN 13689(2002).
- LS6: Local stresses associated with liner in the vicinity of a lateral connection, Figure 1f.



a. Tensile hoop forces from internal pressure. b. Longitudinal wall bending across transition region.



c. Longitudinal liner wall bending at clamped section. d. Moment and wall stretching at ring fracture/joint.



e. Local wall bending where liner spans across void f. Stresses around re-opened lateral.
Figure 1. Potential liner limit states (black=host pipe, grey=liner).

3. FIELDWORK

In the fall of 2003 a 1000m long section of a 75 year old 150mm cast iron watermain along West 2nd street, which exhibited approximately 2.5 breaks per kilometer per year in recent years, was lined with an Aqua Pipe™ by one of Sanexen's licensed installers in Ontario, Fer-Pal Construction Ltd. The site location and pipe segments selected for this pilot project were identified by the City to have characteristics similar to a large number of pipes in the network exhibiting similar failure rates

The operational water pressure in this part of the city is 350 - 420 kPa with periodical surges of 560 to 770 kPa, which are believed to last 10-12 seconds. Following the installation, excavations were performed by Fer-Pal Construction at a number of locations along the alignment, and short sections (~1.2m long) of the lined cast-iron watermain were exhumed for testing and evaluation purposes. A total of twelve samples were recovered, representing a wide range of conditions and configurations including straight sections, sections with stainless repair clamps, a section with a bell-and-spigot joint, a section with a water hydrant and a section with tap connections. Images of the field site (Figure 2), pulling the collapsed liner into place (Figure 3), liner inflation and curing using hot water (Figure 4), and exhumed samples supplied for testing (Figure 5) are provided here to briefly characterize the rehabilitation project.

Figure 2. Field site, Hamilton City.

Figure 3. Resin impregnated liner pulled into place.

Figure 4. Liner inflation and curing using hot water

Figure 5. Exhumed liner samples.

4. LABORATORY TESTING

4.1 Pressure tests.

The internal pressure testing program included seven burst tests and one long-term pressure test. All tests were conducted using a custom-made pressure cell fabricated at the University of Western Ontario. The device was designed specifically for this test program, with emphasis on protection measures to ensure the safety of the operator. The testing apparatus can generate in a pipe specimen filled with water an internal pressure of up to 5 MPa. The internal pressure is read via an external gauge accurate to ± 35 kPa (see Figure 6).

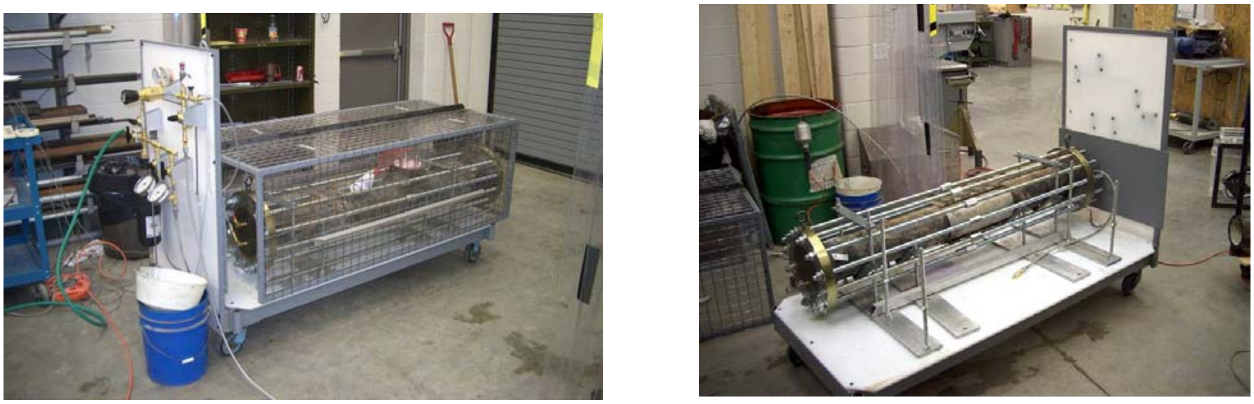


Figure 6. Custom-made pressure cell - 12 equality-space high-strength threaded rods are used to apply a compressive force to the ends of the specimen.

4.2 Specimen Preparation:

Unlike thermoplastic pipes, pressure test of metallic pipes in the water utility industry are not common due to the relatively low operating pressures of the system (420-770 kPa) and the high internal pressure capacity of common metallic pipes (over 7 MPa). Thus, a customized procedure had to be developed for the cast iron specimens. Also, the cast iron host pipe was produced nearly 70 years ago using manual manufacturing techniques. Thus, the internal and external diameters exhibited significant variations, making sealing of the pipe ends for the high internal pressures a difficult task. To facilitate end sealing, the specimens had ends squared using a lathe. The ends were than treated with liquid rubber that acted as a “cast-in-place” seal. Two steel bulkheads were custom fabricated and connected using 12 high-yield threaded bars, thus applying a compression force to the cast-iron pipe to resist the outward force applied to the bulkheads during the internal pressurization operation. This sealing mechanism was found to work well for short-term (‘burst’) tests, with internal pressure as high as 3.8 MPa. Sealing the sample for a long-term (42 days) test was found to be more difficult to accomplish. The following section describes one of the Burst tests. A detailed description of the entire program is provided by Allouche and Moore (2005).

4.3 Description of a Typical Burst Test

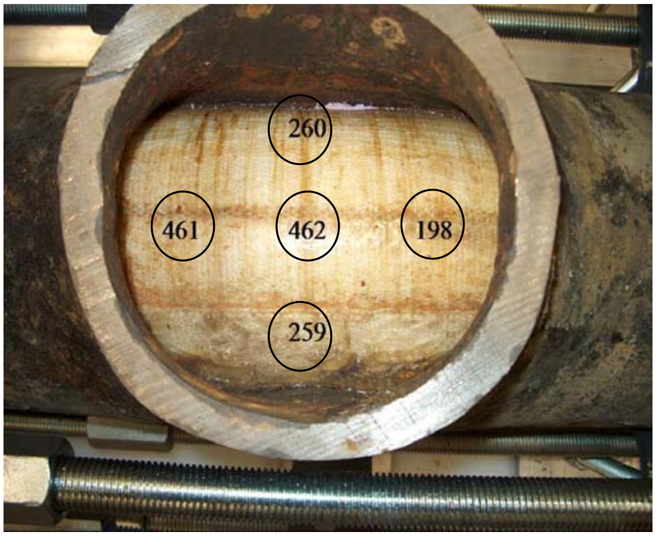
The specimen utilized in this test was a fire hydrant tee with two bells. Prior to testing, the 100mm hydrant feed pipe was removed. Since the hydrant was never re-connected following lining installation, the liner spanned across the opening (approximately 200mm long and 150mm wide; see Figure 7). Five linear variable displacement transducers (LVDTs) were placed along the major and minor axes of the opening to measure the deformation of the liner under internal pressure (see Figures 8). The specimen was pressurized to 3.8 MPa in 350 kPa increments, with the pressure held at each pressure increment for a minimum of 5 minutes as per the ASTM D3139 leakage test. The maximum deformation recorded by the sensors at 3.8 MPa was approximately 7mm. A graph showing the displacement versus internal pressure curve for the five LVDTs is shown in Figure 9. The location of each LVDT and the displacement recorded at selected internal pressure values are summarized in Table 1. During the test loud cracking noises were heard as the liner expanded under the increasing internal pressure. These cracking noises were attributed to the breaking of the stiff resin layer coating which covered the liner’s outside wall. At later stages of the test, when the internal pressure exceeded 3.5 MPa, some of the cracking noises were attributed to the partial failure of the glass fiber reinforcement. The test was discontinued at this stage due to the difficulties in sealing the bulkheads and the potential for catastrophic failure.

4.4 Constitutive tests.

Two test series were performed on liner samples removed from the cast iron host pipes. First, uniaxial test specimens were prepared by extracting samples in the longitudinal direction of the liner. Given sample curvature across their short direction, the ends were built up using epoxy resin to permit effective gripping by a universal test machine (without bending where compressed within the grips). The measurements of stress versus strain are shown in Figure 11 This implies that the short term behavior of the material is characterized by a bi-linear response, with modulus of 2000MPa active up to axial tensions of 1.3%, and a subsequent modulus of 180MPa.

Table 1. LVDT Test Data – Burst Test of a Fire Hydrant Tee

LVDT ID Number	Location	Maximum displacement (mm) vs internal pressure				
		0.7 MPa	1.4 MPa	2.1 MPa	2.8 MPa	3.8MPa
461	2-1/4” from center point along major axis; left hand side	0.4	1.0	2.9	4.4	6.4
462	Center of oval cavity	0.5	1.0	3.0	4.5	7.0
198	2-1/4” from center point along major axis; right hand side	0.4	1.0	2.7	4.0	6.3
259	2-3/4” from center point along minor axis; left hand side	0.2	0.5	1.3	2.0	3.2
260	2-3/4” from center point along minor axis; right hand side	0.2	0.7	3.0	4.8	6.5



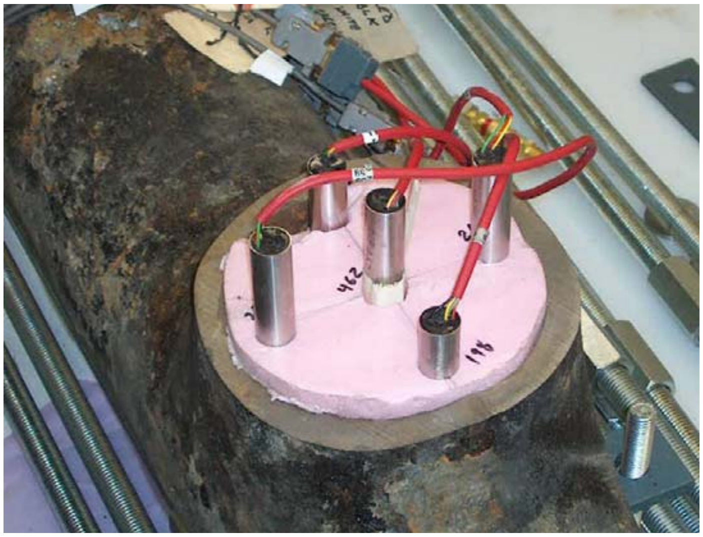


Figure 7. A top view of the simulate gap

Figure 8. Instrumentation of exposed liner

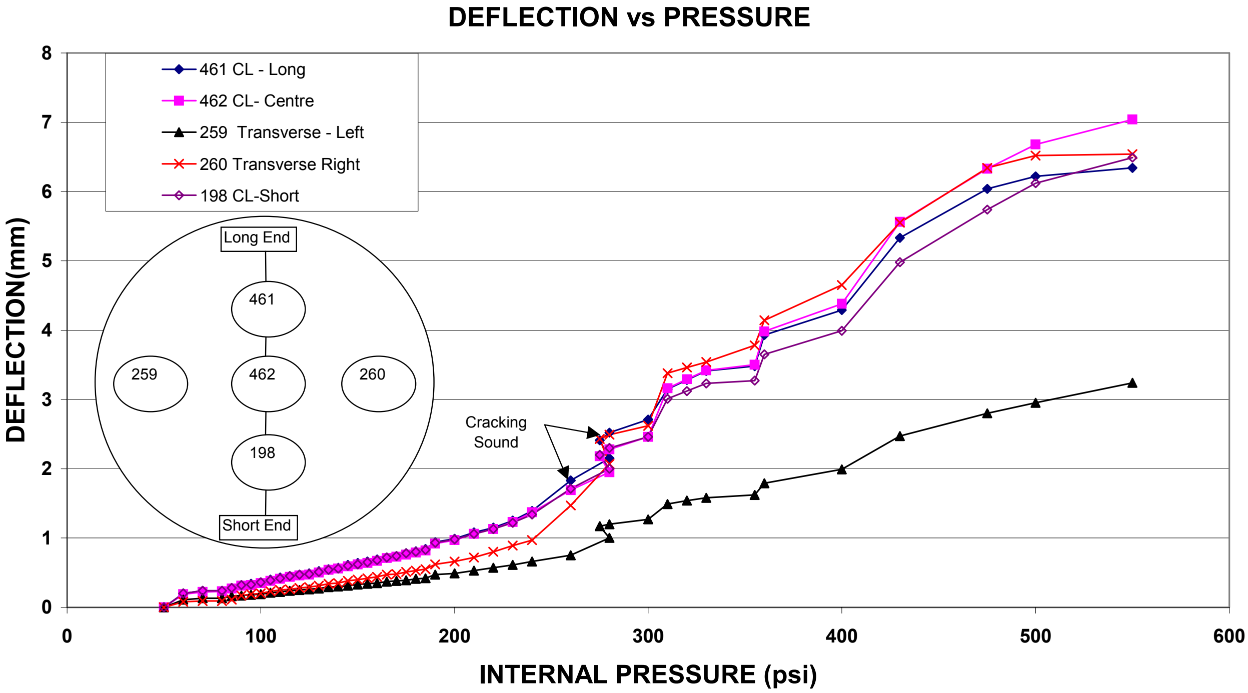


Figure 9. Deflection vs. internal pressure as measured by the LVDTs instrumentation for Burst Test #2

The second test series featured parallel plate loading (e.g. ASTM D2412) of short lengths of the liner. Compression between rigid plates at crown and invert produces nonuniform bending. These tests provided information on the circumferential liner properties, including flexural rigidity of the wall. Analysis using elastic ring theory was used to calculate values of average or representative modulus as the vertical diameter of the samples decreased during testing. Initial modulus value of approximately 1500MPa was somewhat lower than longitudinal uniaxial modulus. Modulus progressively decreased to about 600MPa as the parallel plate loading produced nonuniform strains. Softening commences at the extreme fibers at Springlines, Crown and Invert, then steadily more of the specimen soften as strains increase. Without testing the specimens under uniaxial tension in the hoop direction, it is difficult to be clear of the extent to which the longitudinal and circumferential material characteristics differ.

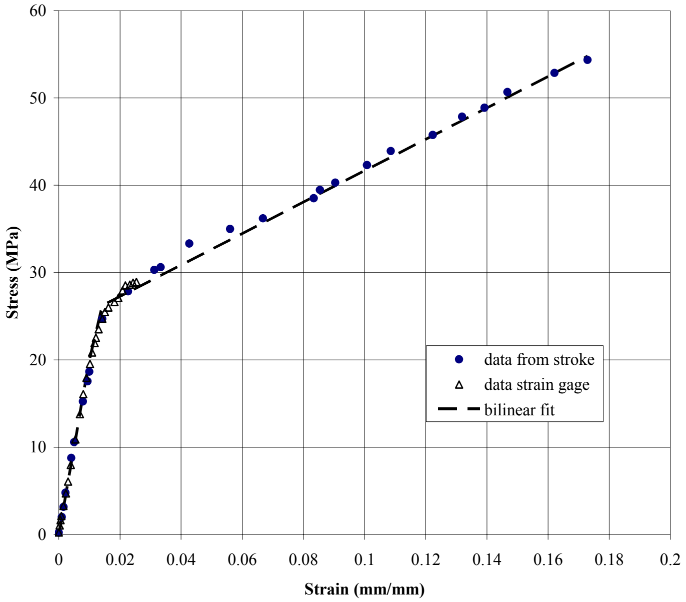


Figure 10. Uniaxial stress-strain behaviour; test data and bilinear fit (E_1=2000MPa, E_2=180MPa, ε_y=1.3%)

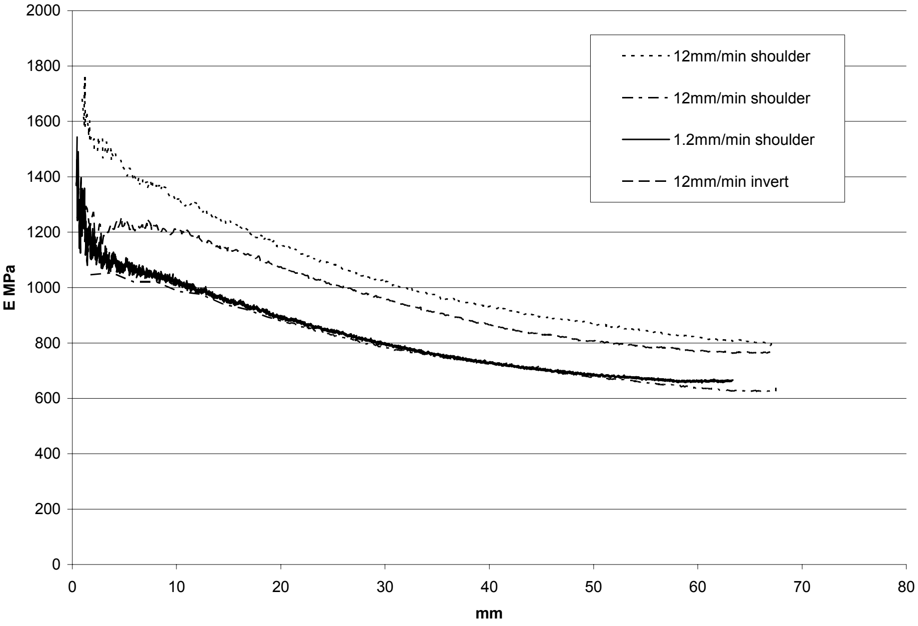


Figure 11. Average modulus relative to vertical diameter decrease during parallel plate loading tests.

5. FINITE ELEMENT ANALYSES

5.1 Analysis of longitudinal bending (Limit states LS2 and LS3)

Finite element analysis was used to investigate bending in the liner within a damaged section of cast iron pipe (where the cast iron host pipe is not confining the liner), past a restriction (such as a clamp, LS3) or into section where the cast iron host is intact (LS2). This analysis was performed using axisymmetric finite element analysis. It indicated that this longitudinal bending produces a small increase in circumferential tension relative to the tensile stress generated in the liner when it is in unconfined hoop tension, and an axial (longitudinal) bending stress about 20% higher than the hoop stress in unconfined tension. Neither the peak circumferential tension nor the peak axial tension were greatly influenced by the length of the restriction. Given these modest increases in tensile stress associated with bending across a restriction, it appears reasonable to employ unconfined tension testing of the liner to characterize liner strength, relying on the factor of safety to support the added stress.

5.2 Analysis of local bending across a void (LS5)

Finite element analysis was used to investigate sections of liner spanning across circular perforations in the cast iron pipe. That analysis indicated that perforations with radius of 10mm and 20mm generate tensile bending stresses less than the tension that occurs in the liner under unconfined hoop tension. For a perforation of 30mm diameter, the tensile bending stresses exceed the unconfined hoop tension by around 30%. A perforation of 40mm generates tensile bending stresses of more than double the unconfined hoop tension. If the liner is used in circumstances where perforations of 30mm or greater are expected, the time to failure should be reduced relative to those obtained from testing of unconfined liner under internal pressure. If lateral connections are expected to have apertures of 25mm or larger, any decision to leave the liner spanning laterals that are no longer active may compromise liner service life.

Finite element modeling was undertaken to study the short term behavior during a burst test of a liner with a protruding fold that is subjected to internal pressure. Protruding folds were found to be a common feature for nearly all specimens recovered, and were shown in the experimental program to create a weakness in an exposed liner due to stress concentrations. A reduction in pressure rating as high as 250% due to then presence of significant geometrical imperforations was suggested by the results of the experimental program. This finite element analysis (FEA) was conducted using the commercial software ADINA Version 8.1. The analysis was conducted using 3D solid elements and considered the physical and geometrically non-linearity of the problem by employing large strain and large displacement theories. The failure criterion of the liner was computed based on accumulated plastic strain. Thus, rupture was assumed to take place when the accumulated plastic strain in the complex stress state reaches the maximum plastic strain in the tensile test.

The numerical model was verified by comparing predictions observations made during the physical testing. Figure 12 displays the three dimensional finite element models developed for the specimen shown in Figure 7. Figure 13 show a 3-D model of the initial and final (at failure) geometries of a longitudinal fold in a liner subjected to an internal pressure. Following verification the model was used to conduct a parametric study. That study then formed the basis for a quality control criterion for maximum allowable over sizing of the virgin liner allowed for maximum operating pressure (840 kPa) with a factor of safety of 2 where a significant gap occurs in the host pipe under the longitudinal fold.

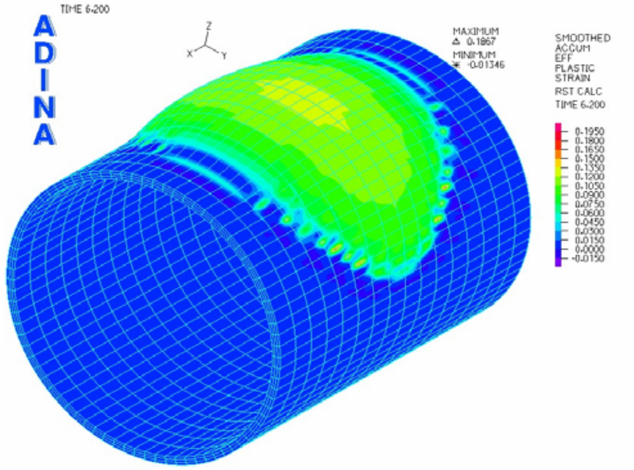


Fig 12. A 3-D FE Model for showing plastic strain

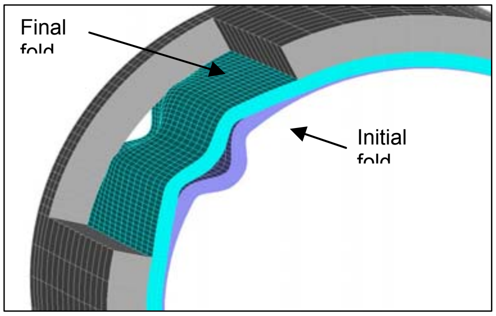


Fig 13. Initial and final geometries of a deformed liner

6. TESTING OF RESTORED TAP CONNECTIONS

One of the advantages offered by the liner system tested in this project is the restoration of the laterals from within the pipe using a remotely controlled robot. Reliance on close fit between liner and host pipe to prevent water penetration between liner and host pipe at an internally restored tap connection has been the subject of debate in the industry. Thus, a test was undertaken to examine the integrity of a tap connection subjected to high, prolonged, monotonic internal pressure; to perform a visual inspection of three internally restored tap connections; and to evaluate potential problems with inserting a new tap into a relined pipe.

A straight section with three tap connections spaced approximately 150mm apart (Figure 14). Brass caps were custom-fabricated to seal the three tap connections and the specimen pressurized to 2.1 MPa in 350 kPa increments, with the pressure held at each pressure increment for a minimum of 5 minutes. The pressure level of 2.1 MPa was maintained for 135 minutes, in an attempt to cause damage to the liner-tap connection interface. At the end of this time period the pipe segment was de-pressurized and cut transversely at the centerline of each of the tap connection, enabling examination of the cross-section of the liner-tap connection interface.

The liner-connection interface inspection revealed a gap between the liner and the pipe wall where the tap connection protrudes into the cast iron pipe. While most of this space was filled with a plug and resin, a small air pocket was also observed.

Another observation was that the cutter did not restore the tapped connection to its original diameter, leaving a liner rim of 1/16” to 1/8” in thickness around the tap connection circumference. Depending on the diameter of the tap connection, the presence of the rim represents a 10-15% reduction on the tap cross-sectional area. A potential solution is to send, following the cutter, a grinding tool that will restore the original diameter of the tap connection.

7. CONCLUSIONS

There is currently no standard to guide the design of polymer liners cast within cast iron water supply pipes. An evaluation program examining a new liner system identified six limit states that had the potential to influence the performance of these liner systems. Based on the laboratory testing and computer analysis:

a. A test conducted on a sample of the liner systems under direct tension indicated that the small strain modulus in the longitudinal direction under direct tension was 2000MPa, yield strain was 1.3%, and subsequent modulus was 180MPa.

b. Flexural tests on four liner samples under parallel plate loading provided modulus that commenced at a value of between 1000 and 1200MPa, and which decreased as the liner ovalized to 800MPa.

Figure 14. Specimen # 3 prior to testing

c. Pressure testing of exhumed liner samples indicated that the liner is capable of resisting internal pressures as high as 3.8 MPa for short durations, even across large gaps in the host pipe. Some permanent liner deformation was noted under a constant pressure of 1.3 MPa over 500 hours.

d. Finite element analysis was used to investigate bending in the liner within a damaged section of cast iron pipe (where the cast iron host pipe is not confining the liner), past a restriction (such as a clamp) or into a section where the cast iron host is intact. Longitudinal bending produces a small increase in circumferential tension. It appears reasonable to employ unconfined tension testing of the liner to characterize liner strength, relying on the factor of safety to support the added stress.

e. Finite element analysis was used to investigate sections of liner spanning across circular perforations in the cast iron pipe. Perforations with radius of 20mm or less generate tensile bending stresses less than the tension associated with unconfined hoop tension. Larger perforations lead to stress increases. Liner use where perforations of 30mm or greater are expected will likely reduce time to failure relative to those obtained from testing of unconfined liner under internal pressure.

f. A tight fitting liner of minimum thickness 5mm can resist buckling under full vacuum (equivalent to about 100kPa of external pressure).

g. The presence of longitudinal folds can significantly reduce the pressure rating of the liner. Adverse impact can be minimized by keeping the over sizing of the virgin liner below a pre-determined threshold.

h. This new option for watermain rehabilitation provides a significant tool in the Cities decision making process. Rehabilitation options of this nature allow infrastructure asset managers to further their goal of making the best life cycle decision. In many cases this type of rehabilitation can provide significant benefits, including economical, social, environmental and risk reduction.

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