Installed Geometry of Cast-in-Place Polymer Sewer Liners

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Abstract: Polymer liners cast within damaged sewer pipes are commonly used in rehabilitation without the disruption associated with conventional trench excavation and pipe replacement. Linear stability depends on both the thickness of the liner, and any out-of-roundness (ovality or other shape imperfections). Field trials of four cast-in-place liner systems permitted samples to be exhumed and inspected. Measurements of liner thickness and out-of-roundness are presented, for use by researchers and others seeking to establish the stability of these pipe repairs. Significant variations in thickness were observed. These took the form of wavelike increases in local thickness. For all four types of lining systems, the maximum thickness was more than double the average thickness, and up to three times thicker than the minimum thickness values. Higher frequency thickness variations were also superimposed on those wavelike changes in wall dimension. Liner ovality of up to 10% was also observed due to ovality in the clay sewer pipes being repaired, even though those pipes were not fractured longitudinally. Postconstruction inspection of liners ideally includes assessment of liner thickness. Wavelike increases in liner thickness might be estimated, where these lead to intrusions into the waterway. However, irregularities on the external surface of the liner or long wavelength thickness variations would be impossible to detect from video inspection alone, and new inspection techniques are likely need to be developed to ensure the installed liner performs successfully over its design life.

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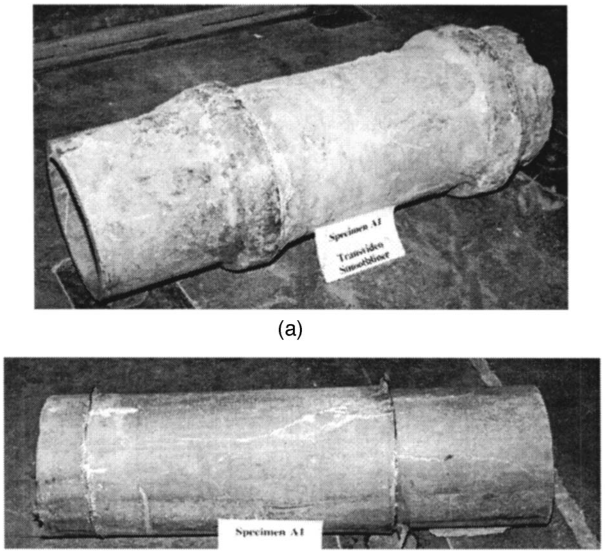
Introduction and Problem Definition

The trenchless rehabilitation of damaged sewers is generally a competitive alternative to conventional methods involving trench excavation and pipeline replacement. By inserting a polymer pipe within an existing damaged sewer (or host pipe), the hydraulic performance problems can be fixed. The structural integrity of the pipe can also be restored.

Many different procedures have been developed for liner installation. While most involve insertion of a preformed tube with fixed wall thickness, the most common methods involve cast-in-place polymer (CIPP) liners, where a resin impregnated tube is inserted and cured using heat or chemical agent. These CIPP systems produce liners with variable wall thickness, leading to questions concerning the measure of wall thickness to be used in design methods that invariably assume uniform thickness. Research performed over the past decade to determine the stability of liners has established the factors affecting liner stability under external fluid pressure (e.g., Moore and El Sawy 1996; El Sawy and Moore 1997; Moore 1998; Boot 1998; Zhao and Hall 2004). The effect of earth loads on local bending in the liner has also been established (Law and Moore 2003). In each case, liner thickness must be selected that satisfies these stability limits. However, liner stability in the field cannot be fully understood unless realistic field geometry is considered, including nonuniform distribution of thickness around the pipe circumference and along the pipe axis. One approach to capture that geometry is to exhume liners installed within a working sewer in the field.

The City of Hamilton conducted a field trial program from October 1997 to September 1998 (Gunn 1998). The purpose of this program was to examine the performance of four sewer rehabilitation techniques using cast-in-place liners. Contractors were asked to rehabilitate short lengths of existing 300 mm nominal diameter nonbroken clay sewers in various locations. Re-



(a)

(b)

Fig. 1. Typical sample

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Table 1. Liner Samples Thickness Measurements from System A

	Section E_1			Section E_2		
	A-1	A-2	A-3	A-1	A-2	A-3
1	3.51	3.75	4.00	4.37	3.64	4.34
2	7.57	3.89	3.25	5.07	3.80	3.72
3	3.73	4.00	8.85	6.66	3.56	3.68
4	3.39	4.07	5.00	8.63	3.56	3.81
5	3.68	4.02	3.53	6.02	3.75	3.60
6	3.44	7.26	3.31	4.03	7.08	3.78
7	3.65	2.25	3.94	3.98	9.05	3.29
8	3.62	5.01	4.02	4.10	3.50	3.68
9	3.67	2.94	4.16	3.60	3.46	3.70
10	3.69	1.93	5.07	3.78	4.29	8.23
11	3.78	3.60	3.95	3.90	3.81	3.42
12	4.21	3.46	—	8.74	3.85	—
Mean	4.00	3.85	4.46	5.24	4.45	4.11
Median	3.68	3.82	4.00	4.24	3.78	3.70
SD	1.145	1.361	1.569	1.862	1.756	1.390

paired pipes were then exhumed and saw-cut into two to four separate specimens [like that shown in Fig. 1(a)]. In all cases, the liner fit tightly inside the host pipe. The repair systems were denoted "A," "B," "C," and "D" and the specimens numbered 1–4, with a total of 12 specimens: from A-1 to A-3, B-1, and B-2, from C-1 to C-3, and from D-1 to D-4.

The host pipes were then removed and the liners were examined [e.g., Fig. 1(b)]. All four systems exhibited significant differences in thickness, texture, and color. The following sections report on the measurements of field geometry of the exhumed specimens. The primary focus is circumferential variations, though the samples also exhibited longitudinal variations associated with resin intrusion into joints and clay pipe misalignment, Fig. 1(b).

Thickness Measurements

Once the specimens were received, each end of a specimen was arbitrarily assigned as either section E_1 or E_2. Internal profiles of the specimens were traced on mylar sheets using approximately 120 points. On each profile, a digital vernier caliper was used to take thickness measurements at eleven or twelve equally spaced locations. Results are summarized in Tables 1–4. These results clearly show that the thickness of the liners is not uniform. For all four types of lining systems, the maximum thickness is more than double the average thickness, and up to three times thicker than the minimum thickness values.

Detailed measurements were also taken on one section of each liner system (Samples A-1, B-1, C-3, and D-3) where thickness was measured at each tracing point. The circumferential variations in thickness are shown on Figs. 2(a–d).

Two types of thickness variations have been observed.

1. Circumferential variations around any given section: From Figs. 2(b–d), it is clear that three of the liners were found to have a dominant imperfection in the form of a single wave (Samples B-1, C-3, and D-3). Fig. 3 shows a photograph of a typical wavelike change in thickness. Fig. 2(a) indicates that the dominant imperfection featured two wavelike imperfections for one specimen, Sample A-1 (also shown in the photograph, Fig. 4). The maximum thickness of the dominant wavelike imperfections was at least twice the average liner thickness in almost all cases. Sample C-3 featured a dominant imperfection with thickness of about 1.5 times the average. Superimposed on those overall shape changes were higher frequency thickness variations. The liner surfaces from Product C were particularly irregular (Fig. 5). This may have been caused by the existence of air bubbles during the curing process.
2. Longitudinal variations along the liner axis: The thickness of the liner was also observed to vary along the liner axis. This variation ranged from approximately 2 to 9% for Samples A-1, B-1, and D-3. The local surface irregularities seen on Sample C-3 resulted in thickness variations along the pipe axis that were more severe, with about a 30% difference between the minimum and maximum values.

Radius Measurements

The tracings were also digitized and the coordinates of each tracing point were obtained using graphics software. Since the thick-

Table 2. Liner Samples Thickness Measurements from System B

	Section E_1		Section E_2	
	B-1	B-2	B-1	B-2
1	4.33	5.05	4.08	4.16
2	4.06	2.61	2.60	2.13
3	2.82	4.54	4.11	2.11
4	2.61	2.77	2.91	2.23
5	2.46	2.62	2.83	2.11
6	2.41	2.52	2.76	1.94
7	2.28	2.87	3.10	3.06
8	2.63	3.02	2.63	3.60
9	2.29	4.20	2.52	2.02
10	2.87	2.92	2.74	2.07
11	2.82	2.62	2.42	2.02
12	2.40	3.94	4.47	3.66
Mean	2.83	3.31	3.10	2.59
Median	2.62	2.90	2.80	2.12
SD	0.671	0.880	0.706	0.797

Table 3. Linear Samples Thickness Measurements from System C

	Section E_1			Section E_2		
	C-1	C-2	C-3	C-1	C-2	C-3
1	6.46	6.82	6.64	5.74	6.36	6.81
2	8.19	6.97	7.70	6.17	8.73	6.92
3	9.23	7.30	9.87	5.88	10.97	5.80
4	9.71	6.87	9.13	7.58	10.73	7.22
5	7.54	7.16	7.51	6.97	11.61	5.64
6	6.72	6.91	6.39	6.05	8.99	6.59
7	6.18	7.00	6.49	7.61	6.32	6.40
8	6.98	7.69	6.38	7.92	6.47	5.63
9	6.24	6.77	5.81	6.26	6.60	6.40
10	6.77	5.95	6.06	7.78	6.41	7.99
11	6.17	6.36	5.92	5.97	6.29	10.11
12	6.47	6.42	6.74	6.19	6.09	6.26
Mean	7.22	6.85	7.05	6.68	7.96	6.81
Median	6.75	6.89	6.57	6.23	6.54	6.50
SD	1.209	0.456	1.285	0.832	2.126	1.241

ness corresponding to each tracing point was also known, the external profile of the liner was then established. The center of the liner was located by fitting a circle or ellipse to the external profile of the liner. The internal and external radius of the liner was then determined by calculating the distance from the center to each tracing point. Figs. 6(a–d) summarize the circumferential distribution of both the internal and external radii of the four liner samples.

Samples A-1, C-3, and D-3 were found to be oval. The differences between the maximum radius and minimum radius were 4.87, 6.04, and 2.52 mm for A-1, C-3, and D-3, respectively (corresponding to 3.16, 3.95, and 1.66% of their average radii). Measurements of the clay pipes confirmed that these differences were inherited from the inner surface of the host pipes.

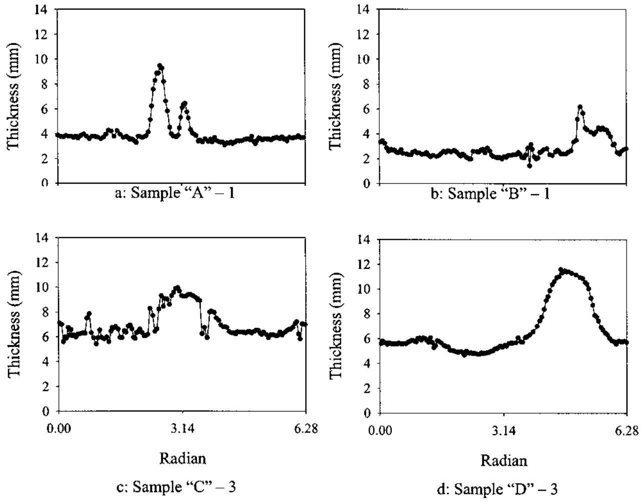
Immediately after the host pipe was removed, Sample B-1 was found to become extremely oval (17.2% of average radius). This was likely caused by the release of a residual bending stress. In each case, the external diameters of the liner samples were larger than 300 mm. This likely resulted because the nominal internal clay pipe diameter was 304.8 mm (12 in.) rather than 300 mm, as well as the original tolerance during clay pipe manufacture.

Discussion and Conclusions

This study is not intended to serve as a comparison of different sewer rehabilitation techniques. Rather, its purpose is to report the details of liner geometries observed in the field associated with four different cast in place liner systems. The dominant collapse mechanism for liners is buckling under the external fluid pressures that develop as groundwater penetrates through fractures and open joints. As the liners are constrained by the external host pipe, the buckling mechanism is nonlinear and imperfection sensitive. In addition, local bending strain in liners responding to earth load induced deformation in the host pipe is also sensitive to

Table 4. Liner Samples Thickness Measurements from System D

	Section E_1				Section E_2			
	D-1	D-2	D-3	D-4	D-1	D-2	D-3	D-4
1	5.80	12.54	4.95	11.32	5.44	11.30	5.80	14.77
2	5.73	9.62	4.86	6.23	5.40	9.60	5.86	16.78
3	5.74	6.64	5.30	5.33	9.57	6.13	5.54	14.25
4	6.26	6.89	5.74	5.64	11.25	5.76	5.54	6.97
5	5.99	6.39	7.43	5.60	8.38	5.76	5.72	5.78
6	6.55	5.88	11.59	5.77	5.52	5.29	6.09	6.28
7	7.00	5.92	10.85	5.65	5.27	5.86	10.62	5.80
8	6.51	5.57	6.46	5.83	5.33	6.15	11.46	6.09
9	9.21	5.70	5.80	5.92	5.25	5.70	7.27	5.81
10	12.66	5.86	5.57	5.25	5.14	6.35	5.82	5.90
11	10.97	5.59	6.04	7.65	5.14	6.40	6.07	5.94
12	6.01	11.63	5.45	11.24	5.25	7.17	5.89	9.85
Mean	7.37	7.35	6.67	6.79	6.41	6.79	6.81	8.69
Median	6.39	6.16	5.77	5.80	5.37	6.14	5.88	6.19
SD	2.310	2.476	2.239	2.187	2.098	1.809	2.036	4.163



a: Sample "A" – 1

b: Sample "B" – 1

c: Sample "C" – 3

d: Sample "D" – 3

Fig. 2. Thickness profiles for liner samples

the liner thickness. Design equations developed by Law and Moore (2003) reveal that higher liner thickness results in higher local bending strain. The data on the actual liner geometries presented here can therefore serve as important input for researchers working to develop limit states design for these structures, and studies are needed to investigate the stability of liners with realistic "field" imperfections.

Significant variations in thickness were observed. These generally took the form of wavelike increases in local thickness, associated with the liner casting process. Higher frequency thickness variations were superimposed on those wavelike changes in wall dimension. Calculations of critical liner buckling pressure based on minimum and average liner thickness would be considerably different.

Zhao and Hall (2004) have recently reported the results of finite element analysis to calculate maximum external fluid buckling pressures for liners with nonuniform thickness. Their calculations were based on liners with multiwave Fourier-type thickness changes, quite different to those observed in the present study. Their idealization implies that other liner thickness patterns may occur in the field.

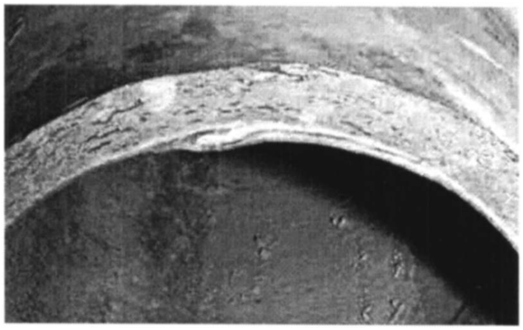


Fig. 3. Typical liner sample with single wavelike imperfection

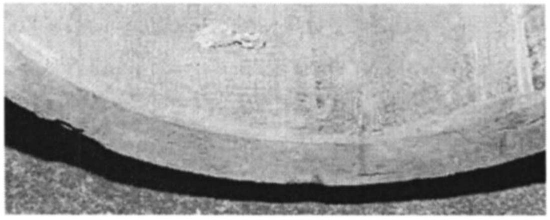


Fig. 4. Liner Sample A-1 with two wavelike imperfections

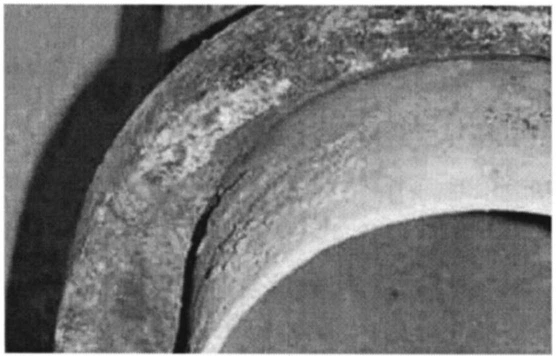


Fig. 5. Liner Sample C-3 with irregularities on the external surface

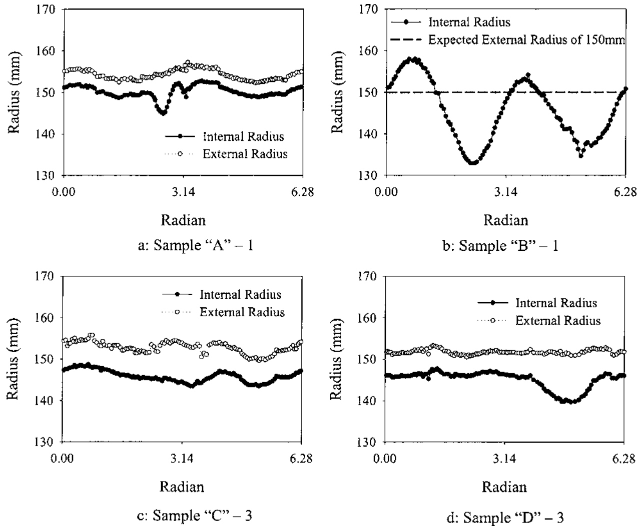
Liner ovality of up to 10% was observed due to ovality in the clay sewer pipes being repaired, even though those pipes were not fractured longitudinally. This type of liner ovality should be considered during design calculations to ensure stability against groundwater buckling. Two approaches are discussed by Moore (1998) for calculating reduction in critical groundwater pressures for elliptical host pipes: Namely a reduction factor adapted from buckling theory for unsupported elliptical shells

$$C = \left[\frac{(1-q)}{(1+q)^2} \right]^3 \tag{1}$$

[used in ASTM F 1216 for example (1998)], and a correction factor obtained using finite element solutions for liners constrained within rigid elliptical host pipes

$$R_q = e^{-q/0.18} \tag{2}$$

(see El Sawy and Moore 1997). Each of these factors used to reduce the critical buckling pressure below that for a perfectly circular host pipe, quantifies elliptical geometry using ovality q defined by



a: Sample "A" – 1

b: Sample "B" – 1

c: Sample "C" – 3

d: Sample "D" – 3

Fig. 6. Radius profiles for liner samples

$$q=\frac{D_H-D_V}{D_H+D_V} \tag{3}$$

where the host pipe has internal horizontal dimension of D_H and vertical dimension of D_V.

Naturally, the contractor installing the liner system needs to ensure that the liner thickness is within the required design limits. However, detailed assessment of liner thickness is difficult or impossible using the standard postconstruction procedures based on the use of closed circuit television. Wavelike increases in liner thickness might be estimated, provided these lead to intrusions into the waterway within the liner. However, irregularities on the external surface of the liner, like those observed on lining System C would be impossible to detect from video inspection alone. New inspection techniques, like the use of sonic sensors, likely need to be developed to ensure the installed liner performs successfully over its design life.

Acknowledgments

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