Laboratory Investigation of Local Bending in Profiled Thermoplastic Pipes

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Abstract: Full-scale pipe tests were conducted to investigate local bending on profiles of different thermoplastic pipes. Five profiled pipes including two lined corrugated, one box and one tubular profile of HDPE material and one ribbed profile of PVC material were considered. The study demonstrates that a three-dimensional bending mechanism governs the strains on some components of the pipe profiles. The local bending was particularly significant in the lined corrugated and the tubular profiled pipes. The mechanism of the local bending at the crown and the springline was different for lined corrugated pipes under biaxial loading. Ratios of the circumferential strains on the liner to those at the inner wall were higher at the crown/invert than the ratios at the springline. The liner with longer span was found to undergo even lesser strain relative to the liner with shorter span. The local bending did not affect the strain on the other elements of the lined corrugated profile.

Key words: profiled pipe, local bending, thermoplastic pipe, box profile, tubular profile, lined corrugated profile, ribbed profile.

1. INTRODUCTION

Underground pipe has been used to transport potable water to city dwellers and to remove wastewater from cities perhaps since the beginnings of modern civilization. Pipes are installed under road and highway embankments to facilitate drainage of the area that would otherwise be blocked by the embankment. Many different pipe products have been developed for these applications, and work continues to improve the economy and performance of these structures.

Use of thermoplastic pipe as underground conduit began in the 1950's in Europe initially without engineering design. Since then thermoplastic pipes have been increasingly used around the world in both gravity-flow and pressure pipe applications. Thermoplastic materials like high-density polyethylene and polyvinylchloride possess light weight, low cost, resistance to corrosion and can provide ease of fabrication and transportation. For gravity flow systems such as storm sewers, sanitary sewers, drainage lines and culverts, earth pressure is the governing source of load on the buried pipes. Accordingly design of these pipes focus on choosing a pipe-section that is strong enough to carry the expected earth loads.

Profiled-wall pipe was introduced to obtain higher cross-sectional stiffness of the pipe wall with less use of material, and a wide variety of wall geometries have been developed by the pipe manufacturing industry. However, the performance limits for this variety of profiles are not well established yet. Observations of full scale pipe behavior (Hashash 1991) have demonstrated that additional modes of deformation should be considered for profile-wall pipes in addition to the conventional limit states such as excessive deflection, wall crushing under circumferential stress and global buckling. Hashash (1991) observed liner buckling and

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circumferential cracking on the inner wall of a lined corrugated pipe under a high embankment (30.5m) near Pittsburgh, Pennsylvania, USA. DiFransisco (1993) also obtained the ripples due to local buckling on the inner liner of a twin-wall HDPE pipe in a hoop compression test. A detailed study of the local buckling on the inner liner of profiled pipes is available in Dhar and Moore (2001a). Dhar and Moore (2001a) utilized the plate-buckling model of metal plate to predict the local buckling on the profile elements.

While the longitudinal wall crushing due to excessive circumferential stress was well recognized for buried pipes, the reason for the circumferential cracking reported by Hashash (1991) was not well understood. Moore and Hu (1995) explained from three-dimensional finite element analysis that the circumferential cracking was due to local bending. Moore and Hu (1995) demonstrated that local bending develops on the pipe wall that produces significant tension at the liner-corrugation junction in lined corrugated HDPE pipe, where sustained high tension can cause cracking on thermoplastic materials. Moore and Hu (1995) also revealed that the local bending is a three-dimensional mechanism and it cannot be estimated using conventional 2-D shell theory (that is strain are not linear function of distance from the neutral axis). Circumferential strain on the inner liner becomes less than the valley strain as a result of the local bending (profile components such as valley, liner etc are shown later in Figure 1), Moore and Hu (1995). However, measurements of strains on the walls of profiled pipes were not available to validate the observation of Moore and Hu (1995). Laidlaw (1999) performed full-scale tests and measured strains on some profile elements of several lined corrugated HDPE pipes under hoop compression. However, strains on the liner of those profiles were not measured.

The localized short-wave deformation and inner wall tearing was also found in honey-combed (Tubular profile) HDPE pipe under 40 ft (12.2m) fill at Ohio, USA, (Hurd et al 1997). Dhar and Moore (2001a) studied the local bending on several other profiles using axisymmetric finite element analyses. However, the mechanism needs to be validated using experimental observations of strains on those profiles.

Local bending and other possible modes of failure of different profile-wall pipes have been investigated in this research using full-scale pipe tests. The “Hoop” and “Biaxial” test cells developed at the University of Western Ontario (UWO) were used in this investigation. The Biaxial Cell approximates geostatic field stresses in the laboratory. The Hoop Cell was used to examine the behavior of pipes under axisymmetric compression. Tests were conducted using five commonly used profiled pipes of thermoplastic materials. Strains on different components of the profiles were measured to capture the effects of the local bending.

2. PIPE PROFILES

Five different types of profiles were investigated in the biaxial and/or axisymmetric loading environments in the test cells. Figure 1 describes details of the profiles used in these pipe-loading tests. Profiles defined in Figures 1(a) and 1(b) are lined corrugated profiles, also known as twin wall profiles. These are designated herein as Pipe (profile) ‘a’ and ‘b’ respectively. Profile ‘a’ possesses pitch of 101 mm and corrugation depth of 55.2 mm whereas Profile ‘b’ has 80-mm pitch and 58.7 mm corrugation depth. The twin-walled profiles are manufactured with annular geometry.

The profile shown in Figure 1(c) is a boxed profile and is manufactured by helical winding of the box section so that the central ribs are oriented at an angle of 2° to the pipe circumference. Box dimensions for this profile are width of 48.3 mm and length of 61.1 mm.

Figure 1(d) shows a complete unit of the tubular profiled section with its inner and outer walls. The pipe is manufactured by spirally winding a unit of four tubes. The units are fused together at the ends (Figure 1(d)). The helix angle for the profile is oriented at approximately 6° to the pipe circumference.

The final profile (Figure 1(e)) is for a PVC (Polyvinyl chloride) pipe with helically wound ribs protruding from the exterior surface of the cylindrical wall. Angle of helix for the profile is about 9°.

The lined corrugated pipes and the ribbed PVC pipe have nominal interior diameter of 600 mm. Diameters for the boxed and the tubular profiles are 760 mm and 1060 mm respectively. Geometric properties and the materials of the five profiles are summarized in Table 1. Sectional property values in Table 1 indicate how the profile shape influences the structural properties of the pipe sections. Both of the lined corrugated pipes possess similar areas per unit length, but pipe ‘b’ has 30% higher moment of inertia than pipe ‘a’. Higher moment of inertia is obtained by decentralization of the material away from the neutral axis of the section. The box profile used about 50% higher area than the lined corrugated profile, while achieving about 60% higher moment of inertia. For the tubular profile, the moment of inertia is at least tripled relative to the lined corrugated pipe ‘a’ with about a 50% increase of material (e.g. the area).

3. LABORATORY FACILITIES

Brachman et al. (2000) designed the Biaxial Cell at the University of Western Ontario (UWO) to model pipe responses under biaxial (geostatic) stresses. The Cell is

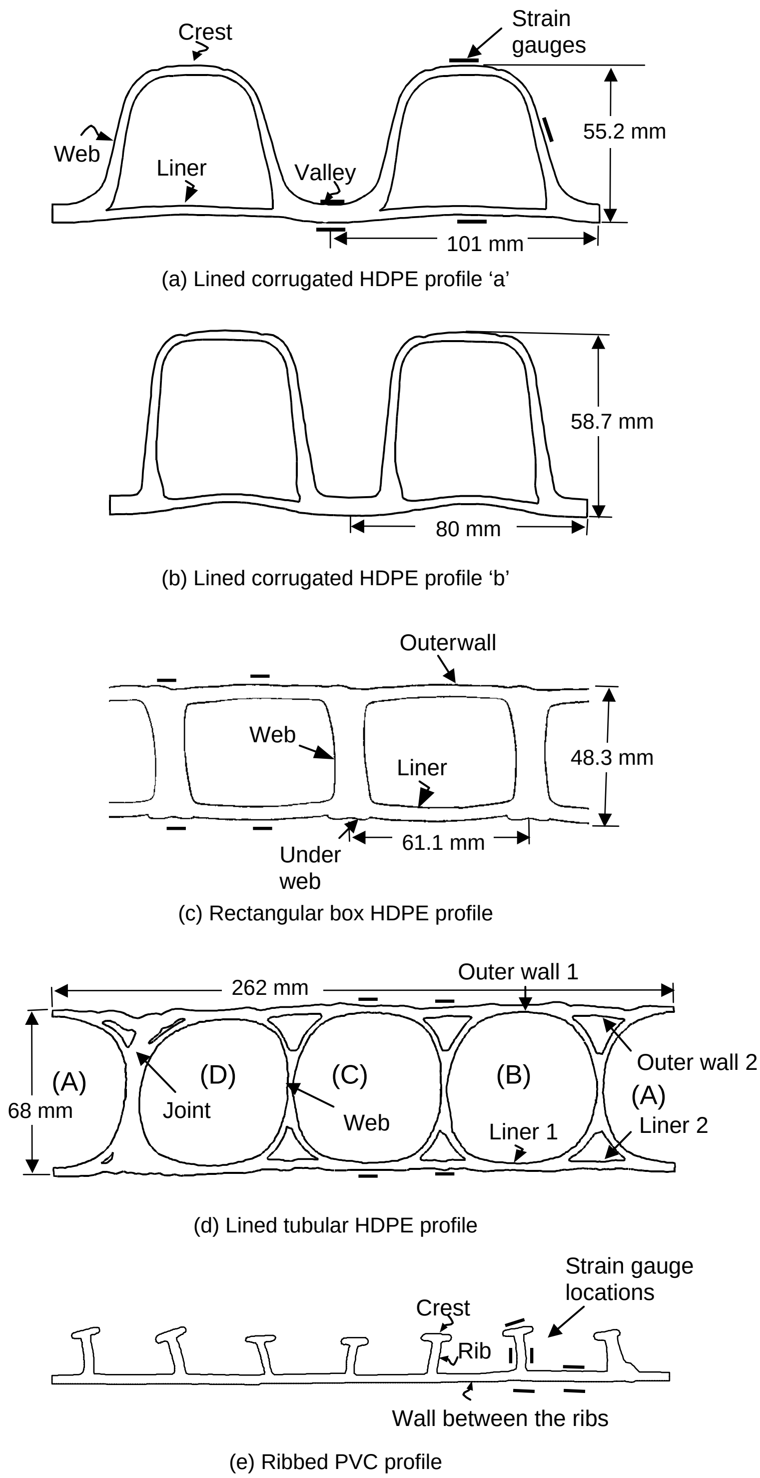

Figure 1. Types of pipe profiles investigated

a high strength steel box. Dimensions of the box are 2 m × 2 m in plan and 1.6 m in height. The sides restrain lateral deformation and thus a close to K_o conditions (where lateral strains are zero) is achieved in the cell. Pipes are placed horizontally on a bed of soil in the cell and are then backfilled within a rectangular prism of soil. An air bladder, placed beneath the stiff lid of the cell, is employed to apply uniform pressures on top of the soil. To ensure that most of the surface loads reach the pipe, a special sidewall treatment is employed to reduce the wall friction.

Although the biaxial test cell is able to simulate the idealized field conditions, the maximum pipe size that can be tested in the cell is limited. Pipes with large diameter can however be tested in a Hoop Cell to examine the behavior under axisymmetric compression

Table 1. Sectional properties of the test pipes

Pipe type	Diameter, (mm)*	Material	Area, A (mm^2/mm)	Inertia, I (mm^4/mm)
Twin wall 'a'	610	HDPE	9.3	3104.3
Twin wall 'b'	610	HDPE	10.1	3978.0
Ribbed profile	605	PVC	7.2	421.0
Box profile	760	HDPE	15.8	4866.0
Tubular profile	1060	HDPE	14.6	10409.0

*Interior diameter.

(Selig et al. 1993). Performance limits associated with local behavior of the pipe profiles are largely controlled by hoop compression, so axisymmetric testing is a useful way of investigating the behavior of pipes under deep burial.

The Hoop Cell developed at UWO is a 12.7-mm thick vertical steel cylinder of internal diameter 1500 mm and height 1450 mm (Laidlaw 1999). The cylinder is bolted at the ends through flanges to two steel circular plates of 19.5 mm thickness. The top plate is fitted with a sleeve of 390 mm diameter to allow access to the instrumentation within the pipe. The end plates restrain longitudinal movement of the pipe during the test. An inflatable polymer bladder lines the internal surface of the cylinder. The instrumented pipe is placed upright concentrically within the cell. The space between the pipe and the air bladder is then filled with backfill soil. The air bladder applies axisymmetric radial stresses upon inflation, placing the soil-pipe system into hoop compression.

4. TEST PROGRAM

A total of 9 tests were conducted on the pipes with wall profiles shown in Figure 1. Four of the tests were in the Biaxial Cell, and the remaining five were performed in the Hoop Cell. A summary of the test program along with the variables considered is described in Table 2. Pipes with smaller diameter (610-mm nominal) were tested under both biaxial and hoop compressions. The local bending of the larger diameter pipes (760-mm box profile and 1060-mm tubular profile pipes) was investigated only in the Hoop Cell.

The pipes were backfilled using poorly graded granular soil (coefficient of uniformity, C_u = 3.4, coefficient of curvature, C_c = 1.1). Test 1 was performed with the backfill soil compacted to a density of 1850 kg/m^3 which corresponds to 95% of the maximum standard Proctor density. However, none of the pipe limit states was reached in this test. The soil for the other biaxial tests was compacted to a lower density (between 1600 kg/m^3 and 1650 kg/m^3) to demonstrate the pipe limit states.

Table 2. Description of the tests

Test no.	Pipe profile	Test type	Diameter (mm)	Backfill compaction (% Proctor)
1	Lined corrugated pipe 'a' (Figure 1(a))	Biaxial	610	95%
2	Lined corrugated pipe 'a' (Figure 1(a))	Biaxial	610	85%
3	Lined corrugated pipe 'b' (Figure 1(b))	Biaxial	610	85%
4	Ribbed PVC pipe (Figure 1(e))	Biaxial	610	85%
5, 6	Lined corrugated pipe 'a' (Figure 1(a))	Hoop	610	**
7	Lined corrugated pipe 'b' (Figure 1(b))	Hoop	610	**
8	Rectangular box profile (Figure 1(c))	Hoop	760	**
9	Lined tubular profile (Figure 1(d))	Hoop	1060	**

**Not measured, but estimated to be 95-100% compaction based on the compaction efforts made.

The mid-range value of the density (i.e. 1625 kg/m^3) corresponds to 85% of the maximum standard Proctor density. A nuclear density-meter was used to measure density of the backfill soil during placement. Soil was placed in layers of approximately 100-mm depth, and density was measured at every alternative layer of soil placement.

In the Hoop Cell, soil was compacted with the purpose of attaining its maximum density. Layers of approximately 150-mm height were compacted in 3 passes with a 4.5 kg (10 lb) tamping rod falling from a height of about 30 cm. However, the final soil density could not be measured during placement due to lack of space between the pipe and the test cell boundary. The soil density was estimated to be 95% to 100% of the Proctor density based on the compaction effort made.

5. INSTRUMENTATION AND TEST CELL ARRANGEMENTS

In order to understand the behavior of the buried profiled pipe, it is important to effectively measure various features of the response during the pipe tests. The pipes were instrumented with electronic strain gauges to capture important features of the local deformations. Pipe instrumentation included rectilinear potentiometers (linear voltage displacement transducer or LVDT) to measure the changes in pipe diameter and resistance strain gauges to measure the wall strains on different components of the profile. Strokes of the potentiometers were 75 mm and 100 mm. These were accurate within the manufacturer tolerance of ±0.25%. Gauge length for the strain gauges was 2 mm and the resistance was 120 ± 0.3% ohms. Excitation voltage for the gauges was selected as low as 0.75 V to minimize the heat generation while obtaining acceptable strain signal (Tognon 1999). Heat on thermoplastic pipe wall should be minimized to avoid any likelihood of burning. The strain gauges are products of Showa Inc.

Both the horizontal and the vertical deflections were measured using the transducers in Biaxial Cell tests. During the hoop tests, four transducers were used to measure changes in pipe diameters in two perpendicular directions and at two positions along the pipe axis.

The principal strain directions were known in advance for profiled pipes with annular geometry, and biaxial strain gauges were used to measure the circumferential and the axial strains. Strains on the helically wound profiles were measured in three directions using strain gauge rosettes, since the major and minor principal strain directions were not known in advance. Instrumentation was placed at two sections to check the reproducibility of the test results and to ensure that representative data are collected in the event that some of the gauges failed to operate successfully. For the samples prepared for testing in the biaxial pipe test cell (where specimens are placed with pipe axis horizontal), strain gauges were placed at crown, invert and both springlines. Strain gauges were placed on two diametrically opposite sections at two axial (vertical) positions for samples prepared for testing in the hoop compression cell. Strains were measured on every accessible component of the profile (e.g. liner, valley, web and crest of the lined corrugated pipe) at each of those locations. Positions of the strain gauges for each of the profiles are marked in Figure 1.

Arrangements were also made to monitor the soil response during the pipe tests in the Biaxial Cell. The behavior of buried pipe is governed by the interaction of the pipe and the soil, rather than the pipe alone. Therefore, observation of the soil behavior during the tests provides valuable information for the development and evaluation of the theoretical models used to predict and interpret buried pipe behavior. Soil instrumentation in the cell comprised earth pressure cells to measure horizontal and vertical soil stresses at the springline level of the pipe and near the top of the block of soil. Soil settlements were measured using settlement plates. Figure 2 shows typical placement of the pipe specimens in the Biaxial Cell and the cell instrumentation. Figure 3 presents a schematic view of the test arrangement in the Hoop Cell tests.

6. SOIL RESPONSE IN BIAXIAL TESTS

Measurements of soil stresses at the springline of the pipe and in the top layer of the soil are plotted in Figure 4 for twin-wall pipe (Pipe ‘a’). Figure 4(a) shows that vertical soil stresses at the springline are higher than those at the top layer in the test with twin-wall pipe (Pipe ‘a’) buried in the dense backfill (soil compacted to 95% of Proctor density). Top layer stresses are similar to the applied cell pressures. For this pipe in the dense backfill, pipe stiffness is expected to be lower than the stiffness of the surrounding soil. As a result, positive vertical arching developed and soil stresses were redistributed from above the top of the pipe around to the sidefill, so stresses increased toward the cell boundary. Arching was not significant for the pipes buried in backfill compacted to 85% Proctor density, and the vertical stresses at the springline and near the top of the soil were almost the same, and approximately equal to the applied cell pressures.

Horizontal stresses in the dense soil are a fraction of the vertical values, as expected. The ratio between them being the coefficient of lateral earth pressure, K. The K value for the dense sand backfill was smaller than for the looser material, also in accordance with typical soil behavior. The ratio of the average horizontal stress to

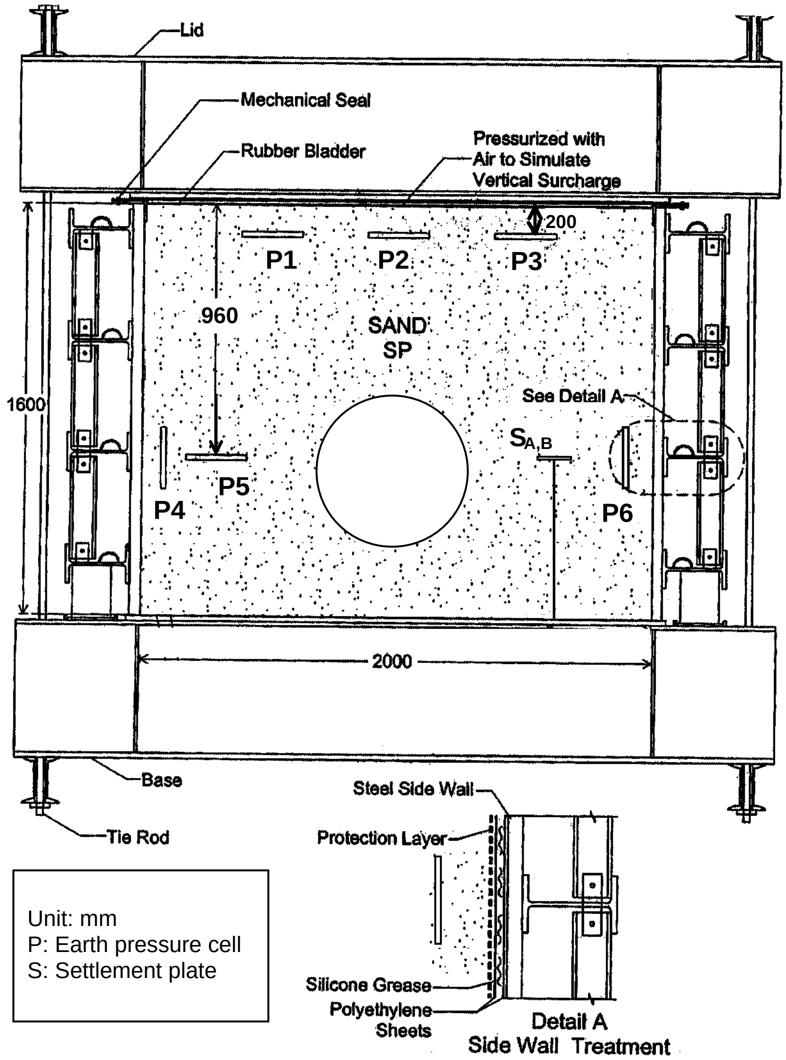

Figure 2. Pipe installation in the biaxial cell (modified from Brachman 1999)

the average vertical stress is about 0.5 in all of the tests with loose backfill whereas for the test in the dense sand it was measured to be 0.28.

Figure 5 shows soil settlement at the springline of the pipe in each of the tests. Behavior of the dense backfill is essentially linear in Figure 5, while a non-linear strain hardening response is evident for the sands in a relatively loose state. Settlement of the soil in Test 1 is much less than those of the other tests. Compaction of the sand from 85% to 95% of the maximum Proctor density increased the soil modulus by a factor of 5 or 6.

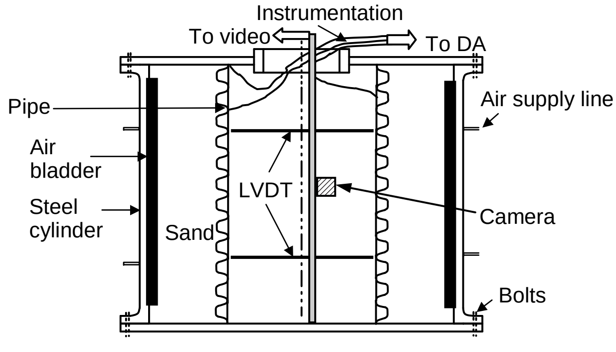

Figure 3. Test arrangement in the Hoop Cell

7. PIPE DEFLECTIONS

Linear variable differential transformers (LVDT) were used to measure the changes in pipe diameter in both horizontal and vertical directions during the biaxial tests. These measurements of pipe deflection are plotted in Figure 6.

Figure 6 illustrates that the vertical deflections (represented by solid symbols) are much higher than the horizontal deflections (hollow symbols). This is noticeably different to what is observed for corrugated metal pipes (Spangler 1941). Spangler (1941) reported equal horizontal and vertical deflections in field-loading experiments with corrugated metal pipes. The "Iowa

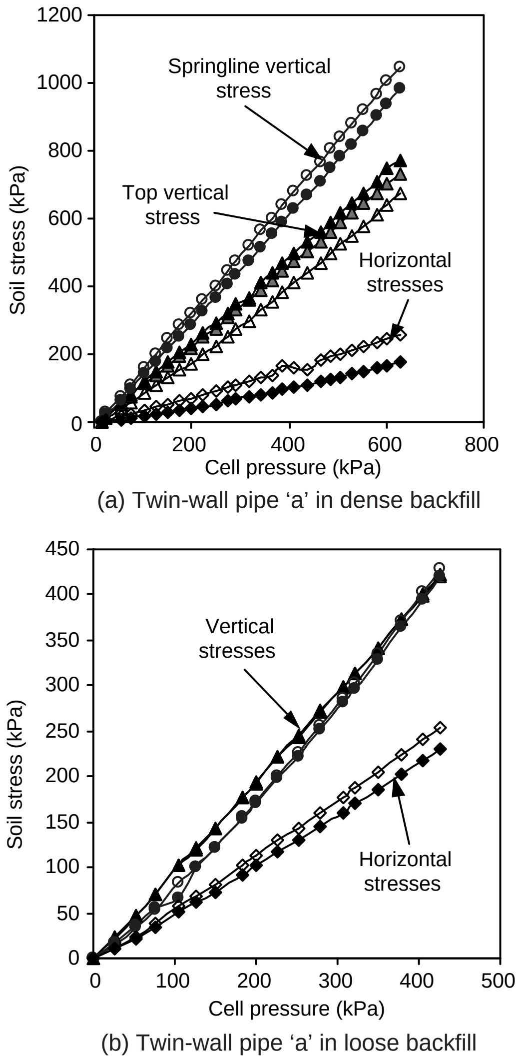

Figure 4. Measurements of soil stresses

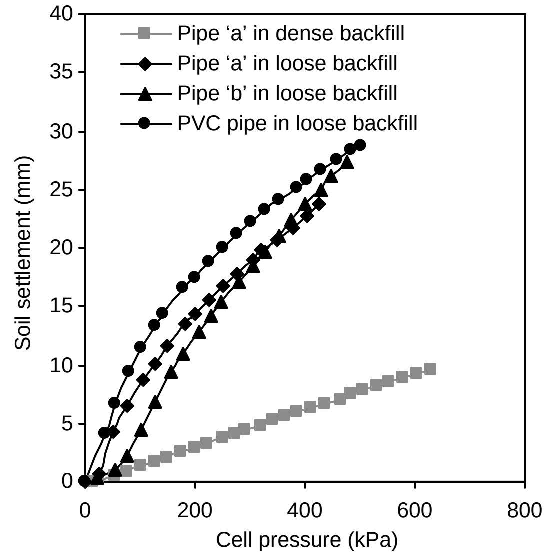

Figure 5. Soil settlements at pipe springline

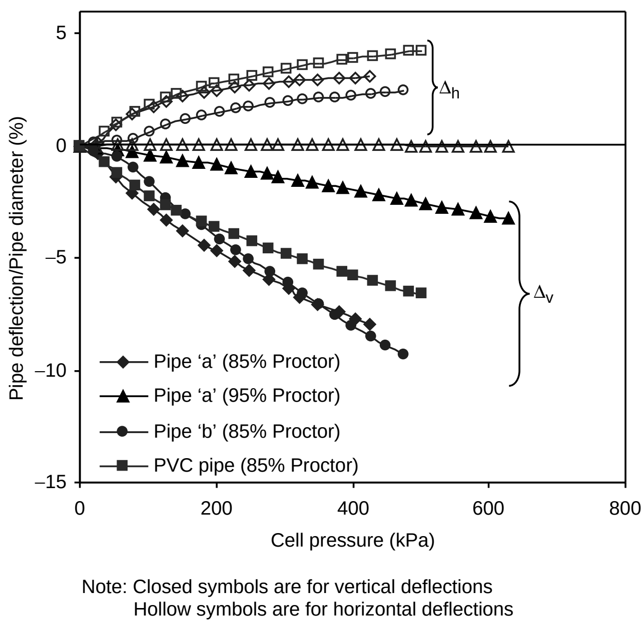

Figure 6. Measurements of pipe deflection

deflection formula" to calculate changes in vertical (rather than horizontal) pipe diameter was based on that observation, Spangler (1941). Less increase of pipe diameter occurred in the horizontal direction for thermoplastic pipes due to circumferential shortening associated with its low hoop stiffness. For the two tests on twin-wall HDPE pipes in the loose backfill (Tests 2 and 3), it is pipe 'b' (the pipe with the higher moment of inertia) that shows less deflection at the beginning, though it eventually deflects more. Soil deformation measured during the test on pipe 'b' also showed similar behavior (Figure 5). Pipe deformations are generally expected to be similar to those of the soil, because soil behavior largely controls the deformation of buried profiled thermoplastic pipe. Pipe response in Test 1 also supports this contention, since both pipe deformation and soil deformations are linear. The reason of pipe 'b' showing stiffer response at the beginning is that the test (Test 3) had to be re-run because the air bladder used in the test failed during the first run at a cell pressure of 75 kPa. The same test was re-loaded using a new bladder. The stiffer initial response of the pipe and soil represents the re-loading path of the soil-pipe system.

Most current design codes feature an empirically derived allowable vertical deflection of 5 to 7.5% (e.g. ASTM F894-95, AS/NZS 2566.1). A vertical deflection of 7.5% is obtained at a vertical stress of 390-kPa for both the lined corrugated pipes tested within the loose backfill (Tests 2 and 3). The 390-kPa value of overburden pressure is approximately equivalent to a 21-m height of embankment. Pipe deflection at the same pressure in the well-compacted backfill (in Test 1) is about 1.9%.

This reflects how profiled HDPE pipe deflection under embankment loads can be reduced by a factor of 4 by increasing compaction of the soil from 85% to 95% of the maximum Proctor density.

The PVC pipe reached 6.5% vertical deflection, at the highest level of overburden pressure achieved during the test (i.e. 500 kPa). This difference in deflections results from the differences in stiffness for the HDPE and PVC pipes. The stiffness factors, EI were estimated for the profiles using the Young's modulus of 400 MPa for HDPE material and 3000 MPa for PVC material, and were obtained as 1.24×10^6, 1.60×10^6, and 1.26×10^6 N-mm^2/mm for the twin-wall pipe 'a', twin-wall pipe 'b' and the ribbed PVC pipe respectively. The respective values of hoop stiffness, EA estimated for these profiles are 3720, 4040 and 21600 N/mm.

8. WALL STRAINS

Wall strains on different components of the profiles were measured using electronic strain gauges. As mentioned earlier, biaxial gauges were used to measure the

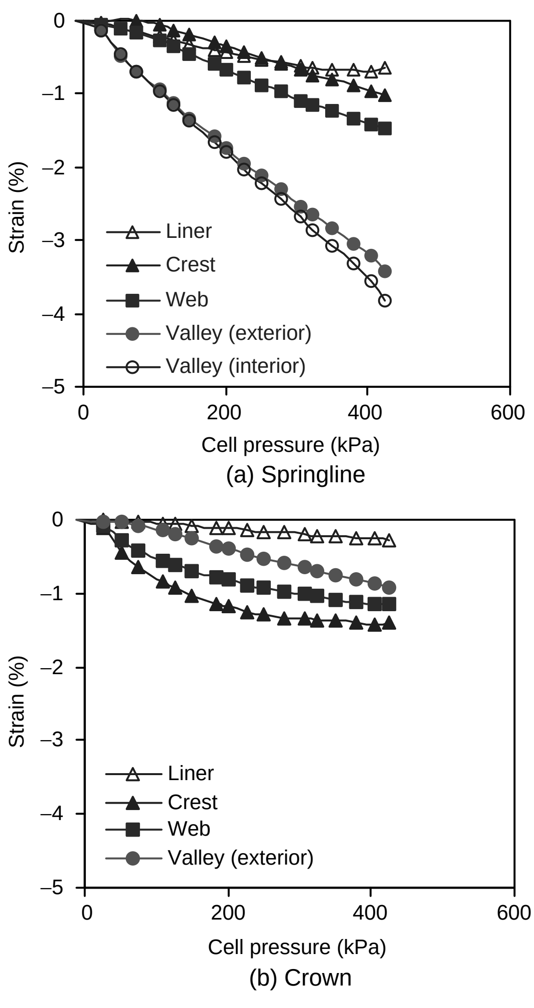

Figure 7. Circumferential strains on lined corrugated pipe 'a' (tested in loose backfill)

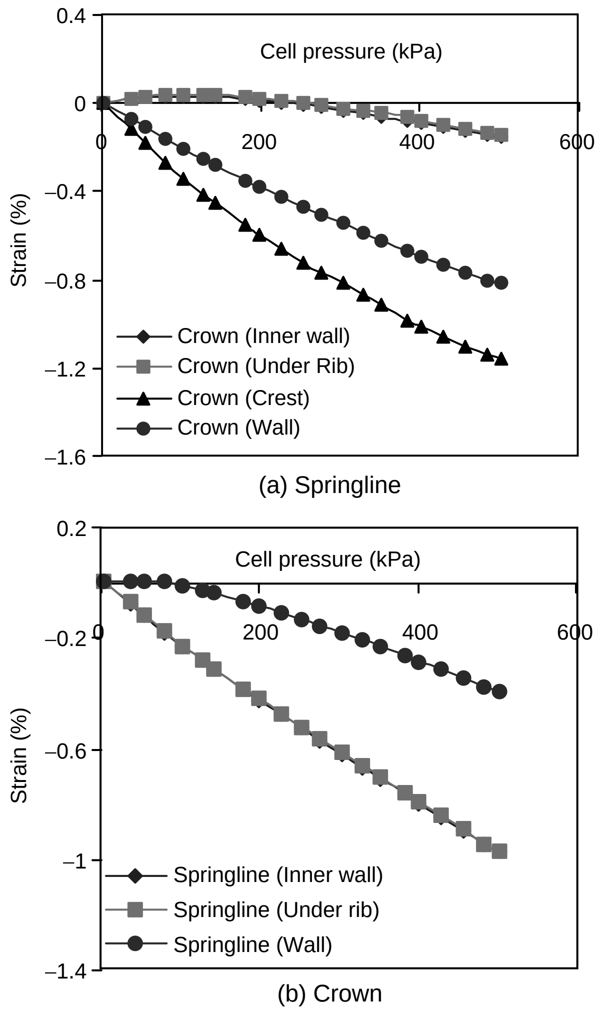

Figure 8. Circumferential strains on the PVC pipe

circumferential and axial strains for the annular profiles. Strain gauge rosettes were used on the helically profiled pipes so that strains in any direction can be calculated from the measured values. All measured strains shown here have been adjusted up for the HDPE pipes, dividing the strain by a calibration factor of 0.7 (Brachman 1999). This accounts for the wall stiffening and strain reductions that occur at the point of gauge placement. In particular, the adhesive used to glue down the strain gauges to the pipe walls stiffens the surface of the high-density polyethylene pipe (Brachman 1999).

8.1. Circumferential Strains

Circumferential strains at the springline and at the crown of the lined corrugated pipe 'a' in Test 2 are shown in Figure 7. Similar strains were obtained in the other tests using the lined corrugated pipes (Dhar 2002). The strains are compressive, with the maximum compression occurring at the springline of the pipe. The springline strain may reach the material strain limit under high earth load. AASHTO (1998) specifies empirical allowable strain limits of 5% for HDPE and 3.5% to 5% for PVC. For the test results shown in Figure 7 the compressive strain is less than the allowable limit even though the performance limit in terms of deflection (7.5% vertical diameter decrease) was reached at overburden pressure of 390 kPa.

Circumferential strains for the PVC pipe are plotted in Figure 8. The figure reveals that the maximum compression for the profile can be located at the crown (or invert) on the profile crest. Circumferential tension may also develop on different components. A reading of the circumferential strain at the springline was not obtained because unfortunately the strain gauge at that location malfunctioned.

An important and interesting observation in Figure 7 for the lined corrugated profiles is that the liner strains for the lined corrugated pipe are much less than the valley strains even though they are located at a similar distance from the centroidal axis of the profile. Strain distributions through the profile depth at the springline of the pipes are drawn in Figure 9 for all four of the biaxial tests. Figures 9(a) to (c) show that the strains are linearly distributed, except those on the liner. Points with closed symbols indicate liner strains in the figure. Similar phenomena were reported and explained as local bending by Moore and Hu (1995) using three-dimensional semi-analytic finite element analysis. Strain distribution through the PVC profile, (Figure 9(d)), is essentially linear. Classical thin shell theory may be applied to calculate the linearly distributed strains within the profiles. However, explicit three-dimensional modeling of the profile is necessary to estimate the strains where the influence of local bending is significant (e.g. on the liner of lined corrugated pipes). Local bending appeared not important for this ribbed PVC pipe.

The circumferential strains on some elements (liner, crest, and web) of the lined corrugated pipe (Figure 7(a, c)) show non-linearity at higher stresses. The strains stabilized to maximum values. The elements were observed to undergo local buckling during the experiments. When any element undergoes local buckling, it looses incremented stiffness and additional loads on that pipe wall element are redistributed to the other components of the profile. As a result, the strain on the element stabilizes. The maximum observed strain was treated as the critical strain in an investigation of the local buckling (Dhar and Moore 2001a).

8.2. Longitudinal Strains

Longitudinal or axial strains measured at the center of elements for the lined corrugated pipe ‘a’ tested in loose backfill are presented in Figure 10. Figure 10 shows that the longitudinal strains are predominantly tensile on

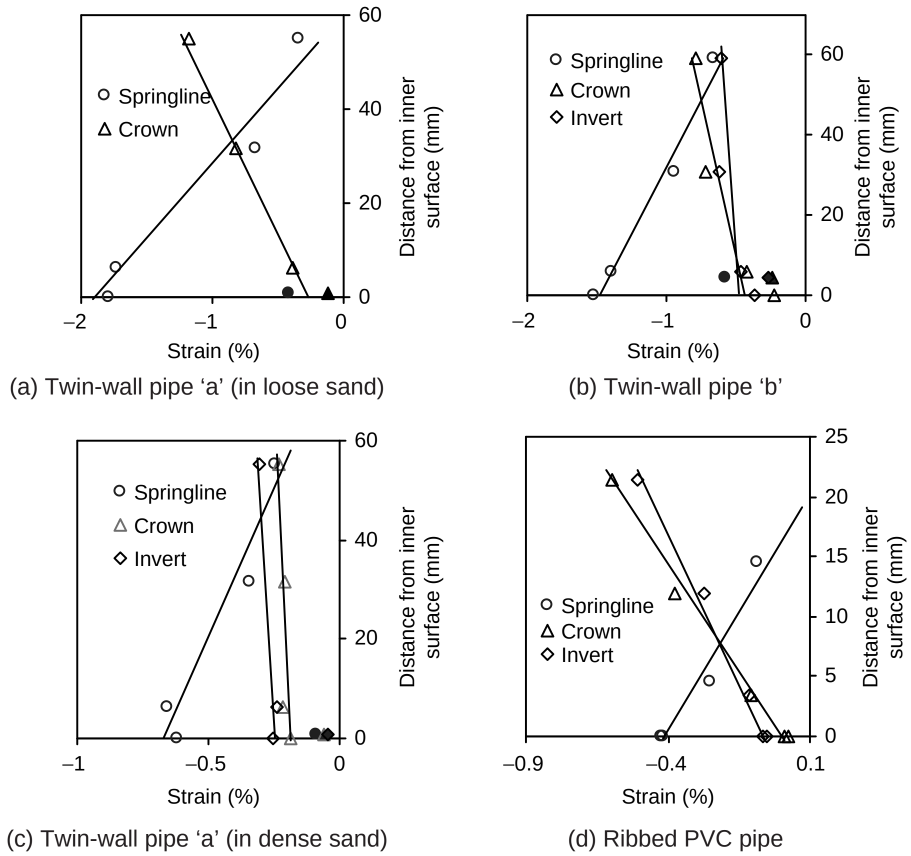

Figure 9. Distribution of circumferential springline strains with profile depth (at cell pressure of 200 kPa)

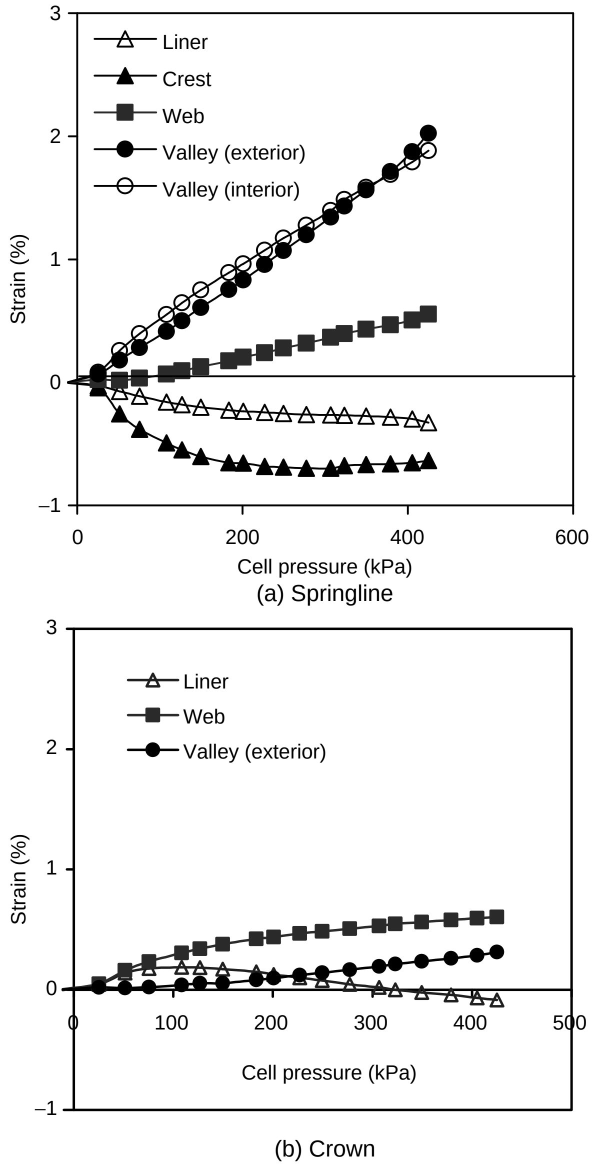

Figure 10. Longitudinal strains in a profile of lined corrugated pipe (Pipe 'a' in loose backfill)

the valley and the web of the lined corrugated pipes. If high tensile stress develops and is sustained over long periods of time, it can result in the development of cracks through the profile, Moore and Hu (1995). However, the magnitudes of the tension obtained during the tests were a fraction (about half) of the circumferential compression of the respective elements. The maximum tensile strain measured on the valley at the springline of the pipe. The strain on the liner and crest were compressive at the springline and stabilized to their peak values. At the crown, the liner strains are initially tensile, but are restored to compression at higher load (Figure 10). Mechanisms of circumferential and local bending might have influenced the longitudinal strains observed on the liner, resulting in differences between the strains at the springline and at the crown or invert. The longitudinal strain that develops in the web and the crest might also be influenced by the local soil support. Longitudinal strains on the ribbed PVC pipe were tensile but of very low magnitude (Dhar 2002) and are not included here.

9. OBSERVATION OF LOCAL BENDING IN HOOP CELL TESTS

Tests in the hoop compression cell were conducted on the 610-mm diameter lined corrugated pipes, 760-mm diameter boxed profiled pipe and the 1060-mm diameter tubular profiled pipe to investigate the local bending on those profiles. Deflections recorded for the pipes tested in the axisymmetric cell showed indication of significant circumferential shortening of the thermoplastic pipes. Deflections of the pipes at an applied cell pressure of 300 kPa are listed in Table 3.

Pipe deformation in the Hoop Cell is governed by the hoop stiffness, EA of the pipe walls. Hoop stiffness for the lined corrugated pipe 'b' is higher by about 8.5% than that of pipe 'a' (EA values 3720 N/mm and 4040 N/mm for pipes 'a' and 'b' respectively). Thus deflection of pipe 'a' is higher, but by about 20%. Similar deflections were obtained in both of the tests with pipe 'a' (Test 5 & 6). Relatively high values of deflection for pipe 'a' may be due to a lower level of compaction and therefore stiffness of the backfill soil. Soil compaction in the Hoop Cell could not be controlled precisely due to the small space between the pipe and the test cell boundary. The biaxial tests also revealed that deformation of the pipe is largely controlled by the behavior of the surrounding soil. However, in the Hoop Cell, the pipe itself is more important since only a thin ring of soil surrounds the pipes.

The deflections recorded for the box and the tubular profiled pipes are also relatively high, despite those pipes possessing higher hoop stiffness (6320 N/mm and 5840 N/mm respectively). The width of the soil ring around the box profile was about 40% of the exterior pipe diameter, while for the tubular pipe it was about 15% of that diameter. The narrow width of backfill for these pipes reduced the contribution of the soil towards resistance to pipe deformation.

Circumferential strain on the pipe wall under hoop compression is expected to be equal to the ratio of the

Table 3. Measured pipe deflections in Hoop Cell test, at 300 kPa

Pipe profile	% Deflection
Liner corrugated (profile 'a')	2.28
Liner corrugated (profile 'b')	1.89
Boxed	2.19
Tubular	2.66

change in pipe diameter (Δ) to the original diameter of the pipe (D), (Δ/D), according to the classical ring theory. However, the measured strain was not always in agreement with the classical ring theory due to the development of local buckling. Similar to the strains observed in the biaxial tests, the circumferential strain on the liner was a fraction of the valley strain under hoop compression. Figure 11 plots the circumferential strains and the longitudinal strains on the elements of the lined corrugated HDPE pipe in Test 5. Percent deflection is also plotted in Figure 11(a) along with the hoop/circumferential strains. Figure 11(a) shows that strains measured on the valley closely correspond to the percent deflection for the profile. This implies that local bending did not affect the valley strains significantly. Longitudinal strains (Figure 11(b)) were tensile on each of the elements. A true plane strain condition was not achieved during the experiments, which might have caused this longitudinal extension. While local bending may result in nonzero axial strain in specific profile wall elements, zero net strain is expected for pipe under full axial restraint.

Figure 12 plots strains on the interior and exterior surface of the boxed profile. Circumferential, axial, and diagonal strains were measured for this helical profile. However, Figure 12 shows that the diagonal strains are low, so will be treated as negligible. Therefore, the circumferential strains and the axial strains can be treated as the principal strains. Measurements of axial

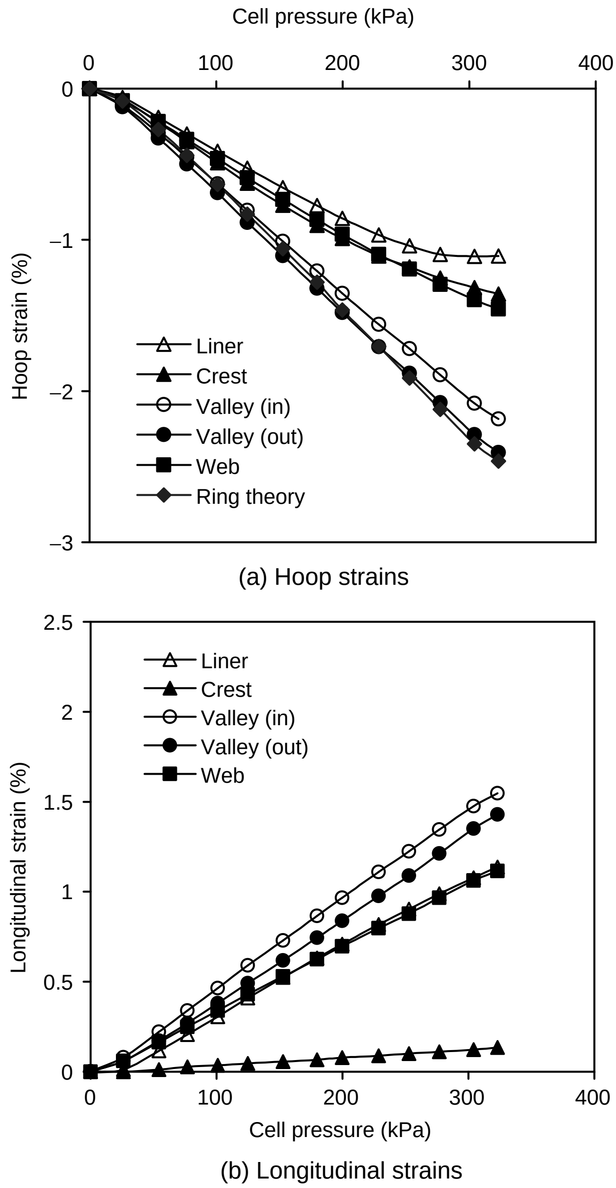

Figure 11. Strains on lined corrugated pipe 'a' in hoop test

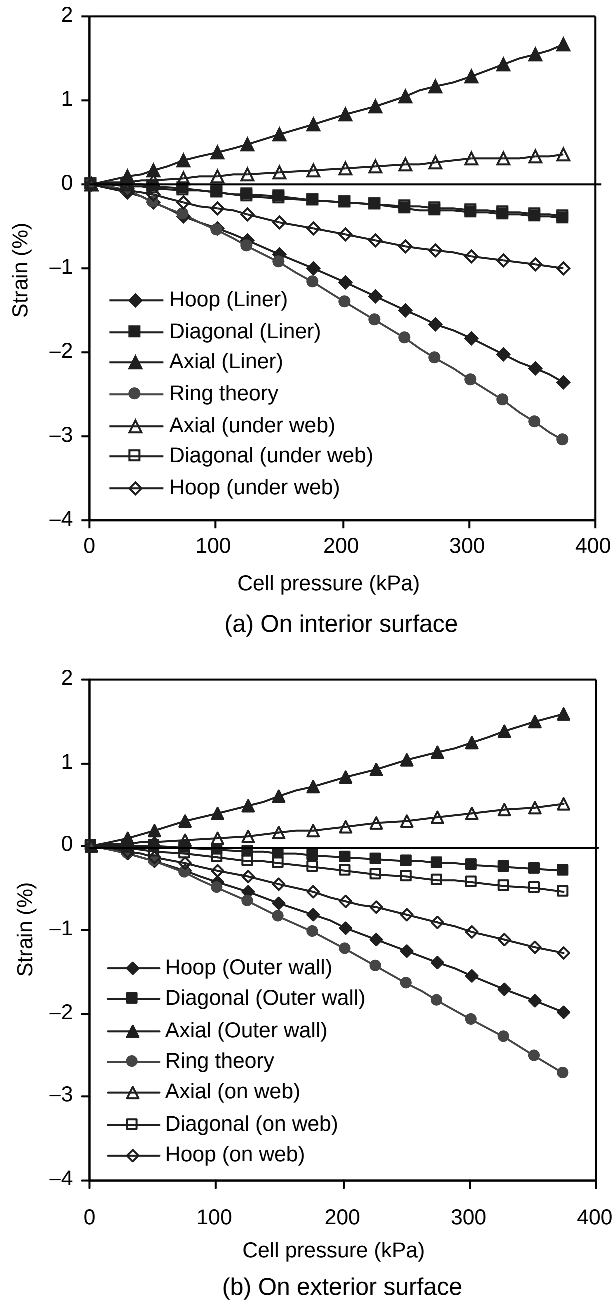

Figure 12. Strains on the box profile

elongation again indicate that the test setup did not have full axial restraint. Strains were measured at the center of the walls and on interior and exterior surfaces of the pipe at webs.

Figure 12 reveals that the hoop strains at the web on both the interior and exterior surface (Figure 12(a and b)) are much less than those measured at the center of the pipe walls. The strains on the center of the wall are close to the deflection ratios. Helical winding of the rib might have influenced the strains on its surface. Therefore the classical ring theory is not applicable for calculating the strain on the box profile with helical geometry. The web for the boxed profile is a thick radial element with dimensions of 35 mm in width and 10 mm in thickness.

For the tubular profiled pipe, strains were measured on walls of different tubes (A to D) as shown in Figure 1(d). Measured strains on the interior and exterior surface of the pipe are plotted in Figure 13 and Figure 14, respectively. Strains on some elements did not increase at higher stress, as they became unstable and buckled locally. Stresses within the profile are redistributed when any of the elements buckles locally, and the strain on the buckled element stabilizes (Dhar and Moore 2001a). Local buckling was visibly evident on the inner pipe walls during the test. The buckling developed at different levels of strain for different elements since the geometries of these elements are non-uniform

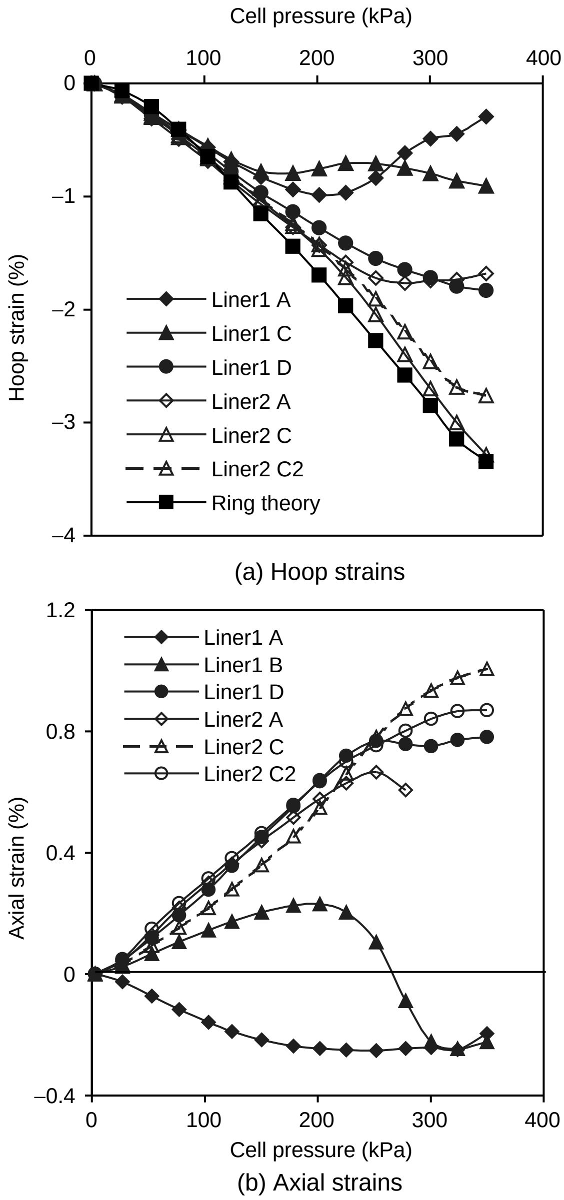

Figure 13. Interior strains on the tubular profiled pipe

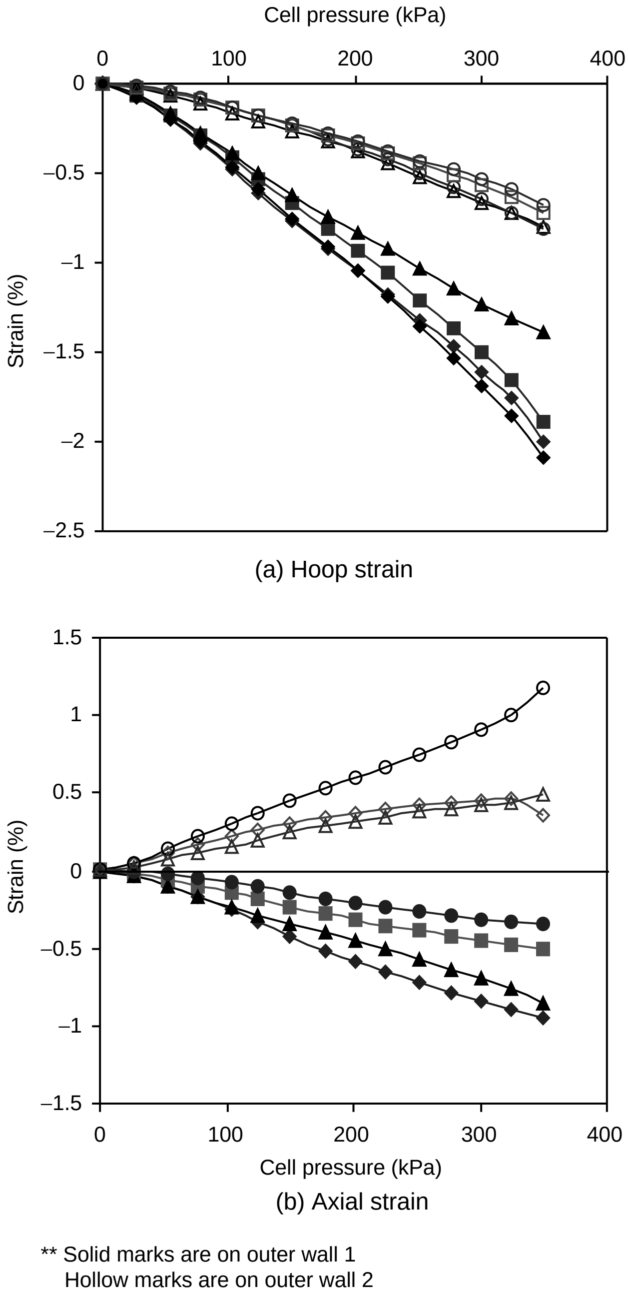

Figure 14. Exterior strains on the tubular profiled pipe

(Figure 1(d)). However, hoop strains on each of the elements were matched with those from ring theory (Δ/D) until local buckling developed. The interior wall strains on the tubular profile do not appear to be affected by local bending, in contrast to the lined corrugated profiles. On the exterior surface, hoop strain on outer wall 2 was observed to be less than the strain on outer wall 1. Longitudinal strains on the pipe walls were generally tensile on the interior surface and tensile or compressive on the exterior surface, reflecting the development of local bending in the wall elements.

10. DISCUSSION

Moore and Hu (1995) performed three-dimensional finite element analysis of a lined corrugated HDPE pipe that demonstrated local bending on the profiles of the pipe. One mechanism of the local bending was explained by Dhar (2002) as shown in Figure 15. Figure 15 shows a deflected shape of a lined corrugated pipe under radial pressure. Solid lines in the figure represent the original shape of the profile, and the dotted lines show the deflected shape. Bending on the liner is evident on the deflected profile, which is characterized by less inward movement of the liner relative to the valley. The local bending causes the liner strain to be a fraction of the valley strain.

Ratios of measured liner strain to valley strain in both biaxial and hoop tests on the same pipes are presented in Figure 16, relative to the values of applied pressure. The ratio of liner to valley strain is about 0.6 in axisymmetric tests with both of the twin-wall pipes. However, the ratio for pipe ‘a’ (Figure 1(a)) decreases once the cell pressure is beyond the point where local buckling developed in the liner. Local buckling stabilized the strain on the liner; however, the valley strain continued to increase with the cell pressure. This resulted in decreases in the ratio at higher load.

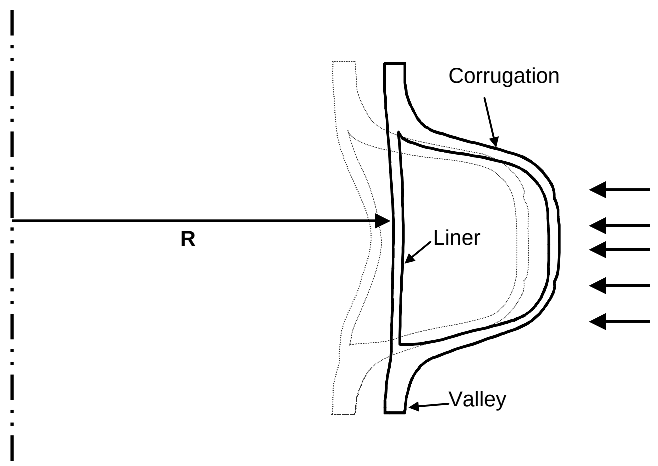

Figure 15. Mechanism of local bending (After Dhar, 2002)

The influence of local bending appeared to vary in the biaxial test, depending upon the circumferential location of the sections (for example, at springline, crown, and invert). Ratio of the liner to valley strain is higher at the crown (average value of about 0.30 in pipe ‘a’, and 0.80 in pipe ‘b’) relative to those at the springline (0.20 in pipe ‘a’ and 0.30 in pipe ‘b’). Pipe sections undergo different signs of bending at those locations, e.g. compression inward at the springline, and compression outward at the crown. Strains at the invert appear to be affected by non-uniformity of the soil support, and may also be influenced by its proximity to the cell boundary. Liner to valley strain ratio at the invert is less for both the profiles.

Between the two lined corrugated profiles considered, pipe ‘a’ showed a lower liner to valley strain ratio than that of pipe ‘b’. Specific values of these ratios are mentioned in the paragraph above. Span of the liner in pipe ‘a’ was longer than the liner span in pipe ‘b’, so the

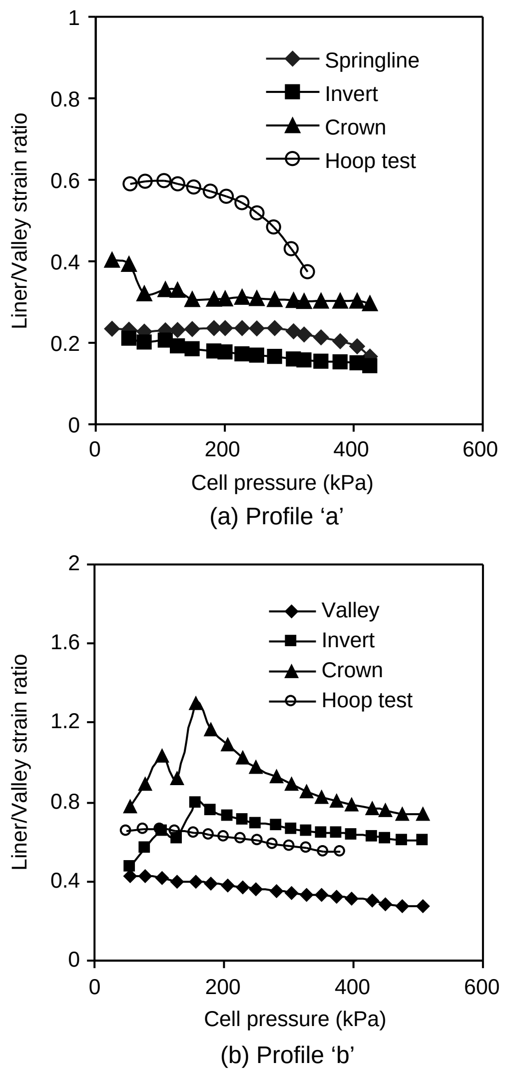

Figure 16. Ratio of the liner to valley strain for lined corrugated pipes

effect of local bending is greater for the longer liner. Similar observations arose from the axisymmetric analysis of the two profiles (Dhar and Moore 2001b).

11. CONCLUSION

The study presented in this paper revealed that, in addition to the commonly used failure modes (e.g. deflection, wall stress, and global buckling), local bending is an important mechanism that should be considered during design of profile-wall pipes. Strains were measured on the walls of different profiled pipes in full-scale tests to capture the local bending in the profiles. Measurements showed that strains on some elements of the profiles were dominated by the local bending. The circumferential strains on the liner of lined corrugated profile were less than the valley strain. The liner with longer span was observed to undergo even lesser strain relative to the liner with shorter span. The ratios of the liner to valley strain at the crown or invert were higher than the ratio at the springline, indicating that the mechanism of local bending is different at those locations. The local bending appeared not to affect the strain on the other elements of the lined corrugated profile. Measurements of strains on the valley in the hoop tests were similar to those given by deflection ratio (Δ/D).

Strains on the helically wound ribbed and box profiles were not affected significantly by local bending. However, the helix angle may affect the strain on the radial element with high stiffness (e.g. the web of the boxed profile). Strain under the web on that profile was much less than the strain at the center of the pipe wall (web strains varies from 40% to 75% of the wall strains). For the tubular profile, strain on the exterior wall 2 (wall between two tubes) was less than the strains on the exterior wall 1 (wall on the tube) due to development of local bending.

Longitudinal tensile strain was measured in each of the tests performed, with maximum tension at the springline in biaxial tests. This longitudinal stretching may need to be considered during the design of thermoplastic pipes. If it leads to tensile stress, high tension sustained for long time periods can result in cracking of the pipe wall.

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NOTATIONS:

C_u	Coefficient of uniformity
C_c	Coefficient of curvature
E	Modulus of elasticity
A	Area per unit length
I	Moment of inertia per unit length
Δ_v	Vertical deflection
Δ_h	Horizontal deflection
D	Pipe diameter

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