Sensitivity of thermoplastic pipe behaviour to profile geometry

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Abstract

Thermoplastic pipe has become popular for storm water sewers and culverts because of its light weight and low cost. Profiled pipe is often used because it provides higher stiffness with less material. There are no standardized profiles for these pipes and a wide variety of wall geometries have been developed. The geometries of the profiles may induce some localized deformations that can influence their structural performance. The effects are investigated for a range of commonly used pipe profiles. Axisymmetric finite element analysis is used to investigate the pipe behavior under axisymmetric loading. The local wall geometry of the pipes is explicitly modeled in the analysis.

Introduction

Thermoplastic pipes with different wall geometries have been manufactured to achieve effective utilization of pipe materials. The geometry of these profiles lead to questions regarding their impact on pipe response. Moore and Hu (1995) investigated the three-dimensional response of lined corrugated pipe in hoop compression and demonstrated that axial bending develops at several locations in the pipe profile. Due to this local bending, the strain field in the profile is non-uniform. Analogous results are obtained from three-dimensional analysis of lined corrugated pipe under biaxial loading (Moore, 1995). Measurements of strains from full-scale laboratory experiments under axisymmetric and biaxial loading have confirmed those results.

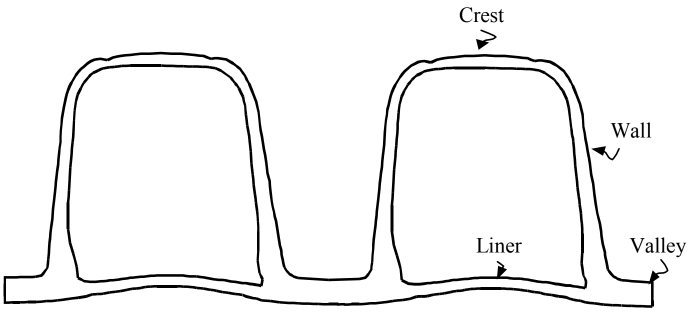
While conventional two-dimensional plane strain finite element analysis is an effective tool for predicting overall pipe response, the method is incapable of predicting the localized phenomena. A full three-dimensional model of the pipe profile is needed, therefore, to develop an understanding of the three-dimensional behavior. The actual wall geometry of a number of pipe profiles is carefully modeled and investigated in the study reported here.

Two different lined corrugated pipe profiles (denoted a and b, Figure 1)are examined to explore the influence of corrugation pitch and depth on the local response. Results for two other commonly used HDPE profiles (a box profile and a tubular profile) are also presented to investigate their three-dimensional behavior, Figures 1c and 1d.

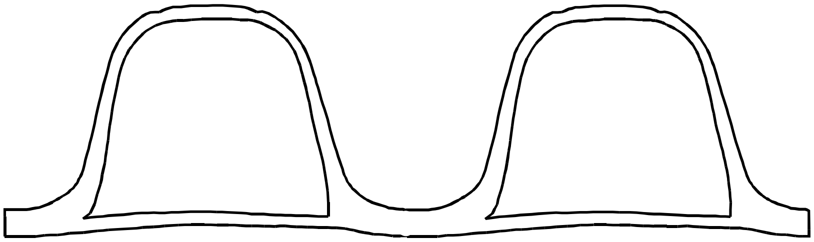
Description of the Profiles

Figure 1 shows detailed views of the pipe sections being considered in this study. The lined corrugated pipes are twin walled annular pipes with internal diameter of 610 mm. Pipe 1 (Figure

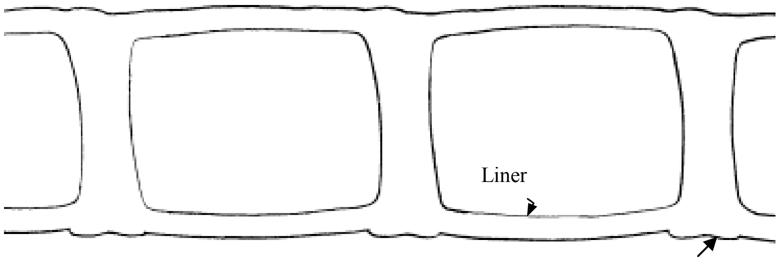
1a) has 80 mm pitch and corrugation depth of 58.7 mm. Pipe 2 (Figure 1b) possesses pitch of 101 mm and corrugation depth of 55.2 mm. Cross-sectional areas per unit length of the pipes are 10.1 mm^2/mm and 9.3 mm^2/mm respectively.



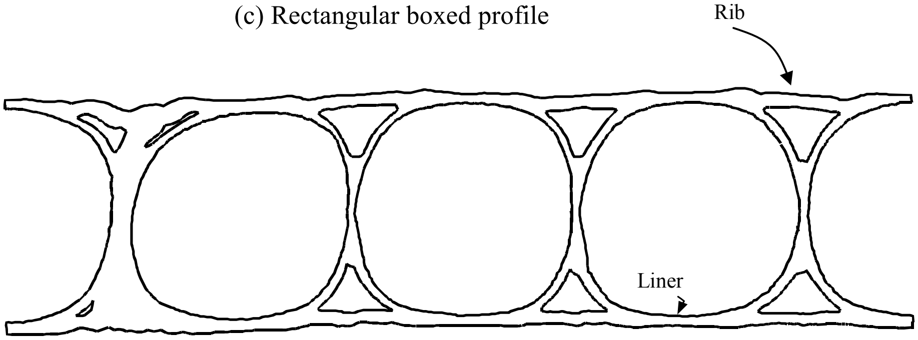
(a) Lined corrugated profile of depth 58.70 mm



(b) Lined corrugated profile of depth 55.15 mm



(c) Rectangular boxed profile



(d) Lined tubular profile

Figure 1: Types of pipe profiles (denoted a to d).

The boxed profile (Figure 1c) has a 760 mm internal diameter, and is formed by helical winding. The angle of helix is about 2^o to the plane perpendicular to the pipe axis. Profile dimensions are 48.3 mm in depth and 61.1 mm in length. Area per unit length of the pipe is 15.75 mm^2/mm.

Figure 1d shows a complete unit of the tubular profiled section. The pipe is manufactured by spirally winding a unit of four tubes. The units are fused together at the ends (Figure 1d). The helix angle for the profile is approximately 6^o. Internal diameter of the pipe is 1060 mm. Profile depth and the cross-sectional area are 67.5 mm and 16.6 mm^2/mm respectively.

Finite Element Modeling

Modeling the geometry. Axisymmetric finite element analysis has been employed to investigate the response of the pipes under hoop compression. Pipes with annular profiles have axisymmetric geometries and therefore, a two dimensional finite element mesh can be used to define the problem. Figure 2 depicts a typical finite element mesh used for annular pipe with lined corrugated profile. Since the pipes are very long, smooth rigid boundaries are used at the top and the bottom of the mesh to model axial restraint. The geometry of the axisymmetric analysis is based on the dimensions of the axisymmetric pipe test cell at the University of Western Ontario (Laidlaw, 1999). The test cell is a 1500 mm diameter steel cylindrical vessel with length of the cylinder as 1450 mm. One of the objectives of this work is to explain and interpret the experimental measurements from a laboratory test program using that cell. Comparisons to soil-structure interaction solutions for deeply buried pipes are briefly made later in the paper. These are used to discuss the likely impact of investigating pipe-soil interaction using test cell geometry.

Finite element meshes for the boxed and the tubular profiles are shown in Figures 3 and 4. Though the geometry of the two helical profiles is non-axisymmetric, axisymmetric geometry is assumed, to avoid the significant complexities of modeling the true spiral geometry. It is expected that this axisymmetric idealization will not significantly affect the pipe behavior for small angles of helix.

Moore (1994) employed simplified finite element model in the analysis of pipes under biaxial loading. The simplified approach uses two-dimensional finite element mesh of axisymmetric geometry to model the pipe in the r, z plane. A Fourier series is used to represent the variation around the pipe circumference. Pipe response to each harmonic coefficient of the load is calculated separately around the circumference and the combined response is obtained using superposition. Given the dependence on superposition, the analyses are limited to materially and geometrically linear problems.

Material model. Use of appropriate constitutive models is necessary to reasonably simulate the physical behavior by finite element method. HDPE material exhibits noticeable time dependent behavior. However, elastic modeling using secant modulus is the simplest and most widely used approach for thermoplastic pipe. AASHTO provides guidelines for short-term and long-term values of modulus for HDPE as 760 MPa and 152 MPa respectively. Finite element analysis has been successfully used to simulate short-term and long-term soil-pipe interaction using the elastic secant modulus (Hashash and Selig, 1990; Katona, 1988). Brown and Lytton (1984) adopted a simple power law formulation to account for the reduction of modulus with time, for thermoplastic material. The elastic model with a constant modulus is chosen for the High-Density Polyethylene (HDPE) pipe in this research. The modulus of elasticity for the high density polyethylene is taken as 450 MPa. The modulus value represents secant modulus for a five hour period according to the power law relation (Moore and Hu, 1996). A linear elasto-plastic model with Mohr-Coulomb's failure criterion has been used for the soil. Table 1 shows the soil and pipe parameters used in the analysis. Research is ongoing to study the effects of the nonlinear time dependent behavior of polyethylene and the stress dependent behavior of the soil.

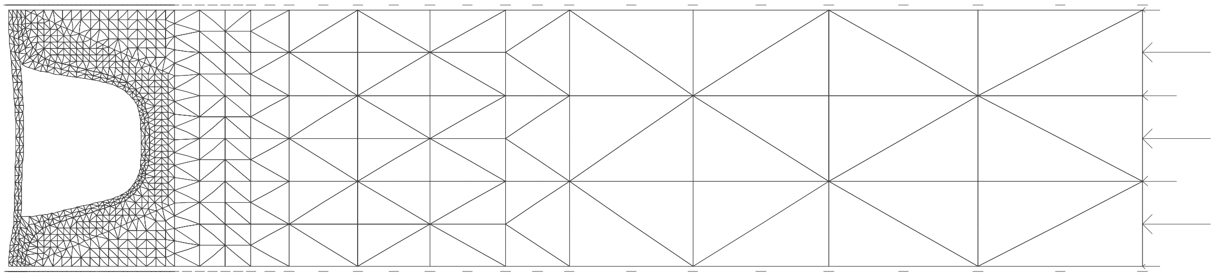


Figure 2: Finite element mesh for lined corrugated pipe

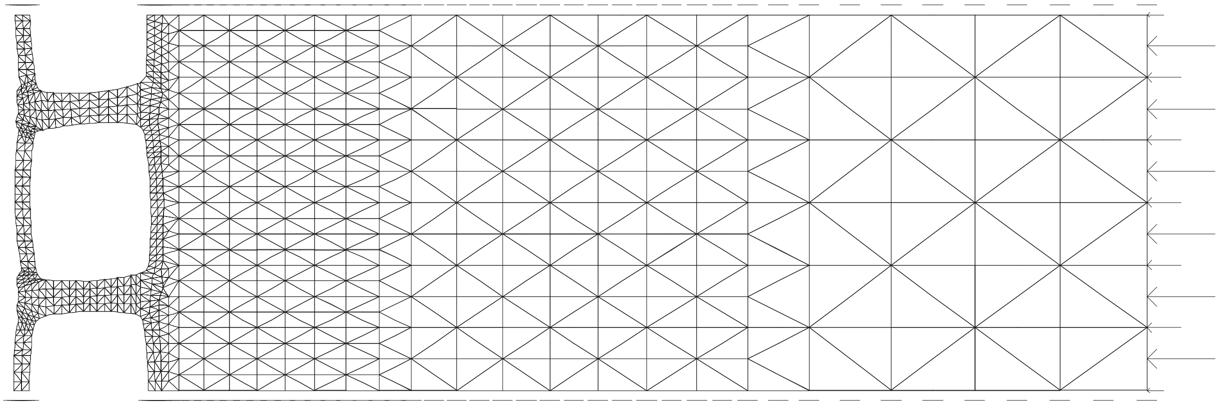


Figure 3: Finite element mesh for boxed profiled pipe

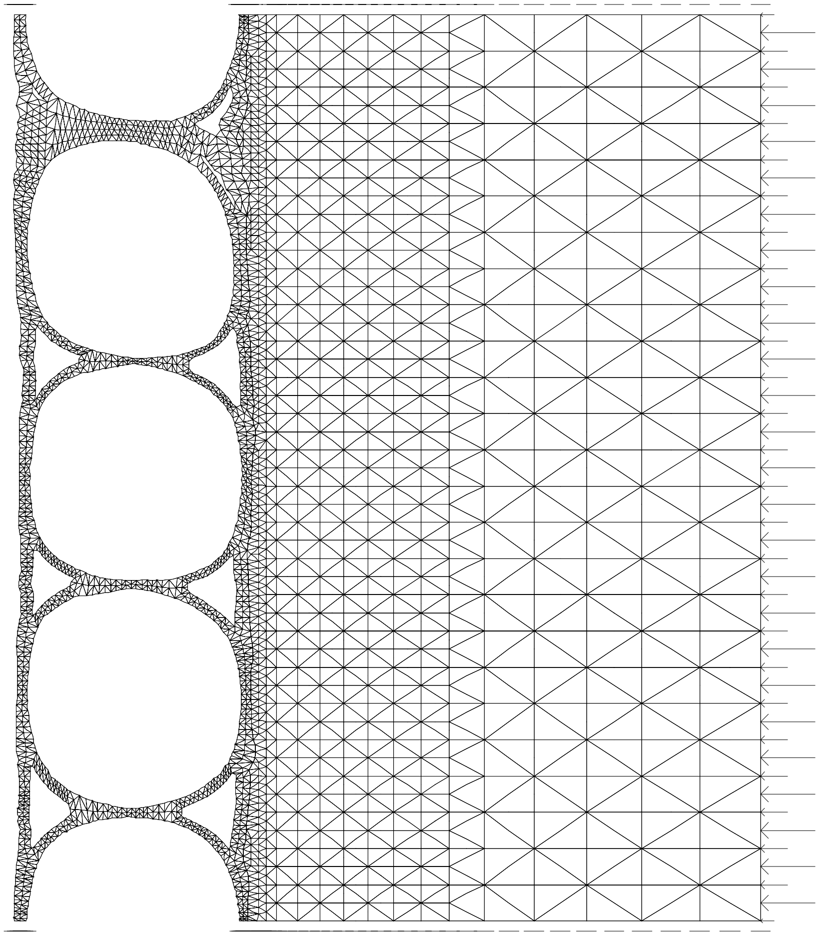


Figure 4: Finite element mesh for tubular profiled pipe

Table 1. Parameters used in the analysis

Material	Parameter
HDPE pipe	Modulus, E= 450 MPa Poisson's ratio, ν = 0.46
Backfill soil	Modulus, E= 30 MPa Poisson's ratio, ν = 0.25 Cohesion, c=0 Angle of internal friction, ϕ = 40^{o}

Results of the Finite Element Analysis

Figure 5 illustrates the deflections of the pipe under axisymmetric compression. Values at an external pressure of 500kPa are listed in Table 2. Similar deflections are obtained for lined corrugated pipe profiles 1 and 2. Figure 5 includes deflection values obtained using the two-dimensional continuum solution of Hoeg (1968). This continuum solution is based on the assumption of an infinite extent of soil around the pipe. The higher deflections obtained using the Finite Element analysis are due to the limited width of soil placed around pipes tested in the hoop compression cell. The narrow width of backfill reduces the soil stiffness resisting the pipe deformations. The deflection of the 1060 mm diameter tubular pipe is even greater since only a thin ring of soil (about 20 % of the pipe diameter) is used around the test pipe. This comparison demonstrates that while the finite element solutions presented here will be useful for interpreting observations during pipe testing, care must be exercised when drawing conclusions about pipe performance expected in the field.

Two-dimensional theory, like that employed in the Hoeg solution, models the characteristics of the pipe wall using integrated properties like area and moment of inertia. Two-dimensional analysis cannot predict the complex local strain distributions that develop across these profiles (Moore and Hu, 1995).

Figure 6 plots distribution of hoop strains on the inner surface of the four profiles at applied radial earth pressure of 400 kPa. Strains are normalized with the deflection ratio so results for each pipe can be compared (deformations are not the same at a given radial test cell pressure. Strain location is defined using z (the axial distance from the liner centerline) normalized relative to L (half the axial length of the meshes shown in Figures 2 to 4). Compressive strain is positive in this figure.

While the boxed profile and the tubular profile have circumferential strains at the surface of the inner wall that are almost uniform, it is evident that the hoop strains are not uniform along the inner surface of the two lined corrugated profiles (even though the distance of the inner wall from the neutral axis of the profile is almost constant). In the lined corrugated pipe, strain at the center of the liner is a fraction of the valley strain. Local bending develops as a result of the interaction of the liner and the corrugation (Moore and Hu, 1995). Three-dimensional effects associated with local bending can be very significant for lined corrugated pipe.

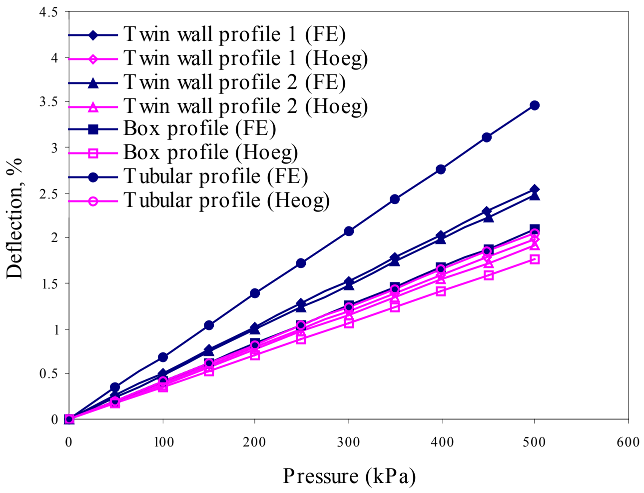


Figure 5. Pipe deflection in hoop compression

For the two different lined corrugated pipe profiles, hoop strains are uniform and similar in the valley (Figure 6). The cross-section areas of the two pipes are similar. The uniform circumferential strain can be predicted using two-dimensional theory. The circumferential strains are a function of the cross-sectional area of pipes in hoop compression. However, profile 1 (the profile with a deeper corrugation and shorter pitch) experiences higher liner strains than profile 2. Strain at the middle of the liner is about 70 % of the valley strain for the pipe with profile 1. The proportion is about 50% for the pipe with profile 2. This implies that the span of the liner has a significant effect on the strain. The local bending that develops within the liner leads to greater reductions in hoop strain when liner "span" (distance the liner stretches between corrugation valleys) is increased.

Figure 7 indicates how the distribution of axial strain leads to axial tensions in the liner element of these two profiles. Maximum tensions are near the liner-corrugation junctions. The high tensile strain is undesirable for polymer material, because it may be associated with tensile stresses that can cause long term cracking in the structure (Moore, 1995). Axial strains in both profiles are similar, except that the maximum compression that develops at the middle of the liner is less for profile 1 (once again as a result of local bending that is more prevalent in the longer liner).

Table 2: Pipe deflections at 500 kPa (FE)

Pipe profile	% deflection
Liner corrugated (profile 1)	2.49
Liner corrugated (profile 2)	2.55
Boxed	2.09
Tubular	3.46

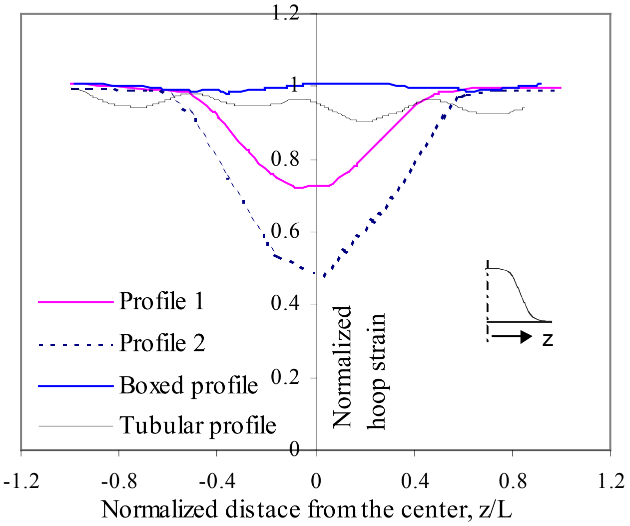


Figure 6. Interior hoop strains on lined corrugated pipe

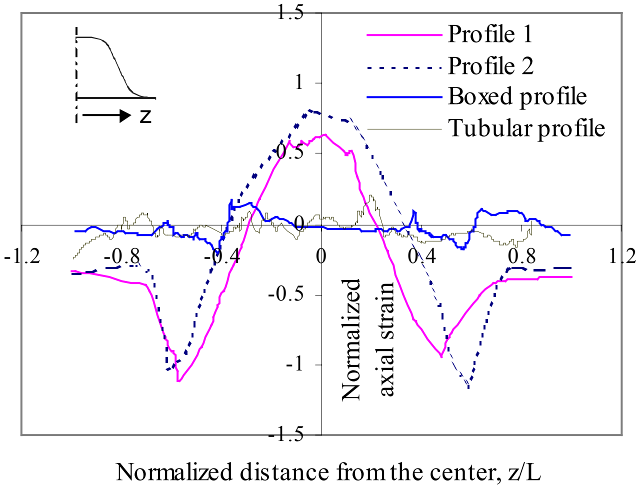


Figure 7. Interior axial strains on lined corrugated pipe

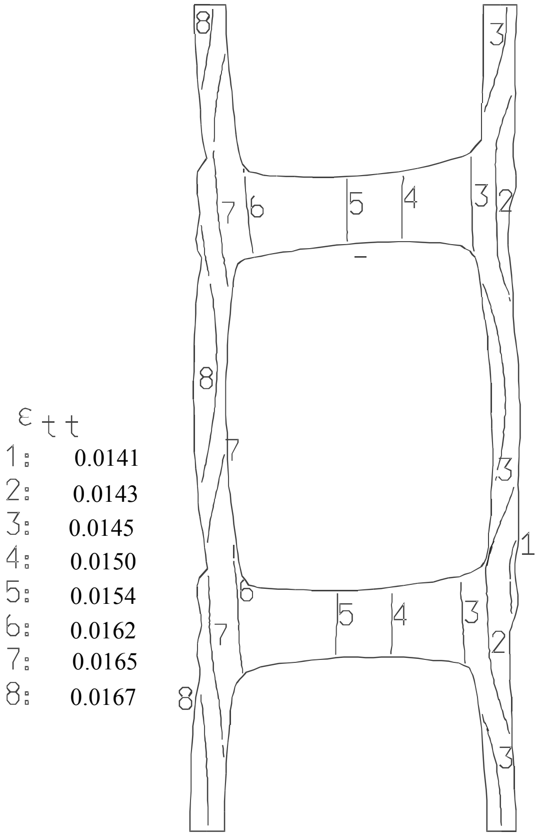


Figure 8. Hoop strain contour on boxed profile

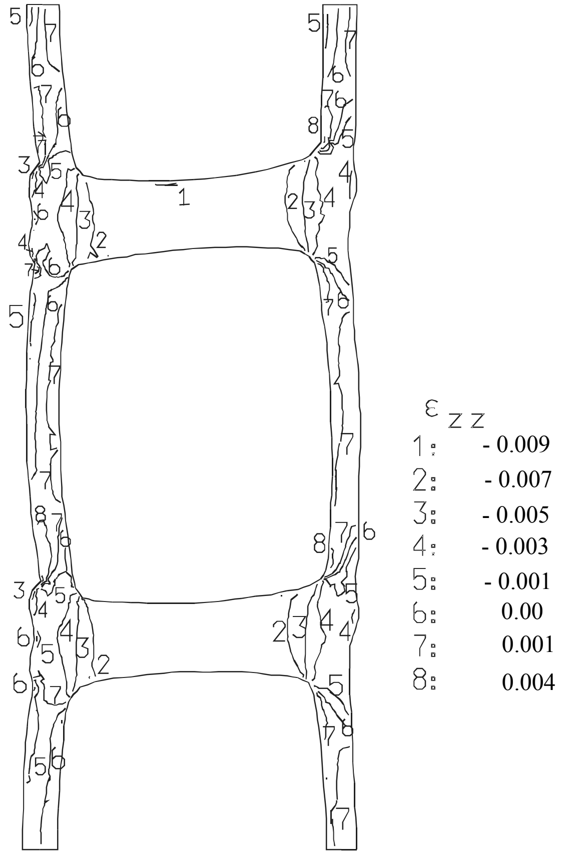
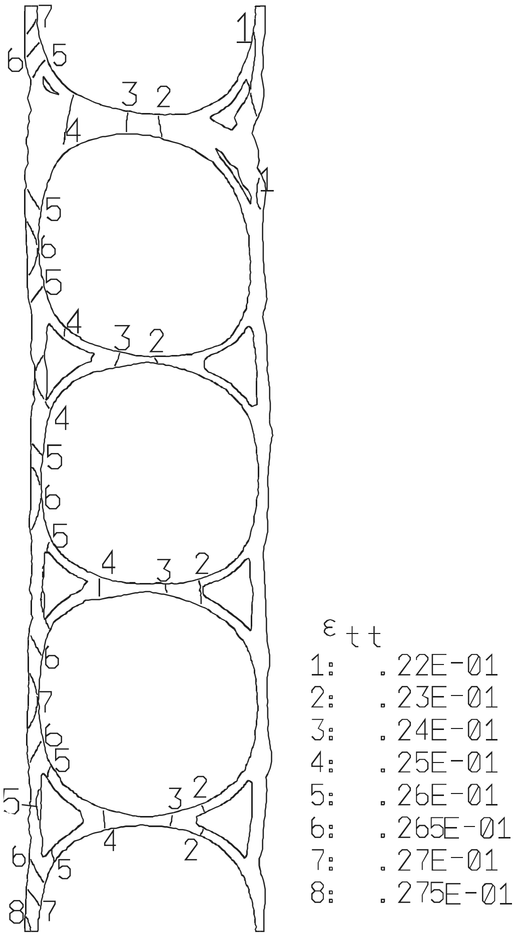


Figure 9. Axial strain contour on boxed profile

Localized bending is not significant for the boxed and tubular profiled pipe. The contours of hoop strain (Figure 8 and Figure 10) show apparently uniform strain over the profiles. Maximum circumferential compressions of the profile are at the inner surface of the liners. Axial tension for these profiles is predominantly on the lateral elements (Figure 9 and Figure 11). These tensile strains are because of the Poisson's effect due to compression in the radial and hoop direction. Therefore, tensile strains are not of great concern for the boxed and tubular profiles.

Contours of strains at the seams for the tubular profile (Figure 9 and Figure 11) show that the shape of the joint has little or no effect on the hoop strain. However, some non-uniformity of axial strains develops around the gaps left following incomplete fusion of adjacent strips during the helical winding process.



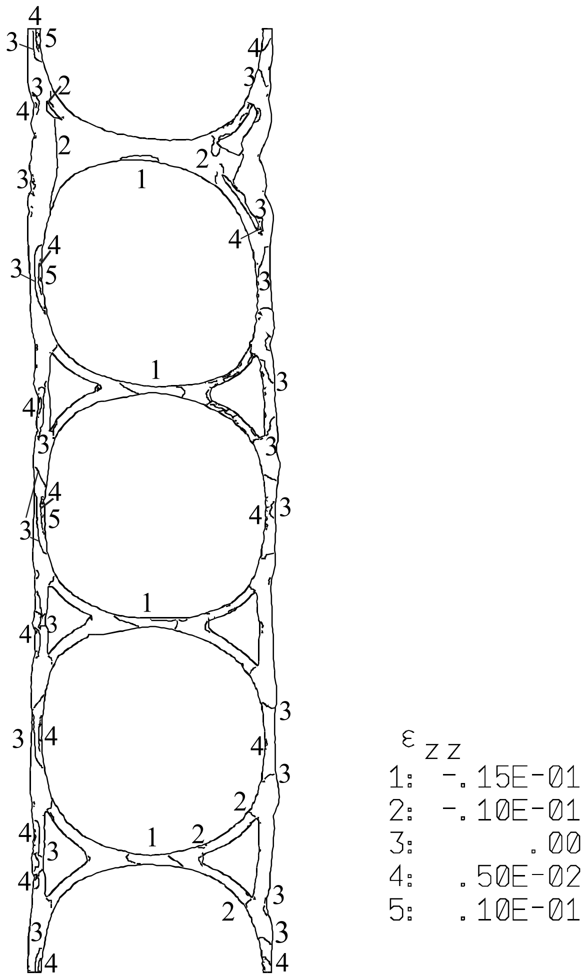


Figure 10. Hoop strain contour on tubular profile

Figure 11. Axial strain contour on tubular profile

Conclusion

The three-dimensional response of profiled HDPE pipes has been examined to develop an understanding of the effect of profile geometries. The pipes are modeled using geometry measured from samples of each of the profiles. Three commonly used HDPE pipe profiles (lined corrugated, boxed and tubular) have been considered in the investigation.

The analysis reveals that significant local bending develops along the inner wall of lined corrugated pipe. Strain distributions in the boxed and tubular profiles are more uniform.

Local bending within the wall of lined corrugated pipe is influenced by the span of the liner (the distance it stretches between corrugation valleys). Localized bending moment is more for the liner with longer span. In one case, local bending was observed to reduce the hoop strain at the mid-point of the liner to one half of the valley strain. Design of these profiles should likely include explicit modeling of the profile to study the effects of local bending, and to optimize use of material within the profile wall. Further work is currently underway to evaluate the magnitude of local tensile stresses, and to assess pipe response for typical field burial conditions.

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