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

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Abstract

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

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1. Introduction

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

A CIPP liner set inside a partially deteriorated cast-iron water main life might be subjected to several types of loading, broadly classified as: external loads and internal loads. External loads include: (a) overburden soil loads; (b) traffic loads; (c) bending of the pipe due to poor bedding, frost action, swelling of soil surrounding the pipeline and/or poor compaction; (d) point loads induced by irregularities in the inner wall of the existing pipeline caused by internal corrosion; and, (e) thermal loads in places where there is a wide variation in seasonal soil temperature. Internal loads include: (a) design/operating loads; (b) loads due to pressure surges (‘water hammer’); and, (c) thermal loads due to temperature changes in the transported fluids. The serviceability of a liner subjected to some of the abovementioned loads could be constrained by several potential limit states including: (a) local bending of the liner as it crosses a corrosion pit or a longitudinal crack in the host...
pipe which along with internal pressure causes a hoop tension in the liner (ASTM, 2002, F 2207-02; EN 13689, 2002); (b) geometrical imperfection in the liner including longitudinal folds; (c) bending of liner wall at a clamped section; (d) local bending in the wall of liner caused by ring breaks or differential settlement across a bell and spigot joint (Rajani et al., 1996); and, (e) combinations of two or more of these limit states.

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

1.1. Longitudinal folds and their formation

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

1.2. Analytical model

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

1.3. Collection of pipe samples

Samples used in this study were collected from a trial relining project in the City of Hamilton, Ont., Canada. A 1000 m long section of a 70 year old 152 mm (6 in.) internal diameter and 12 mm (0.43 in.) thick grey cast-iron water main (Fig. 1), which exhibited approximately two breaks per winter over a five year period, was lined with a fiber-reinforced CIPP liner. The operational water pressure in this part of the city is 340–410 kPa (50–60 psi) with periodical surges to 550–750 kPa (80–110 psi), which are believed to last 10–12 s. Following installation, excavations were performed at a number of locations along the alignment, and short sections (1.2 m each) of the lined cast-iron water main were exhumed for testing and evaluation purposes. It was noticed that many of the samples collected had continuous ‘folds’ running along the pipe’s longitudinal axis (Fig. 2). The folds were continuous, running along the entire length of the samples. In many cases, the void created by the fold had little or no resin in it. The CIPP liner used in this water main was a three component system consisting of an elastomer skin, a jacket and an adhesive. The jacket was a woven textile fabric (polyester) reinforced with glass fibers. Fig. 3 shows a section of an uncured liner (jacket with an elastomer skin). Coupons (dog-bone shaped specimens) were cut from the samples and subjected to uniaxial tensile tests on an MTS multi-purpose testing machine. The tests were done in accordance with ASTM 638 (ASTM, 2000). Data from the tensile test was plotted to derive material parameters. Curves plotted using engineering stress–strain values as well as true stress–strain values are shown in Fig. 4. As suggested in ASTM F 2207-02,
the stress–strain curve was approximated using two straight lines, L1 and L2, with their slopes corresponding to the elastic modulus and strain hardening modulus, respectively. Material parameters are summarized in Table 1.

2. Experimental apparatus

Following material characterization, two Specimens (A and B) were subjected to a short-term burst test to establish the pressure rating of the liner. Tests were conducted using a custom-made pressure cell designed especially for this test program. The testing apparatus can generate in a pipe specimen filled with water an internal pressure of up to 5170 kPa (750 psi). The cast iron pipe used in the main was produced nearly 70 years ago using statically manufacturing techniques. Thus, both the internal and external
diameters exhibited significant variations, making the process of sealing the ends of the pipe under high pressure a difficult task. To facilitate sealing, the specimens were placed on a lathe and their ends were squared. The ends were then 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 (Fig. 5). This sealing mechanism was found to work well for short-term (‘burst’) tests, with internal pressure as high as 3790 kPa (550 psi). The internal pressure was read via an external gauge accurate to ±35 kPa (±5 psi).

3. Finite element modeling technique employed

Short-term burst tests were modeled by 3-D finite element (FE) modeling using the commercial software ADINA. As noted during uniaxial tensile tests, the CIPP liner exhibited a non-linear (bilinear) behavior with failure strain of approximately 18%. These material characteristics were found to be adequately represented by the ‘plastic-bilinear’, an ADINA constitutive model based on the Von-Mises’ yield condition which is temperature and rate independent (ADINA, 2003). The physical and geometrical non-linearity of the material were addressed, respectively, through the ‘large strain’ and ‘large displacement’ capabilities available with 3D-solid elements. Since failure strain of the liner exceeded 5%, parameters of the stress–strain curve (elastic modulus, strain hardening modulus and yield stress) corresponding to that of its logarithmic counterpart were used as the material inputs to ADINA. Logarithmic stress–strain values were obtained from the engineering stress–strain values, based on the assumption that the liner material does not undergo a significant volume change during tensile loading. Material parameters for the liner used in the FE model are given in Table 1.

To determine the failure pressure of the liner, a failure criterion based on accumulated plastic strain was used. When the accumulated plastic strain in the model reached the plastic strain value obtained from the uniaxial tension test, the corresponding liner elements were considered ‘dead’ and the load was redistributed to neighboring elements. This procedure continued till the program reached non-convergence. The pressure corresponding to the last converged load step was considered to be the failure pressure.

Contact surfaces were defined in places where a contact was expected during the bulging action of liner. The cast-iron wall (stiffer material) was treated as the ‘target surface’ and the liner material as the ‘contactor surface’. In order to avoid slippage of liner inside the cast-iron wall and to prevent penetration of nodes of the liner material into the cast-iron, rigid contact surfaces were defined between the liner and the cast-iron in places where the nodes of liner and cast-iron did not overlap. Fig. 6 shows a sample of a contact surface pair.

The cast-iron pipe was modeled as a linear, elastic and isotropic material using 3D-solid elements. Material characteristics for cast-iron were based on an average of values reported in Seica et al. (2004). Values for modulus of elasticity and Poisson’s ratio used were 9.653E + 4 MPa and 0.227, respectively.

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Table 1
Material parameters of the liner tested

<table>
<thead>
<tr>
<th>Material parameters</th>
<th>True values</th>
<th>Engineering values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>2461 MPa</td>
<td>2461 MPa</td>
</tr>
<tr>
<td>(3.57E5 psi)</td>
<td>(3.57E5 psi)</td>
<td></td>
</tr>
<tr>
<td>Ultimate tensile stress</td>
<td>78.6 MPa (11,400 psi)</td>
<td>68.5 MPa (9930 psi)</td>
</tr>
<tr>
<td>Yield strength</td>
<td>27.5 MPa (4000 psi)</td>
<td>27.5 MPa (4000 psi)</td>
</tr>
<tr>
<td>Strain at failure</td>
<td>0.1754 (mm/mm)</td>
<td>0.191 (mm/mm)</td>
</tr>
<tr>
<td>Strain hardening modulus</td>
<td>311 MPa (45,121 psi)</td>
<td>227 MPa (33,000 psi)</td>
</tr>
<tr>
<td>Strain at yield</td>
<td>0.0114 (mm/mm)</td>
<td>0.0114 (mm/mm)</td>
</tr>
<tr>
<td>Poisson’s ratio (assumed)</td>
<td>0.33</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Fig. 5. Custom-made pressure cell (capacity 5170 kPa/750 psi).
4. Specimen ‘A’

4.1. Experimental testing

The burst test was done on a hybrid cast-iron pipe (152 mm internal diameter) lined with a fiber-reinforced thermoplastic liner. The longitudinal fold in the liner was exposed by an opening (300 mm in length and 75 mm wide) in the pipe specimen machined with great care to avoid damage to the liner. The opening was located at the center of the specimen, with the longitudinal fold running along the centerline of the opening. The length of the pipe specimen was 900 mm. Three pairs of linear variable displacement transducers (LVDTs) were mounted on the outside surface of the liner in the immediate vicinity of the fold at three locations to measure radial displacements of the liner during bulging. For each pair, one LVDT was placed immediately above the fold and one immediately beneath it. The LVDTs were connected to a data acquisition system for correlating pressure and displacement measurements. The testing procedure was conducted as per ASTM D 3139 (ASTM, 1998), with the specimen subjected to a gradually increasing internal pressure at 340 kPa (50 psi) increments, each lasting 5 min. Fig. 7 shows the instrumentation setup used for Specimen ‘A’.

4.2. Finite element modeling

Two finite element models were constructed to simulate the burst test of Specimen ‘A’. The first model (A1) exhibited a longitudinal fold at the center of the opening, with dimensions closely resembling the original specimen. The second model (A2) exhibited a perfect circular liner geometry. Fig. 8 shows the un-deformed mesh developed using 3-D solid elements for model A1.

4.3. Comparison of experimental, numerical and analytical results

As the internal pressure was increased, the liner bulged out like a balloon. At an internal pressure of 2137 kPa (310 psi) the liner ruptured along the longitudinal fold. The finite element model (A1) of the experimental test predicted the failure pressure to be 2000 kPa (290 psi), a difference of −6.5%. The maximum stress and strain values in the numerical model were predicted to occur along the outer portion of the longitudinal fold, a location identical to the failure location observed during the experimental test. Fig. 9 shows the strain distribution plot at the failure pressure. On the other hand, model A2, a similar model but with a perfect liner geometry (no fold), predicted a failure pressure of 6000 kPa (870 psi), a threefold increase. Using the analytical solution of ASTM F 2207-02 a failure pressure of 6110 kPa (886 psi) was predicted. This analytical failure pressure corresponds to the ‘maximum stress criterion’ solution, whereas the ‘interactive stress criterion’ solution predicted 7074 kPa (1026 psi). A brief explanation...
of the stress criteria employed by ASTM F 2207-02 is provided in Appendix A. The ASTM F 2207-02 solution can handle only liners with perfect liner geometry and thus an analytical solution for configuration A1 could not be calculated. Table 2 summarizes the results of the pressure ratings for Specimen ‘A’.

The pressure ratings of the CIPP liner for Specimen ‘A’ with and without the fold differed by a factor of approximately three. This difference was a result of the stress concentration developed along the longitudinal fold leading to a premature failure. A comparison of the experimentally measured displacements and those predicted by numerical model A1 (with the fold) is shown in Fig. 10. The model predicted the maximum displacement with an accuracy of ±1.5 mm for all levels of internal pressure in comparison with displacement values recorded by the LVDTs.

Comparison of displacement predictions from numerical models A1 and A2 reveal a phenomenon of ‘unfolding’ (reversed curvature) of the liner material under the increasing internal pressure. This unfolding of the liner in conjunction with the resulting stress concentration, drastically reduces the internal pressure resisting capability of a CIPP liner in the configuration studied. Fig. 11 provides a stage-by-stage illustration of the above described unfolding phenomenon with increasing internal pressure.

<table>
<thead>
<tr>
<th>Method</th>
<th>Model with fold (A1)</th>
<th>Model without fold (A2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>2137 kPa (310 psi)</td>
<td>N/A</td>
</tr>
<tr>
<td>FE model</td>
<td>2000 kPa (290 psi)</td>
<td>6000 kPa (870 psi)</td>
</tr>
<tr>
<td>Analytical – maximum stress criterion</td>
<td>N/A</td>
<td>6110 kPa (886 psi)</td>
</tr>
<tr>
<td>Analytical – interactive stress criterion</td>
<td>N/A</td>
<td>7074 kPa (1026 psi)</td>
</tr>
</tbody>
</table>
5. Specimen ‘B’

5.1. Experimental setup

The specimen utilized in this test was a fire hydrant tee with two bells. Prior to commencement of the pressure test, the 102 mm diameter hydrant feed pipe was cut off, exposing a section of the liner of oval shape approximately 200 mm wide and 150 mm long (Fig. 12). Five LVDTs were placed along the major and minor axes of the opening to measure the deformation of the liner as a function of internal pressure. The specimen was pressurized to 3790 kPa (550 psi) in increments of 340 kPa (50 psi), with the pressure held at each pressure increment for a minimum of 5 min as per the ASTM D3139 leakage test. The maximum deformation recorded by the LVDTs at 3790 kPa was approximately 7.5 mm (0.35 in.). 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 that covered the liner’s outside wall. The test was discontinued at 3790 kPa (550 psi) due to difficulties in sealing the bulkheads.

5.2. Comparison of results from experimental, numerical and analytical modeling

Failure pressures predicted by ASTM F 2207-02 analytical solutions were 5100 kPa (740 psi) and 5653 kPa (820 psi) using the maximum stress criterion and interactive stress criterion, respectively. The failure pressure predicted by the numerical model was 4960 kPa (720 psi), a value lower by 8% from the average (5376 kPa) of the abovementioned analytical predictions. Table 3 summarizes the results for Specimen ‘B’. The liner bulged like a balloon with the maximum displacement occurring at the center of the opening. The highest displacement value corresponded to the center of the opening in the case of both, the finite element model and experimental measurements. Comparison of calculated and measured values in terms of displacement revealed a close agreement for all LVDT locations (Fig. 13). The maximum difference between the predicted and experimental value was 1 mm. The FE model predicted the maximum stress and strain in the liner to develop along the edge of the opening. This was also the region where initial rupture was predicted to occur at an internal pressure of 4960 kPa. Distribution of stresses in the liner at the time of failure is shown in Fig. 14.

5.3. Comparison of experimental results for Specimens ‘A’ and ‘B’

To gain a better understanding of the effect of longitudinal folds on the pressure rating of CIPP liners, experimental
observations from Specimen ‘A’ and ‘B’ were plotted in Fig. 15. The load–displacement curve for Specimen ‘A1’ (longitudinal fold present) revealed that yielding occurred around 1300 kPa (190 psi), whereas for Specimen ‘B’ (no fold) yielding occurred around 1650 kPa (240 psi). This difference is attributed to the development of a stress concentration in the liner (Specimen ‘A1’) due to the presence of the longitudinal fold in conjunction with the unfolding mechanism. Results from the burst tests on Specimens ‘A’ and ‘B’ serve as a testimony to the detrimental role played by longitudinal folds in relation to the internal pressure ratings of CIPP liners. While somewhat different in their geometries, the area of exposed liner in both specimens was sufficiently large to neglect the stiffening effect from the wall of the cat-iron pipe at the center of the gap; thus, the comparison is valid. Fig. 16 compares the FE prediction for Specimens A1 and A2 (with and without fold, respectively). One could notice three distinct phenomena, namely: (a) load–displacement curve for the specimen without the fold exhibited a stiffer response than the one
with the fold; (b) the fold decreased the yielding pressure; (c) displacements during failure of the liner for Specimens ‘A1’ and ‘A2’ remained the same while the corresponding pressures differed by a factor of three. These deductions are also supported by observing the experimental data shown in Fig. 15.

For a given gap size, the longitudinal fold decreased the pressure rating by a factor of approximately 3, whereas ASTM F 2207-02 suggests the use of a safety factor of 2. Thus, the factor of safety provided in ASTM F 2207-02 may not be sufficient to accommodate the geometrical imperfections associated with longitudinal folds. This inadequacy could be rectified using a modification factor which accounts for liner oversizing. The following section describes the results of a parametric study undertaken to establish the relationship between the geometry of the liner imperfection and the internal pressure rating of the liner. While the methodology used is generalized in nature, the results reflect the physical characteristics of the liner examined in this study.

6. Parametric study

Following verification of the numerical models, a parametric study was undertaken to establish an empirical relationship between the fold’s dimensions and the critical internal pressure for the liner. The depth ($d$) and the angle ($\theta$) of the fold with respect to the horizontal axis perpendicular to the bottom of the fold were the two parameters used to characterize the geometry of the fold (Fig. 17). These

![Fig. 15. Comparison of displacement from experiments on Specimens ‘A’ and ‘B’.](image1)

![Fig. 16. Comparison of displacements from FE model of Specimen ‘A’ with and without fold.](image2)
two parameters were also chosen as variables in the parametric study. The thickness of the liner was fixed at 4.5 mm and the radius of curvature at the tip of the fold was fixed at 3 mm. The internal diameter of the cast-iron pipe was fixed at 152 mm. Also, the study focused on single host pipe gap geometry (75 mm wide and 300 mm in length). The fold was assumed to be at the center of the gap throughout the study. The angle of the fold ($\theta$) varied from $30^\circ$ to $90^\circ$. At $90^\circ$ the fold is perpendicular to the wall of the host pipe (Fig. 17). The depth ($d$) of the fold varied from 7 mm to 20 mm. The abovementioned parameter ranges were based on the fold dimensions and geometries observed in the specimens recovered from the field CIPP installations.

The parametric study revealed that the predicted pressure rating of the liner varies significantly with changes in depth and angle of the fold. Overall, the pressure rating was found to be inversely proportional to the depth ‘$d$’ and the angle ‘$\theta$’ of the fold. For a given depth, a fold with an angle of $90^\circ$ exhibited the minimum pressure rating, and thus it was considered to be the critical angle for that depth. Fig. 18 shows a graphical representation of the results. The curves reveal a steep decline in the pressure rating of the liner with an increase in the dimensions of the fold. The greater the depth of the fold, the more pronounced is the decline.

In practice, elimination of folds is not easy because of the non-uniform cross section of the pipes. Tailoring the liner to accommodate the random diametrical variations in the cast-iron pipe could severely compromise cost and ease of installation. Over sizing helps to avoid the formation of voids between the host pipe and the liner, but, if done excessively, could, in turn, give rise to another significant problem in the form of longitudinal folds. Thus, a
threshold for oversizing needs to be determined so that the liner’s structural performance is not excessively weakened by either of these defects (buckling due to gap or yielding due to stress concentration along longitudinal folds).

6.1. A quality control criterion to minimize the adverse effect of longitudinal folds

Specimens used in this research were collected from a municipal water distribution system with surge pressures as high as 830 kPa (120 psi). Assuming a factor of safety 2, the pressure design basis for this system should be equal to twice the surge pressure (1660 kPa). From the results of the parametric study, fold geometries with a depth of less than 10 mm and an angle of 90° have a critical pressure rating somewhat greater than 1660 kPa. Restricting the fold size within the above stated limiting geometry will keep the liner’s pressure rating to be at least twice that of the surge pressure, even in the case of an extreme gap size (75 mm by 305 mm), which is considered to be a conservative design practice. For this design criterion to be applied in practice, an effective approach for controlling the fold dimensions is required. The proposed approach establishes an empirical relationship between the critical pressure and the oversizing ratio of the virgin liner. Let ‘d’ be the perpendicular distance between the tip of the fold and the inner wall of the rehabilitated pipe. Thus, the liner circumference (C_L) is approximately equal to the summation of the inner circumference of the host pipe plus twice the depth (d). The fold’s dimensions depend primarily on the nominal circumference of the virgin liner, and thus the degree of oversizing plays a crucial role. For any depth, the worst case scenario occurs for θ = 90°. Hence, by controlling the ratio of oversizing (i.e., ratio of excess circumference of the liner in the hoop direction to the mean circumference of the inner wall (C_P) of the host pipe in the same direction), the fold dimensions can be controlled and the liner structural capacity can be kept above a minimum predetermined threshold in a fully deteriorated host pipe scenario. This is expressed mathematically as

\[
AOR = \text{allowable oversizing ratio (\%)} = \frac{(\text{Increase in circumference of the liner due to fold width})}{(\text{host pipe circumference})} \times 100 = \frac{(C_L - C_P)}{C_P} \times 100 = \frac{(d/\pi R)}{C_P} \times 100
\]

For the specific case studied in this work (gap size of 75 mm by 300 mm in a 152 mm water main), an AOR value of 4.2% was found to be the maximum permissible value for a minimum pressure rating of 1660 kPa. The authors acknowledge that this is an extreme case, with dimensions of the gap in the specimens tested governed by ease of instrumentation and the ability to obtain multiple data points. However, the proposed methodology is valid for all gap geometries. Also, liners for a partially deteriorated pipeline are designed for a life time of 50 years, and a pipe line that is partially deteriorated now may undergo significant additional deterioration over next 50 years. Expectations for accelerated deterioration with time is supported by mathematical models for the break occurrence rate of pipelines which suggest an exponentially increasing rate of pipe line breaks with time (Shamir and Howard, 1979). In such a case, the presence or absence of longitudinal folds may play a crucial part in the structural integrity of the pipeline over a period of 50 years. An additional factor that require consideration is the effect of cyclic loading caused by water hammer and how a liner with longitudinal fold behave when repeatedly subjected to such type of loading for a prolonged time period. This aspect is beyond the scope of the current study, but is believed to be a suitable candidate for follow up research work.

![Fig. 19. Variation of critical pressure with depth of fold.](image)
Pressure ratings of the critical fold angle (θ = 90°) for varying depths is plotted in Fig. 19. The data points in this plot have been approximated by a curve decreasing exponentially as a function of depth. The pressure rating, as a function of depth, is given by the equation

$$P_C = P_{\text{max}} \cdot \exp[-\alpha \cdot d^\delta \cdot \exp(-\beta \cdot d)]$$  (2)

where $P_C$ is the critical pressure and $P_{\text{max}}$ is the pressure rating for a perfect liner with no folds as predicted by ASTM F 2207-02; $\alpha$, $\beta$, and $\delta$ are constants (or shape factors) determined by the size of the gap in the host pipe. For a rectangular gap considered in Specimen ‘A’ (75 mm by 300 mm), values of the shape factors were determined, based on the shape of curve shown in Fig. 16, to be 4.1, 1.1, and 0.75 for $\alpha$, $\beta$ and $\delta$, respectively. These factors pertain to the particular gap geometry and size studied with a maximum depth of fold of 20 mm.

The fold depth ($d$) can be expressed in terms of the allowable over sizing ratio (AOR) given by Eq. (1). Thus, a critical pressure can be found for different values of over sizing ratios. The proposed approach is generic in nature and could be extended to different geometries and dimensions provided the constants $\alpha$, $\beta$ and $\delta$ are determined for the case in question. Thus, knowing the pressure rating for a perfectly round liner for a given gap geometry from ASTM F 2207-02, the modified critical pressure can be predicted for various oversizing ratios. It is suggested that the proposed approach can be used to enhance ASTM F 2207-02 to account for the longitudinal folds as well as other geometrical imperfections.

7. Conclusions

The primary purpose of this study was to investigate the effect of longitudinal folds on the pressure rating of CIPP liners. Based on the results and observations, the following conclusions were reached:

1. The combination of two previously identified limit states for pressure pipes rehabilitated with CIPP liners, namely, the development of corrosion pits and geometrical imperfections, could result in a new and potentially more critical limit state. This new limit state is the result of the high stress concentrations that develops along longitudinal folds which coincide with corrosion induced gaps in the wall of the host pipe.
2. Predictions from numerical models were in close agreement with the experimental results for burst tests conducted on Specimens ‘A’ and ‘B’ in terms of deformation of the liner (i.e., displacement) at different levels of internal pressure, location of maximum stress/failure, and failure pressure (Specimen ‘A’).
3. Analytical solutions presented in ASTM F 2207-02 for physical burst pressure for Specimen ‘B’ were found to be in close agreement with the results of the numerical model in terms of failure pressure.
4. The magnitude of the decline in pressure rating is a function of the size and geometry of the fold, the presence (or lack) of resin behind the fold and size and geometry of the gap in the host pipe.
5. While longitudinal folds cannot be completely avoided without compromising cost and ease of installation, their potentially adverse effects could be mitigated by controlling the oversizing of the virgin liner.
6. A quality control criterion named “allowable oversizing ratio (AOR)” which is a function of the pipe’s internal diameter, gap dimensions and surge pressure is proposed. Limiting the oversizing of CIPP liners is an effective QC criterion for eliminating the risk of premature failure in heavily deteriorated pressure pipes.
7. A generic derivation of an empirical approach for calculating the pressure rating of a liner with a given oversizing ratio as a function of gap dimension and geometry is proposed. It is suggested that the proposed approach, when fully developed to cover a range of gap geometries, could supplement ASTM F 2207-02.

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Appendix A

ASTM 2207-02 utilizes two failure criteria, namely maximum stress criteria and interactive stress criteria. In the maximum stress criterion, failure is assumed to occur when either hoop load/width ($N_h^\text{uts}$) reaches the ultimate hoop load/width ($N_h^\text{uts}$'), or the axial load/width ($N_a^\text{uts}$) reaches the ultimate axial load/width ($N_a^\text{uts}$). This is stated mathematically as follows:

$$\frac{N_h}{N_h^\text{uts}} = 1$$  (A1)
$$\frac{N_a}{N_a^\text{uts}} = 1$$  (A2)

The interactive failure criterion is mathematically stated as follows:

$$\left(\frac{N_h}{N_h^\text{uts}}\right)^2 - \frac{N_h \cdot N_a}{(N_h^\text{uts})^2} + \left(\frac{N_h}{N_h^\text{uts}}\right)^2$$  (A3)

References


