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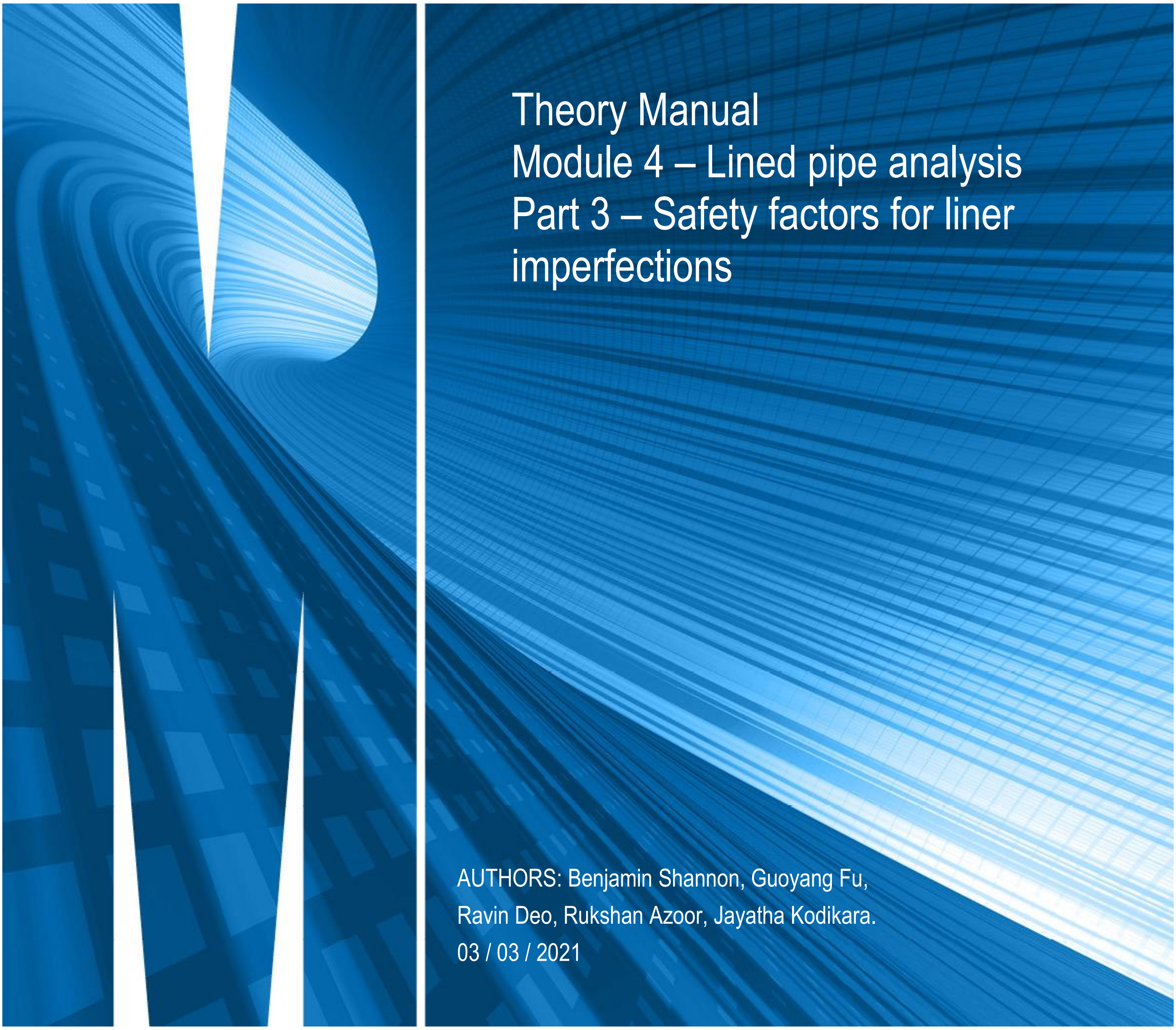

Theory Manual
Module 4 – Lined pipe analysis
Part 3 – Safety factors for liner imperfections

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INTRODUCTION

Monash University were tasked to provide lining innovations to enhance market uptake, including a standard and code of practice of use for CIPP liners and spray liners for pressurised pipes in the CRC-project. This was conducted by undertaking literature reviews, field trials, laboratory testing, and numerical modelling. The research findings were implemented into a standard and code of practice for use in the Australian water industry. A decision tool known as the “Monash Pipe Evaluation Platform” was developed to provide guidance to water utilities, applicators and liner manufacturers in the form of an online web-based platform.

The Monash Pipe Evaluation Platform is split into four modules:

1. Pipe ranking
2. Pipe failure analysis
3. Liner selection
4. Lined pipe analysis

Each module provides tools to help the users to make decisions on pipe rehabilitation.

The following theory manual examines safety factors for two major liner imperfections encountered in spray lining and CIPP. The following imperfections were examined in detail: uneven thickness (spray liner) and folds (CIPP). This manual gives the safety factors to use when either uneven thickness or folds are encountered in the field.

1 LINER IMPERFECTIONS

From the survey conducted during the smart linings for pipes and infrastructure project (see Milestone 3 report), it was found that the following imperfections be examined:

CIPP

- Liner imperfections (folds, wrinkles, dimples, bulges, etc.) – examined through laboratory testing and numerical analysis, to determine reduction factors

Spray

- Variable wall thickness (slump, ringing, etc.) – examined through numerical modelling, to determine reduction factors

Literature review, numerical modelling and testing were conducted to determine the safety factors for folds and slump.

1.1 Effect of uneven thickness in spray liner on liner performance

In the installation process for spray liners, imperfections in the form of uneven thickness may appear due to slumping as shown in Figure 1. The uneven thickness may affect the performance of the liners.

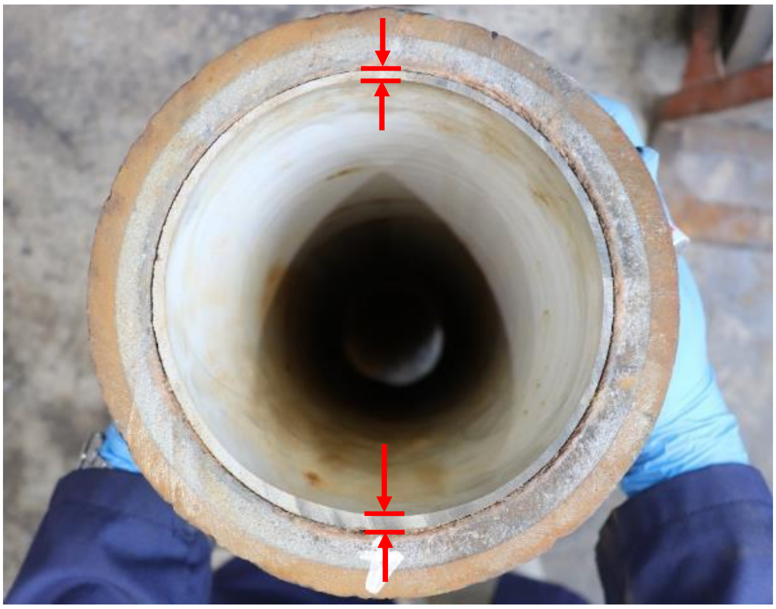


Figure 1. Example of uneven thickness in spray liners

To investigate the effect of uneven thickness of spray lining along pipe circumference on the maximum stress in the liner, finite element models were created to consider the variation of liner thickness along the pipe circumference. For a spray liner with a nominal wall thickness of 3 mm, the minimum and maximum wall thickness of the liner may be 2.5 and 3.5 mm respectively due to effect of slumping. In the numerical models, the values of the wall thickness varied from 2.5 and 3.5 mm, and the minimum wall thickness was considered to be located at the hole area to simulate the worst-case scenario. One of these models is shown in Figure 2.

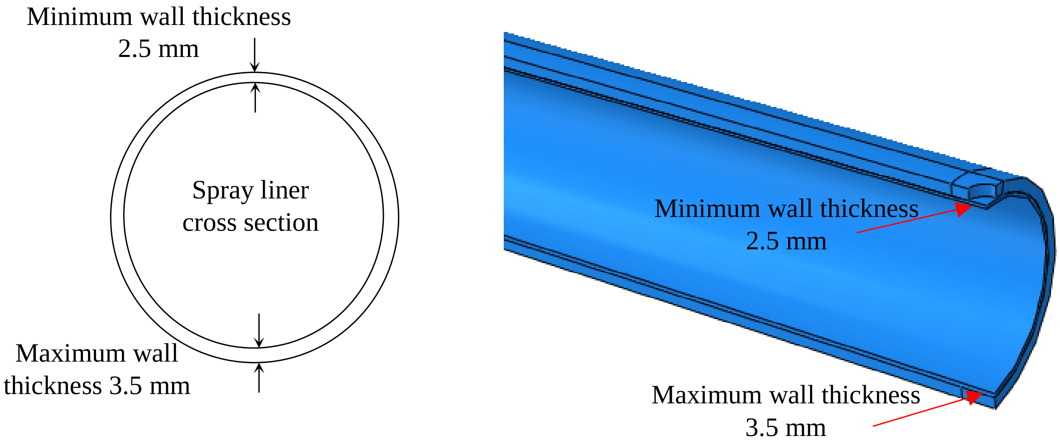


Figure 2. Geometrical model of the spray lined cast iron pipe (DN150) with a circular hole and uneven liner thickness (Quarter model)

The results from the finite element models with uneven thickness are summarised in Table 1 for both the case with friction coefficient 0.3 and the frictionless case. It can be seen that compared with the lined pipes with even liner thickness (3 mm) along the pipe circumference, the maximum stress of those with uneven wall thickness might be increased by up to 35% for the deteriorated cast pipes under an operating pressure of 0.6 MPa. This is more than the 16% that can be attributed solely to the reduction in thickness at the hole from 3.0 mm to 2.5 mm. This shows the importance of limiting the unevenness of the liner thickness to an acceptable level during the installation process. Further testing is required for investigating the effect of slumping and ridging on liner performance.

Table 1. Comparison of maximum stresses in the spray liner with even or uneven thickness

Hole diameter (mm)	**Maximum stress (MPa)**					
	Friction coefficient = 0.3			**Friction coefficient = 0.0**		
	Even liner thickness	**Uneven liner thickness**	**Difference (%)**	**Even liner thickness**	**Uneven liner thickness**	**Difference (%)**
5	0.533	0.61	14	0.526	0.685	30
15	1.9	2.49	31	1.88	2.54	35
25	5.8	7.68	32	5.81	7.71	33
50	18.4	22.57	23	18.9	23.42	24
80	19.9	22.22	12	21.31	23.49	10

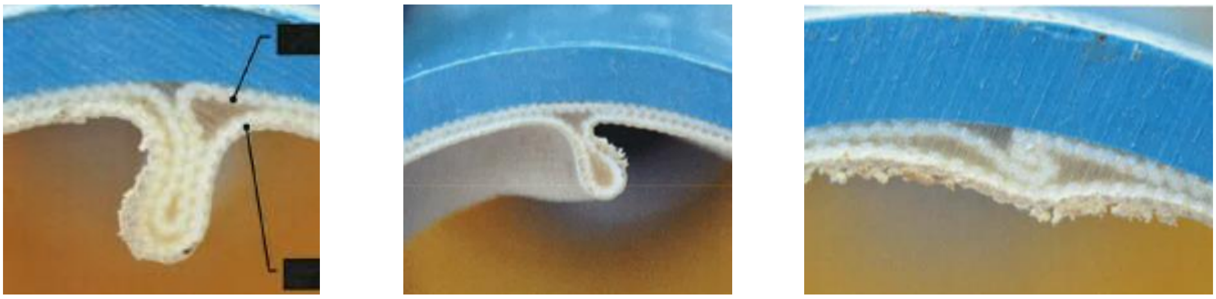
Surface irregularities such as slumping or ridging shall be minimised. For structural performance, the liner shall not introduce surface irregularities in addition to those of the existing pipeline, which exceed the average thickness by ±10% (±0.1 x average thickness). The height of irregularities shall be measured from the internal surface of the liner. A derating factor of 0.67 (Factor of safety for liner imperfections, $N_i = 1.5$) shall be required if surface irregularities are present.

1.2 Effect of liner folds on the strength of CIPP liners

When installing a CIPP liner in a pipeline, the liner may have to be oversized to accommodate the diametrical variations of the host pipe. However, this practice may lead to the formation of liner folds along the entire pipe length. The resulted liner folds may cause large stress concentrations and reduce the designed life of the CIPP liner.

1.2.1 Liner fold geometry

Typical types of folds found in CIPP liners are shown in Figure 3. These liner folds can in general be simplified as a fold shown in Figure 4 and represented by two parameters, namely the depth of fold d and angle of fold θ.



Type I - The inner and outer fabric layers both fold together pushing upwards to form a continuous ridge

Type II - Only the inner layer moves upward and the space between the two fabric layers is filled with epoxy to form a ridge

Type III - Only the outer fabric layer folds over to form a ridge

Figure 3. Types of folds in Aqua-Pipe lining (National Research Council Canada 2015)

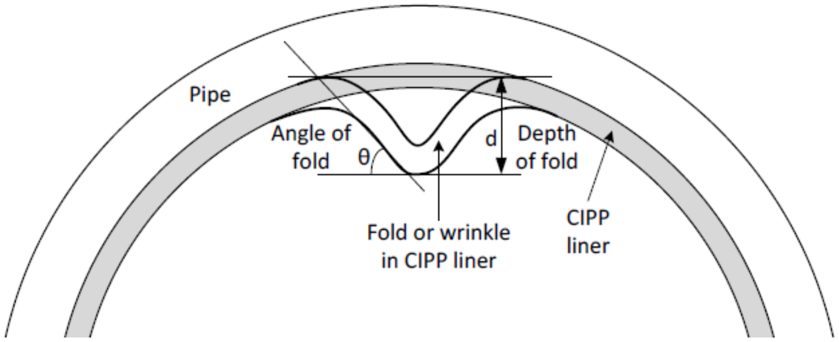


Figure 4. Pipe and liner geometry

1.2.2 Numerical modelling

A bilinear stress strain curve from a CIPP liner was used for modelling. Based on tensile test results, the relevant material parameters for the liner used in the numerical models are given in Table 2.

Table 2. Material parameters of the liner used for the numerical model

Liner Material Parameters	Engineering values	True values
Initial yield stress (MPa)	26.6	26.6
Initial yield strain	0.01	0.00995
Young's modulus (MPa)	2660	2673.3
Failure strain	0.201	0.183
Failure stress (MPa)	74.3	89.2
Strain hardening modulus (MPa)	249.7	361.6
Poisson's ratio	0.17	0.17

CIPP liners were considered to be installed in DN100 and DN150 fully deteriorated host pipes. Liner folds with different angles and depths were considered. The angles are 35˚ and 90˚ while the depth d varied from 5 mm, 7 mm, 11 mm to 15 mm. These parameter ranges were found to fall into the ranges of in-field CIPP observations.

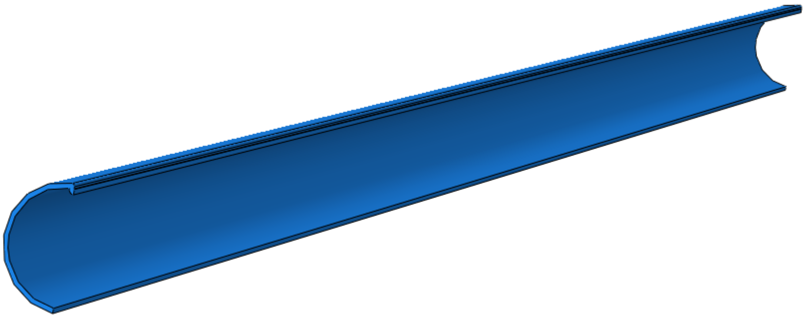


Figure 5. Three-dimensional liner model (DN100, Liner thickness 4 mm)

Finite element models were created to simulate the burst test of CIPP liners with folds. Due to symmetry, a quarter of the liner was created. Figure 5 shows a three-dimensional liner model with liner thickness of 4 mm (DN100). A close view of the liner fold (depth 7 mm and angle 90˚) and its corresponding stress contour around the fold are presented in Figure 6a and Figure 6b respectively. The internal water pressure was applied on the internal surface of the liner until the induced maximum tensile stress reached the liner's tensile strength. It should be noted that the finite element models, the CIPP liners with folds were assumed to be a homogenous material. In other words, the fibres and resin were not considered separately. The CIPP liner was considered to fail when the maximum stress in the liner reaches the ultimate tensile strength of the liner.

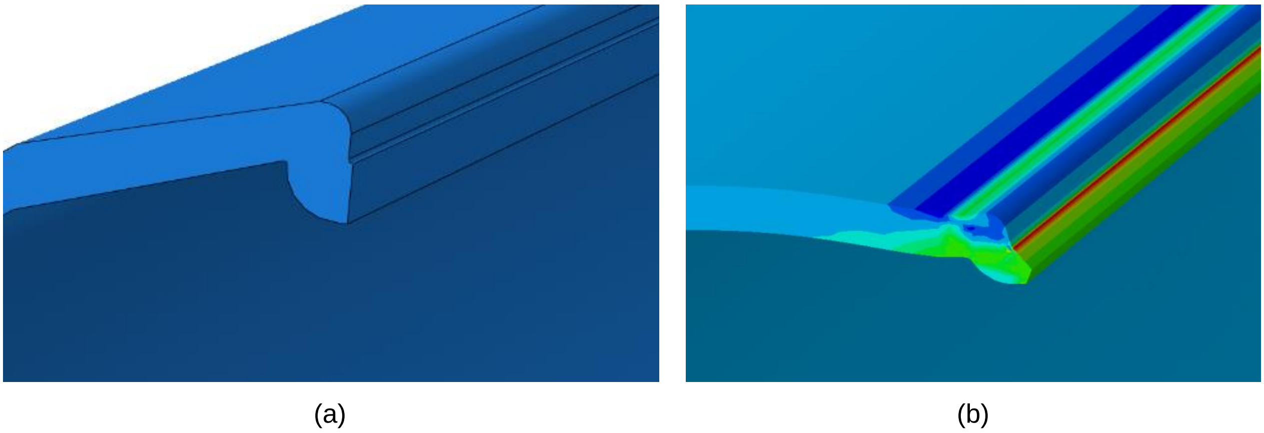

(a) (b)

Figure 6. (a) Close up view of the liner fold in the geometrical model (DN100, fold depth 7 mm and fold angle 90˚) and (b) Close up view of the stress contour around the liner fold (DN100)

1.2.3 Results and analysis

Normalised failure pressure is defined as the failure pressure of the liner with a fold divided by that of the liner without a fold. From Figure 7 and Figure 8, it can be seen that for a given angle of fold, the normalized failure pressure drops quite significantly with the increase of the depth of fold. In addition, in all the simulated cases, for a given depth, a fold with an angle of 90˚ has the minimum normalised failure pressure. Due to the homogenous material assumption and the adopted failure criterion, the numerical models underestimate the failure pressure of the CIPP liners with folds. Further research needs to be conducted to consider the CIPP liner as a composite material and more advanced failure criteria to improve the numerical modelling results.

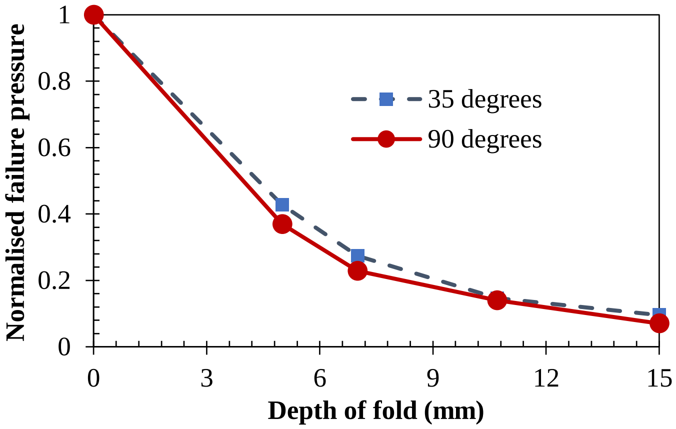


Figure 7. Effect of the depth of fold on the normalized pressure (DN100)

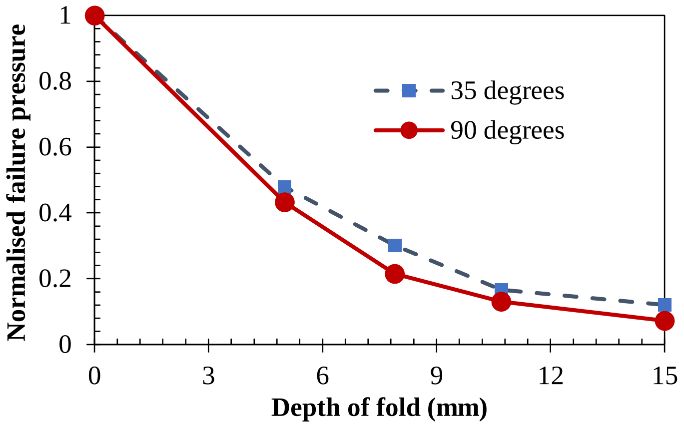


Figure 8. Effect of the depth of fold on the normalized pressure (DN150)

1.2.4 Testing results from Monash

Four burst tests were conducted on a CIPP liner at Monash university. The specimens had oversized liners (this was deliberate to test the effects of folds) and folds of different sizes. The specimens were pressurised until failure. Unfortunately, three specimens had unintentional defects (angle grinder cuts from removing the host pipe) and failed prematurely. Therefore, results of testing should be used as a guide only, with the results influenced by the defects. Figure 9 shows images of the pipe tests at burst.

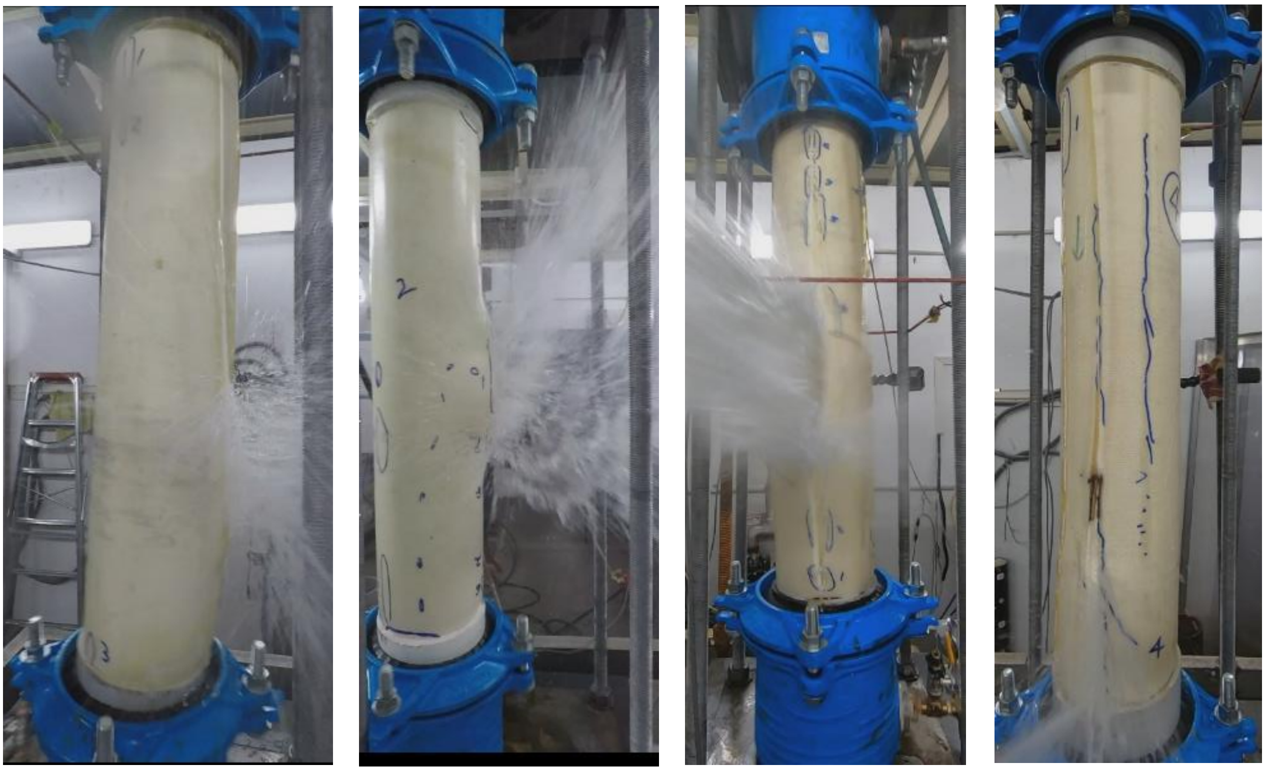

Pipe 1 Pipe 2 Pipe 3 Pipe 4

Figure 9. Images of burst of Aqua-Pipe liners caused by internal water pressure.

Two of the results are plotted in a normalised failure pressure vs. depth of fold graph (Figure 10). Note as the specimens tested all had cutting defects, they are unsuitable for test results. However, as noted no specimen failed below 0.2 normalised failure pressure. The test that was not influenced by grinder cuts had a normalised failure pressure of above 0.4. All tests were conducted at a slower pressurising rate than that accepted by ASTM D1599 (2014).

1.2.5 Results from literature

The NRC report (National Research Council Canada 2015) found no trend between the type of fold, size and the reduction in strength. However, all folds reduced the failure pressure. The results show that the pressure reduction with a fold is generally reduced to around 0.4 to 0.6, regardless of the depth of the fold for a DN150 pipe (Figure 10).

Based on the results of full-scale CIPP liner pressure testing from NRC Canada (2015) and Monash University, the normalized failure pressure decreases with the increase of the depth of the fold for DN150 (Figure 10). However, no obvious trend was found for the normalized pressure for DN300 (Figure 11). The results from split-disk tests by Ampiah *et al.* (2010) showed only small reduction in the liner pressure capacity (Figure 10). This might be due to the short specimens with a length of 250 mm. The study by Jaganathan *et al.* (2007) investigated partially deteriorated cast iron with a through-wall hole and results showed a significantly drop in failure pressure with a maximum reduction of 76% in failure pressure for a 20 mm deep fold. The failure criterion in the numerical analyses (Figure 10) is that the liner is considered to failure when the maximum tensile stress in the liner reaches the liner's tensile strength. Therefore, the predicted failure pressure reduction should be conservative. However, as numerical modelling gives lower normalised failure pressure than laboratory testing, laboratory testing results have been used to determine the safety factors for folds. A normalised pressure line of 0.5 (reduction factor) incorporates the majority of laboratory testing results (Figure 10). Therefore, a factor of safety of 2 is recommended for folds, based on laboratory testing.

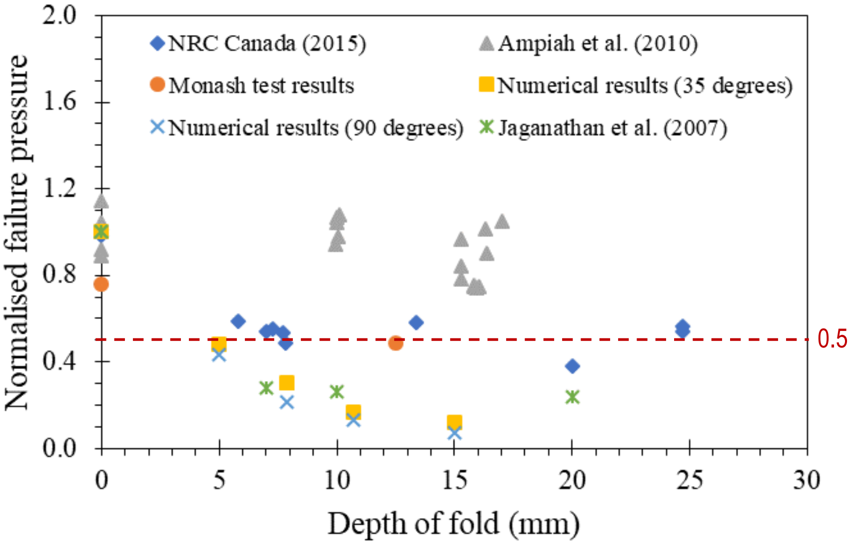


Figure 10. Effect of the depth of the liner folds on the normalized failure pressure (DN150)

Testing conducted on DN300 pipe showed that the reduction in failure pressure ranged from 0.7 to 1, compared with DN150 (Figure 11). It is unknown whether the folds reduce the pressure capacity to a lesser extent due to size effect. As there were no control subjects (with no folds), the failure pressure with no folds could not be determined. Note: fold height is the change in height from the base to the top of the fold. The measured values above include the liner thickness. The DN300 specimens typically exhibited type III folds.

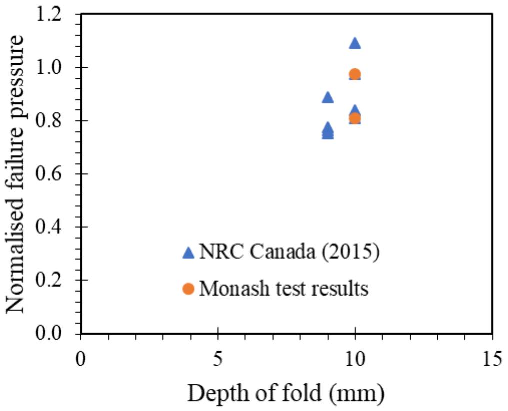


Figure 11. Effect of the depth of the liner folds on the normalized failure pressure (DN300)

Based on Figure 10 for DN150, a limit value of 0.5 of normalised failure pressure used. If the CIPP liner has a fold a reduction factor due of 0.5 (a factor of safety for liner imperfections, small folds, $N_i = 2$) should be used to consider the effect of liner fold on the liner strength (see Figure 10 for reduction factor line). In practice folds should be limited based on standards. For DN300, only very limited data were available and no trend was observed (Figure 11). Further testing is required for investigating the effect of liner folds on liner performance.

1.2.6 Fold safety factor recommendations

To generalize the effect of the depth of the fold on liner strength, the follow recommendation is made:

For hydraulic and structural performance, the liner shall not introduce surface irregularities in addition to those of the existing pipeline, which exceed a height of 2% of the nominal diameter of the pipeline or 6 mm, whichever is the greater. The height of irregularities shall be measured from the internal surface of the liner. If the CIPP liner has a surface irregularity a reduction factor of 0.5 (a factor of safety for liner imperfections, $N_i = 2$) should be used.

Due to the variations observed from the testing results, more experimental tests should be conducted for each liner fold geometry and for pipes with different diameters (e.g., DN100 and DN300). In addition, further testing should be conducted, with experimental and numerical studies for other types of CIPP liners.

Further modelling and experiments are needed to draw firm conclusions.

DISCLAIMER

1. Use of the information and data contained within the Lined Pipe Analysis Module is at your sole risk.

2. If you rely on the information in the Lined Pipe Analysis Module, then you are responsible for ensuring by independent verification of its accuracy, currency, or completeness.

3. The information and data in the Lined Pipe Analysis Module is subject to change without notice.

4. The Lined Pipe Analysis Module developers may revise this disclaimer at any time by updating the Pipe Liner Selection Module.

5. Monash University and the developers accept no liability however arising for any loss resulting from the use of the Lined Pipe Analysis Module and any information and data.

CONCLUSIONS

This document provided a guide on how to gather safety factors for variable liner thickness for spray lining and folds for CIPP. Safety factors were found from a combination of literature review, numerical modelling and laboratory testing. The safety factors found in this document can be used for the Monash Pipe Evaluation Platform and product standards for spray and CIPP.

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