MONASH PIPE EVALUATION PLATFORM

MONASH University

Australian Government
Department of Industry, Innovation and Science

Business Cooperative Research Centres Program

MONASH University Civil Engineering

Theory Manual
Module 4 – Lined pipe analysis
Part 2 – Failure criteria/Limit states

AUTHORS: Guoyang Fu, Benjamin Shannon,
Ravin Deo, Rukshan Azoor, Jayatha Kodikara.

29 / 07 / 2021

QUALITY INFORMATION

Document: Theory Manual, Module 4 – Lined pipe analysis, Part 2 – Failure criteria/Limit states

Edition date: 29-07-2021

Edition number: 1.3

Prepared by: Guoyang Fu, Benjamin Shannon

Reviewed by: Rukshan Azoor

Revision history

Revision	Revision date	Details	Revised by
1.1	17-06-21	Updated to correspond to the standards	B. Shannon, G. Fu
1.2	05-07-21	Updated	B. Shannon, G. Fu
1.3	29-07-21	Added in flow calculations and updated to correspond to the standard version 2.2	B. Shannon, G. Fu

CONTENTS

ACKNOWLEDGEMENTS

The Australian Government, through the Cooperative Research Centre, provided funding for the Smart Linings for Pipe and Infrastructure Project that produced this report. The CRC Program supports industry-led collaborations between industry, researchers and the community.

Australian Government
Department of Industry, Innovation and Science

Business
Cooperative Research Centres Program

The project was led by the Water Services Association of Australia (WSAA) and included the following project partners, all of whom contributed expertise, labour, funding, products or trial sites to assist in the delivery of this project.

Abergeldie Watertech

BASF Australia

Bisley & Company

Calucem GmbH

Central Highlands Water

City West Water Corporation

Coliban Region Water Corporation

Downer

GeoTree Solutions

Hunter Water Corporation

Hychem International

Icon Water

Insituform Pacific

Interflow

Melbourne Water Corporation

Metropolitan Restorations

Monash University

Nu Flow Technologies

Parchem Construction Supplies

Sanexen Environmental Services

SA Water Corporation

South East Water Corporation

Sydney Water Corporation

The Australasian Society for Trenchless Technology (ASTT)

The Water Research Foundation

UK Water Industry Research Ltd (UKWIR)

Unitywater

University of Sydney

University of Technology Sydney

Urban Utilities

Ventia

Water Corporation

Wilsons Pipe Solutions

Yarra Valley Water

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 polymeric 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 in decision making for pipe rehabilitations to water utilities, applicators and liner manufacturers in the form of an online web-based platform.

The 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.

Module 4 Part 2

The following theory manual examines the failure criteria and limit state equations for lined pipe analysis. The limit states are divided into 8 sections that are based on different classes of pipe and host pipe type.

1 LINED PIPE ANALYSIS

Deteriorated pipes lined with polymeric liners may fail by different modes, also known as limit states, depending on the conditions of the host pipes. Host pipes are generally classified into partially and fully deteriorated pipes (ASTM F1216 2016). For partially deteriorated pressure pipes, a liner is considered to support external hydrostatic loads induced by groundwater and/or vacuum pressure, and withstand the internal pressure when spanning any holes, perforations, cracks or gaps in the host pipe wall. For fully deteriorated host pipes, a liner is designed to carry all the external loads and the full internal pressure. Based on AWWA (2019) and latest research outcomes at Monash University, there are in total two limit states for fully deteriorated host pipes and six limit states for partially deteriorated host pipes, considered for the analysis of deteriorated pipes lined with CIPP and polymeric spray liners.

1.1 Failure modes/limit states

1.1.1 Fully deteriorated host pipes

Limit state 1: Internal pressure (hoop failure)

For internal pressure check, the maximum stress in the liner σ_{max} (MPa) shall not be larger than the tensile strength of the liner in the hoop direction (MPa)

$$\sigma_{max} \leq \sigma_{thl} \tag{1}$$

where σ_{thl} is the long-term strength (hoop) of the liner and is the lesser value of either: the tensile rupture strength[1] (hoop) $\sigma_{thl,r}$ determined by either creep rupture (ASTM D2990 2001; ISO 899-1 2017), or hydrostatic design basis tests (ASTM D2992 2018; ISO 7509 2015), based on regression analysis (ISO 10928), or fatigue

[1] Note the value of σ_{thl} can be taken at a time corresponding to the estimated service life. For example, if a liner service life is 50 years, and in that time 50 years of continuous or intermediate pressure (fluid or ground pressure) will be applied on the liner, a σ_{thl} value corresponding to 50 years would be conservative. Alternatively, an estimated duration of internal operating pressure can be used. Note: temperature of testing shall be similar or above the corresponding ground or fluid temperature as σ_{thl} may vary with testing temperature.

strength[2] (hoop) $\sigma_{thl,f}$ based on the likely number of recurring cyclic surge pressure cycles (ASTM D2992 2018; ISO 13003 2003; ISO 15306 2003) in MPa.

The maximum stress shall be determined as follows (ASTM F1216 2016)

$$\sigma_{max} = \frac{P_{max} \cdot \left(\frac{D_L}{T_L} - 1\right) \cdot N}{2} \quad (2)$$

where P_{max} is the maximum allowable pressure, which is the larger of the operating pressure P (MPa) and the sum of the operating pressure P and cyclic surge pressure P_C (MPa) divided by 1.4, $(P + P_C)/1.4$, (AWWA M45 2013), D_L is the external diameter of the liner (mm), T_L is the wall thickness of the liner (mm), N is a factor of safety, which considers the effect of liner imperfections (see TM M4 Part 3 – Safety factors for liner imperfections) and uncertainty in parameters involved in analysis.

Limit state 2: Buckling under external loads (soil, hydrostatic loads, live loads) excluding internal pressure

This limit state applies when the pipe is out of service, e.g. pressure in the pipe is removed for maintenance or the pipe is under vacuum pressure, or when the total external pressure is greater than the operating pressure, P. For buckling check, the total external pressure on pipes q_t (MPa) should be no larger than the liner capacity for total external pressure q_{tc} (MPa)

$$q_t \leq q_{tc} \quad (3)$$

The total external pressure on pipes q_t can be determined as follows (ASTM F1216 2016)

$$q_t = \frac{9.81 \cdot H_w + \gamma_s \cdot H \cdot R_W}{10^6} + w_q \quad (4)$$

where H_w is the height of water above pipe measured from pipe crown (mm), γ_s is the soil unit weight (kN/m^3), H is the pipe burial depth (mm), R_W is the water buoyancy factor (unitless) and shall be determined using Equation (5)

$$R_W = 1 - 0.33 \cdot \frac{H_w}{H} \geq 0.67 \quad (5)$$

where w_q is the live load (pressure) at the burial depth (MPa) from AS 2566.1 (1998), Equation 4.7.2(1). It should be noted that if $q_t \leq P$, the internal operational pressure governs the design (Equation (2)) (AWWA 2019) and buckling under external loads does not need to be checked.

The liner capacity for total external pressure q_{tc} shall be calculated using Equation (6)

$$q_{tc} = \frac{1}{N}\left[\frac{8 \cdot R_W \cdot B' \cdot E_s \cdot C \cdot CRF(\beta t) \cdot E_{LB} \cdot {T_L}^3}{3 \cdot D^3}\right]^{\frac{1}{2}} \quad (6)$$

$$B' = \frac{1}{1 + 4e^{\frac{-0.213H}{10^3}}} \quad (7)$$

where E_s is the modulus of soil reaction[3] (MPa) (AS 2566.1 1998), C is the ovality reduction factor and it is defined as follows

$$C = \left[\left(1 - \frac{\Delta}{100}\right) \Big/ \left(1 + \frac{\Delta}{100}\right)^2\right]^3 \quad (8)$$

[2] Note the value of $\sigma_{thl,f}$ can be taken at a time corresponding to the likely number of recurring cyclic surge pressure cycles estimated for service life. For example, if we predict that a minimum of two surge pressure cycles occur during a day (pump start-up and pump shutdown) the minimum pressure transient cycles to be experienced by a liner in a 50-year service life would be 36,500. From this number we can estimate the $\sigma_{thl,f}$ of the liner.

[3] E_s can be taken from the higher range of values in E'_e and E'_n, in Table 3.2 (AS 2566.1 1998) due to the soil being in its natural state (trenchless installation with host pipe contributing to stiff soil).

where Δ is the percentage ovality of the original pipe[4], $CRF(\beta t)$ is the creep retention factor at time βt, β is the fraction of liner service life when out of service[5], t is the design lifetime of liner (years), E_{LB} is the lesser of: the short-term flexural modulus of elasticity (hoop) of the liner (E_{fh}) (ASTM D790 2017; ISO 14125 1998) or the short-term tensile modulus of elasticity (hoop) of the liner (E_{th}) (ASTM D638 2014; ASTM D3039/D3039M 2017).

where $CRF(\beta t)$ can be found from long-term creep modulus, $E_L(\beta t)$ (GPa) (ASTM D2990 2001; ISO 899-1 2017; ISO 899-2 2017) at any point in time

$$CRF(\beta t) = \frac{E_L(\beta t)}{E_L} \tag{9}$$

1.1.2 Partially deteriorated host pipe

Limit state 3: Hole spanning

A through-wall hole (defect) may form at a zone of graphitization, by a corrosion pit that penetrates through the pipe wall, or at a disconnected service line (Moore 2019).

For hole spanning checks, the maximum stress in the liner σ_{max} (MPa) should be no larger than the tensile strength of the liner (MPa)

$$\sigma_{max} \leq \sigma_{tl} \tag{10}$$

where σ_{tl} is the long-term strength of the liner and is the lesser value of either: the tensile rupture strength of the liner, which can be either in the axial $\sigma_{tal,r}$ or in the hoop $\sigma_{thl,r}$ directions (MPa) or fatigue strength (hoop) of the liner $\sigma_{thl,f}$ (MPa).

σ_{max} shall be determined using the hole spanning equation (Fu *et al.* 2021a) as follows

$$\frac{\sigma_{max}}{P_{max}} = \frac{1.45 \cdot \left(\frac{E_p}{CRF(\mathrm{t}) \cdot E_L}\right)^{-0.183} \cdot \left(\frac{T_L}{D}\right)^{-1.13} \cdot (1 - 0.068 \cdot f) \cdot N}{\left[1 + 21.94 \cdot \exp\left(-20.63 \cdot \frac{d}{D}\right)\right]\left[\frac{T}{D} + 2 \cdot \left(\frac{T}{D}\right)^{-0.052}\right]} \tag{11}$$

where E_p is the modulus of elasticity of the host pipe material (GPa)[6], and E_L is the modulus of elasticity of the liner (GPa). For orthotropic polymeric liners, for E_L the larger value of: the short-term modulus of elasticity in the liner in the hoop (E_{th}) or axial direction (E_{ta}) shall be used. D and T are the internal diameter and wall thickness of the host pipe, f is the friction coefficient of the interface between the host pipe and the liner[7], d is the diameter of the hole (defect) in the host pipe.

Limit state 4: Gap spanning

---

[4] A percentage ovality of the original pipe equals:

$$100 \times \frac{(Mean\ internal\ diamter - Minimum\ internal\ diamter)}{Mean\ internal\ diameter}$$

or

$$100 \times \frac{(Maximum\ internal\ diamter - Mean\ internal\ diamter)}{Mean\ internal\ diameter}$$

[5] A fraction of time out of service is used in this case as in most cases the lined pipe will not be subjected to external loads over a significant period of time, for example 14 days maximum. The creep modulus ($CRF \cdot E_L$) will not experience vacuum and soil loads (host pipe will support a lot of these loads) for the whole service life. Also, the elastic creep modulus will tend to recover when the internal pressure is removed.

[6] The following values of modulus of elasticity of host pipe materials shall be used: Asbestos cement - 15 GPa, Cast iron - 100 GPa, Mild steel - 200 GPa, Ductile iron – 165 GPa.

[7] The friction coefficient ranges between 0 to 0.577 and depends on the adhesion of the liner to the host pipe (or CML). The recommended ranges of friction coefficients for the interfaces between host pipes and polymeric liners are as follows: AC or CML 0.1–0.2 and Metallic 0.3–0.4.

Gaps in deteriorated cast iron pipes may exist due to past pipe repairs, joints or formed due to axial soil movements induced by thermal effects, thrust and/or horizontal vehicle loads etc. In addition, ring fractures or joint failures may occur in pipes subjected to axial tension and/or bending and these ring fractures and failed joints can be considered as gaps with zero width.

For gap spanning checks, the maximum stress in the liner σ_{max} (MPa) should be no larger than the tensile strength of the liner (MPa).

$$\sigma_{max} \le \sigma_{tal,r} \tag{12}$$

where σ_{max} can be a combination of axial, or principal, short-term or long-term tensile stress, $\sigma_{tal,r}$ is the tensile rupture strength (axial) of the liner (MPa).

Three sub-limit states are considered, namely, liner covering existing gap under internal pressure, formation of gaps for lined pipes under internal pressure and lined pipes with ring fractures under internal pressure and bending as shown in Figure 1.

4-1 Liner covering existing gaps under internal pressure

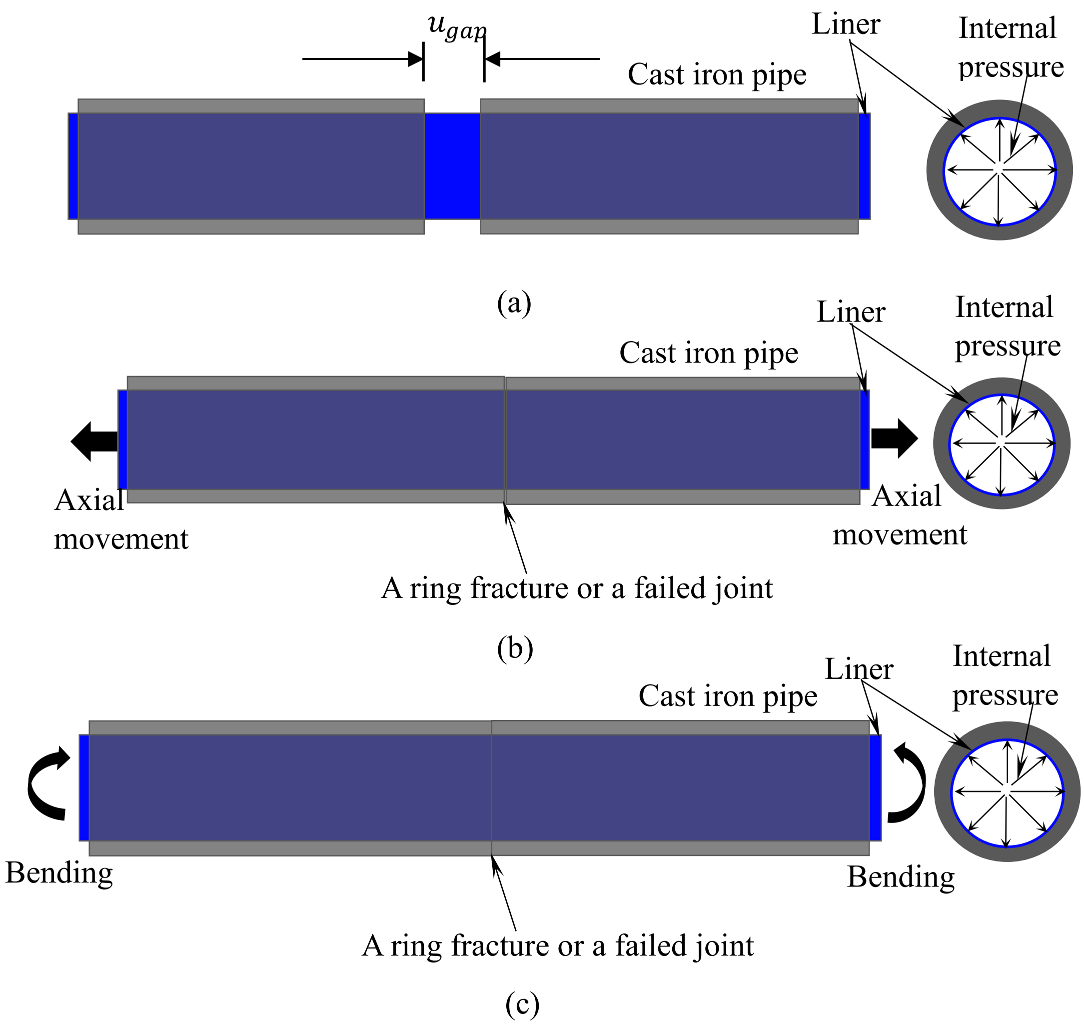

Figure 1. Pressurised cast iron pipes lined with polymeric liners: a) Liner covering existing gaps under internal pressure; (b) Formation of gaps for pressurised lined pipes under axial movements; (c) A lined pipe with a ring fracture under internal pressure and bending

The existing gaps are considered to be formed due to pipe repairs, joints or other causes. When an existing gas is present in a host pipe, the maximum stress in the liner σ_{max} can be determined using the equation as follows (Fu *et al.* 2021b)

$$\frac{\sigma_{max}}{P_{max}} = \frac{2.33 \cdot \frac{u_g}{T_L} \cdot (1 + 0.52 \cdot f - 0.15 \cdot f^2)\left(1 - 0.02 \cdot \left(\frac{E_p}{CRF(\mathrm{t}) \cdot E_L}\right)^{0.5}\right) \cdot N}{1 + 0.39 \cdot exp\left(-2.7 \cdot \frac{CRF(\mathrm{t}) \cdot E_L}{P_{max} \cdot N}\right)} \quad (13)$$

where u_g is the existing gap width of host pipe (mm). Note: Equation (13) is only valid for a gap width of up to 35 mm. For gap widths greater than 35 mm, the pipe should be treated as fully deteriorated (see Limit State 1 - Section 1.1.1). For orthotropic polymeric liners, for E_L the greater value of: the short-term modulus of elasticity in the liner in the hoop (E_{th}) or axial direction (E_{ta}) shall be used.

4-2 Formation of gaps for pressurised lined pipes under axial movements

After a ring fracture has developed in the host pipe, a gap might be formed due to thermal effects, thrust, horizontal vehicle loads or other loads. During the gap formation process, the maximum stress in the liner $\sigma_{a,max}$ (MPa) will develop and can be calculated by the following equation (Fu *et al.* 2021b)

$$\frac{\sigma_{a,max}}{P_{max}} = 31.5 \cdot \left(\frac{u_{gp}}{T_L}\right)^{0.5} \cdot f^{0.4} \cdot \left(\frac{CRF(\mathrm{t}) \cdot E_{ta}}{P_{max} \cdot N}\right)^{0.43} \cdot \left(\frac{E_p}{CRF(\mathrm{t}) \cdot E_{ta}}\right)^{-0.02} \cdot N \quad (14)$$

where u_{gp} is the gap formed due to the axial movement or axial pulling force (mm) and E_{ta} is the short-term tensile modulus of elasticity (axial) of the liner (GPa).

4-3 Lined pipes with ring fractures under internal pressure and bending

The limit state applies when there is a ring fracture or failed joint in the host pipe and the lined pipe is under combined internal pressure and bending. The bending can be caused by ground movements from reactive soils or frost or other sources.

The maximum stress in the liner for a lined pipe with a ring fracture under internal pressure and bending can be calculated using the following equation (Fu *et al.* 2021b)

$$\frac{\sigma_{a,max}}{P_{max}} = \frac{\left(\frac{T_L}{D}\right)^{-0.246}(1 + 0.53 \cdot f - 0.3 \cdot f^2)\theta^{0.82}\left(\frac{CRF(t) \cdot E_{ta}}{P_{max} \cdot N}\right)^{0.81}\left(\frac{E_p}{CRF(t) \cdot E_{ta}}\right)^{0.053} \cdot N}{\frac{T}{D} + 0.043 \cdot \left(\frac{T}{D}\right)^{-0.508}} \quad (15)$$

where θ is the rotation angle of the pipe (°)[8]. Note that this formula was derived based on linear elastic liner properties and therefore underestimates the local capacity of CIPP liners with biaxial stress strain curves or polymeric spray liners with high plasticity.

Limit state 5: Buckling under external pressure

For this limit state, pressure pipes are considered to be depressurized periodically either due to routine maintenance or cyclical events. Note that this is for partially deteriorated host pipe. The polymeric liner is considered to take only the groundwater load while the host pipe takes the soil and surcharge load.

For buckling under external pressure check, the groundwater load P_G (MPa) should be no larger than the groundwater load capacity P_{GC} (MPa)

$$P_G \leq P_{GC} \quad (16)$$

The external pressure capacity shall be determined by the following equation (ASTM F1216 2016)

$$P_{GC} = \frac{2000 \cdot K \cdot CRF(\beta t) \cdot E_{fh}}{(1 - \nu_L^2)} \cdot \frac{C}{\left(\frac{D}{T_L} - 1\right)^3} \quad (17)$$

where K is the enhancement factor of the soil and existing pipe adjacent to the liner. A minimum value of 7 is recommended where there is full support of the existing pipe (ASTM F1216 2016), E_{fh} is the short-term flexural modulus of elasticity in the hoop direction (GPa), ν_L is the Poisson's ratio of the liner.

[8] The recommended range of rotation angle is 0–1°. For a rotation angle greater than 1°, a Class A liner or flexible liner would be recommended, as this could be the equivalent of a broken back failure.

For rigid host pipes, the applied external pressure on the liner P_G shall be determined as follows

$$P_G = \left(\frac{9.81 \cdot (H_w + D_M)}{10^6} + P_v\right) \cdot N \qquad (18)$$

where H_w is the height of groundwater above pipe (mm), measured from pipe crown, D_M is the mean diameter of the host pipe (mm), P_v is the vacuum pressure (MPa) [9].

For flexible host pipes, 50% of the live load is considered to be transferred to the liner (AWWA 2019). This is a conservative estimate since host pipes are assumed to be structurally sound for a Class B design and most host pipes are rigid.

The applied external pressure for flexible pipe shall be determined as follows:

$$P_G = \left(\frac{\gamma_w \cdot (H_w + D_M)}{10^6} + P_v\right) \cdot N + w_q \cdot N/2 \qquad (19)$$

Limit state 6: Thermal effects

When both liner ends are anchored, the lining system shall have sufficient strength in the axial direction to withstand thermal end loads as follows

$$10^3 \cdot \alpha \cdot E_A \cdot \Delta T \cdot N \leq \sigma_A \qquad (20)$$

where α is the coefficient of thermal expansion (mm/mm/°C), E_A is the short-term liner tensile or compressive modulus in the axial direction (GPa), ΔT is the temperature change or maximum range of temperature experienced by the liner during service (°C)[10], σ_A is the short-term tensile or compressive strength of the liner in the axial direction (MPa). Note either tensile or compression can be used but not a combination of the two. For the Monash Pipe Evaluation Platform, the tensile properties are used as the compressive properties are assumed to be similar.

Limit state 7: Adhesion check

Note that a pipe might be depressurised due to routine maintenance, normal operation or cyclical events such as pressure transients. Therefore, given these circumstances, adhesion between the host pipe and liner needs to be checked.

For adhesion check, the external pressure on the liner P_N (MPa) shall be no larger than the adhesion strength of the liner to the host pipe substrate σ_{ad} (MPa)

$$P_N \leq \sigma_{ad} \qquad (21)$$

where P_N shall be determined for two different load combinations as follows

7-1 Combination of external water pressure and vacuum

The external pressure on the liner P_N is the same as P_G as determined in Equation (18).

7-2 Combination of external water pressure and thermal loads

The external pressure on the liner P_N shall be expressed as follows

$$P_N = \frac{\gamma_w \cdot (H_w + D_M) \cdot N}{10^6} + 10^3 \cdot \alpha \cdot E_{fh} \cdot \Delta T \qquad (22)$$

[9] Vacuum pressure ranges from 0 MPa (no vacuum) to 0.1 MPa (high vacuum). If pipe is subjected to vacuum loading a suggested value of 0.1 MPa shall be used if measurements are not available.

[10] The temperature change, fluctuations or maximum range of temperature expected to occur in the host pipe and liner during service. The difference between the maximum and minimum temperature.

Limit state 8: Uniform reduction of pipe wall thickness (for AC pipes)

Due to lime leaching, the effective wall thickness of the AC pipe will reduce over time. Consequently, the maximum stress in the liner σ_{max} will increase over time. To ensure safety, the maximum stress in the liner σ_{max} (MPa) shall not exceed the tensile strength of the liner σ_{thl}

$$\sigma_{max} \leq \sigma_{thl} \tag{23}$$

The maximum stress in the liner σ_{max} can be expressed as follows

$$\sigma_{max} = \frac{E_L P_{max} D_L}{2(E_p T + E_L T_L)} \tag{24}$$

It should be noted that for limit state 8, the maximum stress in the AC pipe σ_p (MPa) shall not exceed the tensile strength of the AC host pipe material $\sigma_{t,AC}$ (MPa).

$$\sigma_p \leq \sigma_{t,AC} \tag{25}$$

The tensile strength of the AC host pipe material shall be determined from either standards (AS 1171 1975; AS A41 1959; BS 486 1933) or AC pipe testing. If no testing results are available the following standard values shall be used:

- for AC pipes buried before 1959, use 15.5 MPa (BS 486 1933)
- for AC pipes buried between 1959 and 1970, use 22.1 MPa (AS A41 1959)
- for AC pipes buried after 1970, use 23.5 MPa (AS 1171 1975)

If this condition is not met then the liner shall be designed as a standalone liner, i.e., the host pipe is considered to be fully deteriorated.

The maximum stress in the AC host pipe σ_p shall be determined as follows

$$\sigma_p = \frac{E_p P_{max} D_L}{2(E_p T + E_L T_L)} \tag{26}$$

1.2 Liner thickness design for a given intended service life

For thickness design, the users are required to select a liner design class first. The liner design class ranges from Class A to D. A Class A liner corresponds to a fully deteriorated host pipe while Classes B and C correspond to a partially deteriorated host pipe. A Class D liner is considered for corrosion protection purposes only. For each liner design class, different limit states need to be check as shown in Figure 2. Take a Class A liner for example, a minimum wall thickness can be calculated for each of the limit states 1 and 2. The minimum design wall thickness of this Class A liner can then be determined as the maximum value of the wall thickness values from limit states 1 and 2.

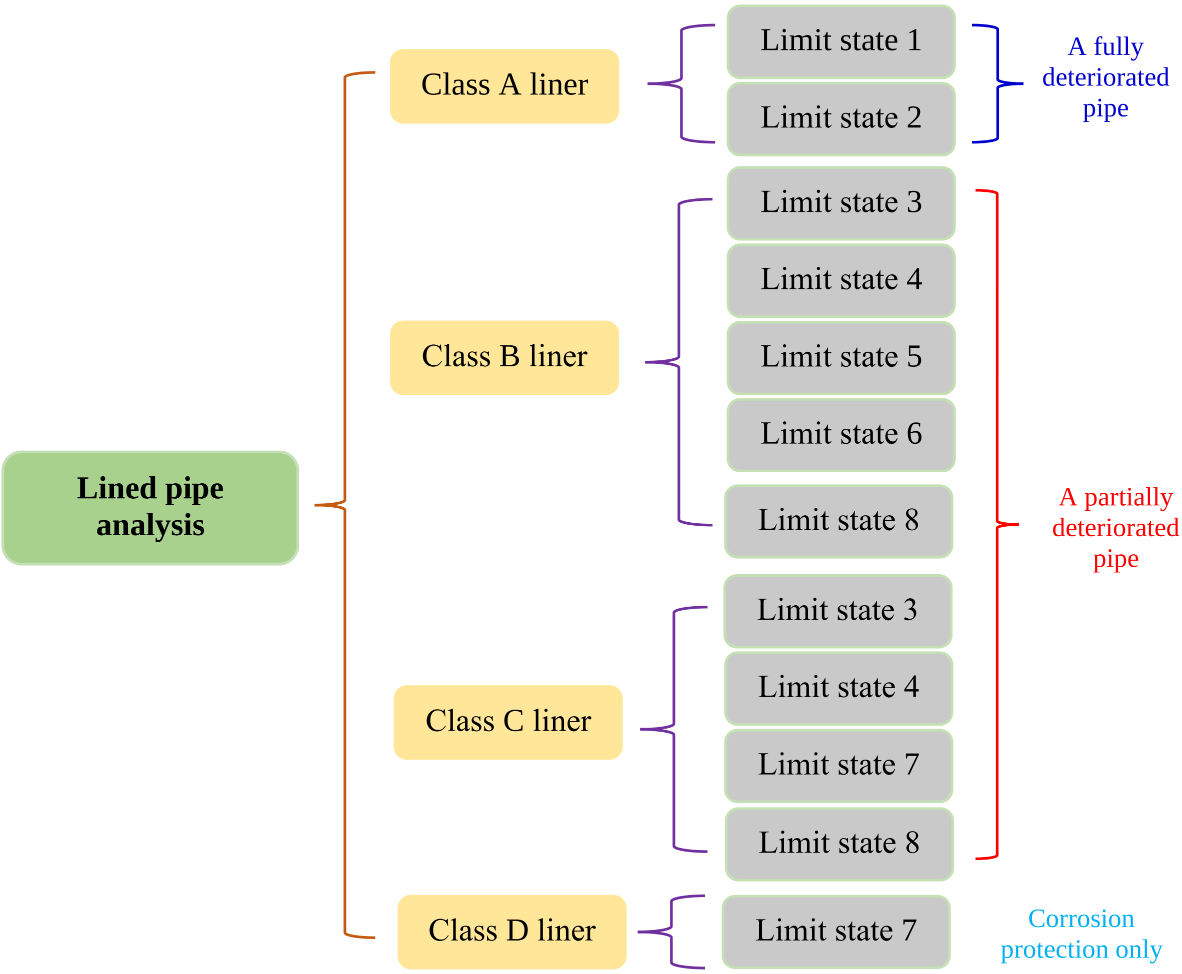

Figure 2. Lined pipe analysis for different classes of linings

1.3 Service life prediction for a given liner wall thickness

For service life prediction of the liner for a given liner wall thickness, the users are required to select a liner design class first, similar to the liner thickness design. For each liner design class, different limit states need to be check as shown in Figure 2. Take a Class A liner for example, a service life can be predicted for each of the limit states 1 and 2. The service life of this Class A liner can then be determined as the minimum value of the service life values from limit states 1 and 2.

2 FLOW RATE CHANGES DUE TO LINING

Two commonly used equations for pipe flow rate/velocity calculation are the Manning's equation and the Hazen-Williams equation. Manning's equation is applicable mainly to open channel flows or partial flows. Hazen-Williams equation has been used commonly for full-pipe-flow problems. Both equations were developed for gravity flows. However, the pressure head may be included in the total head loss gradient for pressurised flow problems.

2.1 Hazen-Williams equation

The Hazen-Williams equation was selected to perform an estimation of the flow rate changes due to lining. The main changes that may occur due to lining are the hydraulic radius and the roughness coefficients.

The Hazen-Williams equation is written as:

$$V = 0.849 C_{HW} {R_h}^{0.63} S^{0.54} \tag{27}$$

where,

V is flow velocity (ms^{-1}), C_{HW} is the Hazen-Williams roughness coefficient (Table 1), R_h is the hydraulic radius (m), defined as the cross-sectional area of the pipe divided by the wetted perimeter. For a circular pipe with full-flow, this is equal to $D/4$ where D is the pipe diameter. S is the slope of the energy grade line, or the head loss per unit length of the pipe (m/m).

2.2 Flow analysis

The lining will result in an inner diameter reduction in the pipe that will alter the hydraulic radius leading to a lower flow rate or velocity. However, the lining surface, being a smooth polymer surface will also alter the roughness coefficient which will improve flow. A simplified schema for the roughness coefficient was used for the Monash Pipe Evaluation Platform and can be modified as required (Engineering Toolbox 2021):

Table 1. Hazen-Williams Roughness Coefficient for common pipe materials

Pipe/Liner type	**Roughness coefficient (C_{HW})**
AC	140
CI	70
CICL	120
DICL	120
MS	100
MSCL	120
CIPP	150
Spray	150

2.3 Results

For common liner thicknesses, the flow through pipes is improved due to a decrease in roughness. The diameter reduction due to lining appears to have a less significant effect.

NOTATION

C Ovality reduction factor

C_{HW} Hazen Williams roughness coefficient

CRF Creep retention factor

$CRF(t)$ Creep retention factor at design lifetime t

$CRF(\beta t)$ Creep retention factor at time βt

d Diameter of the hole (defect) in the host pipe (mm)

D Internal diameter of the pipe (mm)

D_L External diameter of the liner(mm)

D_M Mean diameter of the host pipe (mm)

E_A Short-term tensile or compressive modulus of the liner in the axial direction (GPa)

E_L Short-term modulus of elasticity of the liner (GPa) and is the greater value of: the short-term modulus of elasticity in the liner in the hoop (E_{th}) or axial direction (E_{ta}).

E_{LB} Short-term modulus of elasticity of the liner (GPa) for buckling and is the lesser value of: the short-term modulus of elasticity in the liner in the hoop (E_{th}) or axial direction (E_{ta}).

$E_{l,dry}$ Dry creep modulus of the liner (GPa)

$E_{l,wet}$ Wet creep modulus of the liner (GPa)

E_{fa} Short-term flexural modulus of elasticity (axial) of the liner (GPa)

E_{fal} Flexural creep modulus (axial) of the liner (GPa)

E_{fh} Short-term flexural modulus of elasticity (hoop) of the liner (GPa)

E_{fhl} Flexural creep modulus (hoop) of the liner (GPa)

E_p Modulus of elasticity of the host pipe material (GPa)

E_s Soil modulus (MPa)

E_{ta} Short-term tensile modulus of elasticity (axial) of the liner (GPa)

E_{tal} Tensile creep modulus (axial) of the liner (GPa)

E_{th} Short-term tensile modulus of elasticity (hoop) of the liner (GPa)

E_{thl} Tensile creep modulus (hoop) of the liner (GPa)

f Friction coefficient of the interface between the host pipe and the liner (unitless)

H Burial depth (mm)

H_w Height of water above pipe, measured from pipe crown (mm)

K Enhancement factor

N Safety factor for host pipe

P_{max} Maximum allowable pressure (MPa)

P Operating pressure (MPa)

P_c Recurring cyclic surge pressure (MPa)

P_G Groundwater load (MPa)

P_{GC} Groundwater load capacity (MPa)

P_N External pressure on the liner (MPa)

P_v Vacuum pressure (MPa)

q_t Total external pressure on pipes

q_{tc} Liner capacity for total external pressure

R_h Hydraulic radius (m)

R_W Water buoyancy factor (unitless)

S Slope of the energy grade line, or head loss per unit length of pipe (m/m)

t Design lifetime of liner (years)

T Pipe wall thickness allowing for uniform corrosion (mm)

T_L Liner design thickness (mm)

u_g Existing gap width of host pipe (mm)

u_{gp} Gap formed due to axial movement or pulling force (mm)

V Flow velocity (m/s)

w_q Live load (pressure) at the burial depth (MPa)

α Coefficient of thermal expansion/contraction (mm/mm/°C)

β Fraction of liner service life when out of service

γ_s Soil unit weight (kN/m^3)

Δ Ovality of the original pipe (%)

ΔT Temperature change (°C)

θ Rotation angle (°)

ν_L Poisson's ratio of liner (unitless)

σ_A Short-term tensile or compressive strength of the liner in the axial direction (MPa)

σ_{ad} Adhesion strength of the liner to host pipe substrate (MPa)

$\sigma_{a,max}$ Maximum stress (axial) in the liner (MPa)

σ_{fa} Short-term flexural strength (axial) of the liner (MPa)

σ_{fh} Short-term flexural strength (hoop) of the liner (MPa)

σ_{max} Maximum stress in the liner (MPa)

σ_p Maximum stress in the AC host pipe (MPa)

$\sigma_{t,AC}$ Ultimate tensile strength of AC (MPa)

σ_t Tensile strength of the liner (MPa)

$\sigma_{t,dry}$ Dry tensile strength of the liner (MPa)

$\sigma_{t,wet}$ Wet tensile strength of the liner (MPa)

σ_{ta} Short-term tensile strength (axial) of the liner (MPa)

$\sigma_{tal,r}$ Long-term tensile strength (axial) of the liner (MPa)

σ_{tl} Long-term strength of the liner and is the lesser value of either: the long-term tensile hoop strength, which could be in the axial $\sigma_{tal,r}$ or hoop $\sigma_{thl,r}$ directions (MPa), or fatigue strength, $\sigma_{thl.f}$ (MPa)

σ_{th} Short-term tensile strength (hoop) of the liner (MPa)

$\sigma_{thl,r}$ Long-term tensile strength (hoop) of the liner (MPa)

σ_{thl} Long-term strength (hoop) of the liner and is the lesser value of either: the tensile rupture strength (hoop), $\sigma_{thl,r}$ (MPa) or fatigue strength (hoop), $\sigma_{thl.f}$ (MPa)

$\sigma_{thl.f}$ Fatigue strength (MPa)

ϕ_c Wet creep reduction factor

ϕ_s Wet strength reduction factor

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 provides a guide on the limit states for liner design. The document is used for both polymeric spray and CIPP lining. The Classes of liners can be used to determine the required limit states that need to be addressed for lining. The Monash Pipe Evaluation Platform uses these limit state equations to determine what thickness for lining is required given an intended service life or the service life of the liner given a designed liner wall thickness.

REFERENCES

AS 1171 (1975). Asbestos cement pressure pipes. Standards Australia, Sydney, Australia, pp. 1–28.

AS 2566.1 (1998). Buried flexible pipelines. *In* Part 1: Structural design. Standards Australia, Sydney, Australia.

AS A41 (1959). Asbestos cement pressure pipes and joints. Standards Australia, Sydney, Australia.

ASTM D638 (2014). Standard test method for tensile properties of plastics. *In* ASTM D638. ASTM International, West Conshohocken, PA, USA, pp. 1–17.

ASTM D790 (2017). Standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. *In* ASTM D790. ASTM International, West Conshohocken, PA, USA, pp. 1–12.

ASTM D2990 (2001). Standard test methods for tensile, compressive, and flexural creep and creep rupture of plastics. *In* ASTM D2990. ASTM International, West Conshohocken, PA, USA, pp. 1–20.

ASTM D2992 (2018). Standard practice for obtaining hydrostatic or pressure design basis for "fiberglass" (glass-fiber-reinforced thermosetting-resin) pipe and fittings. *In* ASTM D2992. ASTM International, West Conshohocken, PA, USA, pp. 1–10.

ASTM D3039/D3039M (2017). Standard test methods for tensile properties of polymer matrix composite materials. *In* ASTM D3039. ASTM International, West Conshohocken, PA, USA, pp. 1–13.

ASTM F1216 (2016). Standard practice for rehabilitation of existing pipelines and conduits by the inversion and curing of a resin-impregnated tube. *In* ASTM F1216. ASTM International, West Conshohocken, PA, USA, pp. 1–8.

AWWA (2019). Structural classifications of pressure pipe linings. *In* Suggested proticol for product classification. AWWA (American Water Works Association), Denver, Colorado, USA.

AWWA M45 (2013). Manual M45 - Fiberglass pipe design. AWWA (American Water Works Association), Denver, Colorado, USA.

BS 486 (1933). Specification for asbestos-cement pressure pipes. British Standards Institute, London, pp. 1–20.

Engineering Toolbox. (2021). Hazen-Williams Coefficients [online]. Available from https://www.engineeringtoolbox.com/hazen-williams-coefficients-d_798.html [cited 14-04-21].

Fu, G.Y., Shannon, B., Deo, R., Azoor, R., and Kodikara, J. (2021a). An equation for hole-spanning design of underground cast iron pipes lined with polymeric liners. *Submitted to Tunneling and Underground Space Technology*, **Under review**.

Fu, G.Y., Shannon, B., Deo, R., Azoor, R., and Kodikara, J. (2021b). Equations for gap-spanning design of underground cast iron pipes lined with thermosetting polymeric liners. *Submitted to Tunneling and Underground Space Technology*, **Under review**.

ISO 899-1 (2017). Plastic - Determination of creep behavior - Part 1: Tensile creep. International Standard Organization, Geneva, Switzerland, pp. 1–14.

ISO 899-2 (2017). Plastic - Determination of creep behavior - Part 2: Flexural creep by three-point loading. International Standard Organization, Geneva, Switzerland, pp. 1–14.

ISO 7509 (2015). Plastic piping systems - Glass-reinforced thermosetting plastics (GRP) pipes - Determination of the time to failure under sustained internal pressure. International Standard Organization, Geneva, Switzerland, pp. 1–7.

ISO 13003 (2003). Fibre-reinforced plastics - Determination of fatigue properties under cyclic loading conditions, Switzerland, pp. 1-17.

ISO 14125 (1998). Fibre-reinforced plastic composites - Determination of flexural properties. International Standard Organization, Geneva, Switzerland, pp. 1–18.

ISO 15306 (2003). Glass-reinforced thermosetting platics (GRP) pipes - Determination of the resistance to cyclic internal pressure. International Standard Organization, Geneva, Switzerland, pp. 1–12.

Moore, I. (2019). Engineering ensembles: Addressing technology challenges through research collaborations. *In* No-Dig Down Under 2019, Melbourne, Australia, pp. 1–11.