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# **INTRODUCTION**

Monash University was 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 Smart Linings for Pipe and Infrastructure 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.

Module 4 Part 1 determines the long-term properties of the liner needed to determine the long-term strength, long-term strain and long-term cyclic stress. There are variations of these properties, however, these three properties give a very good indication in to the long-term performance of the liner.

The following theory manual examines the tests used to determine the long-term properties for liners and how to apply these properties. The properties are: strength from creep rupture, long-term strain from creep tests and cyclic long-term strength from fatigue tests.

## 1 LONG-TERM STRENGTH (CREEP RUPTURE)

A Long-term strength curve for the liner materials, either a creep rupture curve (ASTM D2990 2001), hydrostatic design basis (ASTM D2992 2018) or other long-term strength reduction curve, will be used to estimate the remaining strength of the liner for a particular design life input by the user. The experimental testing comprises of a certain number of specimens (minimum 18 specimens) tested under different constant stress levels over time until failure occurs. The time to failure is found for different stress levels. Typically, specimens tested at higher stress levels fail quicker than specimens at lower stress levels. A log tensile strength vs log time curve is plotted to determine the 50-year tensile strength of the material based on all the specimen results (Figure 1). The lower prediction limit (97.5% confident that the next observation will fall above this limit) can be used to determine the safe value of tensile strength to apply at a known year. A safety factor is applied (typically FOS=2), to determine the hydrostatic design stress (HDS).

#### 1.1 Calculate using tensile stress vs. time to failure curve

Consider for example that, the utility has selected a pipe asset with small leakage rates. The intention is to reduce leaking in the pipe and prolong life without burst for another 20 years. The input year was selected as 20 years and during that time the material will degrade at a certain rate. This rate was determined from the creep rupture/hydrostatic design basis curves for the material shown in Figure 1. From Figure 1 it is seen that the material is degrading and can only experience a certain stress (or normalised stress level - testing tensile stress / maximum tensile strength) for a certain period of time. If we were to examine the stress value this liner could withstand at a time period of 20 years (175200 hours), we can use either the lower prediction limit (blue line, LPL) or the equation given. In this case the maximum stress the liner can sustain would be 28.6 MPa (shown by the grey dotted line, not including safety factors).

The calculation method in the Monash Pipe Evaluation Platform uses normalised stress (testing stress / maximum tensile strength) of the creep rupture curves. This is done to account for generic liner properties. The normalised stress value can be multiplied by the initial material tensile strength property to determine a long-term tensile strength value at the intended service life in years. Further properties can be multiplied by this factor for long-term properties.





Figure 1. Creep rupture stress (MPa) vs. time to failure (hours) of (a) CIPP lining material and (b) spray lining material.<sup>1</sup>

## 1.2 Calculating tensile rupture strength based on normalised values

Tensile rupture strength ( $\sigma_{tl,r}$ ) or long-term tensile strength (hoop or axial) at any time is based on creep rupture (ASTM D2990 2001) or hydrostatic design basis (ASTM D2992 2018) for a specified design life (years). The normalised curve can be multiplied by the initial tensile strength in MPa. Wet conditions should be used.

Eq. 1 is used to approximate the deterioration curve based on hydrostatic design basis or creep rupture testing. The equation uses the 95% lower prediction limit (97.5% using lower bound) results, to account for variability in the results and is simplified as a logarithmic curve or power curve. Alternatively, the hydrostatic design stress value can be used if the stress vs. time to failure curve is known.

$$\sigma_{tl,r} = \sigma_t(x_l ln(t_h) + c_l)$$
 Eq. 1

$$\sigma_{tl,r} = \sigma_t(x_l \cdot t_h^{c_l})$$
 Eq. 2

where,  $\sigma_{tl,r}$  is the tensile rupture strength (long-term tensile strength) in MPa at a particular service life/time ( $\sigma_{tl,r}$  can be substituted for  $\sigma_{thl,r}$  and  $\sigma_{tal,r}$  for the hoop and axial values respectively),  $\sigma_t$  is the short-term tensile strength of the liner in MPa ( $\sigma_t$  can be substituted for  $\sigma_{th}$  and  $\sigma_{ta}$  for the hoop and axial values respectively),  $x_l$  and  $c_l$  are coefficients for strength reduction (unitless) and  $t_h$  is the time in hours. For example, if a 50-year service life was required, a time of 438,000 hours would be used. The normalised tensile rupture strength can be multiplied by the initial wet tensile strength to determine the long-term tensile strength at a particular service life.

Note: The same formula can be applied to approximate the long-term flexural strength by substituting short-term wet flexural strength values, however flexural creep rupture testing is preferred.

#### 1.3 Generic coefficients for strength reduction for liners

Table 1 shows the generic coefficients used in the Monash Pipe Evaluation Platform for long-term tensile rupture strength values based on current testing results. These coefficients can be improved if further tests are conducted. Alternatively, users can input a liner products coefficients for strength reduction, based on

<sup>&</sup>lt;sup>1</sup> LPL is the lower 95% prediction limit/interval

LCL is the lower 95% confidence limit/interval



creep rupture or hydrostatic design basis testing, into the Platform (see User manual – UM M4 – Lined pipe analysis). Note: Results are based on the average normalised lower prediction limit values from testing of six different types of liners (3 different CIPP liners and 3 different spray liners). A total of 35 and 57 creep rupture tests were conducted for CIPP and spray liners respectively. The coefficients for strength reduction will vary depending on the liner type and product.

	Hoop (In)		Hoop (power)	
Liner type	x <sub>l</sub>	cl	x <sub>l</sub>	cl
CIPP	-0.017	0.78	0.79	-0.017
Spray	-0.03	0.65	0.65	-0.067

Table 1. Generic coefficients for strength reduction for different liner types.

#### 1.4 Long-term strength calculation based on fully deteriorated host pipe (Class A)

Consider for example that, for a DN150 pipe with an operational pressure (*P*) of 0.7 MPa, in a fully deteriorated condition, a CIPP liner was selected as a possible renovation. The service life required is 50 years. What is the minimum thickness required for the liner to be safe in long-term? Using the long-term strength coefficients (Table 1), and an initial tensile strength in the hoop direction ( $\sigma_{th}$ ) of 75 MPa, and a safety factor (*N*) of 1 (a higher safety factor can be used to account for any imperfections, such as folds, in the liner<sup>2</sup>), the minimum thickness can be calculated. First calculate the tensile rupture strength at 50 years ( $\sigma_{thl,r}$ ), using Eq. 1 and the coefficients for strength reduction in Table 1. Therefore, is  $\sigma_{thl,r} = \sigma_{th}(x_l ln(t_h) + c_l) = 75 \times (-0.017 ln(50 \times 365 \times 24) + 0.78) = 42 MPa$ , so the long-term 50-year tensile strength in hoop direction would be 42 MPa.

Using a factor of safety of 1, the long-term strength, operational pressure and diameter, the minimum thickness required can be calculated (Eq. 3), based on Barlow's formula (ASTM F1216 2016a).

$$T_L = \frac{D_L}{\left(\frac{2\sigma_{thl,r}}{PN}\right) + 1}$$
 Eq. 3

where  $\sigma_{thl,r}$  is the tensile rupture strength (hoop) experienced in a fully deteriorated pipe in MPa,  $D_L$  is the liner external diameter (mm),  $T_L$  is the minimum recommended thickness of the liner in mm, P is the operating pressure in MPa, N is the safety factor (unitless).

The minimum thickness for the liner for a 50-year service life for burst failure only would be 1.23 mm. Note: Further factors of safety may be required, or the hydrostatic design basis strength can be used instead of the long-term strength (For example, if a safety factor of 2 is used, the minimum thickness required would be 2.46 mm). For bending failures, hole spanning, gap spanning and other limit states, further equations will be used to determine minimum wall thickness or service life (See User manual Module 4 – Lined pipe analysis for further details).

## 2 LONG-TERM STRAIN (CREEP TESTING)

Creep is the tendency of polymers to deform over time under the influence of mechanical stresses. It can occur as a result of long-term exposure to constant stress below the yield strength of the material. It is expected that CIPP and spray liners included in this project are susceptible to creep.

Standard creep tests following ASTM D2990 (2001) and ISO 899-1 (2017) for tensile creep were conducted. The CIPP creep specimens are based on ASTM D3039/D3039M (2017), AS 1145.5 (2001) or ASTM D638 (2014) (spray). The CIPP liner specimens, were slightly modified to accommodate the high stress involved on the specimen due to the high thickness (width 20 mm). To avoid specimen movement in the gripping tabs for creep, holes were drilled in the gripping tab lengths with a bolt through the centre (for both spray and CIPP

<sup>&</sup>lt;sup>2</sup> Details of factor of safety for liner imperfections can be found in TM M4 Part 3 – Safety factors for liner imperfections. Users can add additional factor of safeties if needed.



liners). This was used to centre specimen and avoid excess bending and grip slippage. This hole was later removed from CIPP specimens as this was found to reduce tensile stress (due to stress concentrations and fibre slippage). Size effect of using smaller samples for creep testing was examined through tensile testing. Testing was conducted for up to 10,000 hours at a minimum of two stress levels and data were recorded at 30-minute intervals. At some intermediate lengths of time, specimens were removed and tested for remaining tensile capacity (residual tensile strength) to obtain strength degradation curves over time. A total of 60 and 46 creep tests were conducted for CIPP and spray liners respectively. For further test details please refer to individual reports for each of the specific liner type.



Figure 2. CIPP lining tensile creep rig setup

#### 2.1 Determine the long-term creep strain

Findley's power law is used to represent the creep curves from many polymers. Findley et al. (Findley *et al.* 1989; Yang *et al.* 2006) used the following power law to describe the creep behaviour of polymers (Eq. 4 and Eq. 5).

$$\varepsilon_F = \varepsilon_{F0} + \varepsilon_{F1} t^n$$
 Eq. 4

where  $\varepsilon_F$  is the strain,  $\varepsilon_{F0}$  is the time-dependent strain,  $\varepsilon_{F1}$  is the time-dependent term, *t* is time and *n* is the exponent in the Findley power law.  $\varepsilon_{F1}$  and *n* can be found by plotting the creep strain data in a log-log plot

$$\log(\varepsilon_F - \varepsilon_{F0}) = \log \varepsilon_{F1} + n \log t$$
 Eq. 5

Therefore, the slope *n* and intercept at a unit time of  $\varepsilon_{F1}$  are predicted when  $\log(\varepsilon_F - \varepsilon_{F0})$  vs.  $\log t$  is a straight line. Curves under various stresses should be parallel if *n* is independent of stress and state of stress. (this occurs if the strain is below yield or transition from resin to fibre in CIPP). Findley's Power law models the creep curves well for 10,000 hours, except in the case where specimens were tested with loads close to or beyond first yield (CIPP specimens).

For specimens that are significantly affected by humidity, a wet reduction curve should be used. Specimens testing under water is preferred.

Findley's power law was used to determine the tensile creep modulus (gauge and nominal for spray and CIPP respectively) (Figure 3). If specimens were allowed to creep below yield (linear portion of the curve) the tensile creep modulus reduced at a similar rate for each test. Once a modulus reduction curve was found, the average



could be used to determine the tensile modulus at any point in time. However, Findley's law was found to overpredict creep modulus values for CIPP liners that were tested close to yield. In this case the fibres were found to take a higher proportion of the load and subsequently creep was reduced.



Figure 3. Tensile creep modulus (MPa) vs time (hours) for a spray liner (left) and CIPP liner (right).<sup>3</sup>

#### 2.2 Determine the creep retention factor

As initial modulus values vary for each different liner, the modulus reduction was averaged from all the creep test results and then normalised, by using the initial tensile modulus. This is referred to as the Creep retention factor (*CRF*).

$$CRF = \frac{E_{tl}}{E_t}$$
 Eq. 6

where  $E_{tl}$  is the tensile creep modulus (axial or hoop) of the liner (GPa) and  $E_t$  is the short-term tensile modulus of elasticity (axial or hoop) of the liner (GPa). Note: axial and hoop should be kept consistent in Eq. 6.

Findley's power law requires knowledge of the initial strain, which can be calculated from the stress and modulus experienced in the liner. When calculating for thickness, or stress in the liner, in order to determine the creep modulus at any point in time, without resorting to an iterative process, a simplification was made to the creep modulus curve. As modulus reduction is small before 1000 hours, an equation was used for data beyond 1000 hours. In this case if we are solving for long-term, we do not need to use values of less than 1 month. Therefore, by using the CRF the results can be normalised and used for generic liner properties (Figure 4).



<sup>&</sup>lt;sup>3</sup> Spray liner specimens were tested with strain gauges to monitor creep, whereas CIPP specimens were tested with displacement LVDTs, therefore, nominal tensile-creep modulus was used to denote the tensile creep modulus in CIPP specimens.



Figure 4. Creep retention factor (CRF) vs time (hours) for a spray liner (left) and CIPP liner (right).

#### 2.3 Determine the tensile creep modulus

The long-term tensile modulus also known as the tensile creep modulus of the liner  $(E_{tl})$  in tensile and axial directions can be found by multiplying the corresponding creep retention factor by the initial or short-term modulus.

$$E_{tl} = CRF \cdot E_t$$
 Eq. 7

where  $E_{tl}$  is the tensile creep modulus (axial or hoop) of the liner (GPa) and  $E_t$  is the short-term tensile modulus of elasticity (axial or hoop) of the liner (GPa). Note: axial and hoop should be consistent when using either Eq. 7 or Eq. 8. The following equation (Eq. 8) can be used to determine the CRF and subsequently the tensile creep modulus at any point in time.

$$CRF = x_{lc}(t_h)^{c_{lc}}$$
 Eq. 8

where  $x_{lc}$  and  $c_{lc}$  are coefficients for creep modulus reduction. Note: This equation does not predict modulus values well above 1000 hours for CIPP and 100 hours for spray.

#### 2.4 Generic coefficients for creep modulus reduction for liners

The following are the generic coefficients used in the Monash Pipe Evaluation Platform to determine the creep modulus reduction of liners (Table 2) based on testing results. These coefficients can be improved if further tests are conducted. Note: Values are based on average lower bound testing results from 6 different types of liners.

	Axial		Ноор	
Liner type	x <sub>lc</sub>	C <sub>lc</sub>	x <sub>lc</sub>	C <sub>lc</sub>
CIPP Class C	1	-0.106	0.88	-0.14
CIPP Class B to A	1.5	-0.17	1.1	-0.12
Spray <sup>1</sup>	2.16	-0.278	2.16	-0.278

Table 2. Coefficients for creep modulus reduction for different liner types.

<sup>1</sup> Spray lining has the same properties in both the hoop and axial directions

#### 2.5 Long-term calculation based on partially deteriorated host pipe (Class C) – Hole spanning

To renovate an existing pipe system, designing the liner to withstand internal pipe pressures under hole spanning is an approximate method to examine the current and long-term suitability of a liner. In the initial through-wall pit (leak) the host pipe is partially deteriorated causing a leak. This case would be prime for a liner to be applied, reducing the leak rate. Over long-term if this leak is continued the hole may eventually lead to a blow-out. If the pipe was lined when only a small leak occurred, then the lined pipe composite may still function with the larger long-term through wall pit (no leak). For a fully deteriorated pipe, a liner capable of long-term support as a standalone pipe, or pipe replacement (see Section 1.4). In order to calculate the long-term hole spanning capability of a lined pipe composite, a hole spanning equation was developed at Monash University (Eq. 9) (See TM M4 - Lined pipe analysis for further information).

Eq. 9 is used for hole spanning of the composite pipe and liner. Note this equation replaces both equations X1.6 and X1.5 from ASTM F1216 (2016b). Other differences between the Monash equation and ASTM F1216 (2016b) is Eq. 9 uses host pipe properties and tensile strength instead of flexural strength (this is useful when



examining flexible liners<sup>4</sup>). Eq. 9 was validated based on laboratory test results and hole spanning theory (ASTM F1216 2016a; Timoshenko and Goodier 1951).

$$T_{L} = D \left( \frac{\sigma_{thl} \left[ 1 + 21.94 exp\left( -20.63 \frac{d_{f}}{D} \right) \right] \left[ \frac{T}{D} + 2\left( \frac{T}{D} \right)^{-0.052} \right]}{1.45 \left( \frac{E_{p}}{E_{thl}} \right)^{-0.183} (1 - 0.068f) PN} \right)^{-0.885}$$
 Eq. 9

where  $\sigma_{thl}$  is the 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),  $E_p$  is the Modulus of elasticity of host pipe material (GPa),  $E_{thl}$  is the tensile creep modulus (hoop) of the liner (GPa), D is the pipe internal diameter (mm), T is the pipe wall thickness allowing for uniform corrosion (mm),  $T_L$  is minimum liner thickness from hole spanning in mm,  $d_f$  is the future hole (defect) size (mm), f is the friction coefficient of the interface of the host pipe and liner (unitless), P is the operating pressure (MPa) and N is the factor of safety (unitless).

Inputs can be selected from the pre-set values in the Monash Pipe Evaluation Platform.

Consider for example, for a DN150 cast iron pipe with an operational pressure (*P*) of 0.6 MPa, in a partially deteriorated condition, a Class C (Class II) (AWWA M28 2014; ISO 11295 2017) spray liner was selected as a possible renovation. The host pipe wall thickness (*T*) is 7 mm, the pipe modulus (*E*<sub>p</sub>) is 110 GPa and the friction coefficient (*f*) is 0.3. The service life required is 50 years. What is the minimum thickness required for the liner to be safe in long-term? Using the long-term strength and strain coefficients (Table 1 and Table 2), and an initial tensile strength in the hoop direction ( $\sigma_{th}$ ) and initial tensile modulus (*E*<sub>th</sub>), the elastic modulus of the host pipe (*E*<sub>p</sub>) and thickness of the host pipe (T) and a safety factor (N) of 2, the minimum thickness can be calculated. First calculate the long-term hoop strength percentage at 50 years ( $\sigma_{50years\%}$ ), using Eq. 1 and the long-term strength coefficients in Table 1. The initial properties of the spray liner are:  $\sigma_{th}$ = 35 MPa and *E*<sub>th</sub>= 3 GPa. Therefore, is  $\sigma_{50years} = x_l ln(t_h) + c_l = -0.03ln(50 \times 365 \times 24) + 0.65 = 0.26$ , so the strength would be 26% of the initial value after 50 years. So, the long-term 50-year tensile strength in hoop direction would be 9.1 MPa. Then the long-term modulus at 50 years can be calculated using Eq. 7, Eq. 8 and Table 2. Therefore, is  $E_{tl} = x_{lc}(t_h)^{n_{lc}} \cdot E_{th} = 2.16 \times (50 \times 365 \times 24)^{-0.278} \times 3 = 0.17$  *GPa*, so the long-term modulus would be 0.17 GPa after 50 years.

Using the long-term properties and previous information, these values can be input into Eq. 9 to determine the minimum thickness of the liner required in long-term to span a hole (defect) of a certain size. Using the above data, a thickness of 2.56 mm would be required to span a future hole size ( $d_f$ ) of 20 mm. A future hole size can be estimated if corrosion data are available or using the likely corrosivity of the soil (See TM M3 - Liner selection manual for further details).

## 3 CYCLIC SURGE PRESSURE (FATIGUE TESTING)

Dynamic loading (fatigue or cyclic surge pressure) can cause premature failures in pipes (Rathnayaka *et al.* 2016a). Most gravity pressure lines operate under constant pressure, whereas pumped lines frequently do not (PIPA 2010). Cyclic surge pressure (water hammer) from valve open/closures or pump start-up/shut down can varying from a few kPa difference to over 500 kPa difference (over double the operating pressure) (Najafi *et al.* 2015; Rathnayaka *et al.* 2016a). Transients vary by size of the pipe (flow area), speed of the water flow (flow rate), head loss, distance and time (Rathnayaka *et al.* 2016b).

PIPA (2010) mentioned two types of events pipes should be designed for when in fatigue

- Random isolated surge events, e.g., emergency shutdowns, or malfunction (occasional surge pressure)
- Frequent repetitive pressure variations (cyclic surge pressure)

<sup>&</sup>lt;sup>4</sup> A flexible liner is a liner that has no apparent flexural strength (Flexural strength = 0 MPa), however can withstand tensile strength. These liners are very flexible and do not have a rigid resin or polymer component. Flexible liners will not have external buckling resistance.



Random events can be designed based on the maximum and minimum pressure in the system, whereas frequent repetitive pressure variations must be designed according to fatigue. Therefore, when designing for fatigue, it is worthwhile that the engineer knows typical pressure transient cycles and minimum and maximum pressures experienced in the pipes before renovation.

The maximum pressure reached in the repetitive pressure cycle variations should not exceed the static pressure rating of the pipe (PIPA 2010). The following fatigue design was based on PIPA (2010) and PIPA (2018) and modified for CIPP and spray liners.

## 3.1 Previous fatigue testing

Minimal testing has been conducted on fatigue strength reduction in spray and CIPP liners, however testing from similar products can be used as a guide, such as PVC (PIPA 2018), HDPE (Najafi *et al.* 2015) and GFRP. Manjunatha *et al.* (2009) studied the effect of different thermosetting epoxy polymer matrix on GFRP composites. An R-ratio (maximum stress / minimum stress) of 0.1 was used, at a frequency of 1-3 Hz, and in tension-tension cycles. The results of testing show that fatigue is an issue in GFRP composite tested. After roughly 10,000 cycles maximum strength reduction was approximately 50% (364 MPa to 170 MPa). Given the significant reduction of liner strength, this issue should be addressed in CIPP products, especially those reinforced with GFRP.

Loos *et al.* (2012) studied the effect of fatigue on Polyurethanes using S-N curves (stress and the number of cycles to failure) and showed polyurethane was influenced by fatigue. Testing was conducted in tension-tension cycles using R=0.1, f=3 Hz. The initial strength was 70 MPa and decreases to 50% at around 100,000 cycles. Therefore, the effect of fatigue for spray liners should also be examined.

Liners may also have a beneficial effect on reducing fatigue failure of the host pipe, however testing for this was not conducted in the CRC-P program.

## 3.2 Fatigue testing (laboratory)

Fatigue is important to consider for any material but more important for epoxy, fibre-reinforced polymers (FRP), glass fibre-reinforced polymers (GFRP), polyester fibres and polymers. Testing of specimens in fatigue may show accelerated deterioration for both high cycle fatigue and low cycle fatigue. Low cycle fatigue fails in a small amount of cycles, where stress is high and high cycle fatigue fails in a high amount of cycles, however the stress is low.

Testing of specimens in fatigue follows ISO 13003 (2003), fibre-reinforced plastics – Determination of fatigue properties under cyclic loading conditions. The test involves subjecting a flat plate tensile specimen (AS 1145.5 2001; ASTM D3039/D3039M 2017; ISO 527-4 1997) to a maximum and minimum cyclic load. The specimen is cycled until failure and the fatigue life is calculated from the number of cycles to which a test specimen is subjected to until failure of the outer fibres occurs ( $N_f$ ). Specimens will be tested in tension-tension cycles to avoid any compressive forces. A stress ratio ( $R_q$ ) value (ratio of minimum stress to maximum stress) of 0.1 was chosen for specimen testing. The specimen cycling followed a sine wave curve as shown in Figure 5 (values have been normalised using the stress ratio).





Figure 5. Example of cycling fatigue diagram used in testing. Testing is at a frequency of 0.5 Hz.



Figure 6. Cyclic fatigue facility at Monash University.

## 3.3 How to determine fatigue strength

Steady state and transient water pressures all affect the long-term strength of a pipe. Pressure transients can be an issue in water pipe networks. An estimate of pressure transients is particularly difficult without monitoring as the magnitude and propagation of a pressure transient wave will depend on rate of change of flow, hydraulic characteristics of the system components, pipe material, pipe geometry (wall thickness and diameter), and pipe wall friction (Wood *et al.* 2005). Rathnayaka *et al.* (2016a) found moderate pressure transients of 50–200 kPa were able to fail deteriorated cast iron pipes. The pressure transients recorded were dissipated within 2–3 km, however some pressure transients increased the internal pressure 2-fold (Fleming *et al.* 2007). Pressure transients can cause fatigue failure in pipes (Jiang *et al.* 2019). Note: the number of pressure transients per day can be as many as 50 per day (Najafi *et al.* 2015).

A cyclic surge factor  $(n_f)$  is used to incorporate the effect of secondary cycles from cyclic surge pressure (see Figure 8 Cyclic surge pressure). A simplistic approach is to use a pressure cycle is equal to 2 primary cycles due to the decaying surge. Alternatively, the following equations can be used to calculate a factor for number of pressure transients (Joseph 1979; PIPA 2018).



$$n_f = 1 + \frac{1}{\left(\frac{\Delta\sigma_0}{\Delta\sigma_1}\right)^{3.2}}$$
 Eq. 10

where  $n_f$  is the cyclic surge factor (from 1 to 2),  $\Delta \sigma_0$  is the magnitude of the initial pressure cycle wave and  $\Delta \sigma_1$  is the magnitude of the secondary pressure cycle.

Therefore, the total number of pressure transients for the life of the lined pipe  $(n_{TPC})$  would be:

$$n_{TPC} = n_{PC} \times n_f \times t \times 365$$
 Eq. 11

where *t* is the time in years, where in this case is the liner design service life in years.

The number of pressure transient cycles experienced per day  $(n_{PC})$  can be converted into number of surge pressure cycles based on years from Eq. 10. For example, if we assume 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 life would be 36,500. Therefore, if a known range of pressure transient increase in pressure is known for the pipe, a check for fatigue damage could be examined in the liner. The number of pressure transients per day can be as many as 50 per day (Najafi *et al.* 2015).



Fig. 3 Pressure transients generated during events created at section A main pump station: Event set 1

Figure 7. Example of pressure transients in a water network (Rathnayaka et al. 2016a).







#### 3.4 Fatigue strength calculation example

In this example (Figure 7, adapted from Rathnayaka *et al.* (2016a)), examining Site 1, the pressure range of the cycle is from 200 kPa to 500 kPa. The operational pressure is around 300 kPa. The operational pressure (P) + cyclic surge pressure ( $P_c$ ) is 500 kPa. The amount of cycles per day would be 120 cycles/day (5 per hour) and therefore for a 50-year life we would expect approximately 2.19 million cycles (this is an extreme case). This number is multiplied by 2 to account for the secondary cycles (4.38 mil for 100 years), or using Eq. 13 (in this case gives 1.2, less conservative). Note: this was a simulated event, therefore we may not see this in the field as often.

For a DN150 pipe, in a fully-deteriorated condition, a CIPP liner was selected as a possible replacement. The pipe was subjected to the above pressure transients. Using a liner thickness of 5 mm and the following fatigue degradation curves (Figure 9), we can examine the maximum PN rating the pipe can sustain, with and without safety factors.

Therefore, when using a fatigue curve based on pressure class (or stress), we input 4.38 mil cycles into the fatigue chart to examine whether the liner would be safe against fatigue. Using the cyclic fatigue design basis value is for 100 mil cycles. The ultimate tensile strength is approximately 29 MPa after 4.38 mil cycles. Converting to pressure gives a PN rating of 1.93 (with a thickness of 5 mm). Therefore, the pipe is safe ( $P + P_c = 0.5$  MPa). However, this does not take into account any additional safety factors, only the lower confidence and prediction limit factors. Using a factor of safety of 2, the PN rating would be 0.96 MPa, still safe ( $P + P_c = 0.5$  MPa).





Figure 9. Example of fatigue diagram for ultimate tensile strength vs. number of cycles for a CIPP liner.

#### 3.5 Examples on using fatigue curves

How the fatigue curve can be applied with examples for a DN150 CIPP liner with a fully deteriorated host pipe, will be examined in this section. The liner has a short-term ultimate tensile strength of 50 MPa and the fatigue curve is shown in Figure 10.

Example 1: If the liner experiences 50 years of pressure cycles at 1 cycle per day (18250 cycles x 2 =36500 cycles), we can assume the maximum tensile strength from fatigue deterioration will be 45 MPa according to Figure 10 (the example fatigue curve for CIPP). This is a conservative estimate, as we assume the liner is experiencing 45 MPa of stress throughout the 50 years life from the fatigue curve. Therefore, in the design we would use a maximum tensile strength of 45 MPa considering fatigue to determine liner wall thickness. Further guidance for estimating surge frequency in reticulation pipes that are gravity fed will be based on literature.

Example 2: If we examine the same curve (Figure 10), but this time know the operating pressure (0.5 MPa) and cyclic surge pressure (0.5 MPa) the liner will be exposed to, we can get a more accurate answer. The liner outer diameter is 150 mm, and the thickness is 5 mm. The total internal pressure (static and cyclic surge) is 1 MPa, which corresponds to a tensile strength in the liner of 14.5 MPa (this can be derived from pipe strength theory based on pipe diameter, wall thickness, and internal pressure or by using Eq. 13). Based on 1 pressure cycle per day (18250 cycles x 2 =36500 cycles), the liner will be safe from fatigue at this stress level. Therefore, when designing for fatigue deterioration strength, the liner in Example 2 will be safe.

Note: these examples do not use a safety factor.

Example 3: Alternatively, the cyclic fatigue design basis strength, based on 100 million cycles, can be used for design. This includes a factor of safety (N) of 2, however a factor of safety of 1 can be used for a more accurate estimate of life.





Figure 10. Example of fatigue diagram for ultimate tensile strength vs. number of cycles for a CIPP liner.

$$\sigma_{thl,f} = \frac{N_i (P + P_C) (D - T_L)}{2T_L}$$
 Eq. 12

where  $\sigma_{thl,f}$  is the fatigue strength (hoop) of the liner experienced in a fully deteriorated pipe,  $D_L$  is the liner external diameter (mm),  $T_L$  is the minimum liner thickness (mm), P is the operating pressure (MPa),  $P_C$  is the recurring cyclic surge pressure (MPa) experienced by the liner and  $N_i$  is the factor of safety for liner imperfections.

When using the fatigue curves as a check method, the stress level experienced in the pipe should always fall below the fatigue curve for the number of cycles caused by pressure transients to be expected in the renovated pipe. Note: fatigue curves will vary for liner material type and orientation. To check accurately for fatigue damage, relevant fatigue curves for the specific liner product should be used. These can be compared with the transient pressure and actual stress on the liner. Smaller stress ratio values can be tested for if transient pressure is not high in the system, however a stress ratio of 0.1 can be considered conservative.

Note: further testing from ASTM D2992 (2018) should be conducted at higher number of fatigue cycles to get a more accurate deterioration curve. This can either be conducted by the manufactures or others.

## 3.6 Fatigue strength using Monash Pipe Evaluation Platform method

#### Long-term tensile fatigue strength ( $\sigma_{thl,f}$ )

Long-term tensile fatigue strength (hoop) at *x* years is based on fatigue curves (ISO 13003 2003) or cyclic pressure design basis (ASTM D2992 2018) for a specified design life (years). The normalised stress vs. number of cycles to failure ( $N_f$ ) curve can be multiplied by the short-term tensile strength (hoop) of the liner in MPa. Wet conditions (or wet strength reduction factor,  $\phi_s$ ) should be used for spray lining, and CIPP lining as fatigue strength may be impacted by water absorption.

Eq. 13 is used to approximate the deterioration curve based on cyclic pressure design basis or fatigue cyclic testing. The equation uses the 95% lower prediction limit results, to account for variability in the results and is simplified to a logarithmic curve. Alternatively, the hydrostatic fatigue stress value can be used if the service life is 50 years.



$$\sigma_{thl,f} = \sigma_{th} \left( x_{lf} ln(n_{TPC}) + c_{lf} \right)$$
 Eq. 13

$$\sigma_{thl,f} = \sigma_{th} (x_{lf} \cdot n_{TPC}{}^{c_{lf}})$$
 Eq. 14

where,  $\sigma_{thl,f}$  is the fatigue strength (hoop) of the liner (MPa) particular service life,  $\sigma_{th}$  is the short-term tensile strength (hoop) of the liner (MPa),  $x_{lf}$  and  $c_{lf}$  are coefficients for fatigue strength reduction, and  $n_{TPC}$  is the total number of surge pressure cycles for life of pipe/lined pipe. For example, if in a 50-year service life the pipe experiences 1,000,000 pressure cycles this can be inputted into Eq. 13 to calculate the fatigue strength (hoop) of the liner.

## 3.7 Generic coefficients for fatigue strength reduction for liners

The following are the generic coefficients used in the Pipe evaluation platform for cyclic fatigue strength reduction (Table 3). Further testing may alter these values. Note: Results are based on testing from 3 different types of liners.

Liner type	<i>x<sub>lf</sub></i> (ln)	$c_{lf}$ (ln)	$x_{lf}$ (power)	$c_{lf}$ (power)
Spray	-0.0368	1.023	1.1	-0.057
GFRP CIPP	-0.0493	1.146	1.6	-0.12
Other FRP CIPP	-0.0133	0.927	0.94	-0.016

Table 3. Generic coefficients for fatigue strength reduction, caused by cyclic surges, for different liner types.

## 3.8 Step by step guide (modified from PIPA (2018))

To select the appropriate thickness (check if liner is ok) for fatigue loading, the following procedure should be adopted:

1. Estimate or measure the likely cyclic surge pressure ( $P_c$ ). The change in pressure can be assumed as the operational pressure (P) + cyclic surge pressure ( $P_c$ ) (conservative)

2. Estimate the frequency or the number of cycles per day that are expected to occur (can be conducted using a pressure transient logger in the system)

3. Determine the required service life (years) and calculate the total number of cycles that will occur in the pipe lifetime (multiply the number of cycles by 2 to account for cyclic rebound)

4. Using Figure 10 or Eq. 13, look up the maximum stress ( $\sigma_{thl,f}$ ) at the corresponding total number of pressure cycles ( $n_{PC}$ )

5. Convert the stress on the liner into pressure (or use pressure if ASTM D2992 (2018) is used to determine fatigue curves), and determine the minimum thickness required for the liner to internal surge pressure cycles over the service life (including safety factors if required).

6. Alternatively check if the long-term tensile fatigue strength ( $\sigma_{thl,f}$ ) is less the than tensile rupture strength ( $\sigma_{thl,r}$ ) and reassess design using long-term tensile fatigue strength (if  $\sigma_{thl,f} < \sigma_{thl,r}$ ).

Determine whether the pipe is safe for fatigue under required service life.

## NOTATION

- $c_l$  Coefficient for strength reduction
- *c*<sub>*lc*</sub> Coefficient for creep modulus reduction
- $c_{lf}$  Coefficient for fatigue strength reduction
- C Compression modulus (GPa)



- CRF Creep retention factor of the liner
- D Pipe internal diameter (mm)
- *D<sub>L</sub>* Liner external diameter (mm)
- *D<sub>Li</sub>* Liner internal diameter (mm)
- *E<sub>A</sub>* Short-term tensile or compressive modulus of the liner in the axial direction (GPa)
- $E_{fh}$  Short-term flexural modulus of elasticity (hoop) of the liner (GPa)
- $E_{fhl}$  Flexural creep modulus (hoop) of the liner (GPa)
- $E_{fa}$  Short-term flexural modulus of elasticity (axial) of the liner (GPa)
- $E_{fal}$  Flexural creep modulus (axial) of the liner (GPa)
- $E_L$  Short-term modulus of elasticity of the liner (GPa)
- $E_{l,dry}$  Dry creep modulus of the liner (GPa)
- $E_{l,wet}$  Wet creep modulus of the liner (GPa)
- $E_p$  Modulus of elasticity of host pipe material (GPa)
- $E_t$  Short-term tensile modulus of elasticity 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)
- $E_{ta}$  Short-term tensile modulus of elasticity (axial) of the liner (GPa)
- $E_{tal}$  Tensile creep modulus (axial) of the liner (GPa)
- $E_{tl}$  Tensile creep modulus of the liner (GPa)
- *h* Pressure head (m)
- $n_f$  Cyclic surge factor
- $n_{PC}$  Number of recurring cyclic surge pressure cycles per day
- $n_{TPC}$  Total number of surge pressure cycles for the service life of pipe/lined pipe
- N Safety factor for host pipe
- *N<sub>i</sub>* Factor of safety for liner imperfections
- *P* Operating pressure (MPa)
- *P<sub>c</sub>* Recurring cyclic surge pressure (MPa)
- *P<sub>s</sub>* Surge pressure (MPa)
- $P_T$  Test pressure (MPa)
- t Time (years)
- $t_h$  Time (hours)
- *T* Pipe wall thickness allowing for uniform corrosion (mm)
- $T_L$  Liner thickness (mm)
- $x_l$  Coefficient for strength reduction
- $x_{lc}$  Coefficient for creep modulus reduction
- $x_{lf}$  Coefficient for fatigue strength reduction
- *α* Coefficient of thermal expansion/contraction (mm/mm/°C)
- $v_L$  Poisson's ratio of the liner



- $\sigma_A$  Short-term tensile or compressive strength of the liner in the axial direction (GPa)
- $\sigma_{fh}$  Short-term flexural strength (hoop) of the liner (MPa)
- $\sigma_{fhl}$  Long-term flexural strength (hoop) of the liner (MPa)
- $\sigma_{fa}$  Short-term flexural strength (axial) of the liner (MPa)
- $\sigma_{fal}$  Long-term flexural strength (axial) of the liner (MPa)
- $\sigma_{max}$  Maximum stress in the liner (MPa)
- $\sigma_t$  Tensile strength of the liner (MPa)
- $\sigma_{th}$  Short-term tensile strength (hoop) of the liner (MPa)
- $\sigma_{thl,r}$  Tensile rupture strength (hoop) of the liner (MPa)

 $\sigma_{thl}$  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 (hoop) of the liner (MPa)
- $\sigma_{ta}$  Short-term tensile strength (axial) of the liner (MPa)
- $\sigma_{tal,r}$  Tensile rupture strength (axial) of the liner (MPa)
- $\phi_c$  Wet creep reduction factor
- $\phi_s$  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 provided a step by step guide on how to gather long-term properties from the testing conducted at Monash University, with example calculations. Three types of tests were required to gather adequate long-term properties of liners to determine the service life of the liner. The tests are:

- Tensile creep rupture tests or hydrostatic design basis testing (long-term strength)
- Tensile creep tests (long-term modulus / strain)
- Tensile fatigue tests or cyclic long-term hydrostatic strength testing (long-term strength under cyclic surge pressure)

Provided information from these tests (or equivalent testing) is known, the Monash Pipe Evaluation Platform can determine what thickness for lining is required given an intended service life, or to determine the service life of the liner given a designed liner wall thickness. Generic properties from testing can be used in the Pipe Evaluation Platform if the liner properties are unknown.



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