

Advancements in the Experimental Study for the Design and Classification of Cured In Place Pipe (CIPP)
Liners

by

Babajide Ogunbanjo

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Chapters 2 and 3 are advancements of the research works started and reported by Olukayode Awe in his PhD thesis. This thesis presents the results of advanced experimental research which completes, analyzes data generated from longer period of testing, and makes scholarly conclusions on Awe's preliminary research. The initial research findings, testing gaps, and recommendations from Awe's thesis formed the basis for further research works which were completed and reported in this thesis. Dr. Mark Knight supervised all the work completed and reported in this thesis. He also provided technical and editorial feedback on the research work and this thesis.

Abstract

Thermoset Cured In Place Pipe (CIPP) liners have been used extensively in North America to rehabilitate aging buried gravity and watermain pipe networks. The design and performance assessment of CIPP requires a good understanding of its short- and long-term material properties. Unfortunately, the material properties of CIPP have not been studied extensively. This study presents the results of the experimental investigations completed on reinforced and non-reinforced CIPP liners to better understand some of their material properties such as Long-Term Flexural Strengths (LTFS), Strength Retention Factors (SRF), Short-Term Burst Strengths, and Long-Term Hydrostatic Burst properties. Short-term flexural tests and 10,000-hour flexural creep-rupture tests were completed on both reinforced and non-reinforced CIPP flat coupon specimens and the results were plotted and extrapolated to determine their short-term flexural strengths and 50-year (expected service life) LTFS respectively. The LTFS for non-reinforced CIPP liners was determined to be 83.3% - 84.4% of the first break stress. Reinforced CIPP test samples were found to sustain applied stress without failure up to 5% strain limit, and that creep failure will not occur in reinforced CIPP specimens load to 95 percent of the ASTM D790 short-term yield stress. The long-term SRFs of both reinforced and non-reinforced CIPP are greater than the typically applied 50% retention factor.

Full-scale reinforced CIPP pressure liners used for the renovation of watermains were tested using a University of Waterloo designed, built, validated, and commissioned burst testing facility. Short-term burst tests were completed on 150mm and 200mm OD CIPP pressure liners and their short-term burst pressures were determined. Long-term hydrostatic tests were completed on the 200mm OD CIPP pressure liners using the Hydrostatic Design Basis (HDB) standard testing methods. This is in line with the industry-recognized design and classification standard used for other watermain renovation products such as PVC, HDPE, and GRP. The long-term material properties of CIPP pressure liners such as Long-term Hydrostatic Strengths (LTHS), Hydrostatic Design Basis (HDB) stress, Hydrostatic Design Stress (HDS), and Pressure Rating (PR) were determined. The long-term hydrostatic properties of CIPP pressure liners compared well with those of other watermain renovation products. This establishes the HDB design and classification approach as appropriate for designing and classifying CIPP pressure liners. HDB testing found that the CIPP liners is approximately 4 times lower than the short-term burst value.

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Chapter 1

Introduction

1.1 Introduction of CIPP

In North America and across the world, millions of miles of buried water transporting pipeline infrastructure have been in service for many years. The pipeline networks are of different sizes and are buried at varying depths and locations. Most of the buried pipelines are close to the end of their service lives and are at different levels of deterioration. Some are partially deteriorated while others are fully deteriorated. For the pipelines to continue being in service, they must be either replaced or rehabilitated in place. Due to the developments of buildings and other structures in the areas with buried pipelines over the years, open-cut rehabilitation of some buried pipelines has become very challenging. Trenchless rehabilitation of pipe networks using Cured-In-Place-Pipe Liners (CIPP) has been a very viable solution that has been used extensively over the past 20 years. As shown in Figure 1.1, several forces such as hydrostatic load from groundwater, soil load, and live loads act on all buried pipelines. In pressure pipe applications, there is an additional force from internal water pressure acting on pressure pipelines. The effects of the various load types on CIPP liners that are used for the rehabilitation of deteriorated pipelines, both in the short- and the long-term must be understood and factored into the design of the CIPP liners. In North America, CIPP liners are designed using the Non-Mandatory Appendix X1 of the ASTM F1216 design standard equations (Appendix 1). The design equations determine the optimal liner thicknesses based on the mechanical properties of the CIPP liners. Equations X1.2 and X1.6 both require the long-term flexural strength of the CIPP to determine the required thickness. The flexural strength of CIPP is a function of the composition of the liner (reinforced or non-reinforced) which varies from one CIPP product to another. For a CIPP product to be designed correctly, the short and long-term flexural properties such as Short-Term Flexural Strength using the one-minute short-term experimental tests, and the 50-year Long-Term Flexural Strength (LTFS₅₀) using the Long-Term Creep Rupture Test must be experimentally determined.

The Strength Retention Factor property after 50 years of service is then determined from the short and long-term flexural strengths.

In pressure pipe applications of CIPP for watermain pipeline rehabilitation, the material response to the external loads as described in gravity pipe applications, and additional internal water pressure load that can range from 415 to 830 kPa, are considered in the design of the CIPP liner. The internal water pressure exerts tensile force in the hoop or circumferential direction of the CIPP liner which can potentially cause failure in the hoop direction. The CIPP liners designed for pressure applications are classified based on the level of hydrostatic stress they can sustain with a high likelihood that there will not be failure. ASTM F1216 design equations are used to design CIPP for gravity and low-pressure applications such as in low-pressure (140 to 280 kPa) forcemains and siphons. The standard does not have any provision for short- and long-term pressure testing and classification of CIPP liners using hydrostatic internal water pressure as applicable in the field. Hence, there is a need to adopt the industry-recognized Hydrostatic Design Basis testing approach to determine the long-term hydrostatic properties of CIPP pressure liners. The HDB testing approach uses regression analysis of the short-term pressure burst data and the long-term hydrostatic stress test data to determine CIPP liner properties such as the 50-year Long-Term Hydrostatic Strength (LTHS₅₀) which is categorized as the Hydrostatic Design Basis (HDB) stress level of the CIPP liner, the design factor, the Hydrostatic Design Stress (HDS) level and the Pressure Classification (PC) or Pressure Rating (PR) of the CIPP Pressure Liner.

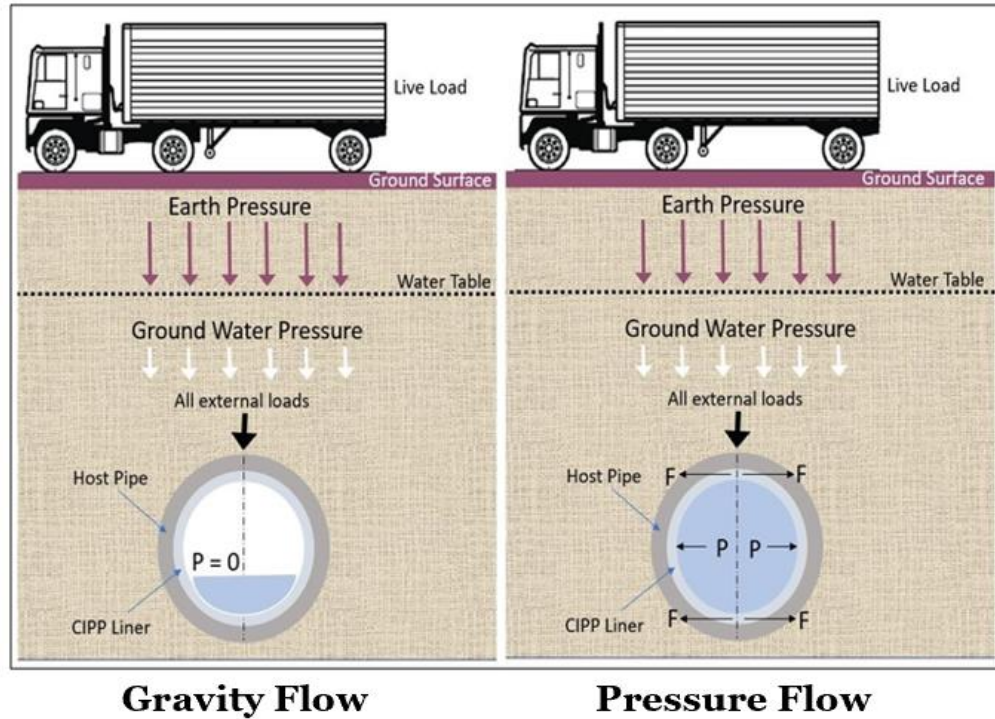


Figure 1.1: Difference between the force distribution in a reinforced gravity CIPP and pressure CIPP liners
(Source: Awe, 2023)

1.2 Background to the Study

In North America and many countries, Cured-In-Place Pipe (CIPP) liners have been used to renovate gravity pipes (wastewater, stormwater, and culverts) and forcemains. Gravity CIPP liners are produced from tubular felt impregnated with polyester or vinyl ester thermosetting resins. The resin-impregnated felt is installed in deteriorated pipes using the inversion method and then cured within the pipe, using heat energy sources such as hot water, steam, or UV light. This forms a CIPP liner within the host pipe. The structural stability of the CIPP liner is based on its design and classification using the American Water Works Association (AWWA) structural classification system (Appendix 1). In the application of CIPP for the renovation of watermain pipe networks, due to the hoop stress caused by the hydrostatic pressure within pressure pipes, there is the risk of failure in the hoop direction of the CIPP liner. This necessitated the

introduction of reinforcements (glass fiber or carbon fiber) to the thermosetting epoxy resins to form a composite polymeric structure.

There are many commercially available non-reinforced and reinforced CIPP liners with varying mechanical properties, depending on their composition and production specifications. They are expected to have service lives of up to 50 years both on gravity and pressure applications. This necessitates the understanding of their short and long-term mechanical properties relevant to their applications.

1.2.1 Design of CIPP for Gravity Applications

In North America, the design of gravity CIPP liners is done using the Non-Mandatory Appendix X1 design equations in ASTM F1216, *“Standard Practice for Rehabilitation of Existing Pipelines and Conduits By The Inversion And Curing Of A Resin-Impregnated Tube,”*. The optimal liner thickness to support all the external loads, internal pressure in spanning holes in the original pipewall, and the operational internal pressure is determined from the ASTM F1216 design equations. The short and long-term mechanical properties of CIPP are fundamental inputs to complete CIPP design. The long-term flexural and tensile strengths of the CIPP liners are determined and used as inputs in the design equations. The long-term flexural properties of CIPP liners are experimentally determined using the Long-Term Creep Rupture Test as specified in the ASTM D2990 *“Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics”* standard procedure. The stress levels at which to complete the Long-Term Creep Rupture Tests are determined by varying the Short-Term Flexural Strength of the CIPP liners estimated using the ASTM D790 - *“Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials”* standard testing procedure. The Strength Retention Factor (SRF) is calculated using the ratio of the 50-year Flexural Strength to the short-term tensile or flexural strength. Typically, the Strength Retention Factor is assumed to be 50% but it has no experimental test data basis to support it. This is based on TTCT Report 302 (1994). Currently, the ASCE MOP 145 design method is being proposed to design circular and non-circular close-fit CIPP gravity pipe rehabilitation liners. This is targeted at addressing the limitations noted in the current ASTM F1216 design method.

1.2.2 Design of CIPP Liners for Pressure Applications

According to Knight and Bontus (2018), watermain pipelines have an average operating pressure of between 415kPa – 830kPa which is much higher than the 140kPa – 280kPa mean operating pressure of forcemains and siphons in gravity pipe systems. Unfortunately, ASTM has yet to develop a standard for the design and pressure classification of CIPP Pressure liners, the ASTM F1216 Non-Mandatory Appendix X1 design equations used for gravity liner designs are still being used to design CIPP pressure liners. Though this method has been used successfully, there is no provision to determine the pressure class of every commercially available CIPP Pressure Liner. Other products in the pressure pipe network renovation industry such as Polyvinyl Chloride (PVC), High-Density Polyethylene (HDPE), and Glass fiber Reinforced Polymer pipes are designed and pressure classified using the industry-accepted Hydrostatic Design Basis design and testing approach. Full-scale pipe products are pressure tested both in short and long terms to determine their hydrostatic pressure and stress properties such as the Long-Term Hydrostatic Strength over 50 years' of service, the Hydrostatic Design Basis, Hydrostatic Design Stress, Design Factor, and Pressure Class are then estimated. The HDB testing approach can be adapted to pressure classify CIPP liners designed with ASTM F1216 design equations, using a hybrid ASTM HDB testing procedure.

1.2.3 Short and Long-Term Flexural Tests of CIPP Coupons

Two types of commercially available non-reinforced and reinforced CIPP coupons were tested in the short term and reported by Awe, 2023. Insituform Technologies Limited supplied all the CIPP coupon specimens used for all the flexural tests. The non-reinforced CIPP coupon types used for the short-term flexural tests were labeled L721 and L758 while the reinforced CIPP pressure liner specimens tested were labeled I-MAIN and I-PLUS. The short-term flexural strengths of the CIPP coupons were experimentally determined per ASTM D790 - *"Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials"* standard testing procedure. The mean short-term flexural strengths of non-reinforced L721 and L758 specimens were estimated as 56.0 MPa with a standard deviation of 0.13 MPa, and 50.0 MPa with a standard deviation of 2.49 MPa, respectively. The mean flexural strain

values for L721 and L758 specimens at mean short-term flexural strengths were 4.56% (with a standard deviation of 0.55%) and 3.97% (with a standard deviation of 0.46%) respectively. The mean flexural strengths of the reinforced I-PLUS and I-MAIN test specimens were estimated as 201 MPa (with a standard deviation of 7.73 MPa) and 219 MPa (with a standard deviation of 3.88 MPa), respectively. The mean flexural strain values for I-PLUS and I-MAIN specimens were approximately 5%.

The non-reinforced CIPP specimens L721 and L758 were tested using the long-term creep rupture test procedure as specified in the ASTM D2990 test standard. The specimens were tested for only 3,000 hours and the test data generated were plotted using regression analysis to estimate the 50-year Long-Term Flexural Strengths (LTFS₅₀) of the non-reinforced CIPP coupons as 32.0 MPa and 34.0 MPa respectively. The Strength Retention Factors were estimated as 55% and 65% for L721 and L758 respectively.

The reinforced CIPP liners I-MAIN and I-PLUS were also tested per the long-term creep rupture test procedure outlined in ASTM D2990 for 3,000 hours to estimate their 50-year Long-Term Flexural Strengths. The LTFS₅₀ were estimated to be 177 MPa and 188 MPa for the I-PLUS and I-MAIN specimens respectively, while the strength retention factors were calculated as 85% and 80% of the mean short-term flexural strengths.

1.2.3.1 Research Gaps in the Experimental Study of CIPP Flexural Properties

The ASTM D2990 specifies that for materials that will be in service for more than six months, a Long-Term Creep Rupture Test for longer than 3,000 hours should be completed. The results of the Long-Term Flexural Properties of both non-reinforced and reinforced CIPP coupons were only adequate for materials to be in service for six months or less. The reported results in Awe (2023) cannot be considered sufficient for the prediction of the long-term (50-year) flexural properties of the CIPP coupon specimens because they only lasted for 3,000 hours which is less than the standard recommended testing time for estimating the long-term properties of materials to be in service beyond 3,000 hours.

1.2.4 Short and Long-Term Hydrostatic tests of Full-Scale CIPP

Short and Long-Term Hydrostatic tests were completed on full-scale CIPP Pressure Liners per an ASTM D1599 short-term test standard, and a hybrid procedure derived from ASTM D2837 and ASTM D2992 respectively. For these tests to be completed, a pipe pressure burst testing facility was designed, built, and commissioned at the University of Waterloo. The performance of the burst testing facility was validated by testing it with PVC 1120 DR-18 pipes 150 mm diameter of 1.5 m lengths. The burst pressures of the PVC pipes ranged from 5.86 to 6.81 MPa with a mean burst pressure of 6.37 MPa. This is close to the 6.49 MPa burst pressure which was mathematically determined for PVC pipes. These results validated the performance of the burst testing facility. ASTM D1599 standard 60-70 seconds short-term burst tests were completed on 150 mm and 200 mm OD full-scale CIPP pressure liners and their mean short-term burst pressures were determined to be 5.47 MPa with a standard deviation of 0.36 MPa, and 5.11 MPa and a standard deviation of 0.34 MPa respectively. The results of the short-term burst tests on the 200 mm OD full-scale CIPP pressure liners formed the basis for the long-term hydrostatic burst tests. The hybrid long-term hydrostatic burst test procedure had five time-sections ranging from <10 hours, 10 – 1,000 hours, 1,000 – 6,000 hours, > 6,000 hours and > 10,000 hours. The long-term hydrostatic tests completed and reported by Awe, 2023 covered the first three-time sections with a maximum testing time of 1,623 hours. The data generated from the tests was analyzed using regression analysis and an interim regression line was developed and extrapolated to estimate the Long-Term Hydrostatic Strength (LTHS₅₀) which was categorized as the Hydrostatic Design Basis (HDB) of 22.2 MPa at 95% Lower Confidence Limit. The design factor (DF) was estimated as 0.4 and the Hydrostatic Design Stress and the interim Pressure Classification of the CIPP were 8.9 MPa and 1.04 MPa respectively.

1.2.4.1 Research Gaps in the Hydrostatic Burst Testing Study

A major deficiency design was observed in the burst testing facility during the long-term hydrostatic tests. Despite the design of the built burst testing facility with detachable components for ease of maintenance, tests had to be stopped and specimens depressurized for any maintenance operation to be completed.

The long-term hydrostatic testing plan derived from the ASTM standards had to have burst stress data for five time-sections, but the results reported by Awe (2023) only covered only the first three time sections. This makes the tests and regression analysis results incomplete and inadmissible as the long-term hydrostatic properties of the CIPP pressure liner specimens.

1.3 Research Goals and Objectives

Based on the identified research gaps, the goals of this study are:

1. To advance the design and classification approach currently adopted for CIPP liners by experimentally quantifying the short and long-term flexural properties of non-reinforced and reinforced CIPP liners at various levels of flexural stress, under specific environmental conditions using flat CIPP coupon specimens.
2. To advance the standardization of the design and classification of CIPP Pressure Liners using the industry-accepted Hydrostatic Design Basis (HDB) testing methods

These goals will be achieved by pursuing the following specific research objectives:

1. By re-analyzing the short-term flexural behavior and properties of both reinforced and non-reinforced CIPP specimens from the results of the tests completed on rectangular coupons using standard ASTM D790 short-term flexural testing methods. To make design recommendations based on the results of the analysis.
2. To determine the long-term flexural creep-rupture properties and the strength retention factors (SRF) of both reinforced and non-reinforced CIPP specimens by completing an additional 7,000 hours of the long-term flexural testing of the rectangular coupons using the standard ASTM D2990 Flexural Creep-Rupture test methods. To make design recommendations based on the results of the tests.

3. To compare the SRFs of both reinforced and non-reinforced CIPP specimens to the generalized 50% SRF to ascertain the potential design error in using this generalized factor. To validate the need to determine the SRF of each CIPP type using standard testing methods and make CIPP design and classification recommendations based on results.
4. To upgrade the design and revalidate the performance of the Burst Testing Facility at the University of Waterloo, and to use it to complete both short-term pressure burst tests and long-term hydrostatic tests on the 200mm OD full-scale reinforced CIPP liners.
5. By determining the short-term burst pressures of the second batch of the full-scale reinforced CIPP pressure liner specimens per the ASTM D1599 standard testing method, as a requirement to use the new specimens to continue the long-term hydrostatic testing.
6. To complete long-term hydrostatic testing of CIPP pressure liners to generate the required failure data for the last two-time sections of the standard experimental plan (> 6,000 hours and > 10,000 hours' time sections) required to complete the development of the first HDB Regression Curve for CIPP in North America.
7. To analyze the long-term hydrostatic test data using regression analysis and extrapolate the regression line to determine the 50-year Long-Term Hydrostatic Strength (LTHS₅₀), Hydrostatic Design Basis (HDB), Hydrostatic Design Stress (HDS), and Pressure Class (PC) of the reinforced CIPP pressure liner specimens. To establish the use of HDB test methods as a standard for the design and classification of CIPP pressure liners.

1.4 Thesis Structure

This thesis is manuscript-based, and the chapters are currently being prepared for publication in academic journals in contribution to knowledge and engineering application. Chapter 2 addresses the first goal and some of the objectives of this thesis. It reviews and re-analyzes the research works completed by Olukayode Awe in his PhD thesis. The chapter reports the identified research gaps that formed the basis of the advancements in the experimental study of the flexural properties of CIPP liners reported in this thesis. Chapter 3 addresses the second goal and the other objectives of this thesis. It also reviews and reanalyzes the research works completed by Olukayode Awe on the short- and long-term properties and pressure classification of CIPP Pressure Liners. It identifies the research gaps and reports the advancements in the experimental study of the design and pressure classification of CIPP Pressure Liners. Chapter 4 details the contributions of this research to knowledge and engineering applications based on the research goals and objectives.

Chapter 2

Flexural Properties of CIPP Liner Specimens: Short- and Long-Term Creep-Rupture Tests

2.1 Overview

In North America, there has been a generalized application of a 50% strength retention factor (SRF) to the short-term flexural strength of Cured-In-Place Pipes (CIPP) to determine the long-term flexural strength. Unfortunately, the practice of using this value has limited experimental flexural creep-rupture test validation to support its correctness. As such, this practice has been controversial in the CIPP design industry. To put an end to the controversy, 3,000-hour plus flexural creep-rupture tests were completed by Awe, (2023), on two resin types each, of non-reinforced and reinforced CIPP specimens at room temperature following the standard testing methods and procedures as stipulated in ASTM D2990 - *“Standard Test Methods For Tensile, Compressive, And Flexural Creep And Creep- Rupture Of Plastics,”*. The results of the 3,000-hour tests showed that the long-term (50-year) flexural SRF for the non-reinforced test specimens (55-65%) and SRF for the reinforced test specimens(80-85%) do not agree with the generalized SRF (50%) typically used for design.

Although ASTM D2990 recommends testing materials for up to 3,000 hours to determine their creep-rupture response of the CIPP liners at a particular temperature, it also states that for the design of parts that will bear constant loads for six months or longer, test times longer than 3,000 hours are usually necessary. That condition makes the results reported by Awe (2023) insufficient to predict material behavior of the tested CIPP liners in the long term. This study reports the findings of the continued creep-rupture tests on the same set of test specimens (used for the 3000-hour test) for up to 10,000 hours (industry standard for long-term tests) and then extrapolated to 50 years to determine the CIPP Long-term (50-year) Flexural Strength ($LTFS_{50}$) and Strength Retention Factor (SRF) values for the four commercially available CIPP products were determined. The results showed that the $LTFS_{50}$ for the non-reinforced test specimens were (31.3 MPa and 30.8 MPa) and SRF of (60% and 61.2%). In applying the test results to the design of CIPP liner products, it was recommended to use 83.4% and 84.4% of the first break

stress values of the non-reinforced CIPP liner specimens as the long-term flexural strength. The reason is that the flexural strength values of both non-reinforced CIPP liners beyond the first break stresses tend to be very unpredictable. For the reinforced test specimens, the $LTFS_{50}$ values were determined to be 178MPa and 191MPa while the SRF values were estimated as 89% and 91% which do not all agree with the generalized SRF (50%) typically used for design. Therefore, using test-established short- and long-term mechanical properties of CIPP products is important to avoid errors in design.

2.2 Goal and objectives of the study

The goal of this study is to better understand the short- and long-term mechanical properties of non-reinforced and reinforced CIPP liners, as well as, to advance the design approach currently adopted for CIPP liners, by experimentally quantifying their short- and long-term mechanical responses to various levels of flexural stress under specific environmental conditions using flat CIPP coupon specimens.

This goal is achieved by pursuing the following specific research objectives:

1. To determine the short-term mechanical properties and behavior of both reinforced and non-reinforced CIPP specimens to flexural stress by testing the rectangular coupons using standard ASTM D790 short-term flexural test methods.
2. To determine the long-term flexural creep-rupture behavior and the strength retention factors of both reinforced and non-reinforced CIPP specimens by testing the rectangular coupons using the standard ASTM D2990 Creep-Rupture test methods.
3. To compare the SRFs of both reinforced and non-reinforced CIPP specimens to the generalized 50% SRF to ascertain the potential design error in using this generalized factor, and to validate the need to determine the SRF of each CIPP type using standard testing methods.
4. To use the short- and long-term material responses of both non-reinforced and reinforced CIPP specimens to various levels of flexural stress to make design recommendations.

2.3 Introduction

The use of Cured-In-Place Pipe (CIPP) liners has been growing in the trenchless rehabilitation of underground pipe systems over the last five decades in North America and across the Western world. Currently, there are two broad designs of CIPP liners - reinforced and non-reinforced CIPPs. They differ in both design and application. Non-reinforced CIPP liners are polymeric materials made from thermoset resins-impregnated needle-felt materials tubes, which are cured using heat sources such as hot water, steam, or UV lights. They are commonly used in circular gravity pipe applications. Reinforced CIPP are composite polymeric materials made by incorporating reinforcement materials such as glass or carbon fibers into thermoset resin-impregnated felt materials to increase their resistance to tensile stress. These incorporated reinforcements make them suitable for pressure pipe and non-circular gravity applications. Creep is the continuous deformation of thermoset resins caused by the slippage of cross-linked polymers when subjected to constant and sustained stress. ASTM D2990 also defines creep as the progressive deformation of a material at constant load stress. This happens in both reinforced and non-reinforced CIPP. Failure in polymeric materials caused by continuous creep is called creep-rupture.

Creep in many polymeric materials, such as CIPP, occurs in three stages which is idealized in Figure 2.1. Creep-rupture, as defined in ASTM D2990, is measured when a constant load is applied to a specimen in selected loading configurations, (such as tension, flexure, or compression) at a constant temperature, and the deformation is measured as a function of time to eventual failure. There is an initial rapid elongation stage in the materials upon application of the load which are the elastic and the plastic strains. This is followed by a primary creep stage where the creep rate decreases rapidly with time. The material then reaches the secondary stage where steady-state creep strain occurs over time. The secondary stage is then followed by a tertiary stage where creep rapidly increases and the material ruptures.

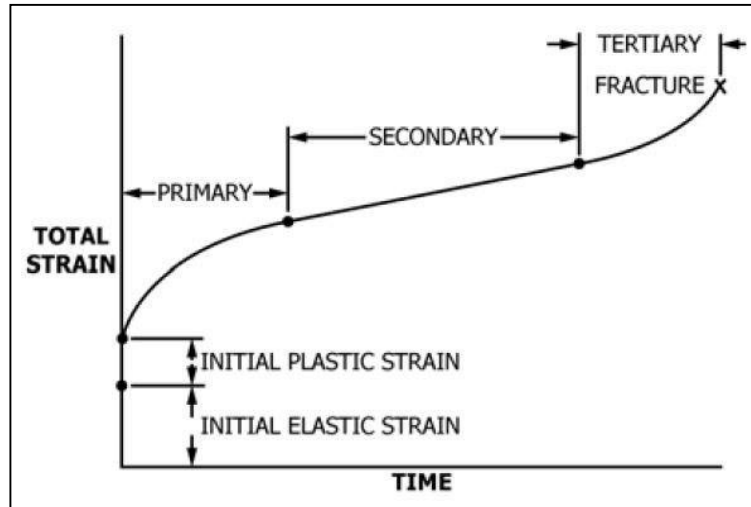


Figure 2.1: Idealized curve showing primary, secondary, and tertiary creep (Source: ASTM D2990)

In North America, the Non-Mandatory Appendix X1 design equations of ASTM F1216, *“Standard Practice for Rehabilitation of Existing Pipelines and Conduits by The Inversion and Curing of a Resin-Impregnated Tube,”* is extensively used to design CIPP liners. As stated in the ASTM F1216 standard, using this method for CIPP design requires completing multiple design checks to obtain an optimum liner thickness that ensures the liner supports external loads such as hydraulic loads due to groundwater, soil, and live loads. It should also be able to withstand the internal pressure spanning across holes in the original pipe wall and sustain other pressures such as traffic surcharge. Depending on the condition of the existing pipe to be lined and other conditions stated above, the required thickness is calculated from a series of design equations. The largest calculated thickness controls the CIPP design and is selected for the installation. Based on the ASTM F1216 design method, Equation 2.1 (ASTM F1216 Equation X1.2) and Equation 2.2 (ASTM F1216 Equation X1.6) requires the long-term flexural strength for CIPP (usually 50 years) to determine the liner thickness. The 50-year flexural strength of CIPP is estimated using the ASTM D790 and ASTM D2990 test methods.

$$1.5 \frac{\Delta}{100} \left(1 + \frac{\Delta}{100} \right) DR^2 - 0.5 \left(1 + \frac{\Delta}{100} \right) DR = \frac{\sigma_L}{PN} \quad (2.1)$$

where:

DR = ratio of the pipe outside diameter to the pipe minimum wall thickness,

Δ = ovality of the host pipe,

σ_L = Long-term Flexural Strength,

P = external pressure on the liner, and

N = Safety Factor.

$$P = \frac{5.33}{(DR - 1)^2} \left(\frac{D}{d} \right)^2 \frac{\sigma_L}{N} \quad (2.2)$$

where:

DR = ratio of the pipe outside diameter to the pipe minimum wall thickness, D = mean inside diameter of the original pipe,

d = diameter of the hole in the original pipe,

σ_L = long-term (time-corrected) flexural strength for CIPP, and

N = factor of safety.

This study assesses the performance of four (4) commercially available reinforced and non-reinforced CIPP polymeric materials to understand their short-term flexural properties, flexural creep-rupture, and strength retention properties in the long term.

2.4 Short-Term Flexural Tests

ASTM D790 short-term test methods were used to determine the short-term flexural properties of both reinforced and non-reinforced CIPP specimens. A three-point loading system was used to induce stress by applying loads to the CIPP coupon specimens mid-span as simply supported beams. This testing method is generally applicable to materials that break or yield in the outer surface of the test specimen within the 5.0 % strain limit. Procedure A of the ASTM D790 standard was used for the tests.

The short-term flexural testing was completed by placing twenty-four rectangular specimens flat-wise on two supports and loading the specimens at mid-span in flexure until they ruptured or reached 5% strain on their outer surface. Mechanical properties such as the maximum flexural strength, flexural strain, initial tangent modulus of elasticity, and yield strength were determined for all CIPP coupon specimens. ASTM D790 defines flexural strength as the maximum flexural stress sustained by the test specimen during a bending test. It defines the flexural strain as the nominal fractional change in the length of the outer surface of the test specimen at mid-span, where the maximum strain occurs. The initial tangent modulus of elasticity is defined as the ratio, within the elastic limit, of stress to corresponding strain calculated by drawing a tangent to the steepest initial straight-line portion of the load-deflection curve. Yield strength occurs at the first sudden deviation from the initial linear portion of the stress-strain plot.

Figure 2.2 represents typical flexural stress-strain curves showing different material behaviors according to ASTM D790. The standard defines the Flexural Stress at Break (σ_B) as the flexural stress at the break of the test specimen during a bending test. It defines the Flexural Strength (σ_M) as the maximum flexural stress sustained by the test specimen during a bending test. Some materials may give a load-deflection curve that shows a breakpoint, B, without a yield point (Curve “a”) in which case the Flexural Stress at Break is equal to the Flexural Strength (σ_M) that is ($\sigma_B = \sigma_M$). Some materials may give a yield deflection curve with both a yield and a breakpoint, B (Curve “b”). Other materials such as (Curve “c”), may have the first break defined as the flexural stress at the 5 percent strain limit.

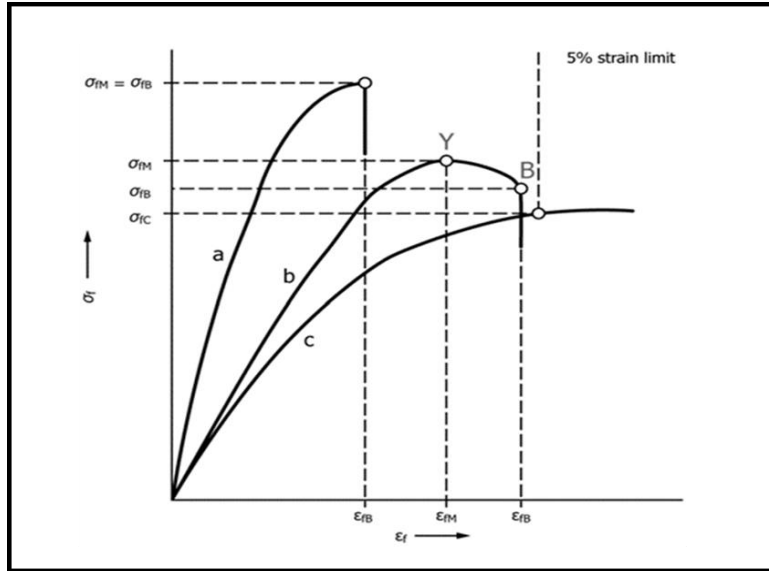


Figure 2.2: Typical Curves of Flexural Stress (σ_f) versus Flexural Strain (ϵ_f) (Source: ASTM D790)

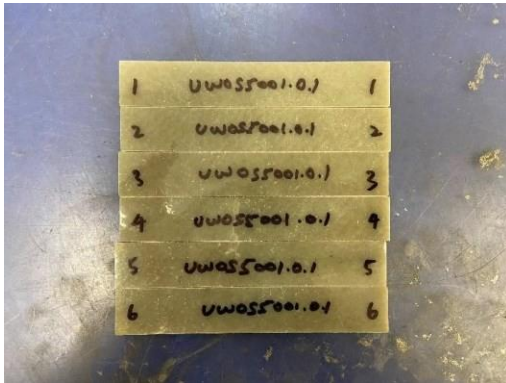
2.4.1 Short-Term Tests of CIPP Specimens

The short-term flexural properties of both Non-Reinforced CIPP (NC) and Reinforced CIPP (RC) specimen types were studied using two commercially available CIPP liners of each type. All the CIPP liner types were manufactured and supplied by Insituform Technologies Limited (Aegion Corporation). All specimens were tested as per ASTM D790 test methods. The specimen specifications, test procedure, and results are discussed below.

2.4.2 CIPP Test Specimens Specifications

The non-reinforced and reinforced CIPP liner specimens used for this research were manufactured under controlled conditions and cured at 71°C. There were two types each of non-reinforced (homogeneous) and reinforced (composite) CIPP liners. The non-reinforced CIPP liners mainly contain a matrix made up of polyester resin, while the reinforced CIPP (RC) liners incorporate two layers of fiberglass to form a polyester-fiberglass composite CIPP product. The CIPP liner coupon specimens for these tests were made from flat rectangular plates that were 275 x 280 mm in dimension. The two NC and RC liner types were cut

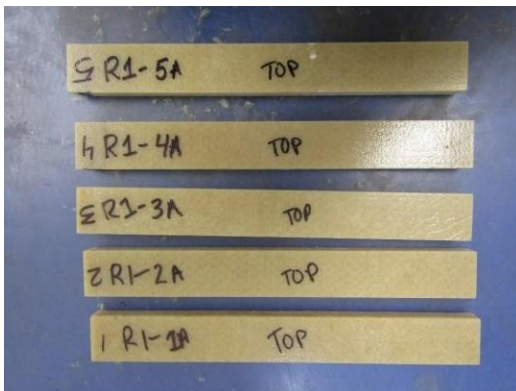
from plates with a nominal thickness of 5.6 mm and 12.8mm. Each specimen was cut into rectangles using a span-to-depth ratio of 16:1 per the ASTM D790 specifications. The specimen types were labeled “NC-L721” and “NC-L758” for the non-reinforced CIPP liner types and “RC-IPLUS” and “RC-IMAIN” for the two reinforced CIPP specimen types as per the manufacturer’s number identification system. Figure 2.3 shows the specimens prepared for testing.



(a) NC-L721 test specimens.



(b) NC-L758 test specimens.



(c) RC-IPLUS test specimens.



(d) RC-IMAIN test specimens.

Figure 2.3: Flexural test flat plate coupons for both Non-reinforced CIPP (NC) and Reinforced CIPP

2.4.3 Short-Term Test Apparatus and Procedures

The test apparatus used for the short-term tests were selected per the ASTM D790 specifications. The load frame had a maximum elastic deformation of 1% of the deflection of the test specimens during tests. The loading frame is a fixed or stationary member holding the specimens during tests. The loading nose and supports had cylindrical surfaces with radii of 5.0 ± 0.1 mm. A load Indicator that showed the total load applied to the specimens during the tests with an accuracy of 1 % of the indicated value was used. A deflectometer was used for accurate determination of the deflection of the specimens.

As required by ASTM D790 test methods, a minimum of five (5) test specimens are required for each sample in the case of isotropic materials. In these short-term tests, six (6) specimens were tested for each of the non-reinforced specimens - “NC-L721” and “NC-L758” and reinforced specimens - “RC-IPLUS” and “RC-IMAIN”. Procedure A of the standard was used in testing the specimens. The NC specimens were measured, and the nominal depth (d) was 5.6 mm, the breadth (b) was 19.9 mm, and the span (L) was 90mm while the RC specimens had a nominal depth (d) of 12.8 mm, the breadth (b) was 30 mm, and the span (L) was 205 mm. Load was applied to the specimens at a constant rate and the deflection was measured simultaneously using a deflectometer in contact with each specimen to generate the load-deflection data for each specimen. The tests were terminated at either the failure (break) or 5% strain of the specimen. Whichever occurs first determines the end of the test. The measured deflections of the specimens were compared with the calculated deflections using Equation 2.3 at a strain (r) of 5%.

$$D_m = \frac{rL^2}{6d} \quad (2.3)$$

where:

D_m = mid-span deflection, mm (in.),

r = strain, mm/mm (in./in.),

L = span, mm (in)

d = depth, mm(in)

2.4.4 Short-Term Test Results and Discussions

The ASTM D790 short-term test results completed on the non-reinforced and reinforced CIPP liner specimens are discussed below:

2.4.4.1 Non-reinforced CIPP Specimens

Six (6) non-reinforced specimens each were tested for CIPP liner types NC-L721 and NC-L758 per the ASTM D790 test procedure described above. The specimens were loaded flat-wise at mid-span in flexure, as simple beams, until they ruptured or reached the maximum 5% strain. Figure 2.4 and Figure 2.5 provide the liner stress-strain plots for specimens NC-L721 and NC-L758 respectively. The plots show that both NC-L721 and NC-L758 test specimens had similar stress-strain responses.

Table 2.1 shows the short-term mechanical properties of NC-L721 specimens determined from the tested specimens. The specimens reached their first-break points at an average of 1.1% strain after the initial elastic portion of the stress-strain curve, and the stress at first break ranged from 27.7 MPa to 42.7MPa with a mean first-break stress of 37.0MPa. After the specimens reached their first break points, persistent fractures occurred within their polymeric structures, causing continuous drops and rebounds in their liner strength causing a saw-tooth graph pattern. Only Specimen S-5 was observed to have failed before getting to 5% strain after several cycles of fractures and rebounds in its response to applied stress. The mean flexural strength was determined as 52.2MPa and the strain at mean flexural strength was 4.5%. The mean initial tangent modulus of elasticity for the tested specimens was 3,380MPa. This saw tooth wave in the graphs indicates the non-reinforced CIPP specimens had a good level of toughness which was evident in their ability to repeatedly withstand the bending stress despite several breaks until they eventually ruptured or reached the 5% strain limit.

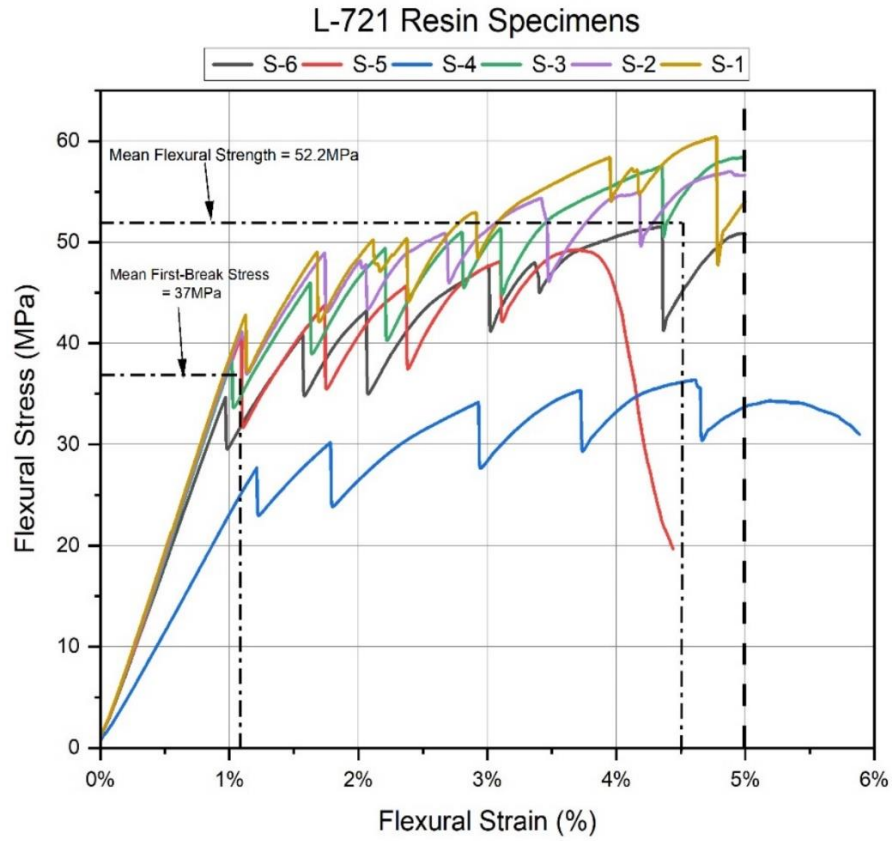


Figure 2.4: Stress-strain plot for six NC-L721 specimens (L721-01 to L721-06)

Table 2.1: L721 resin D790 test specimen mechanical properties.

Test Specimen	Flexural Stress @ First Break		Strain @ First Break	Flexural Strength		Strain @ Flexural Strength	Initial Tangent Flexural Modulus	
	(PSI)	(MPa)		(PSI)	(MPa)		(PSI)	(MPa)
S-1	6,200	42.8	1.1	8760	60.4	4.8	538,504	3,713
S-2	5,967	41.1	1.1	8260	57.0	4.9	520,923	3,592
S-3	5,548	38.3	1.0	8480	58.5	5.0	528,660	3,645
S-4	4,009	27.6	1.2	5275	36.4	4.6	322,894	2,226
S-5	5,891	40.6	1.1	7140	49.2	3.7	526,177	3,628
S-6	5,017	34.6	1.0	7472	51.5	4.3	503,883	3,474
Mean	5,439	37.5	1.1	7565	52.2	4.5	490,174	3,380
Max	6,200	42.8	1.2	8760	60.4	5.0	538,504	3,713
Min	4,009	27.6	1.0	5275	36.4	3.7	322,894	2,226
STDEV	812.0	5.6	0.1	1279	8.8	0.5	82,740	570

Figure 2.5 and Table 2.2 show the plots of the stress-strain response and determined mechanical properties of six (6) NC-L758 specimens. The stress-strain responses of the specimens were very similar. All the specimens reached their first break point before 1% strain (at a mean first-break strain of 0.88%) but at a very close stress range of 36.2MPa to 37.3MPa. This showed more homogeneity in the specimens compared with NC-L721 specimens. Specimens of NC-L758 resins showed a similar level of toughness as NC-L721 specimens as they also had intermittent fractures in their polymeric structure and corresponding rebounds forming a saw-tooth wave graph in their responses to the applied stress. The specimens showed very close mean flexural strengths and mean flexural stress at the first break of 50.3Mpa and 36.5MPa respectively, compared to 52.2MPa and 37.5MPa values for the same set of parameters for NC-L721 specimens, but exhibited significantly higher flexural modulus of 4,027MPa compared to 3,380MPa determined for NC-L721 resin specimens. It was observed that despite having a higher mean modulus, NC-L758 specimens had a higher number of failures (5 out of 6) before the 5% strain limit compared to (1 out of 5) as recorded for NC-L721.

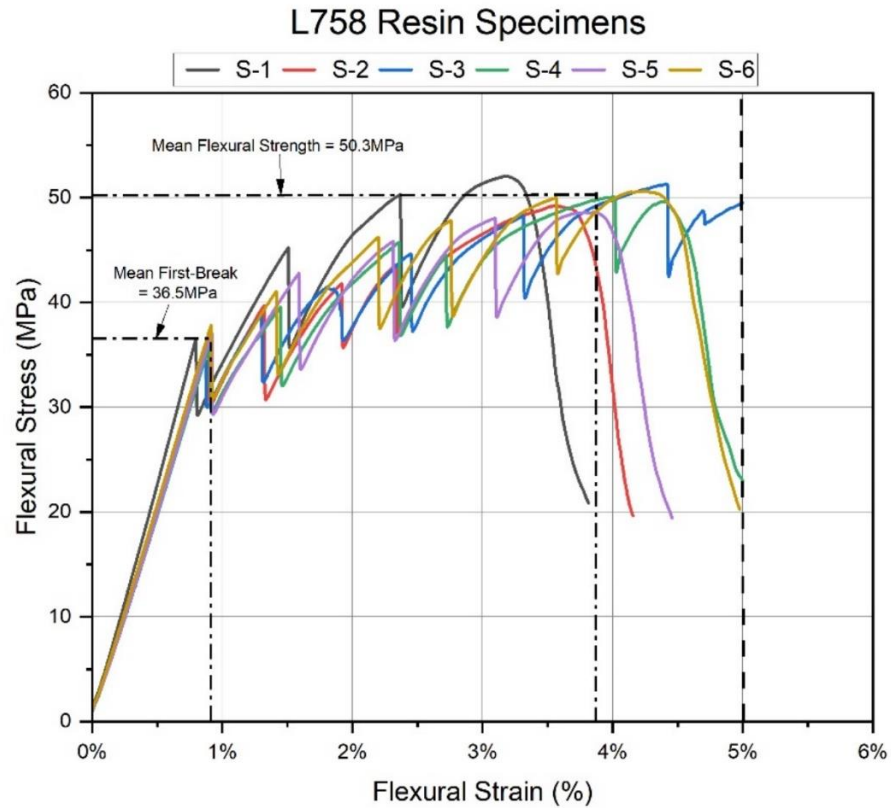


Figure 2.5: Stress-strain plot for six NC-L758 specimens (L758-01 to L758-06)

Table 2.2: L758 resin D790 test specimen mechanical properties.

Test Specimen	Flexural Stress @ First Break		Strain @ First Break	Flexural Strength		Strain @ Flexural	Flexural Modulus	
	(PSI)	(MPa)		(PSI)	(MPa)		(PSI)	(MPa)
S-1	5,292	36.5	0.80	7547	52.0	3.18	643,265	4,435
S-2	5,297	36.5	0.90	7137	49.2	3.56	573,476	3,954
S-3	5,142	35.5	0.87	7439	51.3	4.41	577,059	3,979
S-4	5,190	35.8	0.91	7260	50.1	4.01	558,230	3,849
S-5	5,373	37.0	0.92	7048	48.6	3.79	569,749	3,928
S-6	5,474	37.7	0.91	7341	50.6	4.23	582,913	4,019
Mean	5,295	36.5	0.88	7295	50.3	3.86	584,115	4,027
Max	5,474	37.7	0.92	7547	52.0	4.41	643,265	4,435
Min	5,142	35.5	0.80	7048	48.6	3.18	558,230	3,849
STDEV	120.6	0.8	0.05	186	1.3	0.45	30,132	208

2.4.4.2 Reinforced CIPP Specimens

Six (6) reinforced CIPP specimens were tested for each of the RC-IPLUS and RC-IMAIN specimens to determine their short-term mechanical properties per the ASTM D790 test procedure. The prepared specimens were loaded flat-wise at mid-span in flexure, as a simple beam, until they ruptured or reached the maximum 5% strain. Figure 2.6 and Figure 2.7 show the back and side views of both RC specimens after the ASTM D790 three-point flexural tests. Eleven (11) specimens did not fail before the 5% strain limit. Only one RC-IMAIN specimen failed at 4.9% strain. However, another RC-IMAIN specimen showed a major crack but did not fail before the test was stopped at the 5% strain limit.

Figure 2.8 and Figure 2.9 both provide the linear stress-strain plots for specimens RC-IPLUS and RC-IMAIN respectively. The plots show that both RC-IPLUS and RC-IMAIN test specimens had similar stress-strain responses, increasing relatively steadily until the 5% strain limit was reached. Both specimen types showed minimal yield and their stress-strain responses best suit specimen type “c” described in Figure 2.2 - typical curves of Flexural Stress (σ_f) versus Flexural Strain (ϵ_f) in ASTM D790, which does not yield nor break before reaching 5% strain level. Despite the similarity in their stress-strain responses, the two specimen types differ significantly in their yield stresses and strains at yields of 78MPa and 54MPa, and 1.4% and 0.9% for RC-IMAIN and RC-IPLUS respectively.

Tables 2.3 and Table 2.4 show the short-term mechanical properties of RC-IPLUS and RC-IMAIN specimens respectively. Table 2.3 shows that the flexural strengths of the RC-IPLUS specimens ranged from 192 – 211MPa with a mean flexural strength of 200MPa and a standard deviation of 8MPa. The mean flexural modulus was determined to be 5780MPa with a standard deviation of 261MPa. Table 2.4 provides the material properties of RC-IMAIN specimens. The flexural strengths of the RC-IMAIN specimens ranged from 204 to 212MPa with a mean flexural strength of 209MPa and a standard deviation of 3.5MPa. One of the specimens failed at a stress level of 204MPa. The flexural modulus was determined to be 5,476MPa with a standard deviation of 106 MPa.

It was observed that while the RC-IPLUS specimens showed lower mean flexural strength and yield stress, it had a significantly higher flexural modulus which indicates a higher level of stiffness than RC-IMAIN

specimens. This can be attributed to factors such as variations in the resin composition and the reinforcement structure.

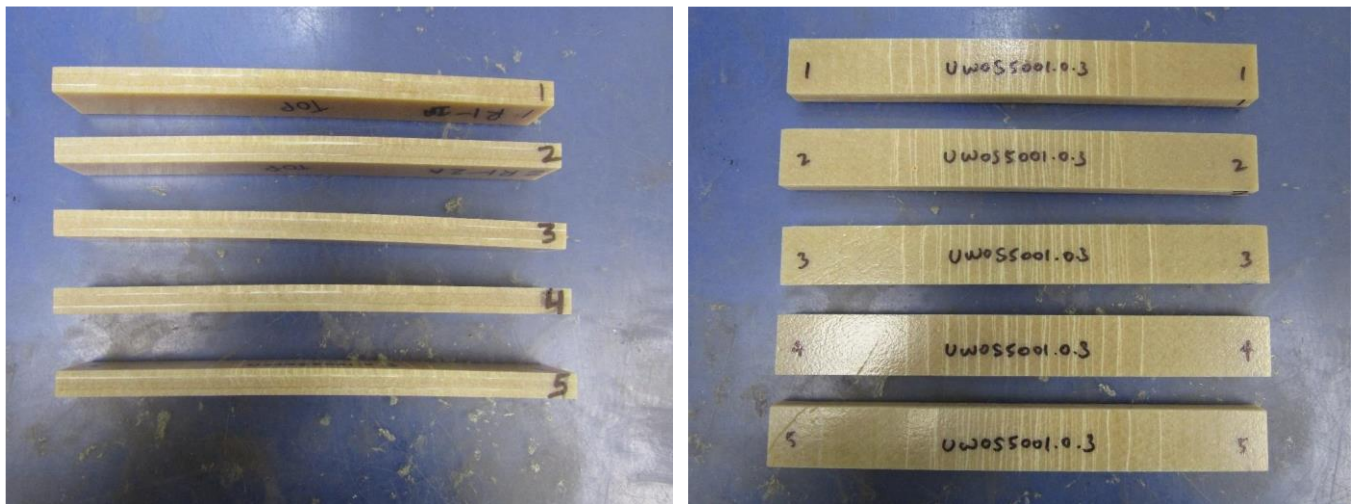


Figure 2.6: RC-IPUS specimens after the ASTM D790 three-point flexural tests.

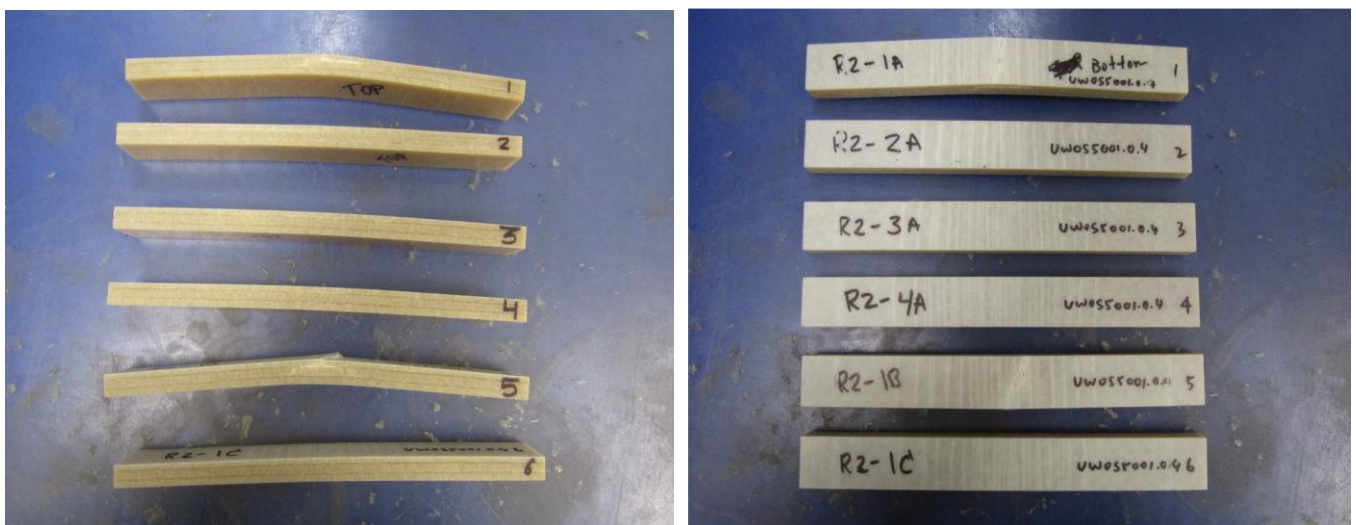


Figure 2.7: RC-IMAIN specimens after the ASTM D790 three-point flexural tests.

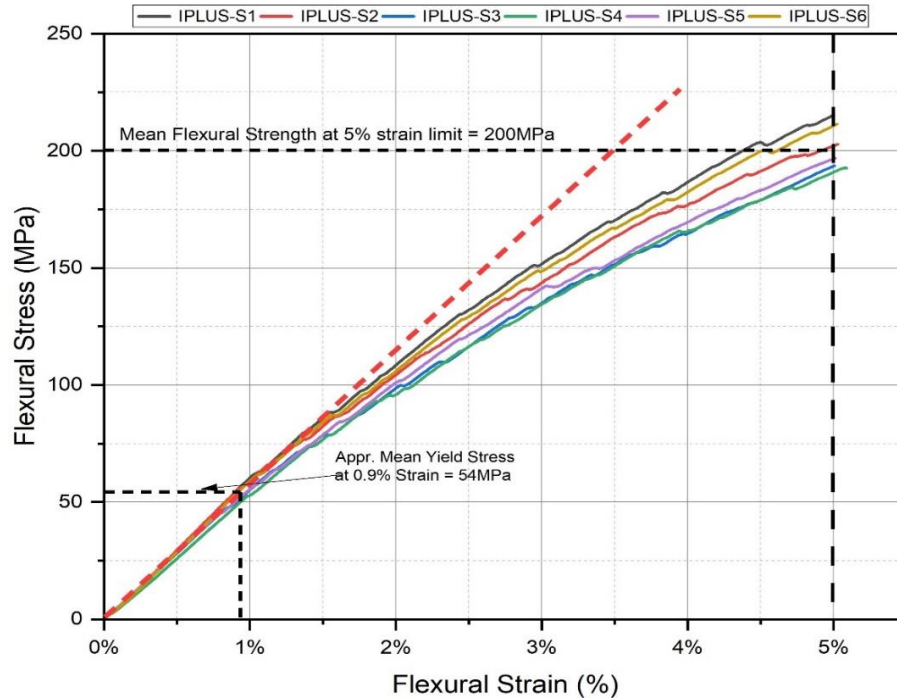


Figure 2.8: Stress-strain plot for six RC-IPLUS test specimens (IPLUS-01 to IPLUS-06)

Table 2.3: L758 resin D790 test specimen mechanical properties.

Test Specimen	Flexural Strength @ 5% Strain		Flexural Modulus		Yield Strain
	(PSI)	(MPa)	(PSI)	(MPa)	
R1-S1	30622	211	875,332	6035	1.0
R1-S2	29151	201	872,976	6019	0.9
R1-S3	27966	193	823,438	5677	0.8
R1-S4	27834	192	775,002	5343	1.0
R1-S5	28200	194	828,618	5713	0.8
R1-S6	30138	208	854,655	5893	1.0
Mean	28985	200	838,337	5780	0.9
Max	30622	211	875,332	6035	1.0
Min	27834	192	775,002	5343	0.8
STDEV	1185	8	37,848	261	0.1

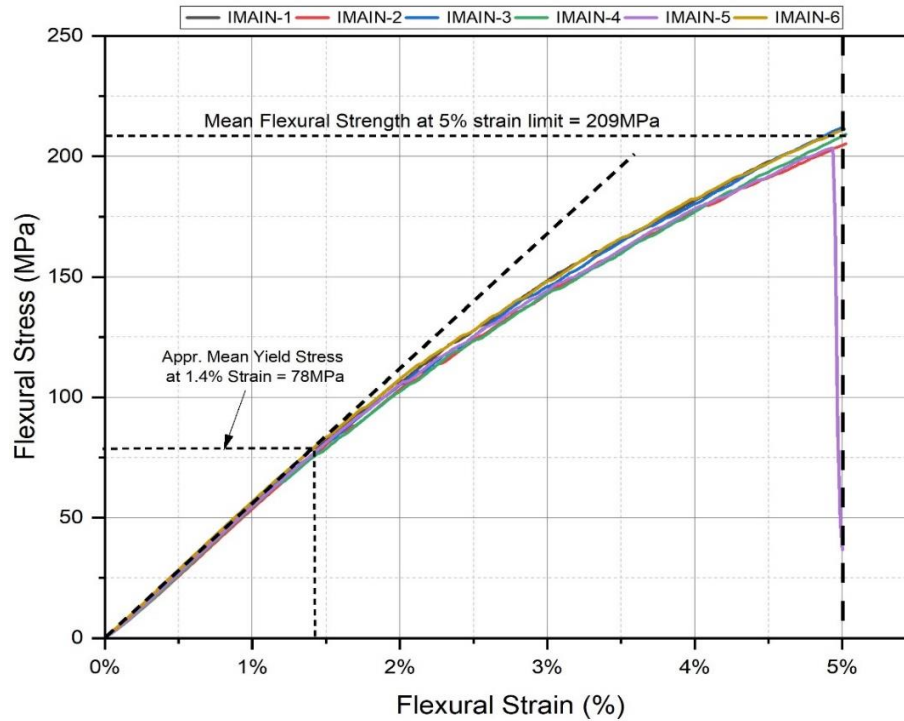


Figure 1.9: Stress-strain plot for six RC-IMAIN test specimens (IMAIN-01 to IMAIN-06)

Table 2.4: RC-IMAIN composite D790 test specimen material properties

Test Specimen	Flexural Strength @ 5% Strain		Flexural Modulus		Yield Strain
	(PSI)	(MPa)	(PSI)	(MPa)	(%)
S-1	30,655	211	809,704	5,583	1.4
S-2	29,766	205	775,749	5,349	1.6
S-3	30,742	212	805,086	5,551	1.2
S-4	30,354	209	789,669	5,445	1.2
S-5	29,531	204	777,607	5,361	1.7
S-6	30,607	211	807,700	5,569	1.5
Mean	30,276	209	794,252	5,476	1.4
Max	30,742	212	809,704	5,583	1.7
Min	29,531	204	775,749	5,349	1.2
STDEV	508.0	3.5	15,346	106	0.2

2.5 Long-Term Flexural Strength Tests

Long-Term flexural tests measure the elongation to failure of materials subjected to flexural stress for extended periods, as a function of time-to-rupture, or failure under specified environmental conditions such as temperature and relative humidity. There are several standards for testing and determining the long-term flexural properties of polymeric matrix composites such as reinforced CIPP. Some of the standards available in North America are ASTM D2990, *“Standard Test Methods For Tensile, Compressive, And Flexural Creep And Creep- Rupture Of Plastics,”* ISO 11296-4, *“Plastics piping systems for renovation of underground non-pressure drainage and sewerage networks — Part 4: Lining with cured-in-place pipes”*, and ISO 11298-4, *“Plastics piping systems for renovation of underground water supply networks — Part 4: Lining with cured-in-place pipes”* that detail testing procedures to characterize the long-term strength and stiffness of coupon specimens fabricated from gravity and pressure CIPP liners under dry or wet conditions. Despite the availability of these standard experimental procedures in these standards, there are currently limited studies completed to determine CIPP long-term 50-year flexural strength using creep-rupture tests (Awe, 2023). Gumbel and Chrystie-Lowe (2015) investigated the long-term flexural strength values and Strength Retention Factor (SRF) for three different CIPP liners using the flexural creep-rupture test in a sulphuric acid environment. The tests were completed using one unreinforced and two reinforced CIPP specimens in three-point loading, and their results found the SRF values to be 68% and 60 -76% for the non-reinforced and reinforced CIPP specimens, respectively.

ASTM D2990 standard test methods were used in this study to determine the long-term flexural strength and the strength retention factors of the four (4) CIPP specimens used for the short-term tests described above. The CIPP liner coupons of NC-L721 and NC-L758 resins and the RC-IMAIN and RC-IPLUS coupons were tested for 10,000 hours and the results were extrapolated to determine the estimated mechanical properties of both CIPP liner types after a 50-year service life.

2.5.1 Long-Term Test Stress Levels Determination

The long-term creep-rupture tests of both reinforced and non-reinforced CIPP liner coupons were completed per ASTM D2990 test methods recommendations. The coupons used for these long-term creep rupture tests were selected from the same batch of NC-L721, NC-L758, RC-IPLUS, and RC-IMAIN used for the short-term D790 flexural tests. This was done to study and understand each resin type's mechanical properties in the long term. Using the ASTM D2990 creep-rupture test stress selection recommendations, stress levels were selected to induce multiple failures within the time ranges of up to an hour, 1 – 100 hours, 100 – 1000 hours, 1,000 – 3,000 hours, and 3,000 – 10,000 hours for materials that will be under constant load for elongated periods during its service life. The creep-rupture data from each specimen type after 10,000 hours of testing is then extrapolated to 50 years to determine its long-term flexural strength. The “mean yield stress”–to–“mean flexural strength” stress window on ASTM D790 stress-strain plots for each set of specimens provided the range of stress levels for the tests to achieve the failure-time distribution recommended in the ASTM D2990 test methods. A minimum of three repetitions were completed for each stress level, starting with 90% of the mean flexural strength of each set of CIPP liner specimens and then reduced by 2.5 – 5% depending on the material response.

2.5.2 Non-reinforced CIPP Flexural Creep-Rupture Tests

The long-term flexural creep-rupture tests of NC-L721 and NC-L758 specimens were completed using stress levels between 90 – 60% of the ASTM D790 determined mean flexural strength of each CIPP resin type. Depending on the material response at a stress level, the percentage stress levels were reduced by 2.5 – 5% to further elongate the time to failure of each subsequent set of tested specimens to ensure the failure points fall within the time bands recommended in ASTM D2990 standard test methods. Figure 2.10 shows the test specimens mounted as beams on a rigid test frame, with loads mounted mid-span via loading noses to induce the desired levels of stress. Linear potentiometers were connected to an electronic data acquisition system to measure and record deflection per second throughout the periods of testing. A total of thirty-three (33) and twenty-six (26) specimens were tested and completed for NC-L721 and NC-L758 CIPP coupons respectively.

2.5.3 NC Flexural Creep-Rupture Test Results

Figure 2.11 And Table 2.5 provide the rupture stress–time-to-failure distribution of the specimen types over 10,000 hours. The rupture-stress point distribution over time indicates that despite the NC-L758

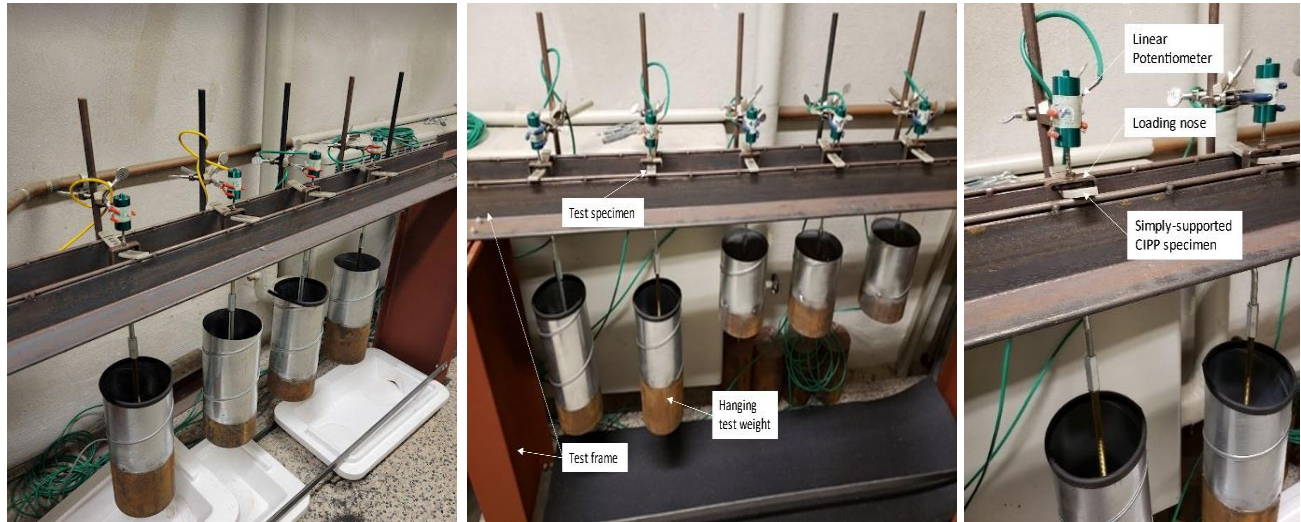


Figure 2.10: L721 and L758 resin test specimens under long-term flexural testing. (Source: Awe, 2023)

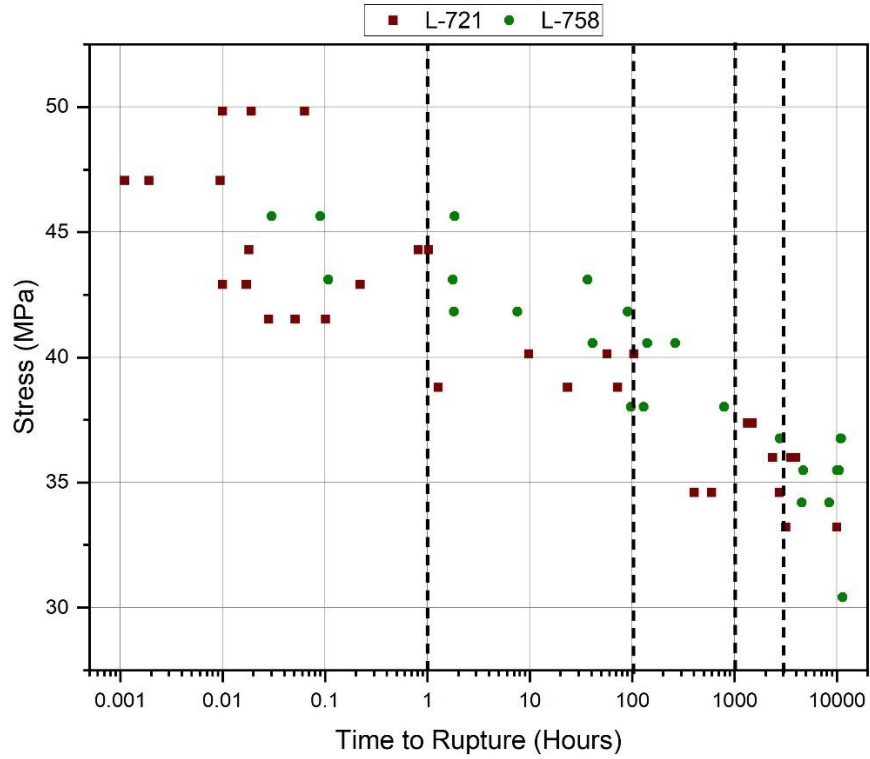


Figure 2.11: Rupture stress-time plots for NC-L721 and NC-L758 test specimens.

Table 2.5: Rupture point distribution within time bands

Rupture Point - Time Distribution				
Hours	L-721		L-758	
	Rupture Points	%tage	Rupture Points	%tage
0 - 1	14	42	3	12
1 - 100	6	18	8	31
100 - 1000	3	9	4	15
1000 - 3000	5	15	1	4
3000 - 10000	5	15	10	38
Total	33		26	

resin specimens having more (4 out of 5) failures before the 5% strain limit in the ASTM D790 short-term tests, compared to the NC-L721 resin (1 out of 5), the number of failures recorded within the first hour of long-term testing was significantly lower for the former than the latter. NC-L721 resin had 42% of the total

number of creep-rupture points within the first hour of testing while NC-L758 resin had a 12% failure rate within the same time frame. The NC-L758 resin CIPP specimens had a 39% failure rate within the 3000 – 10000-hour time band, compared to a 15% failure rate of NC-L721 resin CIPP within the same time band. These observed responses may be attributed to the higher short-term flexural modulus of NC-L758 resin compared to NC-L721 resin, but the real cause can be determined through further investigations.

Using linear regression analysis, NC-L721 and NC-L758 stress rupture points and the time to failure were plotted to determine the creep-rupture responses of each CIPP resin specimen type over a 10,000-hour testing period. The rupture stress was the independent variable on the y-axis while the log of time was the dependent variable on the x-axis. Figure 2.12 and Figure 2.13 show the failure strength regression plots of the creep-rupture points of NC-L721 and NC-L758 specimens tested in flexure over 10,000 hours respectively. The developed regression lines were extrapolated to 50 years to estimate the creep-rupture strengths of the materials over their expected service lives. 31.3MPa and 30.8MPa were the estimated 50-year long-term flexural strength (LTFS₅₀) of NC-L721 and NC-L758 resins respectively.

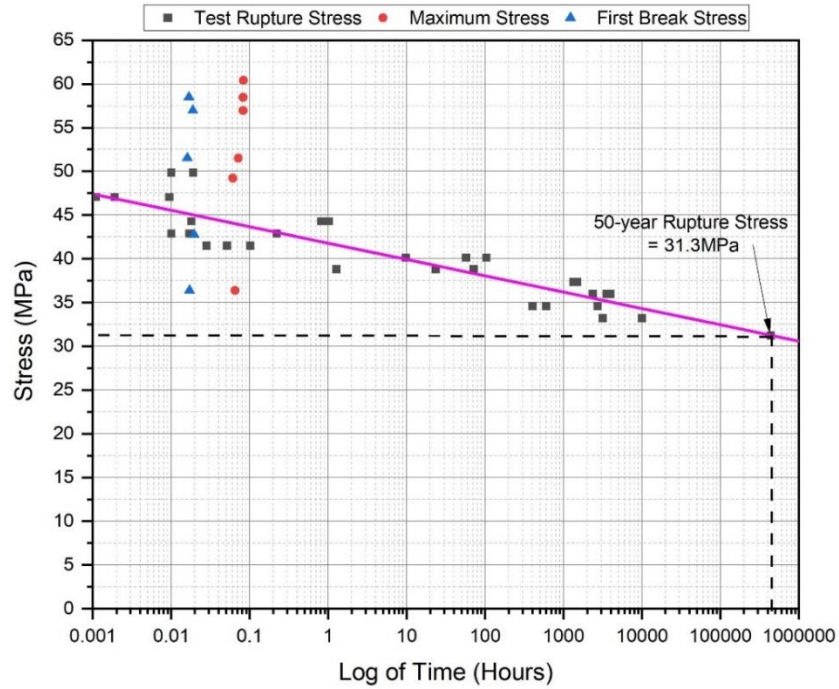


Figure 2.12: NC-L721 Resin 10,000-hour creep rupture curve with estimated 50-year rupture stress

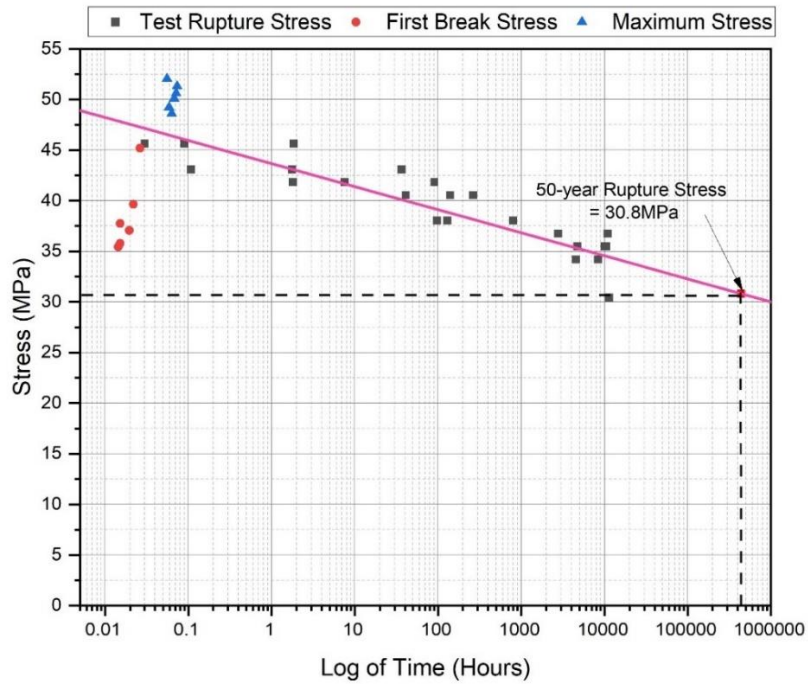


Figure 2.13: NC-L758 Resin 10,000-hour creep rupture curve with estimated 50-year rupture stress.

2.5.4 NC Long-Term Strength Retention Factor (SRF)

The long-term strength retention factor of a CIPP resin is an indication of the percentage of its short-term ASTM D790-determined flexural strength that remains after being under constant load for an elongated service life of 50 years. It is determined by the ratio of the estimated 50-year flexural strength to the mean ASTM D790 short-term flexural strength using Equation 2.4

$$SRF = \sigma_L / \sigma \quad (2.4)$$

where:

σ_L = Estimated Long-term (50-year) flexural strength, and

σ = Short-term ASTM D790 flexural strength.

The 50-year SRF of NC-L721 and NC-L758 CIPP resins calculated from the ratio of their LTFS₅₀ and mean short-term flexural strengths were determined to be 60.0% and 61.2% respectively. These estimates are lower than the results of the research of Gumbel and Chrystie-Lowe, (2015) which estimated the SRF of a non-reinforced CIPP liner to be 68%. Also, the 50-year SRFs are quite different from the 50-year SRF estimates determined by Awe, (2023) after 3,000 hours of testing, which reported the SRF of NC-L721 and NC-L758 CIPP resins as 55% and 65% respectively. The determined SRFs for both non-reinforced CIPP types are higher than the generalized 50% used in the industry. Table 2.6 shows the summary of the estimation of the 50-year long-term SRFs of the two non-reinforced CIPP resin specimens using 3,000 and 10,000-hour data.

Table 2.6: Non-reinforced 50-year SRF

Specimen ID	Mean Short-Term Flexural Strength	50-year Flexural Strength from 10,000-hour data	CIPP 50-year SRF from 10,000-hour data	CIPP 50-year SRF from 3,000-hour data
	(MPa)	(MPa)	(%)	(%)
NC-L721	52.2	31.3	60.0	55.0
NC-L758	50.3	30.8	61.2	65.0

2.5.5 Reinforced CIPP Flexural Creep-Rupture Tests

As shown in Figure 2.14 and Figure 2.15, three RC-IPLUS and two RC-IMAIN rectangular specimens with a span-to-depth ratio of 16:1 were set up for the long-term creep-rupture tests by placing them in a flat-wise position and loaded mid-span with hanging weights that are equivalent to 90% of their respective short-term ASTM D790 mean flexural strengths at 5% strain. The displacements in the outer surface of the specimens in flexure were measured every second via the linear potentiometer placed in contact above the loading nose and recorded on a SoMat eDAQ shown in Figure 2.16. As reported in Awe (2023), though there was a rapid increase in strain and audible crack noises were heard from the loaded specimens, there was no failure within the first hour and beyond. As defined in ASTM D790, the standard procedure for the short-term flexural test, failure in flexure is either when rupture occurs or if the specimen reaches 5% strain. RC-IPLUS and RC-IMAIN specimens were loaded to induce stress levels 181MPa and 188MPa respectively, which were 90% of their mean short-term flexural strengths at 5% strain. Both specimen types did not fail nor reach the 5% strain limit in 3,000 hours, only reaching averages of 1.8% and 2.7% strains respectively. Since no failure occurred after 3,000 hours, and the linear extrapolation to predict the creep strain at 50 years under a stress level of 90% of the mean flexural strength showed that the specimens would not reach the displacement at 5% strain, 96% of the ASTM D790 short-term flexural strengths were investigated using one new specimen of each RC type. Due to limitations in space in the testing facility, one test each was stopped for RC-IPLUS and RC-IMAIN to accommodate the new specimens being tested at 96% short-term flexural strength. This left two (2) specimens of RC-IPLUS running at 90% and one (1) at 96%, and one sample each of RC-IMAIN running at 90% and 96%.

2.5.6 RC Flexural Creep-Rupture Test Results

All samples of RC-IPLUS and RC-IMAIN were tested for 10,000 hours without any failure by rupture or reaching the 5% strain limit. At 10,000 hours, the strain levels of RC-IPLUS and RC-IMAIN loaded to induce

96% of the short-term flexural strengths at 5% were 2.26% and 3.75% respectively. The plotted creep-strain-to-time curves of both reinforced CIPP specimens were extrapolated to 50 years in Figures 2.17 and 2.18 to predict their long-term strain values. At 50 years, the strain of both RC-IPLUS and RC-IMAIN specimens are expected to be 2.45% and 3.95% respectively.



Figure 2.14: IPLUS Specimens under long-term creep-rupture testing



Figure 2.15: IMAIN Specimens under long-term creep-rupture testing



Figure 2.16: SoMat eDAQ for data collection

Table 2.7 shows a comparison of the creep strain at 3,000 and 10,000 hours and a 50-year predicted creep-strain level for both RC-IPLUS and RC-IMAIN resin specimens. The percentage change in the rate of creep strain of RC-IPLUS and RC-IMAIN resin specimens were 2.7% and 0.9% between 3,000 to 10,000 hours, and 5.3% and 8.4% between 10,000 hours to 50 years respectively. This pattern indicates that the stress of the applied load has an insignificant creep impact on the polymeric structure of the resins. The fiberglass reinforcement in the resins bears the stress of the loads and reduces the creep rate of the resins, indicating that flexure is not a failure mode for the material. This shows that the reinforced CIPP specimens will not fail in flexure even after 50 years in service. Further testing research needs to be done in the future to better understand the responses of the materials to other forms of load.

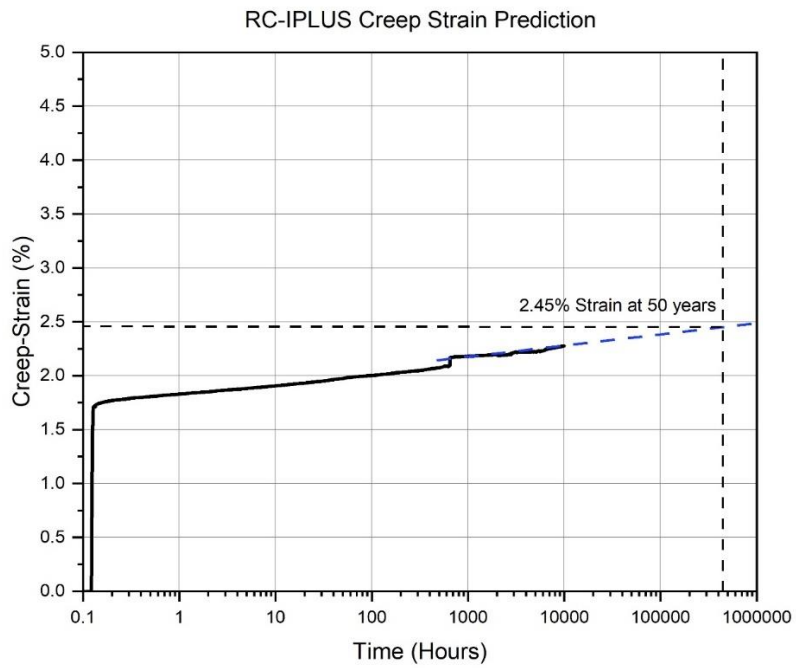


Figure 2.17: 50-year creep-strain prediction of RC-IPLUS specimens at 96% of the short-term flexural strength

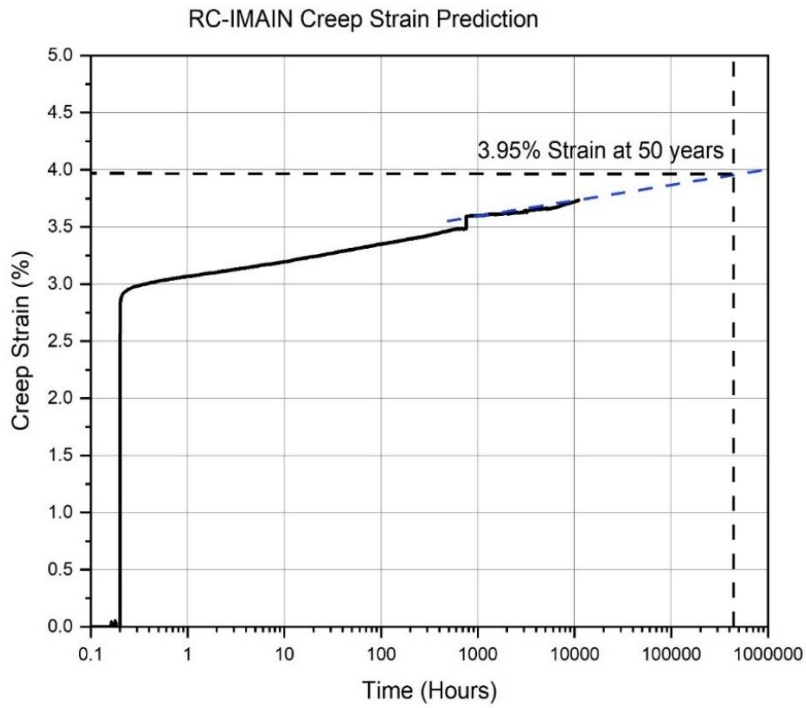


Figure 2.18: 50-year creep-strain prediction of RC-IMAIN specimens at 96% of the short-term flexural strength.

Table 2.7: Reinforced CIPP Creep-Strain Responses over Time

Time (Hours)	Creep-Strain at 96% of Short-Term Flexural Strength			
	RC-IPLUS	%tage change in Strain	RC-IMAIN	%tage change in Strain
	%		%	
3,000	2.24	-	3.65	-
10,000	2.26	0.9%	3.75	2.7%
50-year prediction	2.45	8.4%	3.95	5.3%

2.5.7 Linear Regression Analysis of Creep-Rupture Data – 50-year prediction

The ASTM D790 creep-rupture data and the stress levels of 90% and 96% that were used to test the RC specimens were plotted against the time to rupture to develop their creep-rupture behaviors over time. Though there was no failure in any of the specimens after 10,000 hours of testing contrary to the experience with the non-reinforced CIPP specimens tested earlier, there was enough creep in the materials to form a basis for predicting their mechanical behaviors over their 50-year expected service lives. Figure 2.19 and Figure 2.20 show the strength regression lines developed by plotting the creep-rupture data points and time-to-rupture for both reinforced specimens and the 50-year flexural strength predictions determined by extrapolating the strength regression lines to 50 years. The 50-year flexural strength (LTFS₅₀) predictions of RC-IPLUS and RC-IMAIN resin specimens were 178MPa and 190MPa respectively. These are close to the 177MPa and 188MPa LTFS₅₀ predictions for the respective set of RC specimens reported by Awe (2023) after 3,000 hours of testing.

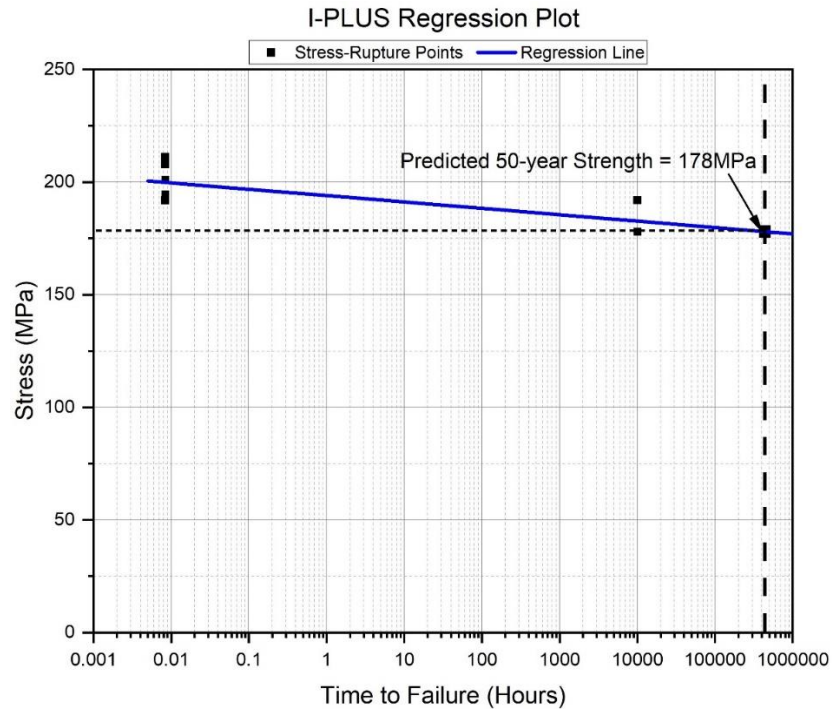


Figure 2.19: Regression line and extrapolation to determine LTF50 of RC-IPLUS CIPP specimens.

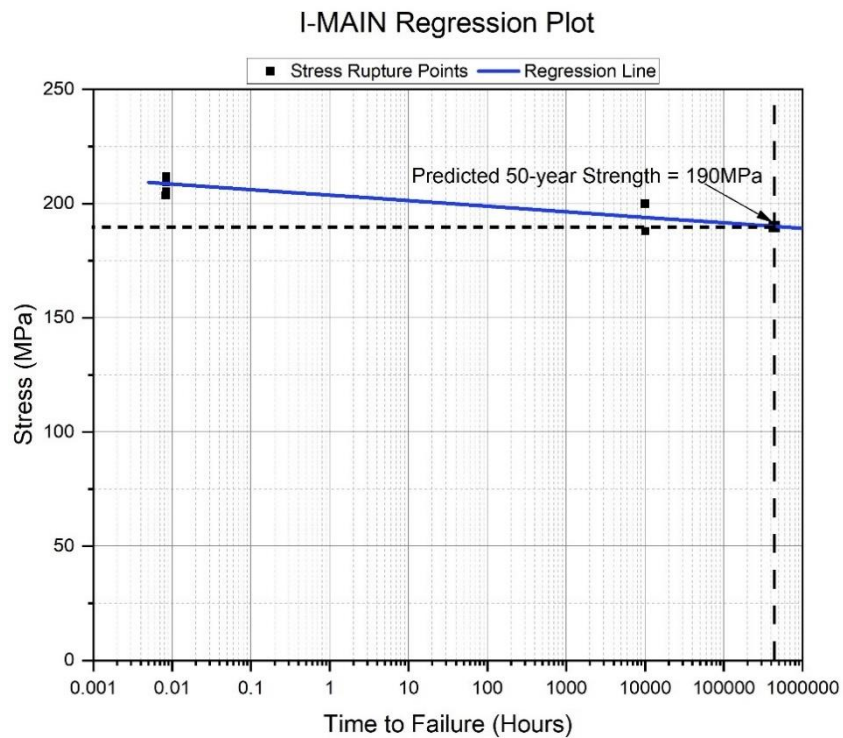


Figure 2.20: Regression line and extrapolation to determine LTF50 of RC-IMAIN CIPP specimens.

2.5.8 RC Long-Term Strength Retention Factor (SRF)

The 50-year SRF of both RC-IPLUS and RC-IMAIN resin specimens were determined using Equation 2.4. The $LTFS_{50}$ of both specimens were divided by their ASTM D790 mean short-term flexural strength to estimate the long-term SRFs of both specimens. The SRFs of RC-IPLUS and RC-IMAIN resin specimens were estimated as 89% and 91% respectively. These are considerably close to the SRFs of 88% and 86% reported for the same set of specimens respectively by Awe (2023). In comparison with reports of SRF determined from research completed by Gumbel and Chrystie-Lowe (2015) on two reinforced CIPP liners which reported 60% and 76% values, the determined SRFs for RC-IPLUS and RC-IMAIN resin specimens are significantly higher and do not agree with their results.

Considering the differences in shape and other manufacturing imperfections in field-manufactured CIPP liners and laboratory-manufactured flat-plate specimens, from a design standpoint, the determined SRFs may be reduced depending on the designing engineer's judgment of the extent of the difference in the outcomes of both manufacturing processes.

The SRF results from these tests and the literature reviewed indicate that the commonly applied 50% of the short-term flexural strength is erroneous and results in overly conservative designs. Creep-rupture test of every CIPP liner is essential in determining the long-term flexural strength and the strength retention factor to be used in the design of such CIPP materials.

2.6 CIPP Design Considerations

2.6.1 Non-reinforced CIPP Design

In this study, the mean short-term ASTM D790 flexural strengths of NC-L721 and NC-L758 resin specimens were used to determine their long-term flexural properties. The materials' responses to stress in the short-term test showed a series of fractures in their polymeric structures between the first break stresses and

eventual failure or reaching the 5% strain limit. 50% of the tested specimens failed before the 5% strain limit. Both NC materials' specimens showed saw-tooth patterns of breaks and rebounds in their strengths ranging from 4 to 8 times during the short-term tests. This material response indicates a high level of unpredictability of the materials' response to stress after the first-break stress level. As such, the mean stress at the first break of 37.5MPa and 36.5MPa for NC-L-721 and NC L-758 resin respectively should be considered the base flexural strength of both materials. The creep-rupture stress levels as a ratio of the mean first break stress were plotted against time to failure as represented in Figure 2.21 and Figure 2.22 for NC-L-721 and NC L-758 resin specimens respectively. Using the plotted regression line, the 50-year flexural strengths were estimated as 83.5% and 84.4% of NC-L-721 and NC L-758 resin specimens' first break stresses respectively. In design, the long-term flexural strengths of the materials should be 83.5% and 84.4% of the first break stresses of NC-L-721 and NC L-758 resin CIPP.

2.6.2 Reinforced CIPP Design

The material responses of both RC-IPLUS and RC-IMAIN resin specimens to stress in the short-term tests showed no significant yield or failure till the 5% strain limit was reached, except for one specimen out of 11 that were tested. That is less than 10% of the total number of tested specimens and cannot be representative of the materials' properties. It is considered a defective sample. Ten samples showed an increasing capacity to support higher levels of stress beyond the 5% strain limit. The mean stresses at the 5% strain limit cannot be considered the true flexural strength of the reinforced CIPP specimens.

The long-term strain prediction shown in Figures 2.17 and Figure 2.18 estimates the 50-year strain of the RC-IPLUS and RC-IMAIN resin specimens at 2.45% and 3.95% respectively. These are 49% and 79% of the 5% strain limit at expected failure. The SRFs determined for both RC-IPLUS and RC-IMAIN resin specimens indicated that 89% and 91% of the mean short-term flexural strengths were retained after 50 years of projected service. These test results are indicative of the materials' high level of resistance to flexural stress. This can only be explained by the presence of fiberglass reinforcement in the composite polymer

which supports the bulk of the stress, resulting in the minimal creep strain pattern shown in the polymers of the resins over

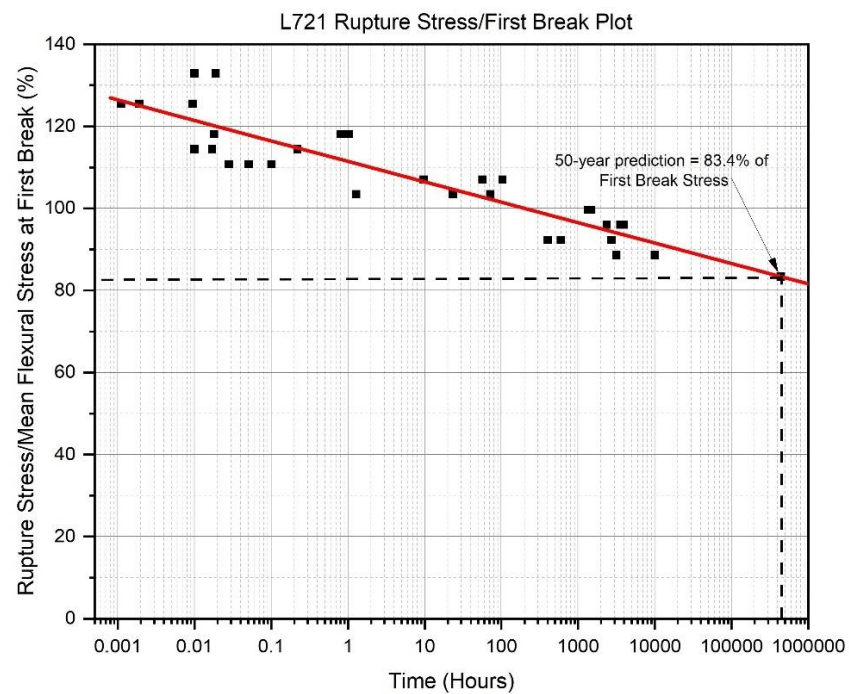


Figure 2.21: L721 Resin 10,000-hour creep rupture curve in terms of mean First Break Stress.

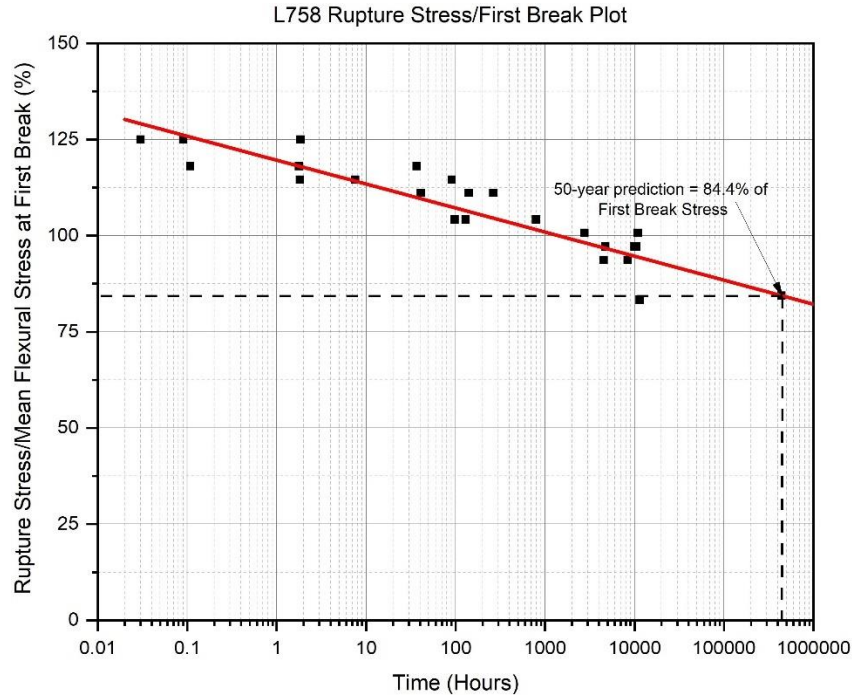


Figure 2.22: L758 Resin 10,000-hour creep rupture curve in terms of mean First Break Stress.

50 years. In design, it is considered safe to estimate the long-term strength of the tested RC-IPLUS and RC-IMAIN CIPP specimens below 89% and 91% of the mean ASTM D790 short-term flexural strength.

2.7 Conclusions

This study is an experimental investigation of the creep-rupture behavior and the short- and long-term flexural strength properties of two specimen types each of non-reinforced and reinforced CIPP liner using ASTM D790 and ASTM D2990 standard testing methods. The short-term flexural tests were completed to determine the short-term flexural strengths and other properties of the four specimens, which formed the basis for the long-term tests. The long-term creep-rupture tests were completed in 10,000 hours and regression lines were plotted with the determined creep rupture points over time. The regression lines were extrapolated to 50 years to estimate the long-term flexural strengths (LTFS₅₀) and the Strength

Retention Factors (SRF) of all the CIPP resin specimens. The data from all the tests were used to make CIPP design recommendations. Based on the tests results, the following conclusions were drawn:

1. The comparison in the material response patterns of the non-reinforced and reinforced CIPP types in the completed short-term tests showed major differences. The non-reinforced CIPP specimens showed unstable material response to applied stress beyond the first break stress level. In safe CIPP design, it is recommended that the short-term flexural strength of the non-reinforced specimens should be limited to the mean stress at the first break. On the contrary, the reinforced CIPP specimens showed a steady response to stress without failure until the 5% strain limit was reached. The results show that the presence of fiberglass reinforcements in the specimens increases the tensile strength of the specimens' outer layer and prevents failure in the short term.
2. Over a test period of 10,000 hours a total of 59 non-reinforced specimens were tested. It was observed that 42% of the NC-L721 specimens failed within the first hour of testing compared with 12% of NC-L758 specimens which failed within the same period. On the contrary, 39% of the NC-L758 specimens failed between a 3,000 – 10,000 hour period compared to 15% of NC-L721 specimens in the same period. This variation may be attributed to the difference in the flexural moduli of the materials, which may be influenced by the composition structure of the CIPP and the orientation of reinforcements. NC-L758 specimens have a 19% higher flexural modulus of 4,027MPa compared to 3,380MPa of NC-L721 specimens. Further investigation needs to be done in subsequent research to assess the strain patterns of both materials to establish the causes of these responses.
3. The resultant data from 10,000 hours of creep-rupture testing completed on a total of fifty-nine (59) NC-L721 and NC-L758 specimens was plotted to generate a strength regression line that was extrapolated to 50 years. The Long-Term Flexural Strength (LTFS₅₀) of NC-L721 and NC-L758 specimens were determined to be 31.3MPa and 30.8MPa respectively. Due to the unstable

material response of the non-reinforced CIPP liners after the first break, it is recommended that in the design of CIPP liners, the $LTFS_{50}$ to be used should be 83.5% and 84.4% of the mean first break stresses values.

4. After 10,000 hours of testing, the RC-IPLUS and RC-IMAIN specimens had no event of failure either by rupture or reaching the 5% strain limit. RC-IPLUS and RC-IMAIN specimens were loaded at 96% of their ASTM D790 flexural strengths showed 2.45% and 3.95% predicted creep-strains after 50 years of service. The predicted strain values for RC-IPLUS and RC-IMAIN specimens after 50 years of service were 51% and 21% less than the standard 5% strain limit for failure. The $LTFS_{50}$ of RC-IPLUS and RC-IMAIN specimens were estimated as 178MPa and 190MPa which resulted in 50-year SRF estimates of 89% and 91% respectively. These show that there is very minimal loss of strength in the reinforced materials after 50 years of service. In conclusion, the reinforcement in both composite CIPP specimens supports the majority of the stress in flexure; failure in flexure as described by ASTM D790 and ASTM D2990 is confirmed not to be a failure mode for the materials.
5. The Strength Retention Factors determined for the tested for NC-L721 and NC-L758 specimens were estimated as 60.0% and 61.2%. These determined values are lower than the estimates available in the literature from past research on non-reinforced CIPP liners (68%) but are significantly higher than the generally assumed 50% SRF value CIPP liners. SRF values of 89% and 91% were determined for RC-IPLUS and RC-IMAIN specimens respectively. This is very much higher than the values available in the literature from past research (60 – 76%) and almost twice the generally assumed 50% SRF for CIPP liners. The 50% generalized SRF is confirmed as wrong and misleading in CIPP design. It will result in over-designing of CIPP liners.

Chapter 3

Advancements in Standardizing the Design and Classification of CIPP Pressure Liner for Watermain Renovation

3.1 Overview

In North America, buried watermain pressure pipe networks that are close to the end of their service lives are renovated with both thermoplastics and thermoset pipes. Thermoplastic pipe products such as HDPE and PVC, and thermoset pipe products such as GRP have established design and classification methods. Their Long-Term Hydrostatic Strengths and Pressure Ratings are determined using the industry-recognized Hydrostatic Design Basis (HDB) standard testing methodology. On the contrary, there is no such established standard pressure testing method for the design and classification of reinforced CIPP Pressure liners used to rehabilitate watermains. Currently, reinforced CIPP pressure liners are designed using the ASTM F1216 Non-Mandatory Appendix X1 standard equations, initially meant to design gravity liners and low-pressure forcemains. This study seeks to advance the standardization of the design and classification of CIPP Pressure liners, by using industry-recognized HDB testing methods to test and classify CIPP pressure liners. Using the HDB testing approach, an HDB Regression curve for CIPP Pressure Liner in North America will be established, and the Long-Term Hydrostatic Strength (LTHS) and the Pressure Ratings (PR) of CIPP pressure liner specimens will be determined. A customized burst facility was designed, built, and commissioned at the University of Waterloo to complete short-term burst tests, and long-term hydrostatic tests. ASTM D1599, ASTM D1598, ASTM D2837, and ASTM D2992 standards were used to complete the HDB testing. The first set of ASTM D1599 short-term burst tests on 150mm-OD and 200mm-OD reinforced CIPP pressure liner specimens resulted in mean burst pressures of 5.47MPa and 5.11MPa respectively. The first phase of the completed long-term hydrostatic tests resulted in twenty-six failure data points for the first three sections of the five time-sections required to complete the HDB Regression Curve. The Hydrostatic Regression Line was plotted based on available data and HDB stress (categorized Long-Term Hydrostatic Strength in 50 years), and the Pressure Rating of the CIPP specimens

were estimated as 22.2 MPa and 1.05 MPa respectively. The Burst Testing Facility was upgraded to complete the second phase of the long-term hydrostatic tests and to generate failure data points for the remaining two time sections required to complete the CIPP HDB Regression Curve. Five 200mm OD full-scale test specimens are being tested in the second phase at internal water pressures of 2.83MPa, 2.90MPa, 2.97MPa, 3.03MPa, and 3.38MPa for about 5,000 hours at the time of this report. At the set pressures, at least three specimens are expected to fail between 6,000 – 10,000 hours, and one is expected to fail beyond 10,000 hours. If the failure data points fall within the expected time frames, they will fill the remaining two time-sections of the standard failure point distribution requirement, needed to complete the CIPP HDB Regression Line. The 50-year Long-Term Hydrostatic Stress (categorized Hydrostatic Design Basis), Hydrostatic Design Stress, and the Pressure Rating will all be determined from the HDB Regression line of the CIPP Pressure Liners. The results will establish the HDB testing approach as a standard design and classification method for CIPP Pressure Liners.

3.2 Introduction

In North America, underground water pipe networks are either gravity pipelines for sewers, wastewater, stormwater, and culverts, or watermains to distribute potable water. Most of the pipe networks are buried under metropolitan cities and are not easily accessible. The majority of the buried pipes have been in use for decades and are close to the end of their service lives. To keep them functional, they have to be either replaced or rehabilitated. Gravity pipe networks operate under gravity and low pressures. While sewers and stormwater pipes operate under gravity, forcemains and siphons components of gravity pipe networks operate at slightly higher pressures (140 -280 kPa). Some aging gravity pipes are rehabilitated in place using gravity CIPP liners. CIPP liners used in gravity applications are typically designed to withstand hydrostatic, dead, and live loads. In large-diameter gravity pipe CIPP liners, reinforcements such as fiberglass may be introduced to increase its hoop or circumferential strength to withstand higher hydrostatic and other external loads. In North America, circular Gravity CIPP liners are designed using the Non-Mandatory Appendix X1 equations in ASTM F1216, *“Standard Practice for Rehabilitation of Existing*

Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube,”. This design method requires completing multiple design checks using the Appendix X1 equations to determine the highest liner thickness required to support the load conditions of installed gravity liners. Gravity CIPP liners are designed as either non-structural or structural liners as described in the AWWA structural classification of liners. Watermains transmit and distribute potable water at much higher pressures than gravity pipes. Unlike gravity CIPP liners, reinforced CIPP liners used for watermains are subjected to internal working pressures ranging from 415 to 830 kPa (Knight and Bontus, 2018). CIPP Pressure liners have been used extensively in the rehabilitation of watermains over the last two decades. CIPP Pressure liners are typically designed with reinforcements in the circumferential direction to prevent failure due to the internal water pressure-induced tensile force acting in the hoop direction (Awe, 2023). Figure 3.1 illustrates the difference between the load distribution on gravity CIPP liners and CIPP pressure liners. Typically, gravity CIPP liners are designed to resist bending and buckling failures due to all external loads, while pressure CIPP liner design further considers the tensile force, F induced by the internal pressure, P (Awe, 2023). The watermain renovation industry in North America uses both thermoplastic and thermoset products. Thermoplastic pipes (HDPE and PVC), and thermoset pipes (GRP) are designed and pressure-classified using industry-recognized HDB testing methods as recommended in ASTM D2837, , - “*Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Products*,” and ASTM D2992 - “*Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for “Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings*,” testing standards respectively. On the contrary, CIPP pressure liners are designed using the ASTM F1216, “*Standard Practice For Rehabilitation Of Existing Pipelines And Conduits By The Inversion And Curing Of A Resin-Impregnated Tube*”, - Non-Mandatory Appendix X1 design equations to determine the thickness of the liner. The ASTM F1216 design standard does not account for the pressure testing, which is required to classify the CIPP pressure liner in line with the pressure classification of other products used in the watermain renovation industry. CIPP pressure liners designed using the ASTM F1216 design standard do not have pressure classification and cannot be compared with other classified watermain renovation products. Hence, there is a need to use the same industry-recognized HDB testing method used for other

watermain renovation products to test and determine the Long-Term Hydrostatic Strength and the Pressure Class of CIPP pressure liner products.

This study focuses on standardizing the design and classification of CIPP Pressure liners using the industry-recognized standard Hydrostatic Design Basis (HDB) testing and classification methods for watermain renovation products.

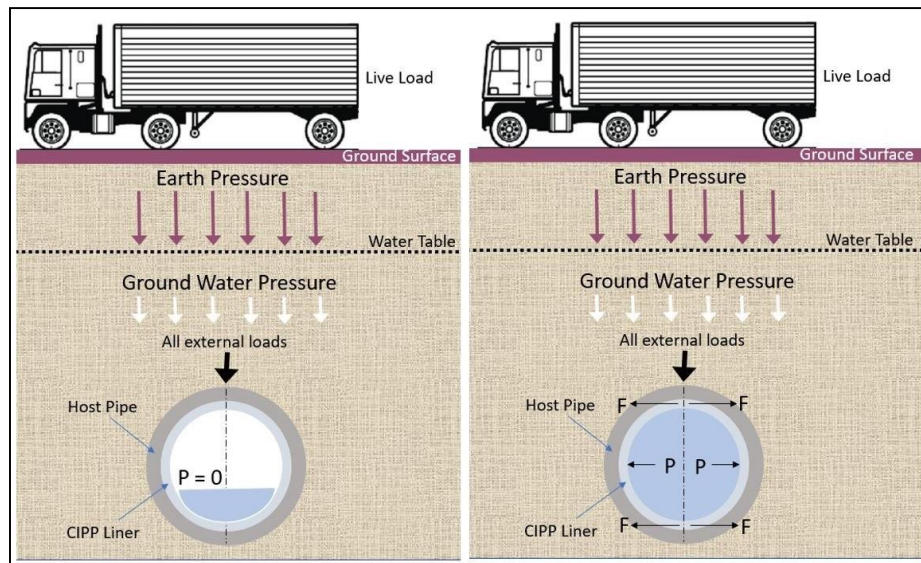


Figure 3.1: Difference between the force distribution in a reinforced gravity CIPP and pressure CIPP liners (Source: Awe, 2023)

3.3 Goal and Objectives of the Study

The goal of this study is to advance the standardization of the design and classification of CIPP Pressure Liners using the industry-accepted Hydrostatic Design Basis (HDB) testing methods. This goal will be achieved through the following objectives:

1. To build, validate, commission, and continuously upgrade a Burst Testing Facility at the University of Waterloo, and to use it to complete both short-term pressure burst tests and long-term hydrostatic tests.

2. By determining the short-term burst pressures of full-scale reinforced CIPP pressure liner specimens using the recommendations of the ASTM D1599 standard testing method.
3. To complete long-term (10,000-hour) hydrostatic testing of CIPP pressure liners to develop the first HDB Regression Curve for CIPP in North America.
4. To establish the use of HDB test methods as a standard for the design and classification of CIPP pressure liners by determining the 50-year Long-Term Hydrostatic Strength (LTHS₅₀), Hydrostatic Design Basis (HDB), Hydrostatic Design Stress (HDS), and Pressure Rating (PR) of the reinforced CIPP pressure liner specimens.

3.4 Standards for Watermain Renovation Products

Thermoplastic pipes (HDPE and PVC), and thermoset pipes (GRP) products used in the watermain renovation industry in North America are designed and pressure-classified using industry-recognized HDB testing methods as recommended in ASTM D2837 and ASTM D2992 testing standards respectively. Currently, CIPP Pressure Liners are designed using the design equations from ASTM F1216 Non-Mandatory Appendix X1.

3.4.1 Thermoplastic Pressure Pipe Design Standard

Thermoplastic pressure pipe products (HDPE and PVC) used in the renovation of watermain are designed and classified based on the internal pressure loads they are rated to sustain without the likelihood of failure. Currently, in the thermoplastic pipeline renovation industry in North America, many thermoplastic products are tested for design and classification based on the ASTM D2837 HDB testing standard. The standard defines the Pressure Rating of a pipe material as the estimated maximum water pressure the pipe is capable of withstanding continuously with a high degree of certainty that failure of the pipe will not occur. The HDB test method requires the determination of the Long-Term Hydrostatic Strength (LTHS) of a material. As defined by ASTM D2837, LTHS is the estimated tensile stress in the wall of the pipe in the circumferential orientation that when applied continuously will cause failure of the pipe at 100,000

hours. It is the intercept of the stress regression line with the 100,000-h coordinate. The HDB refers to the categorized LTHS in the hoop direction for a given set of end-use conditions established and specified by ASTM D2837. The LTHS is determined by plotting failure stress and time-to-rupture (stress-rupture) test data points, that cover a testing period of not less than 10,000 hours, and that are derived from sustained pressure testing of pipe made from the subject material. The long-term pressure testing is completed according to ASTM D1598, *“Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure”*, testing methods. The failure stress and time to failure data are plotted and analyzed by linear regression. The material’s mean strengths at the 100,000-hour intercept (LTHS) and 438,000-hour intercept (for materials that are expected to have service lives of up to 50 years (LTHS₅₀)), are determined by extrapolating the regression line. The resultant value of the LTHS is categorized to determine the HDB strength category to which the material is assigned.

Figure 3.2 is an example of a typical extrapolated stress regression line developed for a thermoplastic material. The figure also shows the lower bound of the LTHS based on a statistical analysis of the regression data, known as the Lower Confidence Limit (LCL) line. ASTM D2837 defines the Hydrostatic Design Stress a material can sustain as the estimated maximum tensile stress that the pipe material is capable of withstanding continuously with a high degree of certainty that failure will not occur. This stress is circumferential or in the hoop direction when internal hydrostatic water pressure is applied to a pipe specimen. PPI TR4 estimates that the HDB of thermoplastic materials (HDPE and PVC) is approximately 1.6 – 2 times the HDS value. Boros (2011) presents the HDB thermoplastic pipe design methodology and determines PVC and HDPE long-term hydrostatic strength (LTHS) based on pressure testing as per ASTM D2837 standard.

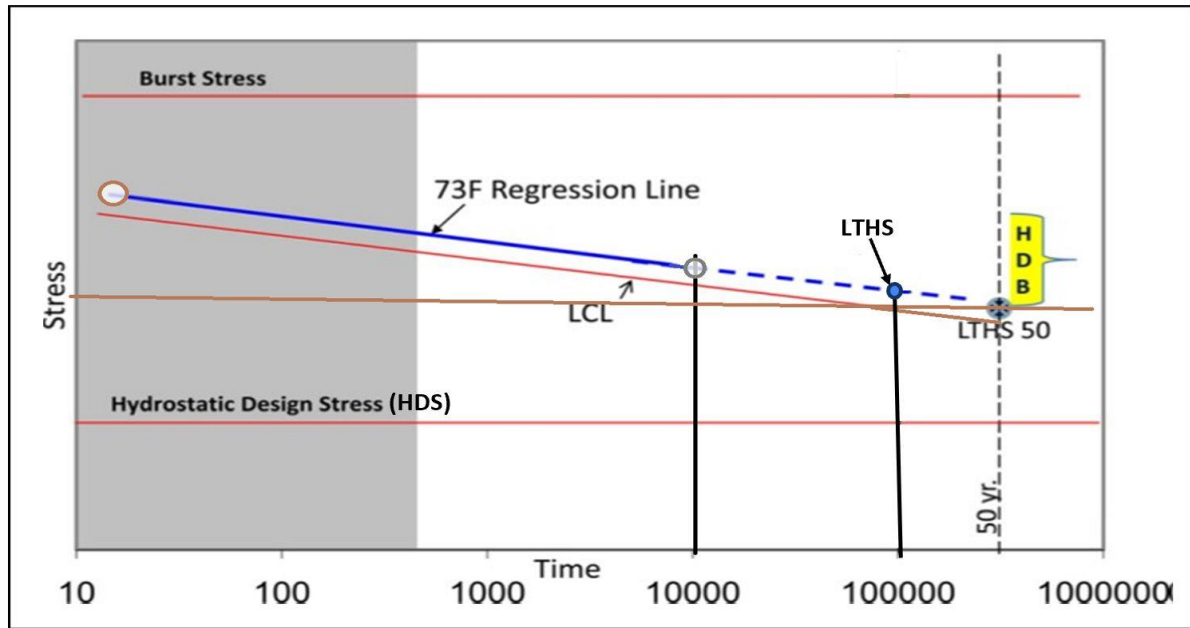


Figure 3.2: Typical HDB regression line, showing extrapolation beyond 10,000 hours of test data.
(Source: Boros, 2011)

The LTHS at 50 years ($LTHS_{50}$) was then categorized as the HDB and further reduced to a Hydrostatic Design Stress (HDS) by dividing it by a factor of 2. The stress/pressure levels for the tests shall be selected to ensure that a minimum of 18 failure stress/pressure-time data points are obtained for each test material in a test environment. Table 3.1 shows the recommended distribution of failure data points over time sections as established in ASTM D2837.

Table 3.1: Long-term ASTM D2837 test failure point distribution

Time Interval	Hours to Failure	No. of HDPE/PVC Failure Points
Time Section I	< 1,000	At least 6
Time Section II	10 to 1000	At least 3
Time Section III	1,000 to 6,000	At least 3
Time Section IV	After 6,000	At least 3
Time Section V	After 10,000	At least 1
Total		At least 18

3.4.2 Thermoset Pressure Pipe Design Standard (GRP)

Glass fiber reinforced polymer (GRP) pipe is a composite watermain renovation product that is widely used in the industry. It is often designed with many layers of glass fiber reinforcements across the cross-section of the pipe with increased reinforcement in the hoop direction to give it high tensile strength. The layers of fiber are bound together within a polymer matrix, typically epoxy or polyester resin. GRP pipes are anisotropic, as such, they have different mechanical properties in the hoop and longitudinal pipe axes. In North America, many publicly available GRP pipes are factory-manufactured using HDB testing methodology in their design and classification by determining their Long-Term Hydrostatic Strengths and Pressure Ratings. The HDB testing methodology prescribed in ASTM D2992 is used to test and develop an HDB regression curve for GRPs. The stress-rupture and time-to-failure data points, over 10,000 hours are used in developing the HDB regression curve, which is then extrapolated to 100,000 hours to determine the Long-Term Hydrostatic Strength (LTHS), or to 50 years (438,000 hours) to determine the LTHS₅₀ of the GRP pipes. ASTM D2992 - Procedure B requires that the specimens be tested according to ASTM D1598, *“Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure”*, testing methods to obtain at least 18 failure points, in a water environment that is maintained within 3°C of the

test temperature. The failure points must have a minimum distribution as shown in Table 3.2 as per ASTM D2992. The failure points are plotted to develop the regression line for the GRP products.

Table 3.2: Long-term ASTM D2992 test failure point distribution

Time Interval	Hours to Failure	No. of GRP Failure Points
Time Section I	10 to 1,000	At least 4
Time Section II	1,000 to 6,000	At least 3
Time Section III	After 6,000	At least 3
Time Section IV	After 10,000	At least 1
Total		At least 18

Sung and Jin (2015) evaluated the long-term structural properties of nineteen (19) GRP specimens using the HDB testing methods for 10,000 hours. The failure points obtained from the tests were plotted and the regression line was extrapolated to determine the Long-Term Hydrostatic Strength after 50 years (LTHS₅₀). The design factor determined from the test results showed that the ratio of the determined failure pressure at 50 years to that of 6 minutes was 0.43. Similar tests completed by Faria and Guedes (2010) on three GRP specimens of 300mm nominal diameter and 1.3-meter length resulted in design factors of 0.42, 0.5, and 0.83 respectively.

3.4.3 Standardizing CIPP Pressure Liner Design and Classification

CIPP Pressure Liners are structural composite thermoset pipes with anisotropic properties (having varied mechanical properties along the hoop and longitudinal axis), similar to GRP pipes. The field-production

nature of CIPP introduces many complexities that affect its physical properties such as wrinkles, folds, and invisible air-voids. All these imperfections impact its tensile capacity to resist internal pressure. These complexities are not commonly found in other pressure pipe renovation products that are manufactured under very controlled conditions in the factory. In the pressure pipe renovation industry, ASTM D2837 is the standard HDB testing method used for the design and classification of GRP pressure pipe products. ASTM D2992 is a similar HDB testing standard used for the design and classification of thermoplastic pressure pipes (HDPE and PVC). CIPP pressure liners have no standard pressure testing method used for their design and classification. The ASTM F1216 Non-Mandatory Appendix X1 equations, which are currently used in the design of CIPP pressure liners, make use of flexural and tensile properties of CIPP determined from flat coupon specimens and not results derived from the pressure testing of full-scale CIPP pressure liner samples. In North America, short-term tests have been performed on CIPP pressure liners to determine the effects of liner imperfections on its response to internal pressure but no known literature presents the result of any long-term tests to determine the Long-Term Hydrostatic Strength of CIPP in 50 years. Knight and Bontus (2018) reported tests on eleven commercially available CIPP liners specimens (Liners A - a set of six CIPP liners specimens were without visible imperfections while the second set of five specimens - Liners B had visible imperfections such as wrinkles and folds). The results showed that the mean short-term burst pressure of Liners A was 5.45MPa with a standard deviation of 0.6MPa while Liners B had a mean short-term burst pressure of 2.92MPa and a standard deviation of 0.7MPa. There was no information reported on long-term tests of the CIPP liner specimens. Alam *et al* (2015) reported a study on the burst pressure test of glass-fiber reinforced CIPP thermosetting-resin specimens. Nine 300mm diameter by 1.2m length specimens with three different glass-fiber reinforcement configurations were investigated. The results showed that the variation in the configuration of the reinforcement materials varied their short-term burst pressures by up to 45%. These high levels of variations in the responses of different commercially available CIPP pressure liners to short-term pressure testing, make it very necessary to standardize their design and classification using an industry-recognized test method such as the HDB testing approach. Standards organizations such as the International Standards Organization (ISO) and the American Water Works Association (AWWA) are

currently working on setting standards for the design and classification of CIPP pressure liners. The outcome of this study will advance to the CIPP pressure liners design and classification standardization project.

3.5 Watermain Pressure Burst Testing Facility

Pressure pipe burst testing facilities are uncommon because a testing facility that meets all the standard testing requirements is difficult to develop. Hence the need to customize, design, and build one at the University of Waterloo. The initial work on this burst testing facility was completed and reported in the PhD thesis of Awe (2023). This report reviews some of the processes and results of the development of the burst testing facility as it forms the basis for the upgrades, result comparison and analysis, and further testing completed with the facility to complete the standard testing procedures.

3.5.1 The Design Framework of the Burst Testing Facility

The Burst Testing Facility was designed and built to overcome all the usual challenges with existing designs that use pressure pumps. As reported by Awe (2023), it was developed to operate as required by the testing standard procedures and requirements. The facility was built to be able to determine the following:

1. Short-term burst pressures of pressure pipes (CIPP)
2. Pressure rating of pressure pipes (CIPP) using long-term HDB testing, and
3. Pressure pipe (CIPP) response to pressure cycles and fatigue life.

For the system to perform the listed tests, the following design objectives were met:

- i. Ability to test full-scale CIPP liner specimens with a maximum Outer Diameter (OD) of up to 250 mm, and longitudinal specimen length of at least five times the pipe OD.
- ii. Maximum burst pressure capacity of 14 MPa (2,000psi).
- iii. Controllable uniform pressure loading ramp rate with no pressure surges.
- iv. Modular components for maintenance and upgrading.

- v. Condition and burst multiple CIPP liner specimens in a controlled temperature water bath at 23°C $\pm$ 2°C.
- vi. Data acquisition system that monitors and collects pressure sensor data at a minimum of 100 samples/sec.
- vii. A computer-controlled pressure monitoring system that can maintain multiple test specimen pressures to within 5% of the target set pressure for at least 10,000 hours (approximately 14 months) and specimen failure.
- viii. Ability to apply controlled pressure cycles to CIPP liner specimens for up to 10 million cycles or liner failure.

3.5.2 The Burst Testing Facility Component Systems

The burst testing facility was custom-designed to perform the stated objectives, as a combination of four major systems. The facility has a water pressurizing system, a specimen pressure control and monitoring system, a specimen conditioning water tank, and a computerized system control and data acquisition system.

3.5.2.1 Water Pressurizing System

The water pressurizing system is an assembly of a reversible electric motor, a speed-reducing gearbox, a screw actuator, and a custom-made gauged stainless-steel piston and cylinder unit for water pressurization. Figure 3.3 shows the assembly of the water pressurizing system. The software-controlled bi-directional electric motor drives the whole system through a speed-reducing gearbox connected to a screw actuator. The screw actuator is connected to the piston rod, and spacer bars were used to create a 200mm stroke distance for piston-actuator movement. The hydraulic cylinder has a water inlet controlled by a 19.05mm ($\frac{3}{4}$ inch) solenoid valve that automatically opens and closes to refill the hydraulic cylinder. The electric motor-driven actuator-piston system pressurizes the water in the hydraulic cylinder. The pressurized water is released into the specimen pressure control and monitoring system via a 2,000 psi rated hose.

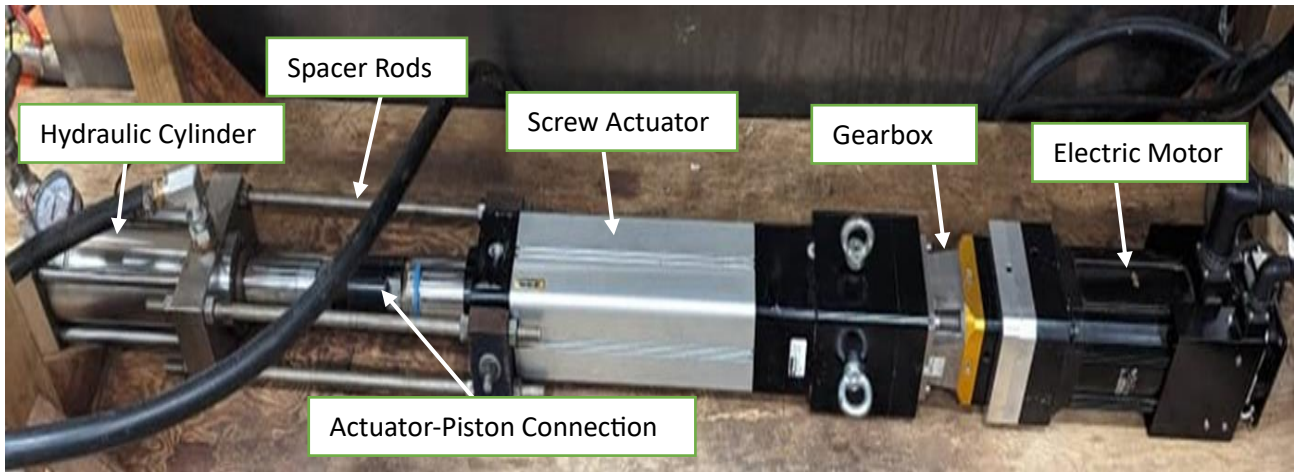


Figure 3.3: Water Pressurizing Assembly

3.5.2.2 Specimens' pressure control and monitoring system

The specimen pressure control and monitoring system has a high-pressure manifold that holds pressurized water, a set of seven (7) specimen pressurizing assemblies (each assembly has a 19.05mm ($\frac{3}{4}$ inch) one-way flow valve, a 6.35mm ($\frac{1}{4}$ inch) solenoid valve, a 13.8 MPa rated pressure transducer, and a 13.8 MPa-rated pressure hose that connects to the specimen). In response to LabVIEW software-controlled specimen pressure monitoring signals, the manifold automatically releases pressurized water into the specimens through the pressurizing assembly. The specimen pressure control and monitoring system regulates the pressures in the specimens to maintain them within $\pm 1\%$ of the set pressures. There are two 10.3 MPa-rated automatic and one manually-controlled safety pressure release valves on the manifold. Figure 3.4 shows the specimen pressure control and monitoring system.

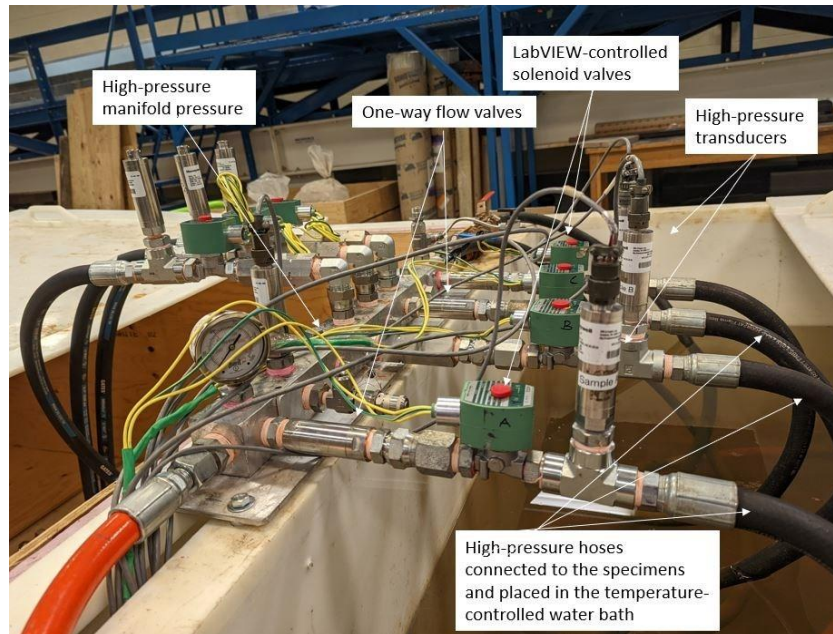


Figure 3.4: Specimen pressure control and monitoring system
(Source: Awe, 2023)

3.5.2.3 Specimen conditioning water tank

The test specimens are placed in two 19-mm thick polypropylene plastic water tanks. The dimensions of each tank are – 2.4 meters long, 1.5 meters wide, and 0.9 meters deep. The two tanks were manufactured to take up to 8 test specimens but they can be adapted to hold up to 14 specimens. To maintain the test specimens at a constant temperature, the tank is filled with water till the specimens are completely submerged. The specimens are conditioned for at least one hour in water maintained at a temperature of $23 \pm 2^{\circ}\text{C}$ before testing. The tanks are filled with water from the manifold and can be emptied through two draining valves at the bottom. Figures 4.5 show the submerged specimens (with both completed short-term and ongoing long-term test specimens) and the plastic water tanks covered with lids. The lids prevent broken pipe fragment projectiles, and water from splashing during pipe burst tests.



Figure 3.5: Plastic water tanks and submerged test specimens

3.5.2.4 Computerized system control and data acquisition system

The computerized system control and data acquisition unit automatically controls all the component systems of the burst testing facility. The system has a computer, a motor controller, a NI- cDAQ (Compact Data Acquisition device), a custom-built LabVIEW software, and a SigmaWIN software for the control of the facility systems. The custom-built LabVIEW data acquisition software is programmed to control actuator movements, open and close solenoid valves, and monitor and store pressure sensor data at 100 samples per second (Awe, 2023). The LabVIEW software controls the operations of the specimen pressure control and monitoring system, the pressurizing system, and interfaces between the cDAQ and all the other systems for automatic control and data acquisition. The SigmaWIN software manually controls the pressurizing system during short-term burst tests after the LabVIEW software has been paused.

3.5.3 Operation of the Burst Testing Facility

All the components of the facility are rated to withstand testing pressure of 2,000 psi (13.8MPa) without leaks. The pipe specimens are bolted with restrained end closures and submerged under water in covered

plastic tanks as shown in Figure 3.5a. The specimens are connected to the pressure control and monitoring system via a 2,000 psi pressure hose, and conditioned at a temperature of $23 \pm 2^{\circ}\text{C}$ in the water tank for at least an hour before testing. The required testing pressure and failure limit for each specimen are set in the LabVIEW software. The hydraulic cylinder of the pressurizing system gets filled with water from the water mains in the laboratory building when the $\frac{3}{4}$ inch solenoid valve opens. It closes when the cylinder is full and the pressurizing system starts to pressurize water within the hydraulic cylinder. Pressurized water is released to the manifold of the specimen pressure control and monitoring system which holds pressurized water. Multiple specimens are pressurized to different levels from the manifold simultaneously. Once each specimen gets to the set pressure, the pressure transducer sends a signal to the cDAQ through the LabVIEW software to activate the solenoid valve connected to the specimen to stop pressurized water from flowing into the specimen. The reverse happens when the pressure in the specimen drops below the set pressure due to the creep expansion of the specimens. The cDAQ acquires and stores pressure data from the specimens based on signals from the pressure transducers. For short-term pressure burst tests, the automatic control of the pressurizing system is paused, and the manual control is activated using the SigmaWIN software to operate the pressurizing system. The SigmaWIN software is used to position and move the actuator and piston to pressurize pipe specimens at the required speed to achieve failure within the required timeframe.

3.5.4 Validation of the Burst Testing Facility

The Burst Testing Facility needed to be validated before it could be certified to be used for the experimental study. Validation requires it to be used to test a material with standard material and mechanical properties. PVC thermoplastic pipes were chosen for the validation because it has published standard properties derived from experimental investigations.

3.5.4.1 Theoretical Determination of PVC Burst Pressure

The built burst testing facility was validated by completing short-term burst tests on some 150 mm OD,

DR-18 PVC pipes with well-established burst pressures. A PVC 1120 thermoplastic pipe is listed in PPI TR-4 to have a 23°C hydrostatic design basis (HDB) and hydrostatic design stress (HDS) of 27.6 and 13.8MPa respectively.

The pressure rating (PR) of PVC pipe is determined using Equation 3.1.

$$PR = \frac{2 \times HDS}{DR - 1} \quad (3.1)$$

where:

DR = is the dimension ratio of the pipe – the ratio of the pipe outside diameter to the pipe minimum wall thickness is 18, and

HDS = is 13.8 MPa as stated in PPI TR-4.

The pressure rating (PR) for the DR-18 PVC pipe was determined to be 1.62 MPa.

The PVC 1120 – HDS value of 13.8 MPa as stated in PPI TR-4 was multiplied by a factor of 4, as provided by Boros (2011), to determine the burst stress as 55.2MPa. PVC burst pressure was then determined using Equation 3.2, as stated in ASTM D2837.

$$\sigma_h = \frac{P(D-t)}{2t} \quad (3.2)$$

where:

σ_h = pipe hoop stress (burst stress at failure)

P = pipe burst pressure

D = outside diameter to the pipe (150mm)

t = minimum wall thickness, and

Thus, the estimated PVC burst pressure is **6.49 MPa**

3.5.4.2 Burst Testing Facility Validation – PVC Short-Term Burst Tests

Six factory-manufactured PVC 1120 DR-18 pipes 150 mm diameter of 1.5 m lengths were bolted with restrained end closures as shown in Figure 3.6. The PVC specimens were connected to the specimen pressure control and monitoring system with a pressure hose and then filled with water while positioned vertically. All trapped air was expelled through the outlet valve on one end cap of the specimen. As specified by ASTM D1599 standard, before pressurizing the PVC specimens, they were conditioned by submerging them in the water bath at a temperature of about 23°C for at least one hour.

The pressurizing system was manually controlled to increase internal pipe pressure at a constant rate to achieve specimen failure within 60 to 70 seconds according to ASTM D1599. While pressurizing the PVC pipe specimens, it was observed that internal water pressure plateaued in different specimens between 5.86 to 6.81 MPa severally before eventual failure. The plateauing occurred due to the elastic expansion behavior of PVC during water pressurization. The limitation of the size of the hydraulic cylinder to pressurize a sufficient volume of water to burst the PVC pipe specimens in one full stroke without recharging was observed. Despite this identified limitation, the burst testing facility maintained the test specimen's pressure level while the hydraulic cylinder was refilled and re-pressurized. Multiple pressure cycles were applied to the test specimens at an increased pressurization rate to get them to burst. Table 3.3 compares the experimental PVC burst pressures obtained through multiple pressure cycles to PVC pipe's calculated burst pressure. The PVC experimental burst pressure range was 5.86 to 6.63 MPa with a mean burst pressure of 6.37MPa. This is close to the 6.49 MPa burst pressure values determined using Equation 3.2. It can be concluded that the experimental data obtained for PVC burst tests that ranged from 5.86 to 6.63 MPa agrees well with PVC theoretical burst pressure of 6.49 MPa. The results of the PVC tests validated the University of Waterloo CIPP liner burst testing facility, and the limitation of the burst testing facility was noted.

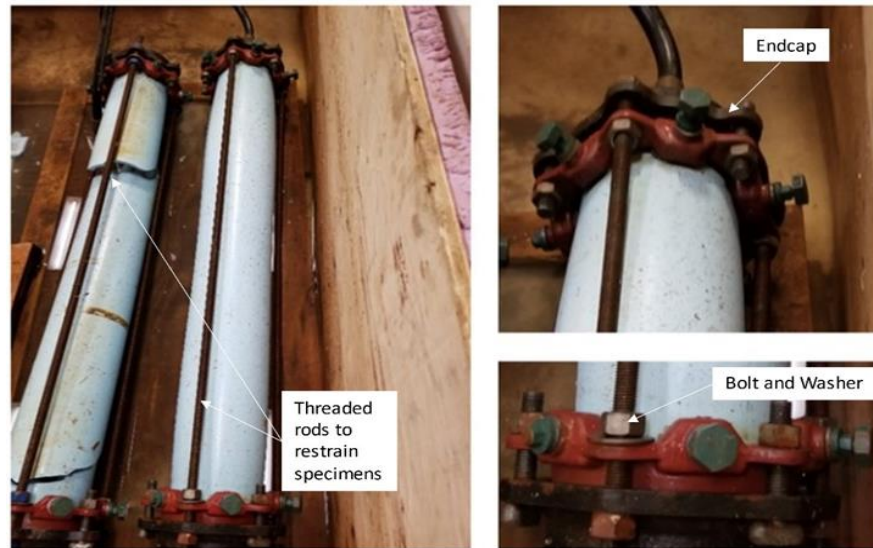


Figure 3.6: PVC burst testing completed to validate the new CIPP test facility.
(Source: Awe, 2023)

Table 3.3: Test results of Six PVC short-term burst tests.

ID	No. of Pressure Cycles to Burst	Burst Time (min)	Maximum Plateau Pressure (MPa)	Min Plateau Pressure (MPa)	Mean Plateau Pressure (MPa)	Test Burst pressure (MPa)	Calculated Burst Pressure (MPa)
P1	4	3.9	6.55	6.21	6.38	6.21	6.49
P2	4	4.2	6.63	5.86	6.25	6.63	6.49
P3	5	4.1	6.61	6.38	6.50	5.86	6.49
P4	6	3.9	6.33	5.86	6.10	6.33	6.49
P5	8	4.2	6.67	6.61	6.64	6.55	6.49
P6	6	4.1	6.81	6.58	6.70	6.62	6.49
						6.37	6.49

3.5.5 Commissioning of the Burst Testing Facility

The burst testing facility was commissioned with 150mm OD, DR-18 CIPP pressure liner specimens. It was used to complete both short- and long-term tests on the CIPP specimens.

3.5.5.1 CIPP Pressure Liner Short-Term Burst Tests - Test Specimens

The CIPP specimens used for this research were produced and supplied by Insituform Technologies Limited (Aegion Corporation). The specimens are a re-engineered version of InsituMain™ called I-Main CIPP Pressure Liners. To ensure consistency in specimens' responses to load and reproducibility of the test results, the specimens were produced in Insituform's laboratory under controlled temperature and other environmental conditions, and strict production processes. This manufacturing process is different from the in-field CIPP installation process that is done within a buried pipe. The test specimens are fiberglass-reinforced CIPP epoxy-resin pressure liners used for watermain renovation. The tensile capacity of the liners was increased by the structural arrangement of the short fiberglass strands in overlapping layers. The new arrangement of the fiberglass reinforcements improves the liner wetting out and expandability during production and installation to ensure close-fit lining of the host pipes. The specimens were 6-inch (150mm) OD and 1.5m long.

3.5.5.2 Short-Term Burst Test Procedure

As reported in Awe (2013), twelve 150-mm outer diameter CIPP specimens were prepared for short-time burst tests. The ASTM D1599 standard test method was adopted for these short-term tests. The CIPP specimens were coupled with restrained end closures – the water-tight cast iron end caps and seals on both ends of each specimen. The end caps were secured with three high-yield threaded bars to ensure the end caps did not blow off and create watertight end seals. Figure 3.7 shows a specimen prepared and used for a short-term burst test. The specimens were connected to the specimens' pressure control and monitoring system with a pressure hose and filled with water. The specimens were filled in a vertical orientation while the ball valves attached to the rear end cap of the test specimens were left open to allow the removal of any entrapped air. Once all air was removed, the ball valves on the specimen end caps were closed. The internal pressure in the specimens was at equilibrium with the water pressure of the water source which is at an average of 60 psi. The specimens were then conditioned at a temperature

of $23 \pm 2^\circ\text{C}$ in the polypropylene plastic tank for at least one hour.

The water pressurizing system was manually operated to ensure the maximum volume of the hydraulic cylinder was filled with water through the $\frac{3}{4}$ inch solenoid valve at the water inlet. The actuator was used to move the piston manually at a rate that increased the internal pressure in the specimens constantly to cause the specimens to burst or fail within 60 to 70 seconds.



Figure 3.7: A 150mm OD CIPP Pressure Liner specimen, prepared and used in a short-term burst test (Source: Awe, 2023)

3.5.5.3 Short-Term Burst Test Results

The twelve tested CIPP pressure liner specimens had a burst pressure range between 3.08 – 6.05 MPa (447 – 881 psi) and the time-to-failure ranged between 31 – 69 seconds as presented in Table 3.4. The modes and locations of failure varied in many of the specimens. The test results that were not compliant with the recommendations of ASTM D1599 standards for an acceptable test based on time-to-failure, location of failure, and mode of failure, were discarded as invalid. A total of six test results were invalidated while the second six were accepted in line with ASTM D1599 standards. The time-to-failure range and burst pressure range of the valid tests were 60 – 69 seconds and 5.04 – 6.05 MPa respectively. The mean short-term burst pressure was 5.47 MPa with a standard deviation of 0.36 MPa. All the valid test specimens failed in the middle. Figure 3.8 presents the plot of the internal water pressure and the time

to failure of all twelve CIPP liner test specimens. This figure shows a linear internal pressure ramp rate with no pressure surges for all twelve test specimens.

Table 3.4: 150mm OD CIPP liner short-term burst test results using ASTM D1599 testing standards

Specimen ID	Time to Burst (sec)	Burst Pressure (MPa)	Failure Location	Failure Mode	Valid Test
SB02	31	3.09	Middle	Line Crack	No
SB03	69	6.05	Middle	Burst	Yes
SB04	62	5.22	Middle	Burst	Yes
SB05	52	5.04	End	Burst	No
SB06	60	5.30	Middle	Burst	Yes
SB07	47	3.92	End	Seam Failure	No
SB08	48	4.00	Middle	Burst	No
SB09	55	4.82	Middle	Burst	No
SB10	66	5.58	Middle	Burst	Yes
SB12	37	3.08	Middle	Seam Failure	No
SB13	64	5.04	Middle	Burst	Yes
SB14	68	5.59	Middle	Line Crack	Yes

(Source: Awe, 2023)

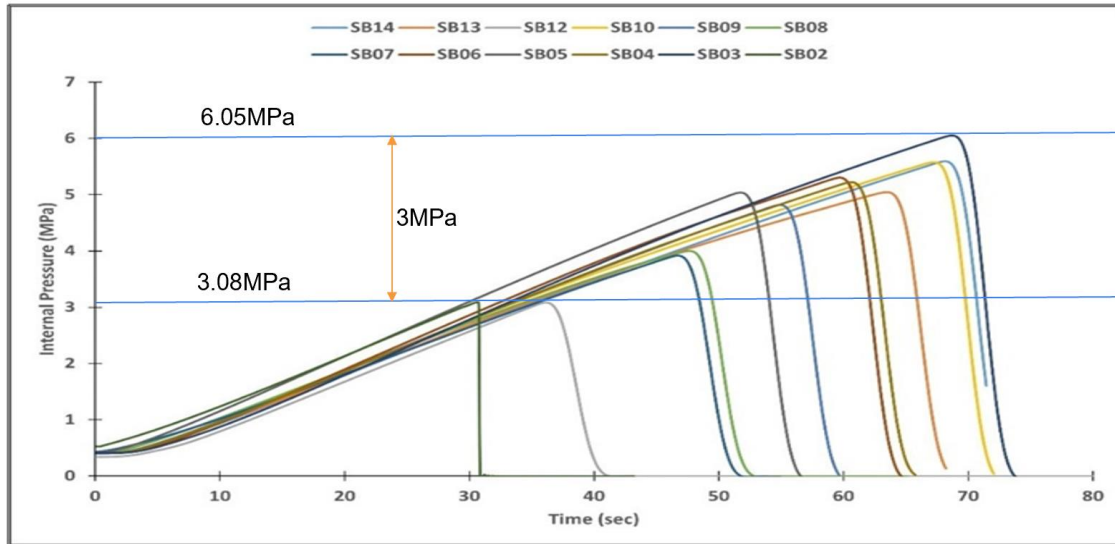


Figure 3.8: 150mm OD CIPP Short-Term Burst Tests Results
(Source: Awe, 2023)

The pressure burst test results and the wide time range to failure show wide inherent variability in the specimens despite the comparable loading rates for all CIPP test specimens. Further investigation into the reason for the large variability in CIPP burst test results found that there was no correlation between the CIPP burst pressures and failure modes. The large variability in burst pressure and time to failure noted were experimentally determined to be independent of the performance of the CIPP testing equipment, as the specimens were pressurized consistently (Awe, 2023). The liner variability may be attributed to invisible liner imperfections such as microscopic air voids, possibly because of Quality Assurance and Quality Control (QA/QC) errors during the liner wetting out process. The test results agree with the results reported by Knight and Bontus (2018) and Almansour *et al.* (2015) which both stated that the impact of CIPP material flaws in the significant reduction in CIPP burst pressure is approximately 45 to 50%.

3.6 CIPP Pressure Liner HDB Testing – Phase I

The first phase of the CIPP HDB testing for the development of the first known CIPP Pressure Liner HDB

Regression Line, as reviewed and summarized in this report, was completed as part of the PhD research work reported in the thesis – Awe (2013). This part of the CIPP pressure liner research formed the basis for the further research that was completed and is reported in this study.

3.6.1 Applying HDB Testing Methods to CIPP Design and Classification

In line with the design of thermoplastics and other thermoset pressure pipes such as HDPE, PVC, and GRP respectively, the Long-term Hydrostatic Strength (LTHS) and Pressure Rating (PR) of CIPP were estimated using the industry-recognized Hydrostatic Design Basis (HDB) testing and design approach. A hybrid/consolidated HDB test procedure of ASTM D2837 and ASTM D2992 standards was used. This study provides an overview of the HDB design approach and its applicability to the design and pressure classification of the Insituform Technologies (Aegion Corporation) manufactured I-Main composite CIPP pressure liner specimens. The CIPP specimen specifications were 200mm OD, DR-18. The validated University of Waterloo customized burst testing facility was used to get Long-Term Hydrostatic test data for CIPP to develop the HDB regression line. This experimental study was completed to standardize the design and classification of CIPP pressure liners. The initial short-term burst tests were completed per ASTM D1599 test methods and the long-term pressure testing was completed per ASTM D1598, *Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure*, test procedural recommendations.

3.6.2 200 mm OD CIPP Pressure Liner Short-Term Burst Tests

To investigate CIPP's long-term hydrostatic pressure performance, short-term burst tests were first conducted to establish the short-term response of the CIPP specimens to pressure, and to determine the initial short-term burst test data that was used as a reference throughout the long-term testing process. Six reinforced CIPP specimens were tested per ASTM D1599 short-term test methods. The specimens had 8 mm wall thickness, 200 mm in diameter, and 1.2 meters long which makes them at least five times the diameter as required in the standard. Cast iron mechanical joint (MJ) end caps were used with three high-

yield threaded bars to secure the ends, create water-tight end seals, and prevent the end caps from blowing off under pressure. The tests were conducted using the custom-built University of Waterloo burst testing facility. The specimens were conditioned in the temperature-controlled water bath of the burst testing facility at approximately 23°C for about an hour before running the tests. The tests were completed, and Figure 3.9 shows a sample of the LabVIEW software plotted internal water pressure–time to failure data of a short-term burst test. Table 3.5 and Figure 3.10 provide the ASTM D1599 standard burst test results for the six reinforced CIPP specimens. The CIPP Pressure liners were noted to have short-term burst pressures that ranged between 4.65 to 5.42 MPa with a mean burst pressure of 5.11 MPa and a standard deviation of 0.34 MPa. There is a variance of 0.7 MPa between the maximum and the minimum burst pressures of the 200 mm OD CIPP specimens is significantly lower than the 3.0 MPa variance observed in the 150 mm OD CIPP specimens. All CIPP test specimen burst failures occurred between 69 and 97 seconds. The short-term burst pressure values were deemed valid, in line with ASTM D1599 standard requirements, when the burst failure location is in the middle or near the middle of the specimens' length. Figure 3.11 shows the sample of a CIPP Pressure Liner acceptable middle burst in a short-term test.



Figure 3.9: A short-term burst test display of the LabVIEW software interface of the burst testing facility. (Source: Awe, 2023)

Table 3.5: ASTM D1599 CIPP Pressure liner short-term burst test results.

Specimen ID	Time to Burst (sec)	Burst Pressure (MPa)	Burst Stress (MPa)	Failure Location	Failure Type
SB_A	97	5.26	63.1	Middle	Burst
SB_B	80	5.36	64.3	Middle	Burst
SB_C	77	5.27	63.2	Middle-End	Burst
SB_D	70	5.42	65.0	Middle-End	Burst
SB_E	75	4.70	56.4	End	Burst
SB_F	69	4.65	55.8	Middle	Burst
Mean	78	5.11	61.3	-	-
St. Dev	10.2	0.34	4.11	-	-

(Source: Awe, 2023)

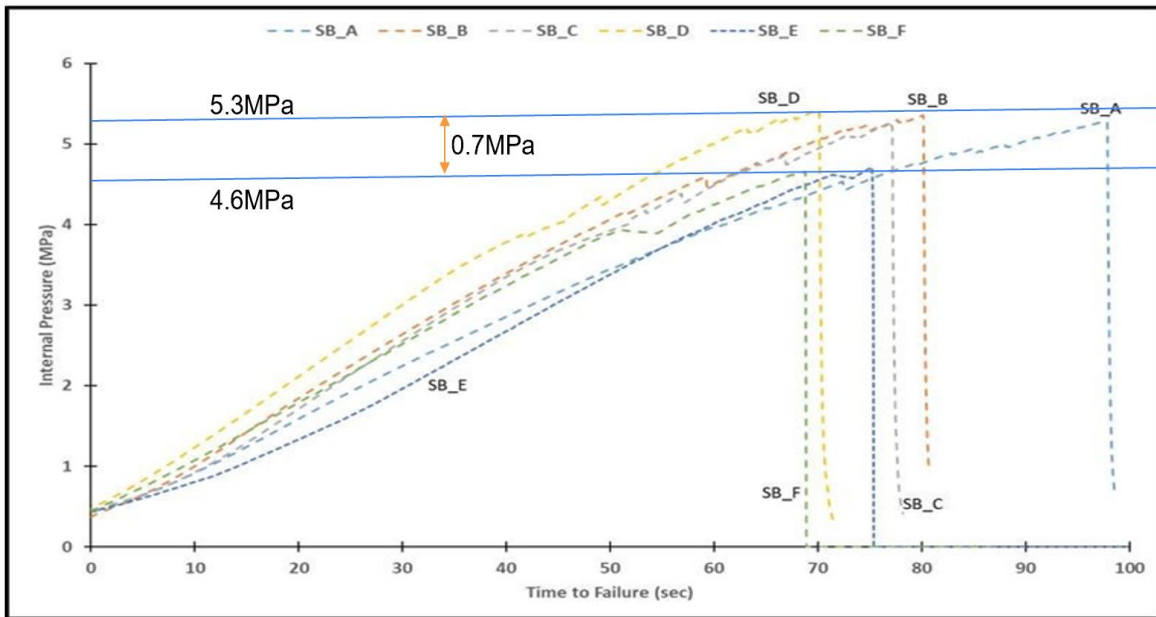


Figure 3.10: Pressure-time plots for six 200-mm OD CIPP specimens. (Source: Awe, 2023)



Figure 3.11: Sample of CIPP specimens' middle failure in a short-term burst test (Source: Awe, 2023)

3.6.3 200 mm OD CIPP Liner Long-Term Hydrostatic Testing

Since there is no established HDB testing and design standard for CIPP pressure liners, the HDB test methods per ASTM D2837 and ASTM D2992 were adopted to create an experimental plan, and test procedure to complete the long-term hydrostatic tests.

3.6.3.1 The Hybrid/Consolidated Experimental Plan

The results of the completed short-term tests formed the reference for determining the test pressures for the long-term tests. Table 3.6 provides a hybrid/consolidated experimental plan of the required number of specimen failures for each time section as specified in ASTM D2837 and ASTM D2992 HDB testing standards. The test pressures were selected based on the mean short-term burst pressure, such that multiple failures occurred before 10 hours, between 10 and 1,000 hours, 1,000 and 6,000 hours, and then greater than 6,000 hours up to 10,000 hours and beyond. Table 3.6 provides the CIPP experimental plan.

Table 3.6: Long-term hydrostatic tests experimental plan for the CIPP specimens.

Time Interval	Hours to Failure	GRP	HDPE/PVC	Hybrid/Consolidated Plan for CIPP HDB Testing
Time Section I	<10	At least 6	-	At least 6
Time Section II	10 to 1,000	At least 3	At least 4	At least 4
Time Section III	1,000 to 6,000	At least 3	At least 3	At least 3
Time Section IV	After 6,000	At least 3	At least 3	At least 3
Time Section V	After 10,000	At least 1	At least 1	At least 1
Total		At least 18	At least 18	At least 18

3.6.3.2 The Long-Term Hydrostatic Test Results

Table 3.7 shows the failure pressure and strength, time to failure, and failure location of twenty-six CIPP specimens for long-term performance prediction and design using the HDB approach. For the first eleven CIPP specimens tested, internal pressure ranging from 3.66 to 5.42 MPa was applied to induce failure within Time Section I (< 10 hours). Twelve CIPP specimens with a pressure range from 3.24 to 4.07 MPa caused failure within Time Section II (10 to 1,000 hours). For three CIPP specimens, test pressure ranging from 3.31 to 3.38 MPa was applied to induce failure within Time Section III (1,000 to 6,000 hours). Long-term pressure tests were conducted on the composite CIPP specimens for up to 1635 hours. No specimen failed between 6,000 - 10,000 hours or beyond 10,000-hour time-sections as required to complete the HDB Regression Line. Further tests need to be completed to fill the minimum number of data points for Time Sections IV and V.

Table 3.7: CIPP specimens failure distribution in long-term testing for the development of HDB Regression line

Time Section	Hours to Failure (hr)	Failure Pressure (MPa)	Failure Strength (MPa)	Time to Failure (hr)	Failure Mode
Time section I	< 10	5.42	64.9	0.02	Burst
		5.36	64.1	0.02	Burst
		5.27	63.1	0.02	Burst
		5.26	63	0.03	Burst
		4.65	55.6	0.02	Burst
		4.38	52.4	1.38	Burst
		4.25	50.6	1.16	Weep
		4.14	49.6	1.45	Burst
		3.94	47.2	3.93	Burst
		3.65	43.7	7.31	Weep
Time section II	10 to 1,000	4.07	48.7	46.4	Burst
		3.97	47.5	10.15	Burst
		3.97	47.5	41.72	Burst
		3.66	43.7	64.12	Burst
		3.59	42.9	242.57	Burst
		3.52	42.1	12.64	Burst
		3.52	42.1	183.19	Burst
		3.45	41.3	309.86	Burst
		3.45	41.3	35.34	Burst
		3.38	40.4	714.1	Burst
		3.24	38.8	382.16	Burst
		3.24	38.8	454.48	Burst
Time section III	1,000 to 6,000	3.38	40.4	1041	Burst
		3.31	39.6	1634.82	Burst
		3.31	39.6	1386.82	Burst

(Source: Awe, 2023)

3.6.4 CIPP HDB Regression Line

Data analysis was completed using a logarithmic treatment on the long-term test data. A linear regression analysis on a logarithmic time scale was completed using the failure stress (σ_f) as the independent variable on the y-axis and log time (t) as the dependent variable on the x-axis. Long-term hydrostatic strength (LTHS) in the hoop direction was estimated at 50 years, which was categorized to determine the hydrostatic design basis (HDB). The long-term hydrostatic stress of the tested reinforced CIPP product was extrapolated using Equation 3.3.

$$\sigma_f = a \times \log(t) + b \quad (3.3)$$

where:

σ_f = failure stress,

t = time to failure, and

a and b are regression constants.

Figure 3.12 shows the regression line representing the long-term behavior of the composite CIPP liner subjected to HDB testing of up to 1,635 hours. Using the linear equation (Equation 3.3) and residual analysis, a 95% lower confidence limit (LCL) line was included on the graph. The LCL line is the lowest value of the LTHS, based on a statistical analysis of the regression data that can be expected.

From the developed CIPP HDB regression line, a conservative approach was adopted, using the 95% LCL line to predict the long-term behavior of the tested CIPP pressure liners. It was noted that the 10,000-hour burst stress would be approximately 30 MPa. CIPP LTHS at the 100,000-hour coordinate was estimated to be 25 MPa, and CIPP 50-year LTHS ($LTHS_{50}$) was estimated to be 22.2 MPa.

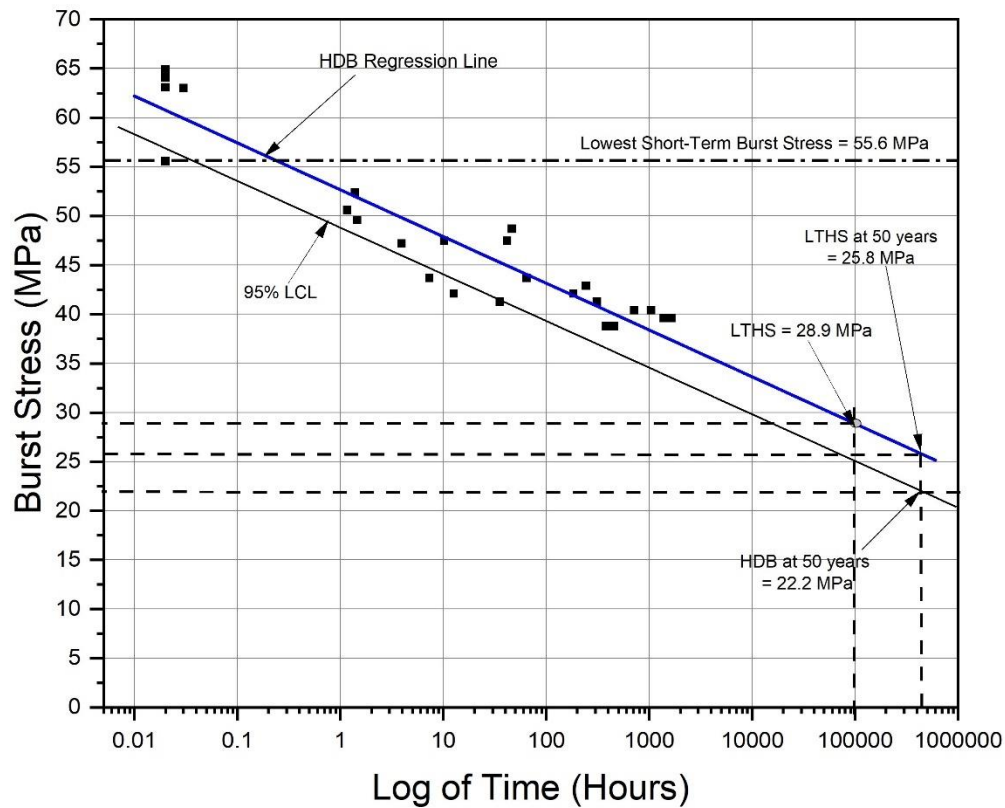


Figure 3.12: HDB Regression line and extrapolation to determine CIPP 50-year Long-Term Hydrostatic Strength and Hydrostatic Design Stress.

3.6.5 CIPP Design Factor and Pressure Rating Determination

ASTM D2837 and ASTM D2992 did not specify how to determine the Design Factor because of the number of variables that need to be considered. Based on available data provided by PPI TR-4 [48] and Boros (2011) for PVC and HDPE pipe materials, the typical design factor (DF) applied to the HDB value to estimate the pressure rating (PR) of thermoplastics was based on the ratio of the short-term burst strength to the categorized $LTHS_{50}$ values. For example, PVC 1120 has a short-term burst strength of 55.2 MPa and a categorized $LTHS_{50}$ (HDB) of 27.6 MPa, allowing a typical DF of 0.5 (i.e., $27.6/55.2$). Similarly, test results herein show that the 200-mm CIPP has a minimum short-term burst strength of 55.6 MPa and an HDB (categorized $LTHS_{50}$) of 22.2 MPa, allowing an approximate DF of 0.40 (i.e., $22.2/55.6$).

The HDS of the tested reinforced CIPP specimens was determined by applying a Design Factor of 0.40 to the HDB of 22.2 MPa is 8.9 MPa. The Pressure Rating of the specimens was determined as 1.04 MPa (151 psi) using Equation 3.1.

3.7 CIPP Pressure Liner HDB Testing – Phase II

The first phase of the reinforced CIPP Pressure Line HDB testing was completed using the 200 mm OD specimens. Short-term burst tests were completed with six specimens, while the long-term tests ran for 1,635 hours. Both ASTM D2837 and ASTM D2992 specify testing for up to 10,000 hours and having the required number of specimen failures per time section to develop an HDB regression line with the data points. The tests were discontinued because all available specimens had been tested to failure. The data points for time sections IV and V had to be determined from further long-term tests. Insituform Technologies (Aegion Corporation) supplied new CIPP pressure liner test specimens. The new specimens got to the University of Waterloo nine months after the request was made. When tested, the burst testing facility couldn't maintain the required pressure in the specimens as the water pressure from the manifold was leaking into the specimens due to faulty solenoid valves. Other systems of the facility also showed inconsistent performances and they had to be either replaced or upgraded.

3.7.1 Upgrade of the Burst Testing Facility

The second phase of the HDB long-term hydrostatic testing was scheduled to run for over 10,000 hours. Due to the length of time the facility parts were planned to run for, there might be a need for routine maintenance activities. The following problems were identified, replacements and upgrades were completed on the burst testing facility before testing was started.

1. The specimen pressure control and monitoring system

The Problem: The components of the specimen pressure control and monitoring system were connected as shown in Figure 3.5. There was no way to perform any maintenance operation on any part of the system without stopping the tests and depressurizing all the test samples.

The solenoid valves' disc and bleed orifice were often clogged or blocked by dirt particles from water, causing failure-to-close problems and the leakage of pressurized water from the manifold into the test specimens. The leakages made it impossible to maintain test pressures in specimens within $\pm 1\%$ of the set pressures.

The Upgrade Solution: Figure 3.13 shows the upgraded specimen pressure control and monitoring system. Two 2,000 psi rated ball valves were placed on either side of the solenoid valve/pressure transducer connection. With this, the solenoid valve/pressure transducer connection can be isolated for maintenance by turning off both valves. With the introduction of the valves to the system, faulty parts can be isolated, removed, and reconnected to the system without stopping or losing pressure in any of the specimens being tested.

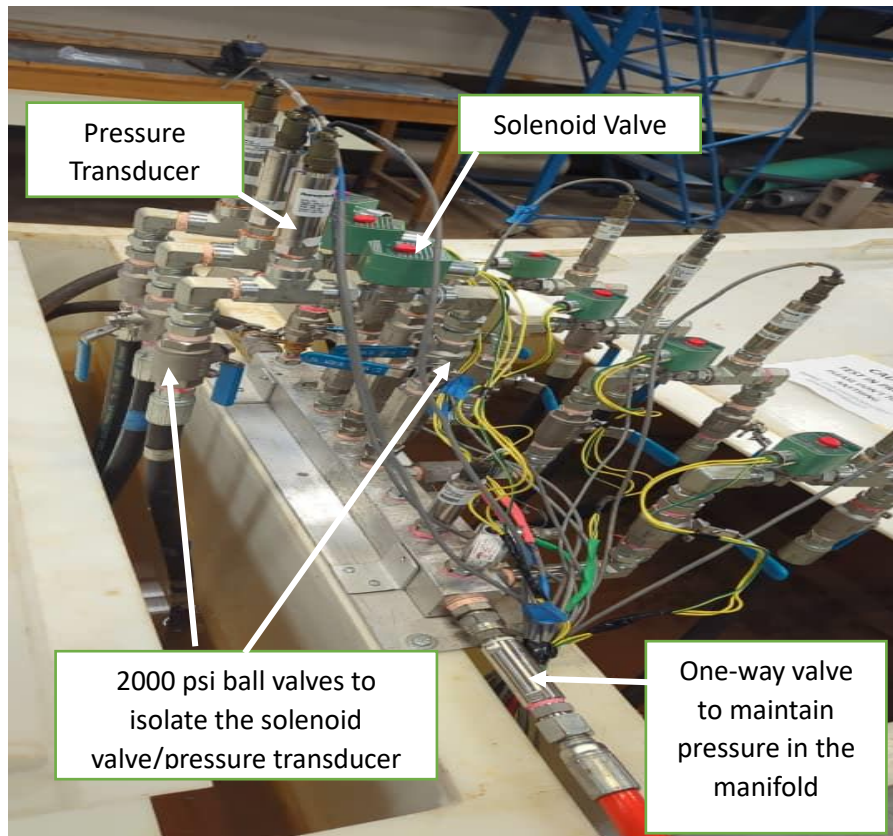


Figure 3.13: The upgraded specimen pressure control and monitoring system

Also, a one-way flow valve was introduced between the manifold and the pressurizing system to maintain the pressure in the manifold while the pressurizing system is being maintained.

2. The power backup for the computerized system control and data acquisition system

The Problem: Due to the occasional power shutdown in the laboratory for routine maintenance, the computer system shuts down, and test data is lost.

The Upgrade Solution: The system control and data acquisition system and the electronic components of the specimen pressure control and monitoring system were connected to a 1800W, 16 Amp UPS to continue running whenever there is a power outage. This will ensure data logging and storage processes are not interrupted all through the tests. The UPS also powers the computer system that hosts the LabVIEW software. Figure 3.14 shows the UPS power backup.

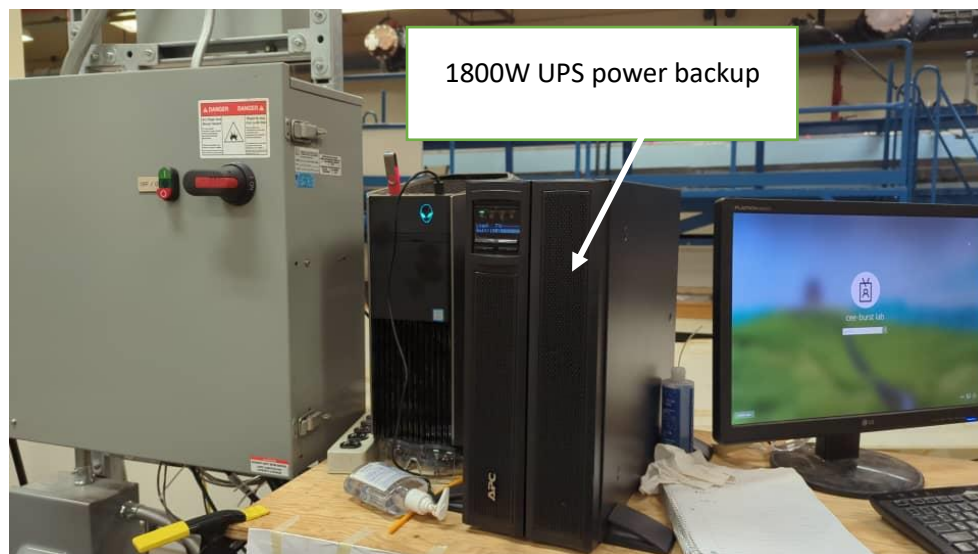


Figure 3.14: 1800W UPS power backup

3. LabVIEW and SigmaWIN softwares

The Problem: There were two softwares with overlapping functions. The LabVIEW software controls all the systems in the facility except for the control of the actuator/piston control during short-term burst tests. The SigmaWIN software controlled only the pressurizing system using different control parameters during short-term burst tests.

The Upgrade Solution: The manual control function of the SigmaWIN software was incorporated into the new LabVIEW software. The new LabVIEW software can now switch from automatic mode to manual mode and concurrently control both short- and long-term tests without stopping either test. The control parameters were synchronized into one software for ease of use and better control. Figure 3.15 shows the new LabVIEW software Visual Interface with real-time plots of the specimens' pressure levels.



Figure 3.15: New LabVIEW software Visual Interface

4. Water Pressurizing System

The Problem: Figure 3.16a shows the custom-made 19.05 mm size water inlet solenoid valve that automatically controls water inflow into the pressurizing cylinder. After the burst testing facility was restarted, it was observed that the solenoid valve was malfunctioning. Being custom-made, it was going to take a long time to either repair or replace it. The operation of the solenoid valve was based on received signals from the LabVIEW software whenever the cylinder had to be refilled.

The Upgrade Solution: The faulty solenoid valve was removed and the mechanism of control of water inflow into the cylinder was changed into a one-way-valve-controlled pressure gradient flow. The pressure in the hydraulic cylinder drops to about zero whenever the piston retracts to refill. This causes a pressure gradient to develop between the hydraulic cylinder and the water source in the laboratory, which is at about 60 psi. The pressure gradient causes water to flow into the cylinder through a 2,000 psi rated one-way flow valve till the cylinder is full and a pressure equilibrium is reached. Once the piston starts to pressurize the water in the hydraulic cylinder, the pressure in the cylinder rises above the pressure in the water source, the one-way valve automatically prevents flow back into the water source. Then, the water in the cylinder can be pressurized as required. Figure 3.16b shows both the solenoid valve and the one-way valve mechanisms.



Figure 3.16: Faulty 19.05mm Solenoid Valve and One-way flow mechanism

3.7.2 Revalidation of the Burst Testing Facility after the Upgrade

With the introduction of new software, new components to the systems of the burst testing facility, and changing the water inflow control mechanism of the pressurizing system, there was a need to revalidate the performance of the testing facility. IPEX Inc. manufactured 200 mm OD DR-18 PVC pipes with test-standardized short-term pressure properties, were tested using the ASTM D1599 standard short-term burst testing procedure. The PVC pipes exhibited high levels of expandability when pressurized due to the viscoelastic properties of the material. The volume limitation of the hydraulic cylinder of the pressurizing system was more evident when testing larger PVC pipes. The pipes had to be repressurized severally before eventual failure. Figure 3.17 shows the tested PVC Specimens and their failure patterns. The two PVC specimens failed at 5.14 MPa and 5.65 MPa after 8 and 5 cycles of re-pressurization respectively. One PVC specimen exhibited a ballooning response without bursting till the test was stopped after 9 cycles of re-pressurization that lasted for 13 minutes. It is considered failed as it plateaued at about 5.30 MPa but was not considered valid for this validation test. Figure 3.18 shows the short-term pressure responses of the PVC specimens to increasing internal pressure. The time required to refill the hydraulic cylinder before repressurizing led to several pressure drops in the PVC specimens as

evident in the saw-tooth pattern of the graphs. The mean burst pressure for the two successful burst tests was 5.40 MPa with a standard deviation of 0.4 MPa. Table 3.8 shows the short-term burst test results of the PVC pipes compared to standard material specifications of the pipes determined from the manufacturer's completed short-term and HDB tests.

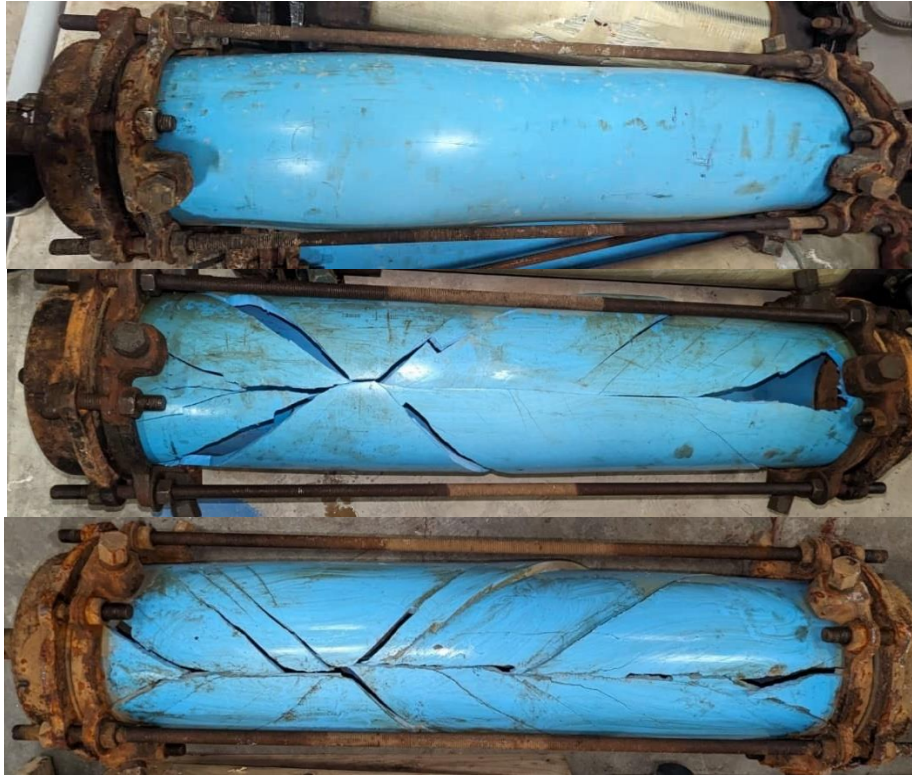


Figure 3.17: PVC Pressure pipe specimens after the short-term burst tests.

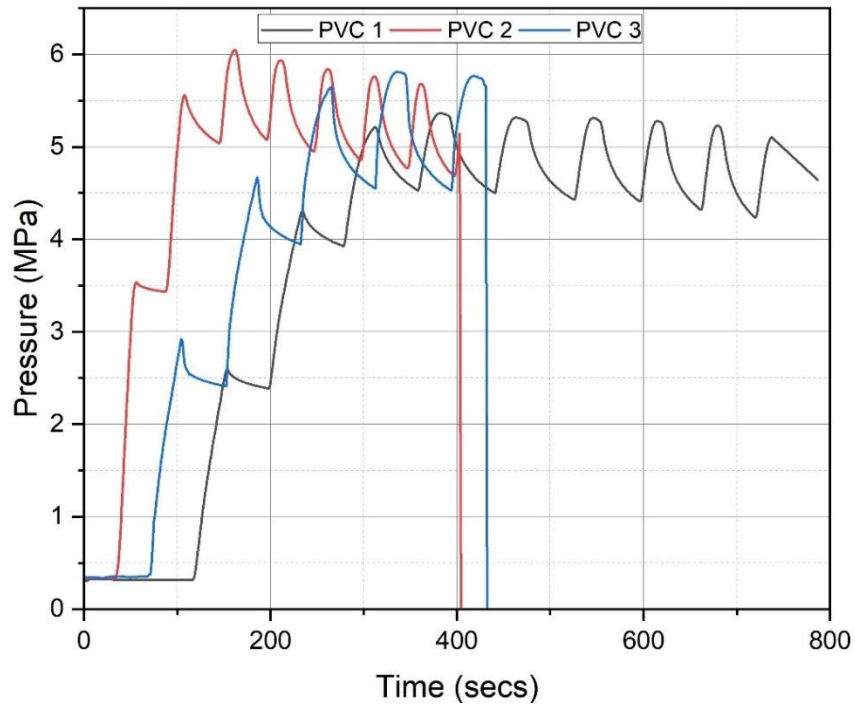


Figure 3.18: Pressure–Time test results plots for PVC pressure pipes

Table 3.8: Burst Facility Re-Validation Results using 200mm DR-18 PVC Pipes

Specimen ID	No. of Pressure Cycles to Burst	Burst pressure (MPa)	Total Time to Burst (incl. cylinder refill) (min)	Manufacturer's Short-Term Burst Pressure Range (MPa)
P1	8	5.14	6.25	5.14 - 6.89
P2	5	5.65	6.20	
	Mean	5.40		
	STD	0.4		

The burst pressures of the PVC pressure pipes as determined by the short-term burst tests completed with the upgraded University of Waterloo Burst Testing Facility were 5.14 MPa and 5.65MPa with a mean of 5.40 MPa and a standard deviation of 0.4. The test results fall within the burst pressure range of 5.14 – 6.89 MPa as specified by the manufacturers. This re-validates the performance of the burst testing facility after the upgrade.

3.7.3 Re-commissioning of the Burst Testing Facility

A new set of nineteen 200 mm OD, DR-18 I-Main reinforced CIPP pressure liner specimens with the same specifications as the set used for the first phase of testing was provided by Insituform Technologies to continue the long-term tests. The test data from the second phase of the long-term hydrostatic testing is meant for the completion of the CIPP HDB Regression Analysis. The suitability of the specimens for the tests was tested, and eleven specimens were confirmed to be leaking and unsuitable for testing. Three CIPP specimens were tested in the short-term while five were tested in the long-term hydrostatic tests. The University of Waterloo burst testing facility was re-commissioned with the short-term burst tests completed on the new CIPP specimens.

3.7.4 New CIPP liners - Short-Term Burst Tests

Three I-Main CIPP pressure liners were tested in short-term burst tests completed per ASTM D1599 short-term burst testing methods. The tests were completed to establish the similarity in the short-term burst pressure properties of the first and second batches of I-Main CIPP pressure liner specimens. The short-term burst pressure test results of the three CIPP pressure liners are presented in Table 3.9. The mean burst pressure was 5.42 MPa with a standard deviation of 0.5 MPa. This is close to the mean burst pressure of 5.11 MPa with a standard deviation of 0.34 MPa. Figure 3.19 shows the internal pressure plotted against the time-to-failure of three CIPP pressure liner specimens.

Table 3.9: ASTM D1599 CIPP Pressure liner short-term burst test results - Phase II

Specimen	Time to Burst (sec)	Burst Pressure (MPa)	Burst Stress (MPa)	Failure Location	Failure Type
1	72	5.30	63.6	Middle	Burst
2	71	5.95	71.4	Middle	Burst
3	62	5.01	60.1	Middle-End	Burst
Mean	78	5.42	65.0	-	-
St. Dev	10.2	0.5	5.8	-	-

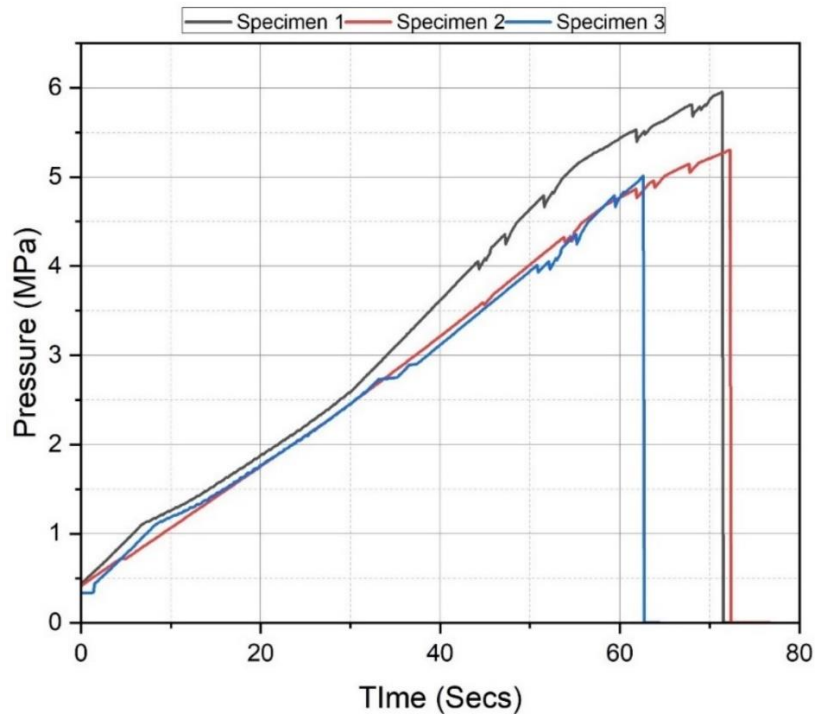


Figure 3.19: Pressure-Time test result plots for three 200-mm OD CIPP specimens.

The graph shows a uniform pressure loading rate achieved with the upgraded burst testing facility. Figure 3.20 shows the three failed CIPP specimens tested using ASTM D1599 short-term test methods.

3.7.5 New Long-Term Hydrostatic Testing

The first phase of the long-term hydrostatic testing resulted in twenty-six failure points data that the first three time-sections (<10 hours, 10 – 1,000 hours, and 1,000 – 6,000 hours) of the consolidated CIPP HBD testing experimental plan. The test pressures for the second phase of the long-term tests were selected after a careful analysis of the HDB Regression Line plot as shown in Figure 3.21. The test pressures were selected to ensure there are at least three failure points between 6,000 – 10,000 hours and at least one failure point above 10,000 hours of testing. In the analysis of the regression line, 95% upper and lower confidence limit lines were plotted. The ranges between the regression line and the upper confidence limit line (UCL) on



Figure 3.20: Failed CIPP Pressure Liners during Short-term Tests

the y-axis and 6,000 – 10,000 hours on the x-axis were chosen. The intersection of the UCL and the 6,000-hour timeline, and the intersection of the regression line and the 10,000-hour timeline were chosen as the pressure range to be tested. The range was determined as 2.69MPa to 3.10MPa.

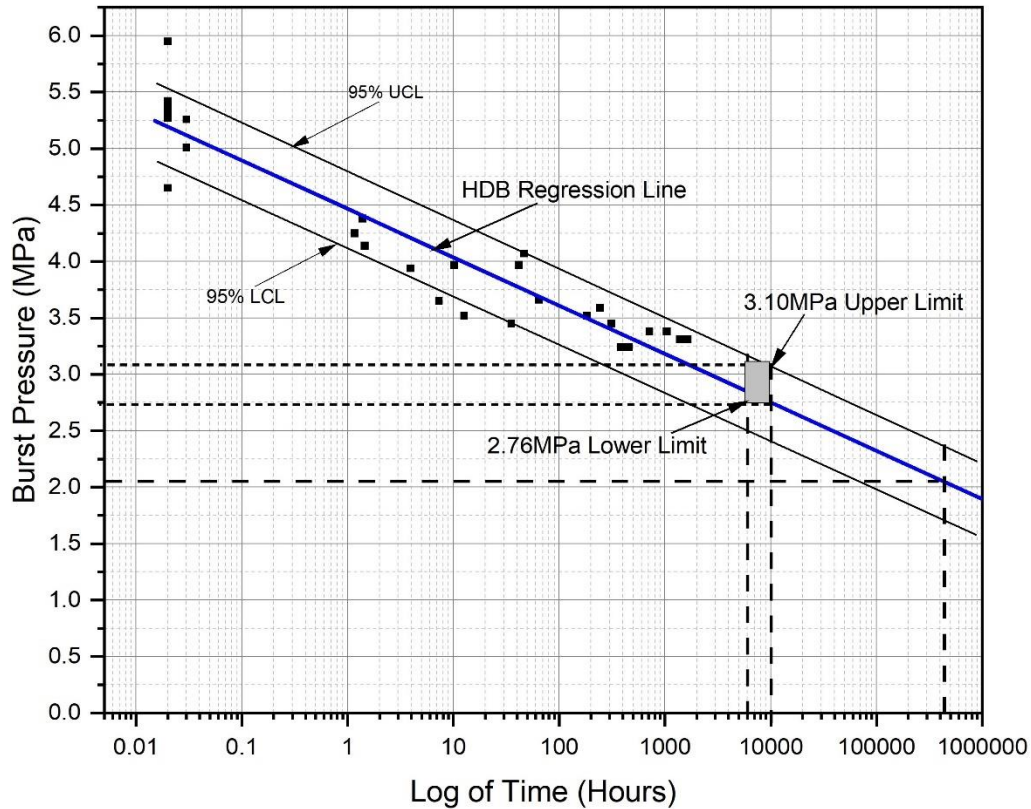


Figure 3.21: Test pressure analysis to have failure points for Time Sections IV and V

There were only five CIPP pressure liner specimens available for the long-term tests. Considering that 78% of the failure points between 100 – 1600 hours were in the upper confidence limit, and the need to have most of the failure points between 6,000 – 10,000 hours, 2.83MPa, 2.90MPa, 2.97MPa, and 3.03MPa test pressure levels were chosen. A specimen was set at 3.38MPa to test for an overlap with the test pressures of the first set of tests. Table 3.10 shows the updated long-term test's failure points distribution, and the ongoing tests to complete the required standard distribution for the first known CIPP pressure liner HDB Regression Line.

Table 3.10: Updated CIPP long-term tests failure points distribution

Time Interval	Hours to Failure	Hybrid/Consolidated Plan for CIPP HDB Testing	No. of Failed Data Points
Time Section I	<10	At least 6	14
Time Section II	10 to 1,000	At least 4	12
Time Section III	1,000 to 6,000	At least 3	3
Time Section IV	After 6,000	At least 3	On-going
Time Section V	After 10,000	At least 1	On-going
Total		At least 18	

3.7.6 Long-Term Hydrostatic Test Data Update

Table 3.11 shows the monthly average test pressure in each of the five test specimens currently being tested in the second phase of the long-term hydrostatic tests. The current test duration is about 4,800 hours without any occurrence of a specimen failure. The two specimens set at 490 psi in the first phase of the long-term hydrostatic tests failed at 714 and 1,041 hours respectively. A 480% difference in time to failure of specimens set at the same pressure, under the same test conditions requires further investigation into the manufacturing or material compositions of the two batches of specimens. Table 3.11 presents the monthly mean pressure maintained in all the five CIPP specimens being tested in the long-term hydrostatic tests. It is observed that the burst testing facility has successfully maintained the test pressures in the CIPP specimens within the standard required range of $\pm 1\%$ of the set test pressure.

Table 3.11: Monthly average test pressure – Phase II of the Long-Term Hydrostatic Tests

		Set Test Pressure				
	Duration of Test (Hours)	410	420	430	440	490
		Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
Nov. 2023	730	409.9	420.5	429.8	440.0	489.8
Dec. 2023	1446	410.6	420.7	430.1	440.5	490.8
Jan. 2024	2187	411.8	421.6	430.9	441.4	491.0
Feb. 2024	2883	410.1	420.0	430.1	440.4	490.6
Mar. 2024	3603	410.8	420.2	431.0	440.5	490.5
Apr. 2024	4323	411.9	420.6	430.9	440.6	491.2
	Average	410.9	420.6	430.4	440.6	490.6

3.8 Conclusions

This study describes two phases of full-scale long-term hydrostatic tests on composite glass fiber-reinforced I-Main CIPP pressure liners. The first phase lasted for 1,635 hours and was extrapolated to 50 years to predict the material's long-term hydrostatic properties based on HDB testing methods. The second phase of the tests has been ongoing for over 4,800 hours without any failure. Following the HDB standard test methodologies to investigate the long-term material response of CIPP to sustained internal pressure, a testing methodology to standardize the design and classification of CIPP pressure liners is being established. From this research, the following conclusions can be drawn:

1. A pressure burst testing facility was designed and built at the University of Waterloo. Its performance was validated by comparing its burst test results on 150 mm OD and 200 mm OD PVC pressure pipe specimens tested according to ASTM D1599 test standards, with theoretically derived burst pressure and manufacturer's material short-term burst

specifications for PVC respectively. The results of the experimental burst tests were within 90-96% of both theoretically determined PVC short-term burst pressure and the manufacturer's test-derived specifications. The results confirmed that the burst testing facility can perform pipe pressure tests according to standard specifications.

2. The short-term burst pressures of both 150mm OD and 200 mm OD reinforced I-Main CIPP pressure liner specimens were successfully determined using ASTM D1599 test methods. The short-term burst test results of the 200 mm OD reinforced I-Main CIPP pressure liner specimens from the two phases of tests were 5.11 MPa and 5.40 MPa. These short-term tests data formed the basis for determining the test pressures used in the long-term hydrostatic tests, and part of the data for developing the first HDB Regression Line for CIPP pressure liners in North America.
3. The first phase of long-term hydrostatic testing of 200 mm OD reinforced I-Main CIPP pressure liner specimens was completed after 1,635 hours. A total of twenty-six specimen failure points were recorded for the first three time-sections (< 10 hours, 10 – 1,000 hours, and 1,000 – 6,000 hours) of testing according the HDB test method specifications derived from a consolidation of ASTM D2837 and ASTM D2992 test standards. The long-term hydrostatic test data was used to develop part of the first HDB Regression Curve for CIPP in North America. The preliminary categorized Long-Term Hydrostatic Strength in 50 years (LTHS₅₀) - HDB, the Hydrostatic Design Stress (HDS), and Pressure Rating (PR) of I-Main CIPP pressure liner were estimated as 22.2 MPa, 8.9 MPa and 1.04 MPa respectively. The second phase of long-term hydrostatic testing on 200 mm OD reinforced I-Main CIPP pressure liner specimens to have failure points to fill the last two time-sections (6,000 – 10,000 hours and >10,000 hours) is ongoing. When completed, the failure data will be used to complete the HDB Regression Line, and the long-term properties re-calculated.
4. When completed, the first HDB Regression Curve for CIPP in North America will establish HDB testing and design approach as a standard for the design and pressure-classification

of CIPP pressure liners and make its comparison with other watermain renovation products more valid. It will also contribute to the efforts of the International Standards Organization (ISO) and the American Water Works Association to develop standards for the design and classification of CIPP pressure liners.

Chapter 4

Research Contributions

4.1 Research Findings and Conclusions

This thesis covered the experimental investigation of the flexural properties of reinforced and non-reinforced CIPP liners. The short-term flexural tests and the long-term creep-rupture properties of two types of reinforced and non-reinforced CIPP liners were experimentally determined. Also, the short-term pressure burst behavior and the long-term hydrostatic strength properties of commercially available full-scale CIPP pressure liners were experimentally determined using the watermain industry-recognized HDB testing method.

The key findings and conclusions for each chapter are summarized below:

1. The results of the experimental investigation of the short-term flexural tests of non-reinforced and reinforced CIPP liner coupons indicated that the non-reinforced CIPP specimens showed unstable short-term flexural behavior after the first break at about 1% strain. However, the fiberglass-reinforced CIPP specimens had a relatively steady response to stress without failure until the 5% strain limit was reached. The presence of fiberglass reinforcement in the composition of the reinforced CIPP matrix prevented failure in flexure during the short-term test.
2. After completing 10,000 hours of testing, the long-term flexural strength ($LTFS_{50}$) generated from NC-L721 and NC-L758 specimens were 31.3 MPa and 30.8 MPa which are slightly lower than 32 MPa and 34 MPa reported by Awe (2023) after 3,000 hours of testing. The Strength Retention Factors of both non-reinforced specimens were estimated as 60% and 61.2% respectively after 50 years. The 50-year flexural strength ($LTFS_{50}$) estimates of reinforced CIPP IPLUS and IMAIN resin specimens were 178MPa and 190MPa respectively, which are close to the 177MPa and 188MPa $LTFS_{50}$ predictions for the respective set of

RC specimens reported by Awe (2023) after 3,000 hours of testing. The Strength Retention Factors of both specimens were estimated as 89% and 91%. The SRFs of both CIPP specimen types are well above the generalized 50% which concludes that using the generalized figure will lead to under or over-designing CIPP. Also, the inclusion of fiberglass reinforcement in the composition of the reinforced CIPP specimens has made flexure not a failure mode for the specimens both in the short and long term.

3. The design upgrade of the systems of the pipe burst testing facility built at the University of Waterloo has made it possible to perform short and long-term tests concurrently without having to stop one for the other. Also, performing maintenance operations without affecting the specimen pressure and the operation of the facility is now possible. The standard PVC pipe revalidation test re-validated the performance of the burst testing facility.
4. The ASTM D1599 short-term burst tests completed on three specimens from the second batch of 200mm OD reinforced full-scale CIPP liners resulted in a mean short-term burst pressure of 5.40 MPa which is close enough to the 5.11 MPa result reported by Awe (2023) as the mean burst pressure for six specimens tested in short term. This validates the use of the second batch of samples for the second phase of long-term hydrostatic tests.
5. From the 1.628 hours of testing completed and reported in Awe (2023), the preliminary categorized Long-Term Hydrostatic Strength in 50 years ($LTHS_{50}$) - HDB, the Hydrostatic Design Stress (HDS), and Pressure Class (PC) of the tested CIPP pressure liner were estimated as 22.2 MPa, 8.9 MPa and 1.04 MPa respectively. The regression line and the upper confidence limit line were used to analyze the pressure range to test the specimens with a high likelihood of failure between 6,000 – 10,000 hours and beyond.
6. These results are comparable to the long-term hydrostatic properties of other watermain renovation products such as PVC, HDPE, and GRP which are designed and pressure-classified using the industry-recognized HDB testing and design approach. This establishes

the HDB design and classification approach as an acceptable standard for the design and classification of CIPP pressure liner products.

4.2 Research and Design Recommendations

1. Due to the unstable material response of non-reinforced CIPP specimens after the first break, resulting from repeated fractures in their polymeric structures under stress, it is recommended that the stress at the first break should be adopted as the maximum flexural strength in the design of the CIPP for field application.
2. Since failure in flexure did not occur in both short- and long-term flexural tests of the reinforced CIPP specimens due to the incorporation of fiberglass reinforcement, it is recommended that a different failure mode be investigated and established for reinforced CIPP specimens.
3. The results from the long-term hydrostatic tests using the HDB testing approach are comparable to the results of the same test methods used to design and classify other products in the watermain renovation industry such as PVC, HDPE, and GRP. Based on this finding, it is recommended that the HDB design and classification approach be adopted as an industry standard for the design and classification of CIPP pressure

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Appendices

Appendix 1: AWWA Structural Classification Table

Liner Characteristics	Non-Structural	Semi-Structural		Fully Structural
	Class I	Class II	Class III	Class IV
Internal corrosion barrier	Yes	Yes	Yes	Yes
Bridges holes/gaps at pipe operating pressure	No	Yes	Yes	Yes
Inherent ring stiffness	No (Depends on adhesion)	No (Depends on adhesion)	Yes	Yes
Long-term independent pressurizing $\geq$ pipe operating pressure	No	No	No	Yes
Survives “burst” failure of the host pipe	No	No	No	Yes

Appendix 2: PPI TR-4: Standard pipe material designation codes

The standard pipe material designation codes covered by this report are: Pipe Material Designation Code	Maximum HDS at 73°F (23°C) psi	HDB at 73°F (23°C) psi	ASTM Specification
Polyvinyl Chloride (PVC)			
PVC 1120	2,000	4000	D1784
PVC 2116	1,600	3150	"
Chlorinated Polyvinyl Chloride (CPVC)			
CPVC 4120	2,000	4000	F441
Polyethylene (PE)			
PE 1404	400	800	D 3350
PE 2406	630	1250	"
PE 2708	800	1250	"
PE 3408	800	1600	"
PE 3608	800	1600	"
PE 3708	800	1600	"
PE 3710	1000	1600	"
PE 4608	800	1600	"
PE 1404	400	800	"
PE 2406	630	1250	"
PE 4708	800	1600	"
PE 4710	1000	1600	"
Crosslinked Polyethylene (PEX)			
PEX 0006	630	1250	F876
PEX 1006	630	1250	"
PEX 3006	630	1250	"
PEX 5006	630	1250	"
PEX 5206	630	1250	"
PEX 0008	800	1600	"
PEX 1008	800	1600	"
Polyacetal (Polyoxymethylene)			
POM 21110	1,000	2000	D4181
Polyvinylidene Fluoride (PVDF)			
PVDF 2016	1600	3150	D3222
PVDF 2020	2000	4000	"
PVDF 2025	2500	5000	"
Polyamide (PA)			
PA 32312	1250	2500	D6779
PA 32316	1600	3150	"
PA 42316	1600	3150	"

Appendix 3: Long-term parameters in ASTM F1216 design equations.

ASTM F1216 Equations		Long-Term Parameters
X1.1	$P = \frac{2KE_L}{(1 - \nu^2)} \cdot \frac{1}{(DR - 1)^3} \cdot \frac{C}{N}$	E_L is the long-term flexural modulus
X1.2	$1.5 \frac{\Delta}{100} \left(1 + \frac{\Delta}{100} \right) DR^2 - 0.5 \left(1 + \frac{\Delta}{100} \right) DR = \frac{\sigma_L}{PN}$	σ_L is the long-term flexural strength
X1.3	$q_t = \frac{I}{N} \left[32 R_w B' E'_s \cdot C (E_L I / D^3) \right]^{1/2}$	E_L is the long-term flexural modulus
X1.4	$\frac{E}{12(DR)^3} \geq 0.00064$	Not Applicable
X1.5	$\frac{d}{D} \leq 1.83 \left(\frac{t}{D} \right)^{1/2}$	Not Applicable
X1.6	$P = \frac{5.33}{(DR - 1)^2} \left(\frac{D}{d} \right)^2 \frac{\sigma_L}{N}$	σ_L is the long-term flexural strength
X1.7	$P = \frac{2\sigma_{TL}}{(DR - 2) N}$	σ_{TL} is the long-term tensile strength

(Source: Awe, 2023)