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Experimental and numerical evaluation of cured in place pipe lining system for high temperature applications in sewer pipes

Shaurav Z. Alam

Louisiana Tech University

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**EXPERIMENTAL AND NUMERICAL EVALUATION OF CURED IN
PLACE PIPE LINING SYSTEM FOR HIGH TEMPERATURE
APPLICATIONS IN SEWER PIPES**

by

Shaurav Z. Alam, M.S.

A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

COLLEGE OF ENGINEERING AND SCIENCE
LOUISIANA TECH UNIVERSITY

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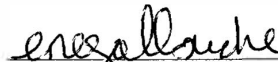
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We hereby recommend that the dissertation prepared under our supervision
by SHAURAV Z. ALAM

entitled Experimental and Numerical Evaluation of Cured In Place Pipe Lining System
For High Temperature Applications In Sewer Pipes

be accepted in partial fulfillment of the requirements for the Degree of
Doctor of Philosophy in Engineering



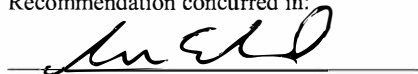
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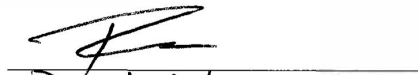


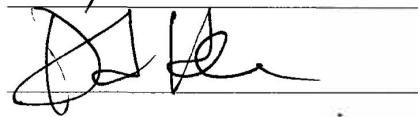
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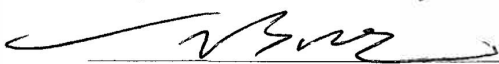
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CHAPTER 1

INTRODUCTION

1.1 General Introduction

The City of New York operates 6,375 miles of storm, sanitary and combined sewers, ranging from 6" to 90" in diameter. Over 65% of the current system was built prior to 1940, and suffers from varying degrees of deterioration. The city is currently considering the reconstruction of Times Square, a world famous tourist site in downtown Manhattan. The project limits are 7th Avenue 42nd Street to 48th Street, and Broadway 42nd Street to 49th Street. As part of the proposed construction program, selected sewer pipes within the project limits were identified as candidates for rehabilitation or replacement. Seven of these sewer segments are known to be subjected to intermittent steam condensation discharge. These pipe sections vary from circular 12" pipes to 5'-7" x 3'-6" egg-shaped pipes. In most cases, these pipe segments are placed beneath subway platforms or tracks, or are attached to the tunnel wall (Figure 1). The locations and characteristics of these segments are summarized in Table 1. Thus, replacement of these pipe-segments using the cut-and-cover construction method is not a viable option. However, having been exposed to steam injection for nearly 75 years, these pipes require rehabilitation.

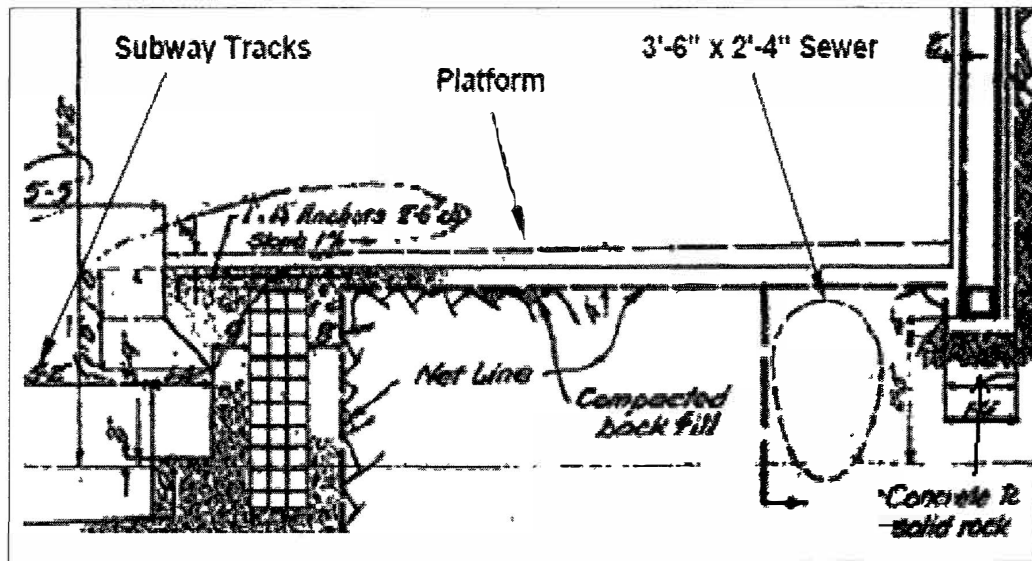


Figure 1: An Egg-shaped Sewer Located Underneath the Subway Platform at 7th Avenue Roadway (modified after Dino Ng, 2008)

**Table 1: Segments of Sewer Affected by Steam Discharge within Project Limits
(modified after Ng, 2008)**

Street	From	To	M#	M#	Size	Comments
W. 43 rd Street	Broadway	East	51	52	12"	
			52	53	4' × 2'-8"	
W. 45 th Street	7 th Avenue	West	68	15	36" (2 pipes)	Located beneath the base of a subway rail bed.
W. 47 th Street	Broadway	7 th Avenue	Tee	85	3'-6" × 2'-4"	Located under subway a platform.
			85	87	4' × 2'-8"	Located under subway a platform.
W. 49 th St	7 th Avenue	West	1	2	18"	Sewer is attached to a tunnel wall.
Broadway	W. 45 th Street	W. 46 th Street	68A	63	5'-7" × 3'-6"	Located under subway rail at 30'-0" depth.

Manhattan is the largest steam system district in the US, with its roots going back to the New York Steam Company, which opened for business in 1892. Con Edison purchased the NY Steam Company in 1936, and presently operates 104 miles of main and services, which serve 1811 customers. In FY 2004, sales were 26 billion pounds of steam and revenues were estimated at US \$531 M. The steam is generated at the B.N.Y.C.P. power plant and distributed via a network of transmission and distribution mains. The transmission mains range between 24" and 30" in diameter and operate at 400 PSIG and

475° F (total of 12 miles). The distribution mains range between 6" and 30" in diameter and operate at 200 PSIG and 413° F (total length 80 miles). The remainder of the system consists of service lines.

A schematic diagram of the steam distribution system is given in Figure 2. The distribution system delivers the steam to hundreds of buildings between Battery Park and 96th Street powering air-conditioning compressors or passing through a series of pressure reducing valves, allowing it to be used directly in heating systems. The steam condensation is then discharged into the sewer system. At the outlet of the steam trap, the temperature of the condensate is at a minimum of 212° F. The discharge temperature could be higher if backpressure develops in the drainpipes. Under normal operation conditions, the condensate spends considerable time in a cooling chamber and gets down to 150° F before it is discharged into the sewer. Malfunctioning of the steam trap could result in condensate discharged into the sewer system at temperatures as high as 212° F.

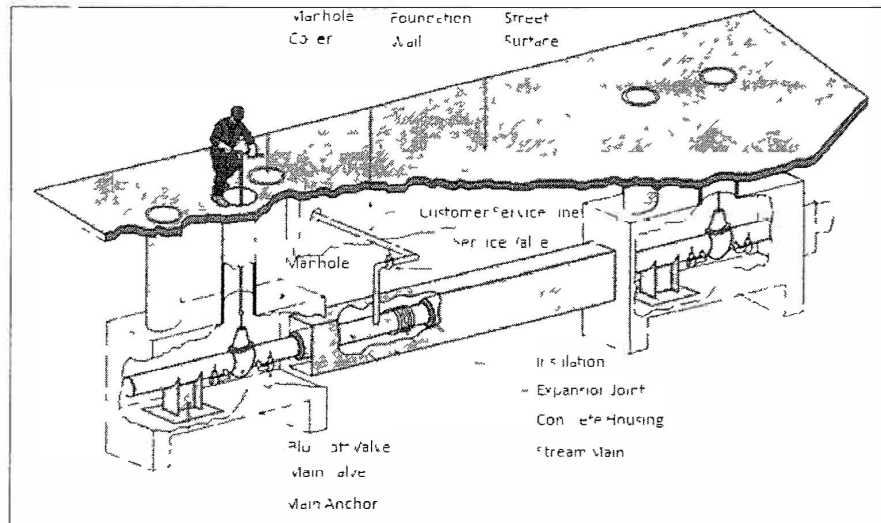


Figure 2: Schematic Diagram of Manhattan's Steam Distribution System (modified after Dino Ng, 2008)

1.2 Interaction between Sewer Pipe and CIPP Liner

The depth of the flow in gravity sewers changes due to daily fluctuations in water use. As shown in Figure 3, around 7:00 AM sewer flow is considerably higher compared with 3:00 AM. The head space and hydraulic perimeter inside the sewer changes with the depth of the flow. When a high temperature steam condensate enters the sewer, it releases latent heat, causing an uneven temperature distribution at the surface of the liner (i.e., much higher temperature above the water level than beneath it). If the temperature of the waste water stream and the host pipe wall is significantly lower than that of the steam condensate, strains (both circumferential and longitudinal) induced by the steep temperature gradient might develop across the liner. The magnitude of these strains will fluctuate with the volume of the head space and the temperature difference between the steam and that of the waste water stream.

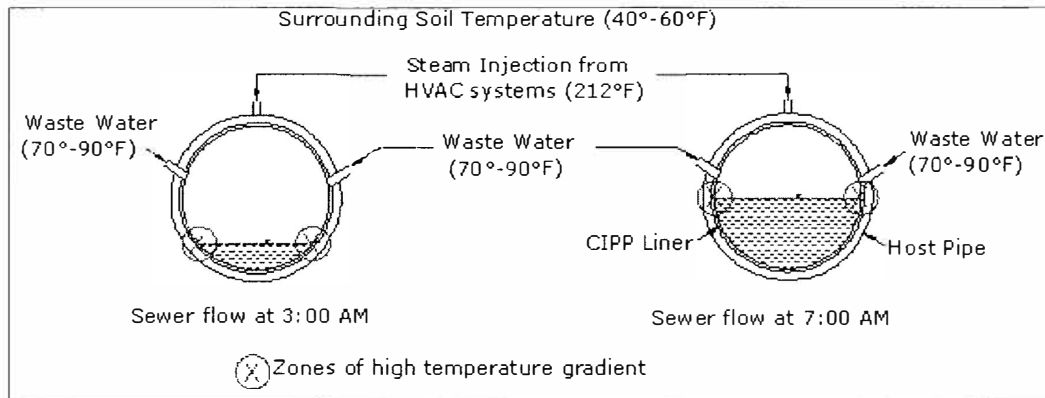


Figure 3: Change in Depth of Flow Due to Daily Fluctuations and Locations of Temperature Gradients

Current design practices assume little or no bonding between the host pipe and the CIPP liner. Thus, the liner might experience localized relative movements due to changes in thermal energy, as shown in Figure 4. This relative movement may take place in either the longitudinal or the circumferential directions, or simultaneously in both directions. The impact of these thermally induced strains could be amplified by geometrical imperfections such as folds, annular gaps, interior bulges and sags, causing the formation of localized high stress zones.

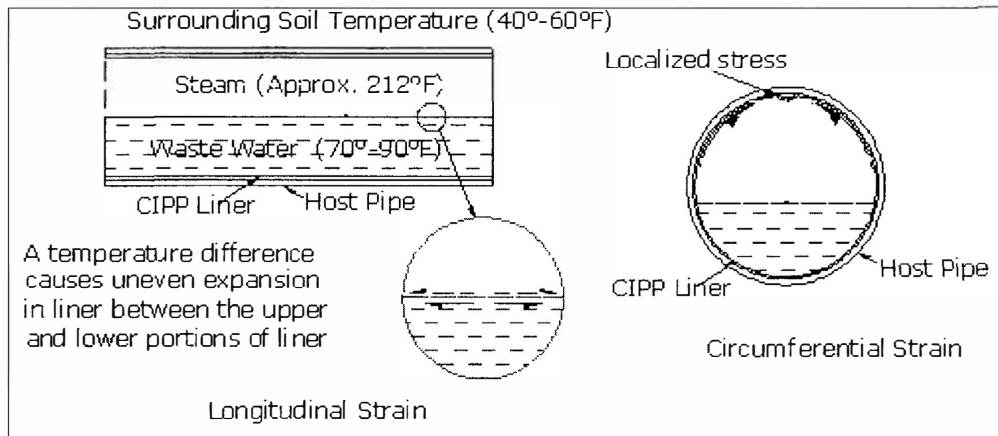


Figure 4: Relative Movement in CIPP Liner Due to Changes in Thermal Energy
1.3 Objectives

The main objective of this research was to identify resin-liner combinations that are expected to perform well under prolonged exposure to elevated temperature (up to 212° F). In addition to this quite broad goal, a number of lesser goals were identified which are listed below:

- Estimate the magnitude of the resulting thermally induced strains in the case of the Times Square project.
- Determine if any modifications to current design procedures are needed.
- Evaluate the resulting stresses from thermally induced in-plane shear strains and to examine ways in which these strains could be accounted for by current design procedures.

1.4 Scope of Work

The research described herein investigates the effect of elevated temperature on CIPP liner over a prolonged period of time. Inspired by a research project funded by the City of New York, Department of Design and Construction (Infrastructure Division) and Consolidated Edison, Inc., it was quickly determined that the resin was playing the key role to withstand elevated temperature. Therefore, the research was mainly divided into three phases, namely:

- Phase – I: Material characterization and bench scale testing of resin-felt candidate systems. The bench scale testing program was developed and performed for one year on different resins to determine the type of resin suitable for elevated temperature application.
- Phase – II: Full scale testing of lined host pipes under cyclic temperature loading. The full scale testing was performed on lined specimens for more than 1080 temperature cycles (three cycles per day) and thermally induced strains and corresponding stresses were measured.
- Phase – III: Next a third phase was added where it was planned to perform 3-D numerical simulation of liner-pipe interaction systems with and without annular gap between the host-pipe and liner under thermal loading condition.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This dissertation presents the interim's findings of a State of Technology assessment through industry survey and experimental testing of the suitability of purpose-developed cure-in-place pipe (CIPP) resin-felt systems for the relining of sewer pipes in the Manhattan area, which must tolerate elevated temperatures due to discharge of steam condensate. The study was undertaken with the recognition that most commercially available resins used in CIPP lining systems are not intended to perform at temperatures as high as 212° F. Furthermore, the current design methods and practices do not account for stress conditions that could be induced due to combined hydrostatic pressure and cyclic thermal loads. A literature review revealed that little information is available in the public domain regarding the installation of CIPP rehabilitation systems in pipes subjected to elevated temperatures. Nevertheless, there are several resins products that claim to be suitable for such applications.

2.2 Background History

In 2007, a 24-in. steam pipe that was laid in 1924 exploded in Midtown near Grand Central Terminal. Investigator found that apparently cold water got into the steam pipe, producing a change in pressure which caused the blast. In August 19, 1989, people had to evacuate from their homes in Manhattan due to a steam pipe blast. Several related accidents occurred in NY in a small time span reported by Ms. Laurie Goodstein in the Washington Post, and published in the Star Tribune November 24, 1989 are listed in Table 2.

Table 2: Steam Pipe and Water Main Blast in NY in 1989

Date	Description
Sept. 3	In Midtown Manhattan a water pipe burst.
Sept. 6	In upper west side steam pipe exploded.
Sept. 25	Steam pipe exploded six blocks from the united nations office.
Oct. 6	30-ft section 6 th Avenue collapsed due to a broken water main.
Oct. 10	8 th Avenue Subway station was closed due to a burst water main.

Although only a handful of steam pipes have exploded in the past decade, the threat remains because the 105 miles of steam mains and service pipes that pump steam beneath the streets of Manhattan are near other utilities, including gas and electrical

equipment. Therefore, problems with one system can often affect the others. Aftermath of a steam pipe blast is shown in Figure 5.



Figure 5: Steam Pipe Blast in the City of NY (modified after The New York Times, 2007)

Rehabilitation of these old pipes is difficult but not impossible, and again closing traffic for several weeks will incur enormous financial loss for a city like New York. So, little to no digging trenchless method is preferable to the traditional "dig and replace" methods.

2.3 Effect of Thermal Strain

Recently, a paper was published notifying the thermal aspects of designing a CIPP liner during and after the installation (McKim et al., 2010). ASTM F1216 assumes some structural support from the host pipe by including the “*K*” (Enhancement Factor) and does not consider any mechanical or chemical bonding between the liner and the host-pipe. But there is a contradiction that the thermal strain experienced by the liner as it cools off from

the installation temperatures depends on the host pipe and when the host pipe fails to restrain the liner's thermal strain, the liner can fail under tension.

2.4 Pipe Rehabilitation Methods

Trenchless technology refers to family of methods and equipment used for the installation of new or replacement or rehabilitation of existing underground infrastructure with minimal disruption to surface traffic and other surface activities. Cured-in-place pipe (CIPP) technology consists of protecting/sealing/reinforcing the inner wall of the host pipe with a thermosetting composite liner that is cured in place. It is a system in which a thin flexible tube of polymer or glass fiber fabric is impregnated with resin and forced to harden the material. Once inserted into the pipe, the tube is expanded with hot air or hot water to make it assume the shape of the inner wall of the pipe and cured under elevated temperature (Wood E. 1977, and Bruzzone et al., 1987).

2.5 Components of CIPP

The basic components of CIPP include a flexible fabric tube and a thermosetting resin system. The fabric tube is made up of woven or non-woven material, mainly felt, glass fiber composite cloth, and impermeable plastic. The tube should be strong enough to withstand installation stresses. Impermeable plastic coatings are used on the interior or the exterior of the tube to protect the resin during installation. The major function of the tube is to carry and support the resin until it is placed within the existing pipe and cured. Primary resin systems used include polyester (filled and unfilled), vinyl ester and epoxy. Polyester resins have high water resistance and are the most economic among the three. Styrene is added to reduce the viscosity of polyester resins. Styrene also helps in the curing of the resins by cross-linking of the molecular chains of polyester. The major

application of polyester resins is in the municipal sewage system. Vinyl ester and epoxy resins are tougher and more resilient than polyester resins. They are used for industrial and pressure pipeline applications where their enhanced corrosion and solvent resistance properties are required. The epoxy resins are the most costly of these three resin types and are used in drinking water pipelines (Robert et al., 1995).

2.6 CIPP Method

The existing pipe is first inspected to assess the extent of damage to the pipe. It is then cleaned of roots, sediments, and debris and the flow is bypassed. A flexible tube impregnated with thermosetting resin is then inserted into the pipe through an entry point. The installation is done by winching mechanically or by inverting it under air or water pressure. In the inversion process, the tube is cuffed back and clamped to an inversion ring at the entry point. It is then fed into the pipe through the ring with the tube being turned inside out. Water or air pressure is then applied to turn the tube inside out and to push it inside the pipe. The pressure keeps the tube expanded against the pipe wall as it inverts along the installation length. In the winching technique, the tube is pulled through the pipe length. An inflation bladder is then inverted through the tube to expand it against the wall of the host pipe.

After the tube is inserted and expanded, heated water or steam is circulated through the pipe to initiate the curing of the resin. After the curing cycle is complete, the CIPP is cooled. The ends of the cured pipe are then trimmed. At the service connections and laterals, dimples are created owing to the pressure. In big pipelines where personnel entry is possible, a cutting device is used to reopen the connections. In small pipelines,

robots and closed-circuit television (CCTV) cameras are used to locate the dimples and reopen the connections (Robert et al., 1995).

2.7 Vendors of High Temperature CIPP Liner Components

An extensive literature review was undertaken to identify commercially available CIPP products that are expected to perform well in elevated temperature environments. Chemical resistance of CIPP liners depends on the type of resin used. Unsaturated polyester resins provide good chemical resistance to municipal sewerage; however, vinyl ester resins and epoxy resins provide further increased chemical resistance where special corrosion and higher temperature performance is needed.

2.7.1 Reichhold Chemicals, Inc.

The Composites Division manufactures two resins that can be used at elevated temperatures.

2.7.1.1 DION 382-20

This is polyester-based (bisphenol-A fumarate) resin. This is a highly corrosion-resistant resin with over 30 years history of good performance at high temperatures. It has been converted for use in CIPP liners and the customers include Novel Pipe, Inliner, etc.

2.7.1.2 DION 9800-20

Formerly known as ATLAC® 580-20, this vinyl ester resin has been specifically designed for CIPP applications requiring the high degree of chemical and temperature resistance. This vinyl ester is urethane modified. Urethane-modification creates a tough, resilient polymer that combines outstanding corrosion-resistance and high-temperature performance with excellent laminating characteristics. The resin wet-outs really well and has good wetting characteristics with carbon and ARAMID fibers, as well as conventional

glass fibers. The resin can be thickened using regular (not hydrophobic) grades of fumed silica, and will not foam when used with standard MEKP initiators. Until a few years ago, Insituform was the main customer, but now, this resin is mostly sold to several smaller customers such as Improved Technologies in Knoxville, TN.

The mechanical properties of the DION 9820-20 and DION 382-20 resins have not been tested at elevated temperature for the application of CIPP liners but have been tested in laminates and listed in Table 3 and Table 4.

Table 3: Typical Properties of DION 9800-20 at Elevated Temperatures

Temp.	Tensile Strength		Flexural Strength		Flexural Modulus	
	psi	MPa	psi	MPa	Psi	MPa
77	19,500	134	26,300	181	1,010,000	6,960
150	19,500	134	25,600	176	870,000	5,995
200	19,500	134	23,100	159	740,000	5,100
250	13,000	90	19,200	132	580,000	4,000
300	9,000	62	7,400	51	320,000	2,205

Table 4: Typical Laminate Properties of DION® 382-20 at Elevated Temperatures

Temp.	Flexural Strength	Flexural Modulus	Tensile Strength	Tensile Modulus
° F	psi	×10 ⁶ psi	psi	×10 ⁶ psi
77	25,500	1.21	18,000	1.45
150	27,000	1.10	21,500	1.40
200	23,500	1.00	21,500	1.35
250	17,500	0.88	20,000	1.20

2.7.2 Neopoxy International, Inc.

The company manufactures high heat resistant epoxy named NPR-1571. This epoxy resin is designed for medium and large diameter CIPP structural liners having an operating temperature of over 300° F. For application in smaller diameters and/or different operating temperatures, NPR-1571 can be further modified to meet specific needs. NPR-1571 is a slow curing resin, with initial cure at ambient temperature and post cure at 70° F (higher better) in duration on several hours (e.g. 2-3 hrs) to provide improved heat resistance and chemical resistance. One known case history involves the lining of a pipe 18” in diameter and 110-ft long conveying chemicals at elevated temperatures at the Shell Deer Park Refinery, approximately 20 miles east of downtown Houston, TX. The contact person was Mr. Ron Soots, BEI Engineering, 3741, Red Bluff Road, Ste 200, Pasadena, TX. 77503. Tel.: (713) 246-7314.

2.7.3 Noveon, Inc.

Noveon, Inc., an integral part of the Lubrizol Corporation, offers Estane® thermoplastic polyurethanes (TPUs). Estane TPU is a coating used in felt that is impregnated with a resin and is built for toughness and durability and provides a combination of heat, chemical and abrasion resistance. High melting point (~145° C / 293° F) allows the use of hot water and steam across a wide range of pipe thicknesses and can be used in combination with a wide range of thermosetting resin matrix systems.

2.7.4 Belzona, Inc.

Belzona, Inc. manufactures several ceramic coatings; however, they are too viscous to be poured and are not suitable as resins for CIPP application. This can only be applied with a brush or spray.

2.7.5 AOC LLC

AOC is a leading global supplier of resins, gel coats, colorants, additives, and synergistic systems for composites and cast polymers. They are the North American leader in resins for corrosion resistant applications and produces Vipel F085 resin in ISO 9001:2000-certified facilities that use proprietary process control technology for ensuring batch-to-batch consistency. Vipel® resins have excellent process ability and high levels of consistency. It has high organic solvent resistance with improved high temperature properties. Pipelines totaling 5,044 ft. in length with diameters ranging from 15 to 48 in. were rehabilitated in the city of Columbus, Ohio using Vipel F085 products. The city of Pittsburgh, Pennsylvania rehabilitated 1,372 ft of 54 in. diameter pipe. The Orange County, Florida used Vipel F085 to rehabilitate 18.9 miles of pipes with diameters of up to 72 in.

A list of potentially suitable resins for high temperature CIPP applications is given in Table 5.

Table 5: List of Potentially Suitable Resins

Product	Characteristics
CoREZYN VE8738	A vinyl ester resin suitable for highly corrosive and elevated temperature applications.
CORVE 8190	A vinyl ester resin for sewer applications.
DION 9800-20	Vinyl ester resin specifically designed for CIPP applications that require higher degree of chemical and temperature resistance.
Quik PE	A polyester resin featuring polymer composition that prevents degradation in corrosive environments.
Quik POX	A modified cycloaliphatic hardener featuring high strength and high heat distortion temperature (HDT) post cure.
Vipel F085	F085 series is an epoxy novolac vinyl ester resin dissolved in styrene.

2.8 Related Work and Theories

2.8.1 Introduction

Linings are used for the rehabilitation of sewers to restore hydraulic integrity and extend the structural life duration. Lining takes the shape of the existing sewer. Therefore, the shape can be oval (Figure 6), horse-shoe or circular. Cured in place linings closely match the inside shapes of the sewers. The lining system is designed to act as a flexible pipe within the old deteriorated rigid host, with the soil providing the necessary support to maintain stability (WRc/WAA 1994). No bond is required between the liner and host pipe. From the mechanical standpoint, lining can be affected by deformations of the host structure or by internal or external hydrostatic pressures when the pipe is below groundwater table. Deformations of buried structures are generally small, and the resulting stresses produced in the liner are almost negligible. Conversely, external pressure due to groundwater can cause lining failure by geometric instability or material breakdown. Therefore, a lining must be designed to resist the action of external hydrostatic pressure and this is the only loading case having any major probability of occurring (Trenchless Technology Research Colloquium, 2000). Thus, failure may take place in the form of buckling due to excessive compressive forces. Therefore, a properly designed sewer must comply with the deflection limit and buckling criteria. The stress-limit criterion is defined so that the maximum buckling stress developed under hydrostatic pressure must not exceed the allowable bending stress of the lining material.

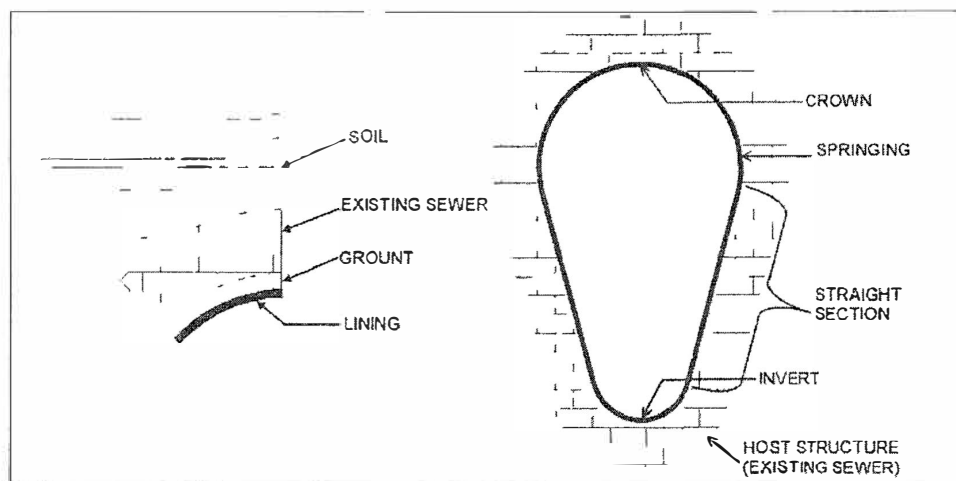


Figure 6: Close-fit Lining in an Oval Shaped Sewer

For deflection-limit criteria, a maximum allowable deflection in the liner should not exceed 3% of the width of the liner (Oliver, 2001). With buckling criteria, the lining must be designed such that failure is not triggered by buckling due to large hoop compression. There are many design methods for circular linings and an equal number of published experimental data (Oliver, 2004, Falter, 1996, and Boot et al., 1996). Conversely, there is far less information, both in terms of theoretical and experimental results, for non-circular linings (especially egg-shaped and oval-shaped linings). Currently, only the WRc recommendations (WRc/WAA 1994) offer a design method for non-circular linings (see Figure 7), but the calculation model is linear and does not allow for the risk of buckling under hydrostatic pressure.