Summer 2016

Experimental and numerical evaluation of a new composite pressure pipe for a Trenchless Rehabilitation Technology

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EXPERIMENTAL AND NUMERICAL EVALUATION OF A NEW COMPOSITE PRESSURE PIPE FOR A TRENCHLESS REHABILITATION TECHNOLOGY

by

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A Dissertation Presented in Partial Fulfillment
of the Requirements of the Degree
Doctor of Philosohy

COLLEGE OF ENGINEERING AND SCIENCE
LOUISIANA TECH UNIVERSITY

August 2016

LOUISIANA TECH UNIVERSITY

THE GRADUATE SCHOOL

MAY 10, 2016
Date

We hereby recommend that the thesis prepared under our supervision by

Xuanchen Yan, B.S.,M.S.

entitled **Experimental and Numerical Evaluation of A New Composite Pressure Pipe for A Trenchless Rehabilitation Technology**

be accepted in partial fulfillment of the requirements for the Degree of

Doctor of Philosohy in Engineering

Supervisor of Thesis Research

Head of Department

Engineering

Department

Recommendation concurred in:

Advisory Committee

Approved:

Director of Graduate Studies

Dean of the College

Approved:

Dean of the Graduate School

GS Form 13
(8/10)

ABSTRACT

The information presented in this dissertation is based on research work conducted at Trenchless Technology Center (TTC) at Louisiana Tech University. This work was performed through a contract with China University of Geoscience (CUG) for a gas company. China's gas pipelines need replacement or rehabilitation after 15 to 30 years of service. China's gas industry is looking for suitable techniques to transfer into their market.

When compared to conventional excavation pipeline renewal or replacement methods, there are obvious advantages of TRT for gas pipelines that can impact the triple bottom-line of economic, social and environmental benefits. An introduction of TRT for gas pipelines has been provided. Also, an overview of international and China's TRT for gas pipelines is provided. The focus is on specific questions existing for urban gas pipeline networks. Based on the international survey and literature review of TRT, TTC evaluated the candidate technologies and developed a selection criterion. A new composite hose was selected as the specific candidate technology for China gas pipelines.

TTC performed mechanical and material property tests on the composite hose for pressure gas pipeline rehabilitation. These tests included long-term and short-term tension and bending tests, as well as tests for hardness and thickness. The performance of the hose has been completed including flexibility, strength and burst testing with connections. Taking advantage of the material parameters and the burst testing results, the Finite Element Analysis (FEA) and Approximate Analytical Calculation (AAC) of the pressure carrying capacity of the hose has been completed.

The purpose of the theoretical analysis was to find a simple and practical design principle and equation for the composite pipe with the Pipe-in Liner (PIL) method.

The hoop stress equation was validated and set up as the design principle for the multi-layer hose. The PIL construction scope and technical advantages were determined. Installation details and technical parameters for the lowest Life Cycle Cost (LCC) were optimized. Industry Standards and Testing Requirements for Fiber Reinforced Polyethylene Hose for Trenchless Rehabilitation were completed in English and Chinese versions.

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Author Xuanchen Yang

Date 07/29/2016

GS Form 14
(5/03)

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ACKNOWLEDGMENTS

I would like to acknowledge Dr. Tom Iseley, Ms. Wu Xiaonan and Dr. Shaurav Alam for their constant involvement and encouragement in both the technical and the professional aspects of this research work. They have been very helpful throughout this endeavor with their intellectual support and with their expertise regarding the equipment.

I am also grateful to my lab instructor, Mr. Chris Morgan and lab mates, Mr. Lane Elien, Mr. Urso Campos, and Mr. Yu Yan for their continuous support in apparatus preparation and data collection, and Ms. Jadranka Simicevic and Mr. Saleh Behbahani for reviewing the research proposal, Ms. Greta Vladeanu for submitting the dissertation and Mr. Ni for providing materials and data as well as Dr. Ma for reviewing the project report.

I am thankful to the members of my advisory committee, Dr. Iseley, Dr. Hall, Dr. Wang, Dr. Jaganathan, and Dr. Alam for their valuable advice. I acknowledge the project funding made available by China University of Geoscience, Trenchless Technology Center, and the staff for their support undergoing the experimental work. Without their support, this research would never have been accomplished.

CHAPTER 1

INTRODUCTION

1.1 Background and Objectives

China has experienced a rapid growth in the amount of urban natural gas consumption. Based on official data from 2014, total supplies and the pipeline's length of natural gas, liquefied petroleum gas, and coal gas are shown in **Table 1-1**. The decreased and increased percentages are compared with those from 2013. There were 421 million gas customers in 2014. Gas utilization in 2014 was 94.56%, which had increased by 0.31% over 2013 (Liu 2014).

Table 1-1: Official data for the gas market in 2014 in China.

Item	Supplies in 2014	The length of pipeline in 2014
Natural gas	96.44 billion cubic meters (Increased by 7.0%)	270,296 miles (435,000 km) (Increased by 11.9%)
Liquefied petroleum gas	10.827 million tons (Decreased by 2.4%)	6,835 miles (11,000 km) (Decreased by 4.7%)
Coal gas	5.6 billion cubic meters (Decreased by 10.9%)	18,020 miles (29,000 km)

The poor condition of the pipeline is due to many factors, including construction and installation practices, urban development, soil conditions, erosion, corrosion, materials, etc. Risks of catastrophic failures and other dangerous accidents have increased.

This affects the reliability of gas supply, leads to greater waste, serious casualties, huge economic losses, and negative social impacts. As time progresses, more gas pipelines will need replacement or rehabilitation. China's gas management is very concerned about these issues.

When compared with the development and utilization of trenchless technical solution in other countries, the adoption of trenchless technologies application in China is much lower. We need to accelerate the development and utilization of trenchless technologies in China (Yue 2003). However, this will require some overall planning to address several significant issues, such as:

1) Selecting technical solutions and contractors based on low bid rather than minimum life-cycle cost.

2) Utilizing inadequate specifications which do not address quality expectations.

3) Construction quality and safety issues.

4) Lack of trenchless rehabilitation standards.

5) Lack of professionals trained in the design of trenchless rehabilitation projects.

6) Lack of construction managers and skilled workers trained in the installation of trenchless rehabilitation.

There exists regional imbalance with the trenchless rehabilitation work done in China for gas pipelines. Five provinces, including Guangdong, Shanghai, Zhejiang, Jiangsu and Shandong, accounted for over 90% of China's trenchless rehabilitation technologies (TRT).

1.1.1 Kunming's Gas Pipeline Network

The business scope of Yunnan PetroChina Kunlun Gas CO.LTD (KG) includes the planning, design, construction, operation and maintenance of urban gas pipeline networks, city gas distribution, natural gas and liquefied petroleum gas sales and after-sales service, and other related services. Kunming gas network data in this paper is provided by KG.

Since 1983, KG has upgraded the gas mains in the urban districts two times. KG provides gas service to 760,000 residential customers, 44 industrial users, and 1,578 commercial users now. The information about urban gas pipelines in Kunming is listed in **Table 1-2**.

Tabie 1-2: Statistics for Kunming's gas pipeline network.

Pressure type	Pipe material	Outer diameter	Pipe length
Medium 1.45-56 psi (0.01-0.4 MPa)	Seamless steel pipes, PE pipes, polyethylene plastic composite pipes with steel skeleton	8.6"(219 mm) 12.8" (325 mm) 14.8"(377 mm) 16.8"(426 mm) 18.8"(478 mm) 20.8"(529 mm) 24.8"(630 mm)	2,300 km (1,430 miles)
High Pressure 56-560 psi (0.4-4 MPa)			

At present, the media of the Kunming city's gas pipeline system is coal gas. It contains hydrogen, carbon monoxide, methane, nitrogen and carbon dioxide, trace amounts of hydrogen sulfide and naphthalene. Natural gas replacement work is underway since 2014 in Yunnan province. Natural gas is coming from the gas fields of Myanmar by the Sino-Burmese gas pipeline. For Myanmar natural gas, the methane content of the gas is up to 99.07%, with the low calorific value 33.4 MJ/m^3 and high calorific value 37.8 MJ/m^3. After thirty years' operation, Kunming's gas pipeline network has the following problems.

1.1.1.1 *Pipelines corrosion*

A subsidiary company Kunming Coal Gas Holdings Limited detected the corrosion for parts of gas pipelines in May 2001, which was based on the dual-frequency Eddy current method to evaluate the metal's loss by pipe corrosion and to assess the external coating of the pipe.

Based on the detection results, although Kunming's Gas Pipeline Network used the special anticorrosive coating and cathodic protection (sacrificial anode) and other anticorrosion measures, serious corrosion problems existed. Corrosion became more serious as it was near the end of service life for gas pipelines, which were constructed in the mid 1980s. The reasons for pipeline corrosion are (Wei 2009) :

(1) Corrosive gases resulting in internal wall corrosion, which results in thinner and uneven thickness,

(2) Poor quality pipe materials and poor quality installation practices,

(3) The natural periodic and repeating vibrations resulting in fatigue damage to pipe and fittings and produced electrical corrosion,

(4) Failure of preservation, resulting in increasingly high corrosion rate, including aging of coating and cathodic protection failure.

1.1.1.2 *Pipeline blocking and fouling*

Kunming's Gas Pipeline Network has been in operation for more than thirty years. Impurities, such as the tar, naphthalene, ash and corrosion, result in pipes, sumps, and regulators being blocked. The poor coal gas transmission affected the normal use and delivery and accelerated the corrosion rate.

1.1.1.3 *Natural gas replacement*

The transition to natural gas has started in Kunming. Based on other cities' experience, such as Shanghai and Ha'erbin, when the urban gas pipelines previously used to transport the wet coal gas saturated with steam, tar and other impurities were converted to transport dry natural gas, several challenges arose (Ma and Su 2009).

(1) The pressure, flow rate, pressure drop, and pipeline materials need to be adjusted.

(2) The impurities chapped to dust particles and flowed with the gas, resulting in pipe blockage or equipment damage and affected the normal gas supply.

In summary, KG began to develop an urban gas system since the 1980s. Pipeline corrosion perforation has caused a large number of gas leaks in recent years. Kunming owns more than 1,429 miles (2,300 km) of medium and high pressure pipelines. It needs to do pipeline condition surveys to locate serious corroded pipelines, and to do replacement or rehabilitation. Because of the environmental limitations, some sections cannot be renewed by the cut-and-cover method, so rehabilitation by trenchless technology is required. One purpose of this dissertation is to select a suitable gas rehabilitation technology and to conduct laboratory and field tests to ensure the successful implementation of this technology in Kunming.

1.1.2 Significance

Gas pipeline corrosion is increasingly serious and natural gas replacement is underway in Kunming. Pipeline replacement by the open-cut method resulted in an excessive amount of road damage, environmental pollution, traffic congestion, and other problems. TRT are alternative good solutions and can meet the requirement of operating pressure after natural gas replacement.

The application of TRT for gas pipelines is still in its infancy in China. The demonstration in Kunming will play an exemplary role in China's promotion of TRT.

1.2 Overview of TRT for Gas Pipeline

According to the definition from CJJT 147-2010, "Technical specification for trenchless rehabilitation and replacement engineering of urban gas pipeline." no-dig rehabilitation and replacement are to use non-excavation technologies to do in situ pipe repairs, or to do in situ pipe replacement to improve performance. According to the definition of the North American Society of Trenchless (NASTT), TRT are to utilize micro-excavation or non-excavation technologies to renew pipelines. Generally, some specific benefits of TRT include (Ma 2014) :

- Much lower carbon footprint,
- Minimizing impact of traffic and congestion,
- Minimizing negative economic impact on local businesses,
- Requiring less space underground, minimizing chances of interfering with existing utilities or abandoned pipes,
- Providing the opportunity to upsize a pipe without open-trench construction,
- Requiring less-exposed working area, and is safer for both workers and the community.

Thus, when compared to conventional excavation pipeline renewal or replacement methods, there are obvious advantages of TRT for gas pipelines that can impact the triple bottom-line of economic, social and environmental benefits. They can be applied on both gravity and pressure pipelines, but the main research and application is for gravity pipelines. TRT have begun to be applied on pressure pipelines but has faced some challenges, including the lack of experience and industry standards and much needed marketing, etc.

Trenchless technologies for gas pipelines application have experienced a rapid development in Shanghai, Beijing, Jiangsu and other places in China, but are mainly used in the new pipes' installation. TRT is a revolution in pipelines' rehabilitation methods. Trenchless renewal and replacement methods include Sliplining (SL), Cured-in-place pipe (CIPP), Sprayed in Place Pipe (SIPP), Close-Fit Pipe (CFP), Coating and Linings (CL), Pipe Burst (PB) and Pipe Replacement by Horizontal Directional Drilling (HDD), etc.

1.2.1 Sliplining (SL)

SL is also known as the traditional lining or insertion lining, which is to insert the smaller diameter pipe into the larger diameter original pipe. Then grout is forced into the annular spaces between the new and old pipes. Today, this early rehabilitation method is still an internationally convenient and economical way (**Figure 1-1**) (Infra 2016).

Figure 1-1: Sliplining process.

1.2.2 Cured-in-Place Pipe (CIPP)

In the 1970s, the British engineer Eric Wood invented the CIPP. It is later referred to as the Insituform pipeline rehabilitation method. The CIPP process involves the insertion of a resin-impregnated fabric tube into an existing pipe by use of water or air inversion or winching. Usually, the fabric is a polyester material, reinforced fiberglass, or similar. The pliable nature of the resin-saturated fabric prior to curing allows installation around curves, filling of cracks, bridging of gaps, and maneuvering through pipe defects. CIPP can be applied to structural or nonstructural purposes. At present, CIPP has been widely used in water systems. It mainly provided leak-proof, sealing and non-structural rehabilitation in natural gas pipeline systems (Tabor, Newman *et al.* 2014). Starline® from Germany uses a seamless fabric hose with circular diameter made from polyester yarn and provided with plastic surface of a layer polyurethane. The hose is attached to the internal gas pipeline wall with a polyurethane resin-based adhesive and is widely used in New Jersey. **Figure 1-2** shows the structure and construction technology of Starline®.

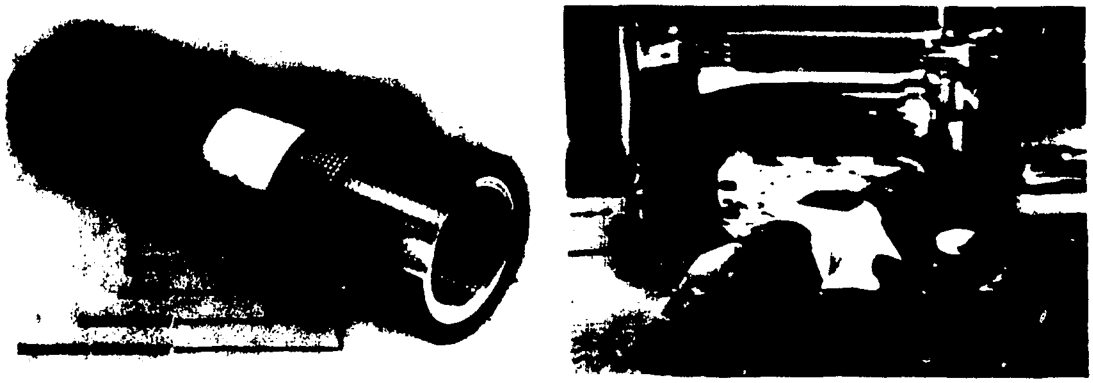


Figure 1-2: The structure and construction technology of Starline®.

1.2.3 Sprayed in Place Pipe (SIPP)

SIPP utilizes a robotic pipe lining system for installation of impenetrable liners in In-Situ Pipes. A robotic lining process is in place for rehabilitation. The SIPP repair process utilizes a rotational grouting apparatus to build new smooth pipe walls robotically where the existing ones deteriorated. Additionally, the technology is utilized as preventive fortification for new pipe installations (EA Services 2012). The sprayed in place pipe system functions with a computer-controlled robot traversing through the pipe at the calculated formula based on speed, flow, thickness, and diameter. The procedure uses various robotic sizes and configurations depending on the pipe's diameter (**Figure 1-3**). SIPP advantages are:

- Arrests deterioration from extremely aggressive effluents, microbiological/sulfur reducing bacteria, oxidation/reduction and erosion,
- Navigates multiple pipe convolutions,
- Offers real time video of the process,
- Offers precision location capabilities for localized repairs, joint sleeves, etc,

- Has multiple pipe geometries and material compositions,
- Has horizontal through vertical piping systems,
- Has a long design life.

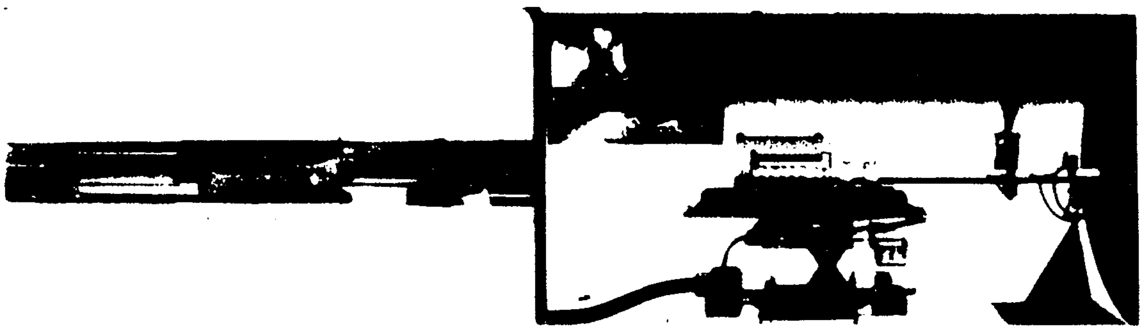


Figure 1-3: Process of SIPP.

1.2.4 Close-Fit Pipe (CFP)

The Close-Fit Pipe is also known as cross-sectional area modification, with over 940 miles (1,500 kilometers) of rehabilitation length worldwide, including the United States, Britain, Canada, Germany, Denmark, and other countries. It holds a 25% market share of pipeline repair and is suitable for high density polyethylene (HDPE) pipe, medium density polyethylene (MDPE) pipe, and ordinary PE pipe. It has been used in gas pipeline rehabilitation.

The process temporarily reduces the cross-sectional area of the new pipe before it is installed. After placement, the liner expands to its original size and shape at the jobsite to provide a close fit with the existing pipe. This method can be used for both structural and semi-structural purposes for pressure (more common) and gravity pipelines. The thin polyethylene lining can be reduced and reformed by heat and/or pressure on-site. **Figure 1-4** presents a process of the deformed lining entering the main pipe (Najafi and Perez 2016).

Figure 1-4: The process of U liner entering the main line.

Thermoformed Pipe is an example of Close-Fit Pipe and used in North America. Pipes with a reduced cross-section by folding for insertion are then heated to thermoform them to conform to the dimensions of the host-pipe (Najafi and Gokhale 2005). The pipe is made of folded PVC or PE pipe. A sample of thermoformed pipe (THP) is illustrated in **Figure 1-5**.

Figure 1-5: Thermoformed pipe.

1.2.5 Coating and Linings (CL)

Both internal lining and external coatings provide protection against gasoline, kerosene, alcohols, crude oils, and natural gases. Epoxy-based metal repair composites and high temperature coatings and linings have been used in the oil and gas industry since the late 1970s. CL materials are specifically designed to provide outstanding erosion, corrosion protection and chemical resistance for equipment operating at various temperatures and pressures. Corrosion-resistant composite materials and coatings can be used to repair rubber joints and pitting damage and corrosion prevention for host pipes. Epoxy coatings are designed to provide long-term chemical protection against a wide range of substances including acids and alkalis even at high temperatures (**Figure 1-6**) (Belzona 2016). Most of the difference between CL and SIPP is the construction method, robotic pipe lining and manual coating.

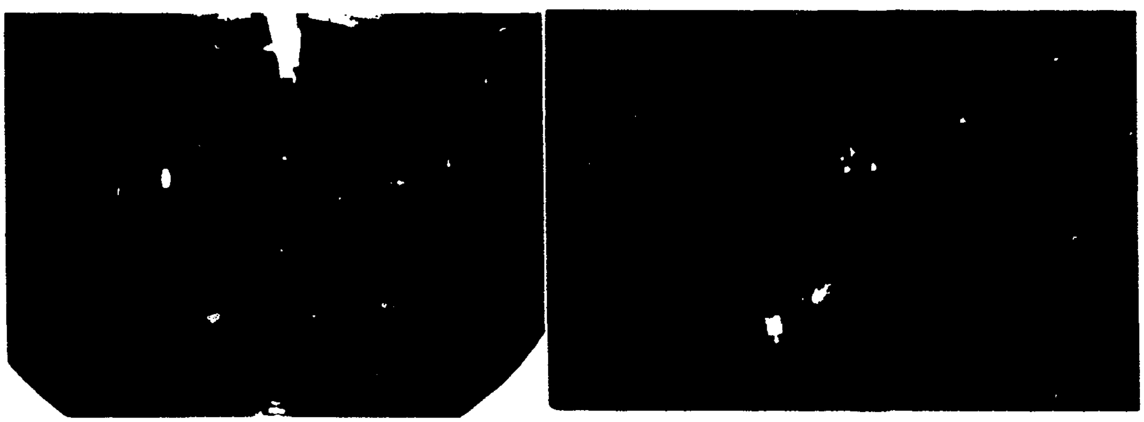


Figure 1-6: Gas pipeline protected against corrosion by coating.

1.2.6 Pipe Bursting (PB)

Pipe bursting, as the name implies, uses a burst head to break the existing pipe and force broken pipe fragments into the surrounding soil while a new pipe is pulled and/or pushed in its place simultaneously. There are different variations of the pipe bursting method (Najafi 2007):

• Pneumatic pipe bursting: a pneumatic hammer is used to break the existing pipe.

• Static pipe bursting: the energy to break the existing pipe is in the pulling with no percussion action. Compared to the pneumatic method, this is a quiet operation and action preferable in clayey soils or when there is need to cut (split) cast iron, ductile iron steel pipe.

• Hydraulic pipe bursting: the bursting head articulates to create the bursting action, without the noise of the pneumatic systems, but pulled along with a cable like the pneumatic systems.

• Insertion method (also called pipe expansion): this method jacks a new rigid pipe (such as clay) into the existing pipe. Clay and ductile iron are the two most widely used segmental pipes.

Figure 1-7 illustrates a schematic of the pipe bursting operation. This method can be used to replace natural gas, water, and sewer pipes. This technique is useful in size-for-size replacement and up-sizing of pipeline sections. A pit is excavated to make new insertion possible based on the required bending radius of the new pipe. Pipe bursting is applied to pipes ranging from 4" to 48" (101.6 mm to 1219.2 mm). The length of installation is based on the project and site conditions and can be in the 400 ft (120 m) range (Murphy pipeline 2016).

The pipe bursting technology is popular in Europe. It may not be applicable when replacement occurs in hard soil conditions, such as "expansive" clays, densely compacted soils and backfills, or soils below the water table. In addition, pipe bursting projects could be complicated further by close proximity to other underground utilities (less than 10 times outside the diameter of the new pipe), past point repairs that reinforce the existing pipe with ductile materials, and a collapsed section of the existing pipe.

Figure 1-7: Pipe bursting method.

1.2.7 Horizontal Directional Drilling (HDD)

Pipe removal, also known as pipe eating, can be performed by use of a HDD rig, a Horizontal Auger Boring (HAB) machine, or a Modified Micro-tunnel Boring Machine (MTBM). In this method, the existing pipe is broken into small pieces and taken out of the ground by means of a slurry (in HDD or MTBM method) or an auger (in HAB method). See **Figure 1-8** (TransCanada 2016).

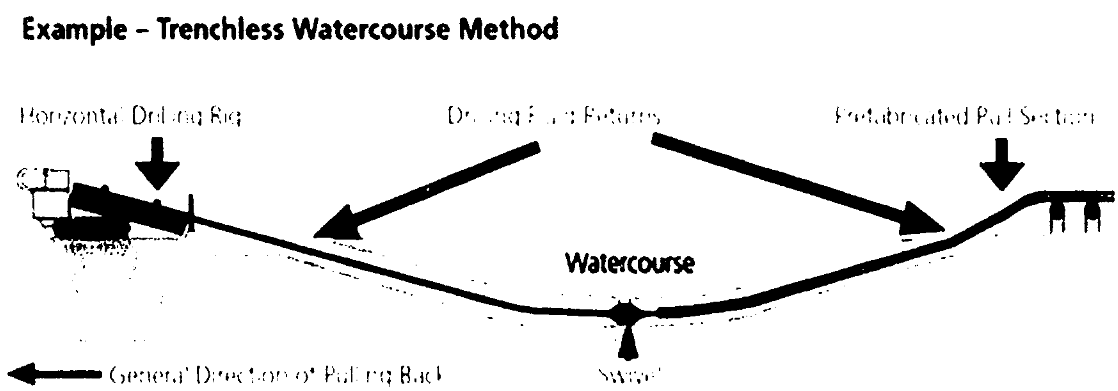


Figure 1-8: HDD for watercourse.

1.2.8 Overview of International TRT

Trenchless technologies were formed in developed countries in the 1980s. ISTT, the International Society for Trenchless Technology, an international trade association, was established in 1986. It aimed at promoting the development and exchange, and expanding the use of trenchless technologies. More than 30 countries and regions have joined ISTT [Committee on Underground Engineering for Sustainable Development (U.S.) 2013].

TRT were first used in the UK. CIPP and Close-fit Pipe are widely used for the rehabilitation of water pressure pipes with leakage and internal corrosion problems. Over 6,214 miles (10,000 km) of potable water pipelines have been repaired by CIPP and Close-fit Pipe in the UK [Bruce and Institution of Public Health Engineers (Great Britain) 1985].

CIPP has been widely used on gas pipeline rehabilitations in the United States, Britain, France, Germany, Spain, Sweden, Singapore, Japan, and other countries. It has been a growing subset of trenchless technology since its 1971 debut and is now a substantial market for composite materials. Due largely to research and development on the part of various resin producers, CIPP structures can be designed to satisfy virtually any need for underground pipe rehabilitation, from industrial plants to potable water lines. It has won the high valuation and promotion in Europe and the US, with good social and economic benefits (Kirmeyer 2000).

Germany is one of the world leaders in trenchless technologies. The pipelines needed to be rehabilitated or renewed have increased in Germany (Baawain, Chou *et al.* 2015). The length of the water pipelines network is approximately 285,830 miles

(460,000 km) in Germany. The length of gas pipelines was 16,777 miles (27,000 km). The rehabilitation length by the trenchless method has reached the 2% of total pipeline length since 2009. The rehabilitation length of water pipeline has reached 5,716 miles (9,200 km) and the natural gas pipeline has reached 336 miles (540 km).

Starline®, belonging to CIPP technology, is from Germany. This technology was originally developed by Karl Weiss in Berlin. It has been used for gas pipeline rehabilitation under complex conditions. The liner is inverted and installed by compressed air, which is a non-permeable polyethylene and seamless polyester braided hose, with inner air bags, making the pad become an airtight barrier. In the process of repair by Starline®, multiple cameras were used to check to ensure that unknown or abnormal protrusion does not occur to ensure the efficiency of the repair work. Once the liner was in place for a few hours, under ultraviolet light (UV) that cured the liner, the adhesive was applied directly to the host pipe. Once the rehabilitation was completed, the natural gas pipeline services recovered quickly (Progressive pipe 2014). Starline® has been applied to over 435 miles (700 km) of pressure pipe rehabilitation since 1991. It met the requirements of rehabilitation and ensured the 50 years lifetime (George 2011).

Primus Line production appeared in the 1990s in Germany (Wannagat, Friedhelm *et al.* 2008). It is a flexible high pressure pipeline with special connectors and max operating pressure 3.4 MPa~3.9 MPa (493 psi~566 psi) and can be applied in pressure pipelines. Primus Line has been widely used in the urban water supply, gas and oil pipeline rehabilitation in Germany, Russia, Sweden, and Italy. The maximum single installation length was reached 0.62 miles (1 km) in Russia. The total length of gas pipeline rehabilitation is up to 9.9 miles (16 km).

Pipe bursting is a well-established method for trenchless replacement of pipes throughout the world. Pipe bursting was first developed in the UK in the late 1970s by D. J. Ryan & Sons in conjunction with British Gas, for the replacement of small-diameter, 3- and 4-inch cast iron gas mains. This method was patented in the UK in 1981 and in the United States in 1986; these patents expired in April 2005. Since the late 1970s, pipe bursting has grown into a mature market internationally with significant potential for continued growth in the North American water, sewer, and gas markets (International Pipe Bursting Assocation 2012).

North America has the world's largest growing pipe rehabilitation market. The U.S. is identified as the leader in the field of pipeline rehabilitation. Based on Advantica's estimation, the expenses of pipeline rehabilitation will be $300 billion over the next 20 years in the U.S. TRT are the most beneficial rehabilitation technologies. A recent survey by Jim Bush showed that a majority of utilities were routinely using trenchless relining methods (Michael 2015). For example, approximately 4.7 miles (7.5 km) of gas distribution pipelines with 45 and 90 degree elbow structures have been rehabilitated by German CIPP technology Starline® in New Jersey, and the total cost savings were $6.75 million dollars (George 2011). Miller Pipeline Corporation took advantage of HDD to replace the gas pipelines parallel to the existing pipeline route and abandoned the existing pipeline directly (Millerpipeline 2016).

Tomahawk ™ System Process technology from Canada is a new technology to clean, inspect and renew pressure pipelines. It is a dry process used to clean and line pressure pipelines such as gas, potable water and sewer force mains. The clean process uses a vacuum system to convey abrasives to clean and dry deteriorated pipes and surface preparation prior to lining the pipe. Proper surface preparation is critical for the successful application of non-structural, semi-structural or structural lining systems (Tomahawk System 2016).

Asia is becoming a new attractive area for the pipeline rehabilitation industry. Japan spent nearly fifty years developing TRT for sewer pipelines and provided a unified specification for TRT. PALTEM rehabilitation technologies from Japan has been used in natural gas pipelines since 1980 and is the pioneer for natural gas pipeline rehabilitation by CIPP. It has been used in the United States, Britain, France, Germany, Spain, Sweden Singapore, and Japan. The rehabilitation length of the gas pipelines has reached 90 miles (144 km) in the worldwide excluding Japan. The range of the diameter is from 4" - 24" (101.6 mm - 609.6 mm). The rehabilitation length of the gas pipelines has reached 731 miles (1169.6 km) in Japan. The range of the diameter is from 2" - 36" (50.8 mm - 914.4 mm) (Ashimori Industry 2016). On the rehabilitation front in Hong Kong, a number of trenchless relining projects were successfully completed for clients such as the MTRC (underground railway), the Drainage Services Department (DSD) and the Hong Kong Airport Authority, some dating back to 1990. However, the widespread use of Trenchless Technology did not really take off until the Hong Kong Water Supplies Department (WSD) commenced a massive program to replace or rehabilitate almost half of all the water mains in the Hong Kong Special Administrative Region. This is probably one of the largest pipeline rehabilitation programs in the world, and approximately 1,875 miles (3,000 km) of water mains have been targeted for renewal or rehabilitation in four stages at an estimated total cost of approximately HK$11 billion (US$1.4 billion). The work commenced in 2000 and is scheduled for completion by 2015. A range of trenchless techniques have been used so far in the program, including pipe jacking, pipe ramming, directional drilling, pipe bursting, slip lining, fold and form close fit lining, and CIPP (Trenchless Australasia 2007). With cooperation between local government and international contractors, CIPP also has been used to repair the urban sewer system blocked for more than twenty years in India (Trenchless ASIA 2016).

TRT is widely developed and applied in Australia and New Zealand. The problems of maintaining aging pipe infrastructure is highlighted by the knowledge that there are some 80,778 miles (130,000 km) of water mains and 49,710 miles (80,000 km) of sewers and sewerage pumping mains in Australia. A significant proportion of these have exceeded, or are approaching, their design life. Conservative estimates indicate annual replacement costs of over $200 million dollars, with an increasing awareness of the favorable economics of renovating, or maintaining an already expensive hole-in-the-ground. The potential use and application of trenchless technology in Australia and New Zealand is huge. The full deregulation of the Telecommunications Industry in Australia has resulted in some 2,796 miles (4,500 km) of new cable network installation, with trenchless technology playing a major role in these installations. The use of directional drilling and guided boring provided cost savings of some 35% compared to open cut installation. In Western Australia, pilot projects are underway to test the feasibility of placing the electrical system underground which is currently on overhead lines. Fifty percent of the system has used trenchless technology. The transferring of the whole system underground was estimated to cost around $2.4 billion in 2010 (Pemberton and Harvey 2011). There are two problems in TRT [Committee on Geological and Geotechnical Engineering (U.S.) 2013].

1. The liner needs to be improved to meet the operation internal pressure of the water and gas pipes.

2. It needs to develop and improve the application on structural rehabilitation, especially for gas and oil pipelines.

1.2.9 Overview of China's TRT

The CIPP method has been introduced in China in the 1990s. China Society for Trenchless Technology (CSTT) was established in 1998, and it played a great role in the development of China's trenchless technology and the introduction of international advanced technologies. A corresponding trenchless technology journal named *Trenchless Technology* was released. CSTT formally signed to join ISTT in July 1998. Shanghai, Guangdong, Beijing, and Sichuan have set up their Societies for Trenchless Technology. China University of Geosciences, Chengdu University of Technology, Jilin University, and other institutions have set up trenchless courses and trained graduate students. China and US Joint Trenchless Engineering Research Center was also established by China University of Geosciences (Wuhan) in 2007. The application of TRT has changed from emergency replacement and repair to the preventive replacement and repair in China. Replacement and repair projects are increasing rapidly (Ma 2014).

Trenchless rehabilitation projects began to increase after a breakthrough of the application of CIPP for 5 mile (8 km) pipelines in 1998 in China. A gas pipeline company named HuaYan Engineering Ltd was set up for the replacement work (transferring from coal gas to natural gas) in Shanghai in 1999. Cooperating with the Shanghai Urban Gas Management Department and Tongji University, they focused on the scientific and technological project named "Trenchless rehabilitation technology for natural gas pipelines." They developed the TRT to adapt to conditions and characteristics of Shanghai urban gas pipelines based on international advanced technologies. Three methods were used in the program, including CIPP, Sliplining and Closed-fit pipe. They have been successfully applied to the big project "West–East Gas Pipeline into Shanghai" and have made remarkable success. More than 621miles (1,000 km) of natural gas pipes have already been repaired completely in Shanghai by TRT (Li and Liu 2001).

According to CSTT, 112 miles (180 km) of pipelines have been rehabilitated by trenchless technologies in 2003 and have increased 4 times more than the length of 21 miles (35 km) in 2002. The main technologies are Pipe-Lining Methods, including Close-fit pipe, CIPP and Coatings and Grouting. The length rehabilitated by Close-fit pipe was up to 93 miles (150 km), accounting for 75%. The length rehabilitated by CIPP was 11 miles (18 km) accounting for 10% ~16%. China's trenchless rehabilitation was mostly applied to gas and sewer pipelines. A small part was used in water pipes. The average cost per kilometer was $ 44,776 dollars (300,000 Chinese yuan). The output was $8 million dollars (54 million Chinese yuan) in 2003.

The adoption of trenchless technologies in China has been much lower than other countries. Trenchless technology application for underground pipeline projects was only 0.2% at the end of 2004. The application of trenchless technology was mostly in Shanghai, Beijing, Jiangsu, and other developed areas in China in recent years. However, the majority of applications focused on trenchless installation. Trenchless rehabilitation was only at the initial stage in China (Yue 2003). With the advances in the application of trenchless technology in the past decade, trenchless methods account for 7 percent of the construction activities in China in 2007 (Admin 2007). Therefore, China represents potentially the largest and fastest growing worldwide market for the application and further development of trenchless technology and underground infrastructure technologies. The rehabilitation lengths by TRT in China for the years 2008 and 2009 are listed in **Table 1-3**.

Table 1-3: The rehabilitation length by TRT.

Year	The pipeline length of trenchless replacement and rehabilitation	The difference
2008	143 miles (230 km)	
2009	188 miles (303 km)	It was increased 31.8%

Saertex, a German Company, established its branches in Dongying and Taicang in China in 2008. Then, glass fiber reinforced lining technology by UV curing was officially introduced to China by Saertex (Ji 2012).

The first instance of the large-scale use of CIPP technology in China was the 6 miles (10 km) of sewage pipe rehabilitation by CIPP in Hangzhou in 2010. Then CIPP was applied successfully to the sewer pipelines with a large diameter of 31.5" (800 mm) by Saertex in Guangzhou Road, Taicang, Jiangsu Province in July 2011.

Close-fit pipe, CIPP and Sliplining are still the largest proportion of applications (more than 70%) of TRT in China in the 21st century based on statistics (Ma 2014).

The length of urban pipelines was shown in **Table 1-4** (Zhang and He 2012). The length of gas pipelines, water pipelines and drainage pipelines was more than 18,641 miles (30,000 km) in all. Every year, 373 miles (600 km) of pipelines that were coming to the end of their 50-year lifespan needed to be rehabilitated or replaced. However, the total amount of trenchless construction was less than 124 miles (200 km) over the past five years in Beijing. Close-fit pipe, CIPP and Sliplining were most widely used and were quickly developed in Beijing. The amount of trenchless rehabilitation and replacement projects in 2014 is 15 times more than the one in 2009 in Beijing, and it is up to 1,864 miles (3,000 km) per year (Ma 2014).

Table 1-4: Statistics for Beijing urban pipeline network in year 2009.

The total length of urban pipelines		26,719 miles (43,000 km)	
Gas pipes	Potable water pipes	Heating pipes	Drainage and other pipes
5,195 miles (8,630 km)	4,350 miles (7,000 km)	4,380 miles (7,048 km)	4680 miles (7352 km)

Beijing Gas Group spent more than $ 3 million dollars (20 million Chinese yuan) on transferring CIPP technology Starline® from Germany to Beijing in 2011. It was the first time that Starline® was successfully applied to the rehabilitation for the 0.5 mile (700 m) high-pressure gas pipeline in Beijing in October, 2011. Based on the International Organization for Standardization (ISO), this project of high-pressure gas pipeline rehabilitation by Starline® was fully qualified. The repaired gas pipeline has successfully met the summer peak demand for natural gas. Another 2.7 miles (4.3 km) of high pressure gas pipeline rehabilitation project was applied by Starline® in Beijing in June 2012 (Beijing Gas 2011).

1.3 Research Content and Outline

Following the research process flow chart **(Figure 1-9)**, we selected the suitable TRT to solve practical problems for China's gas pipelines. A simple and practical design principle and equation for the composite pipe with the Pipe-in Liner (PIL) method was validated and set up. The Engineering Manual for the hose was completed and we are promoting this TRT to China gas pipeline rehabilitation.

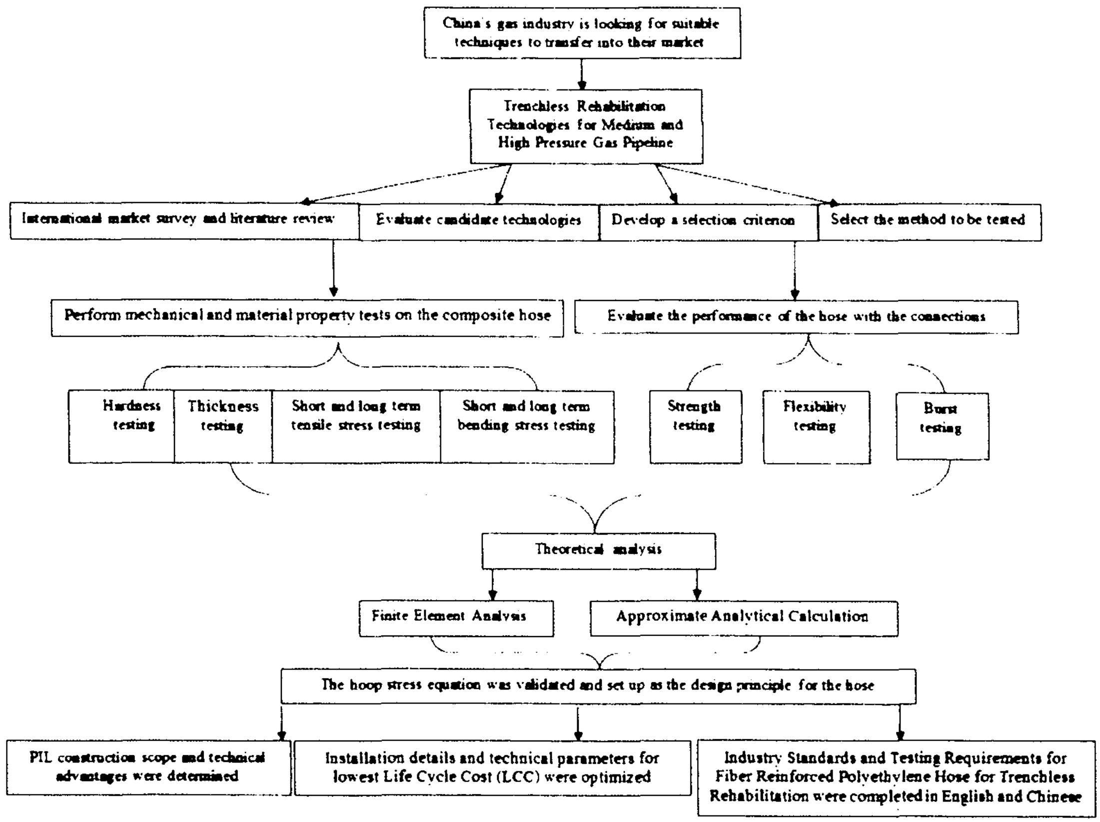


Figure 1-9: Research process flow chart.

CHAPTER 2

CANDIDATE TECHNOLOGIES SELECTION

2.1 Evaluation of Candidate Technologies

Trenchless renewal and replacement methods can be used to renew both gravity and pressure pipelines. The decision process to select a specific method should consider many factors, including nature and extent of existing pipeline deterioration and problems, type of application, pipe geometry, as well as plans for future pipe applications, costs, and availability of contractors and technology providers. Although numerous cross-sectional shapes are available, the circular shape is the most common shape for a pipe because it is hydraulically and structurally efficient under most conditions. A pipe-renewal selection should also consider the following factors in **Table 2-1** (Najafi 2013).

Table 2-1: The decision process to select a specific TRT method

Type of application		Conditions to be considered
Gravity pipe	Pressure pipe	Potential for clogging by debris
Sanitary and storm sewers	Potable water pipes	Limitations on headwater elevation
		Pipe geometry and depth
Culverts and drainage structures	Natural gas pipelines	Hydraulic performance of the new pipe
Sewer manhole structures	Oil pipelines	The site conditions (soil conditions, surface conditions, and availability of space for installation)

There are a wide variety of factors (**Table 2-2**) that affect performance of existing pipes (Najafi 2010). Existing pipe performance is closely related to the rate of deterioration and the service life. Non-inspected and non-maintained pipes deteriorate faster than expected due to various service, environmental, hydraulic, and social conditions, which often lead to emergency repairs. **Table 2-2** provides a summary of factors to consider when a project is considered for trenchless renewal and/or replacement. The pipeline renewal and replacement method selection process is indeed a complicated one. As mentioned above, many parameters and factors must be considered to reach an optimum solution. The decision must be made according to the following aspects.

Table 2-2: A summary of factors to consider.

Factors to be considered for TRT	Common factors affected performance of existing pipes
Grouped under surface conditions	Structural loads (soil and live loads)
Subsurface conditions	Corrosion
Existing pipeline conditions	Excessive fluid pressure
Pipe service requirements conditions	Inadequate flow capacity
Constructability conditions	Scour
Strengths and limitations conditions	Erosion of streambed and embankments

Contact the company to learn about the techniques, previous tests, and history data, including

- Nominal sizes,
- Max operating pressures (depends on diameter),
- Max burst pressures (depends on diameter),
- Wall thickness,
- Hose length per drum depends on diameter,
- Bendability,

- Continuous operating temperature,
- Service life duration (years).

The field performance evaluation is also included. Contact the owners, designers, contractors, installers and operators to collect related information about this technology, including

- Surface conditions,
- Subsurface conditions,
- Existing pipeline conditions,
- Determination of the new pipe service requirements,
- Constructability and site limitations,
- Strengths and limitations of potential renewal/replacement methods.

2.2 Development of Selection Criteria

TRT can be used either to rehabilitate or to replace existing pipelines in situ (Najafi 2010). TTC actively contacted the manufacturers of various methods with field trips. Meetings were held with the relevant contacts. Following the requirements of medium and high pressure pipelines in China, the suitable TRT and manufacturers are shown in the figures.

Smartpipe® (**Figure 2-1**), from Houston, is a non-intrusive pipeline replacement technology. It uses the existing pipeline infrastructure to bring in a new generation of pipeline. Smartpipe® is predominantly inserted into an existing pipeline, but it is designed and can be laid as a stand-alone system. However, the company was restructuring when we tried to contact them (Smartpipe Technologies 2016).

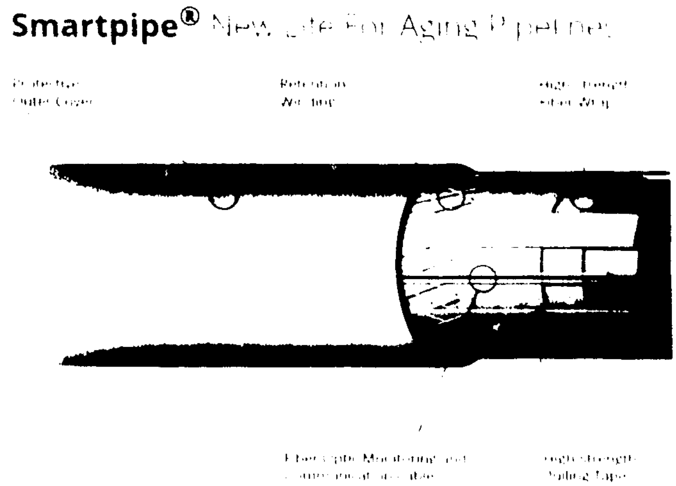


Figure 2-1: Smartpipe® from Houston.

PipeMedic® (**Figure 2-2**) from the U.S. is the fibre-reinforced plastic (FRP) product that has been tested by the Gas Technology Institute (GTI) and has been approved for repair of pressurized natural gas pipelines. The thin laminates can be remotely installed, allowing the pipe to resist internal pressures in excess of 250 psi. However, the FRP was in the experimental stage then (PipeMedic 2011).

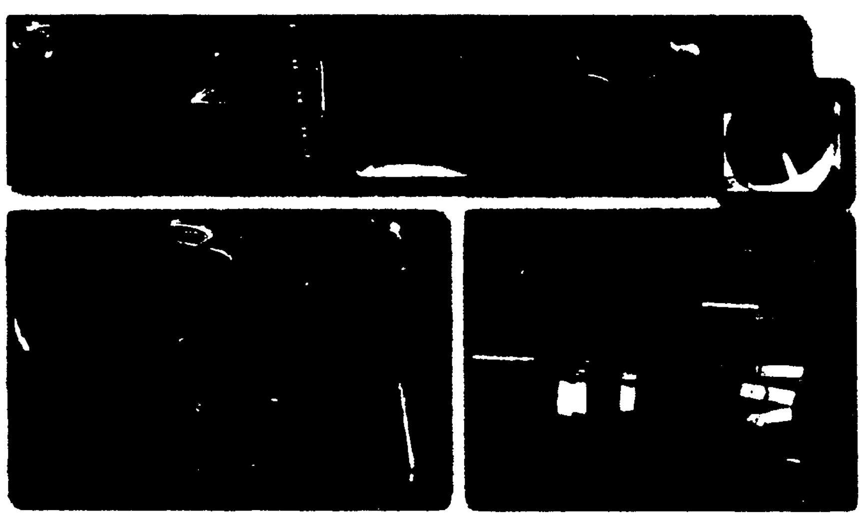


Figure 2-2: Pressure tests for PipeMedic®.

PALTEM HL (Hose Lining) (**Figure 2-3**) is a method of rehabilitating pipes by inserting a liner inside out into the pipe using air pressure. What characterizes HL is a structure composed of a base hose (a seamless woven jacket with an extruded cover) treated with various reinforcement layers, making it adaptable to a wide range of construction and engineering conditions. However, the company was not focused on China's market then (Ashimori Industry 2016).

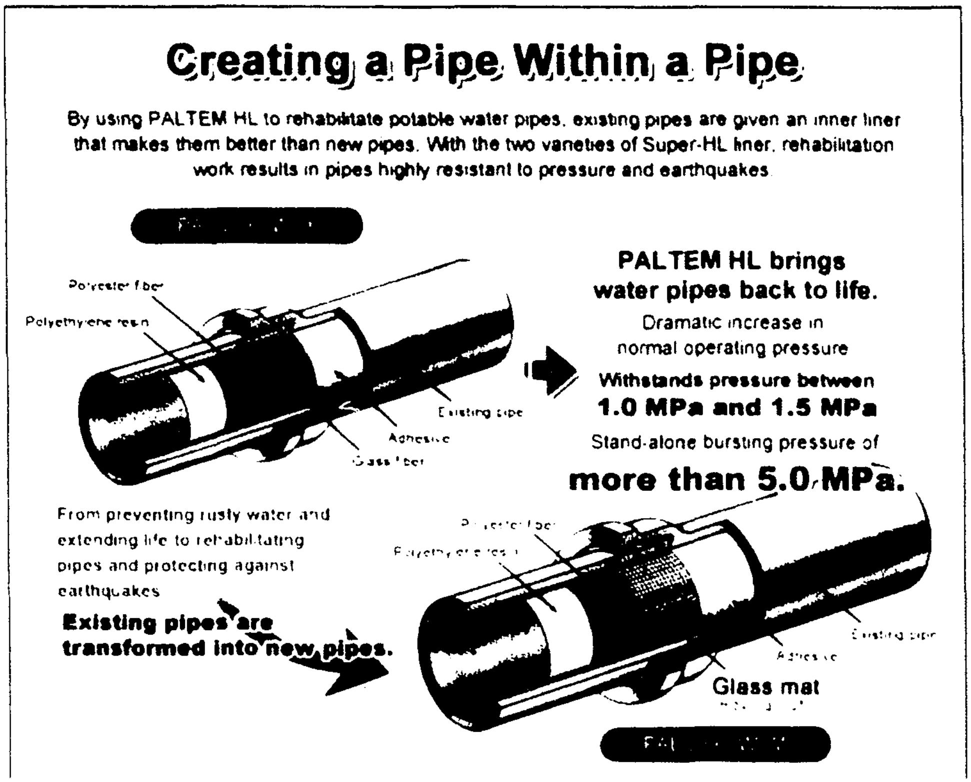


Figure 2-3: PALTEM HL method.

Primus Line® (**Figure 2-4**) is a trenchless technology for the rehabilitation of pressure pipelines for different media such as water, gas and oil. The process is based on a flexible high-pressure hose and a specially developed connection technique. However, Primus Line® was not specific interested in China's market then (Primus Line 2016).

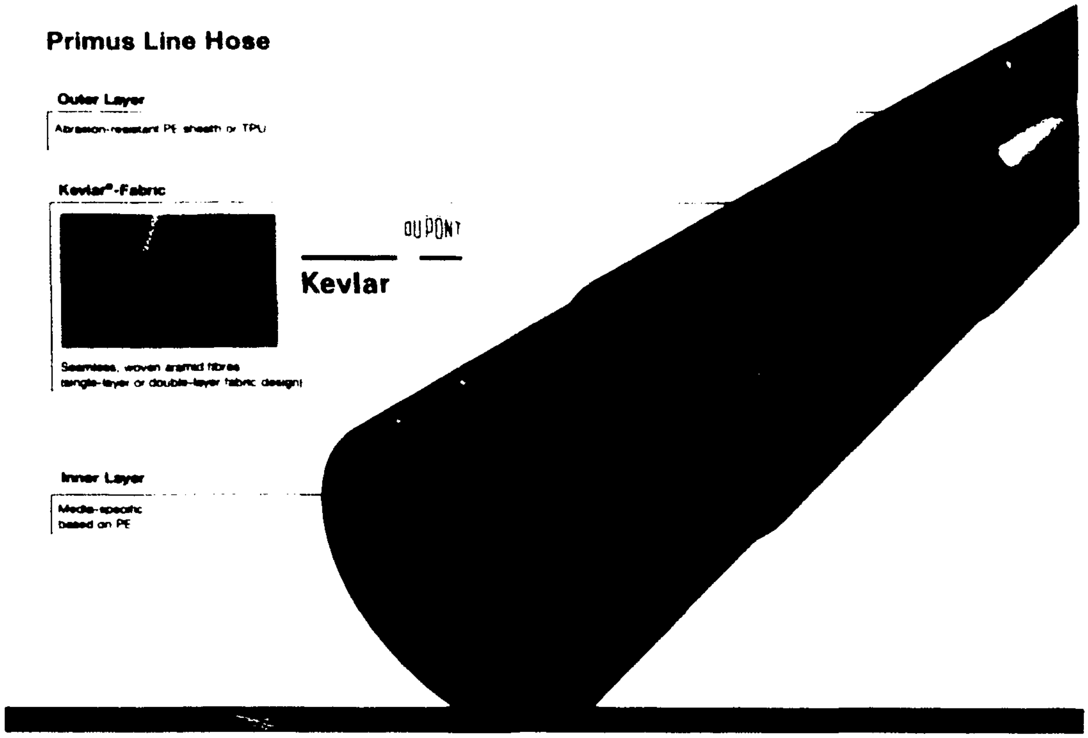


Figure 2-4: Multilayer structure of Primus Line®.

Natural gas mains 3 inches to 24 inches in diameter (up to 100 psi) can be rehabilitated with Starline® 2000 technology. With this system, pipe segments that are not easily accessible can be lined using Starline® mobile lining equipment. The actual lining procedure can be completed in approximately one hour for sections up to 700 feet, with the total process taking from 12 to 24 hours. The pressure drum can be disconnected from the line so that additional sections can be rehabilitated with a single installation system in one working day. A specially developed cleaning technique and proprietary resin adhesive allow the fabric hose to be uniformly bonded to the interior wall of the pipe, ensuring the high quality of the rehabilitation. However, Beijing Gas is the exclusive contractor of Starline® for gas application in China (Starline 2016).

2.3 Selection of the Testing Product

A flowchart depicting the selection steps for the candidates technologies are shown in **Figure 2-5**.

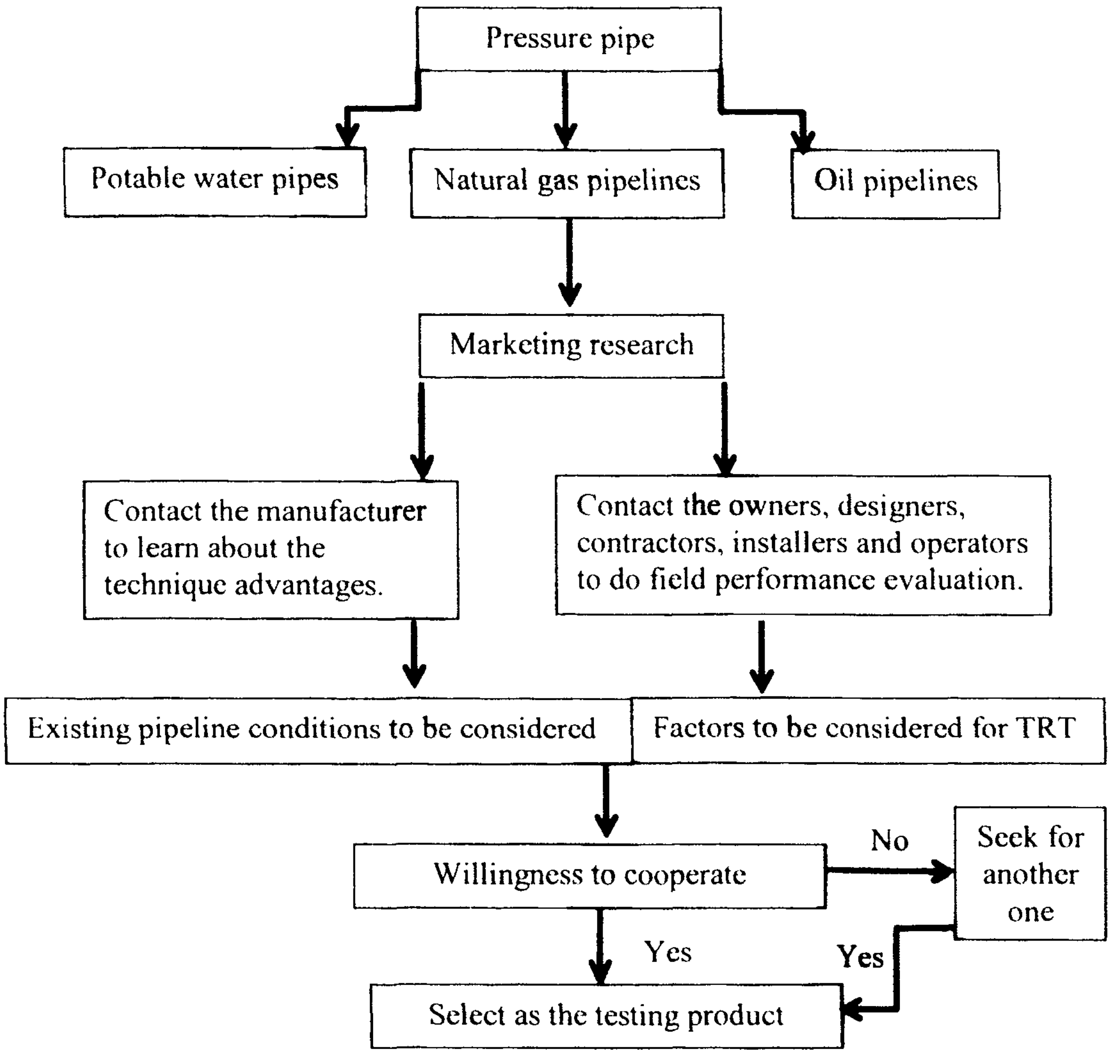


Figure 2-5: Decision support system for selection of TRT for pressure pipelines.

A fiber-reinforced composite hose for TRT with the Pipe-in liner method (PIL) is selected as the testing product (**Figure 2-6**). The Pipe-in Liner Solution can be used for rehabilitating water mains, oil pipe and gas pipe. It is comparable to the Primus Line®. Its manufacturer is Asoc, from China.

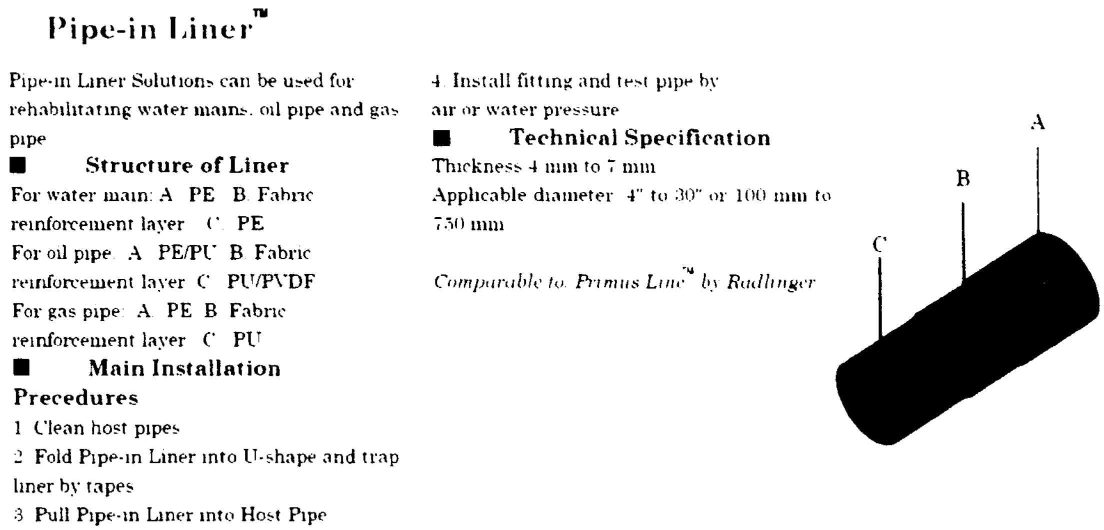


Figure 2-6: Pipe-in Liner.

For gas pipe rehabilitation, its inner design layer is smooth TPU material and the outer layer is PE cover. The middle layer is the fabric reinforcement layer. Its operating temperature range is from -60°F to 176°F (-50°C to 80°C). Its standard color is black. Other colors are available per request. Its diameter is from 3" to 12". Its standard length includes 50 ft (15.25 m), 100 ft (30.5 m), 300 ft (91.5 m), 330 ft (100 m) and 660 ft (200 m). Other lengths are available per request. The test hose and specific connector are shown in **Figure 2-7**.

Figure 2-7: Test hose and connectors from Asoe.

CHAPTER 3

MECHANICAL TESTING

3.1 Hose Information

Five three-layer sample hoses with 12" (305 mm) inside diameter and 3' (1 m) length were shipped from Shanghai to TTC by the Asoc Company. For the shipped hoses, both the inner and outer layer are smooth PU. The medium layer is the fabric reinforcement layer. The testing hose (**Figure 3-1**) information is shown in **Table 3-1**. The hoses were received and checked at the TTC South Campus Lab Facility on Friday, May 1st, 2015.

Figure 3-1: Sample hose shipped from China.

Table 3-1: Hose information.

ID		Wall thickness		Weight		Working pressure	Burst pressure
Inch	mm	Inch	mm	lbs/ft	kg/m	Psi/bar	Psi/bar
12	305+3	0.138-0.236	3.5-6	3.36	5.01	150/10	450/30

3.2 Thickness of Hose

3.2.1 Testing Standards

ASTM D1777 for Textile-thickness measurement is suitable for most fabrics, including woven fabric for airbags, carpets, pile fabrics, knitted fabrics, multilayer fabrics, and velvet fabrics. The specimen was placed on the meter base with a heavy object on it. The thickness can be measured randomly by a micrometer.

3.2.2 Sample Size

Specimens for thickness testing as described in ASTM D1777 were cut from the hose using the chainsaw and water jet cutter (**Figure 3-2**). A micrometer with the resolution of ± 0.0025 mm was used to measure the samples' thickness (**Figure 3-3**). Ten samples were cut with size 2" (50.8 mm) × 2" (50.8 mm) and a test thickness was conducted in five different positions for each sample randomly.

Figure 3-2: Procedure of sample cutting.

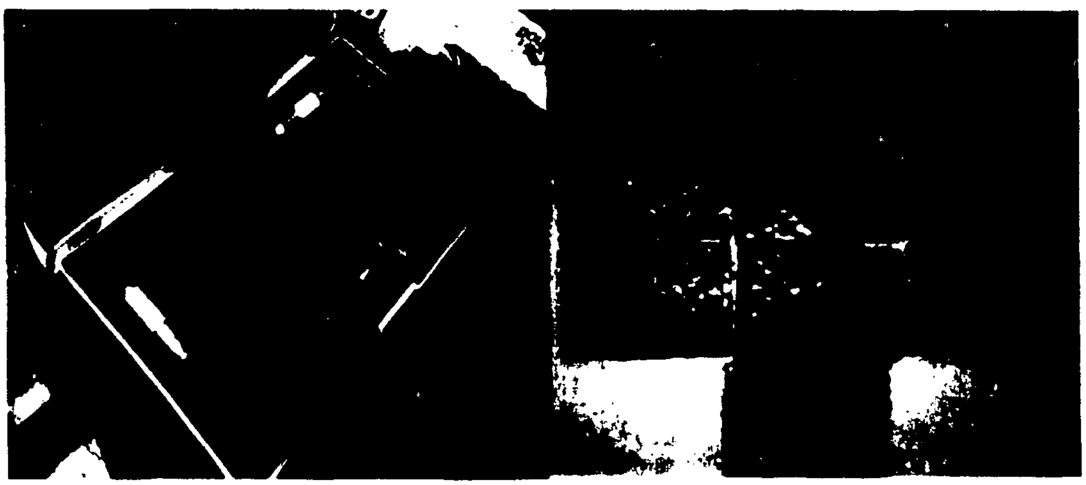


Figure 3-3: Micrometer (left) and samples (right).

3.2.3 Testing Procedure and Results

A total of 50 readings were on ten 2" × 2" (50.8 mm × 50.8 mm) samples cut from different sections of the liner specimen. The average thickness was determined to be 0.219" (5.56 mm) as shown in **Figure 3-4**.The thickness was an important parameter of the tensile and bending testing.

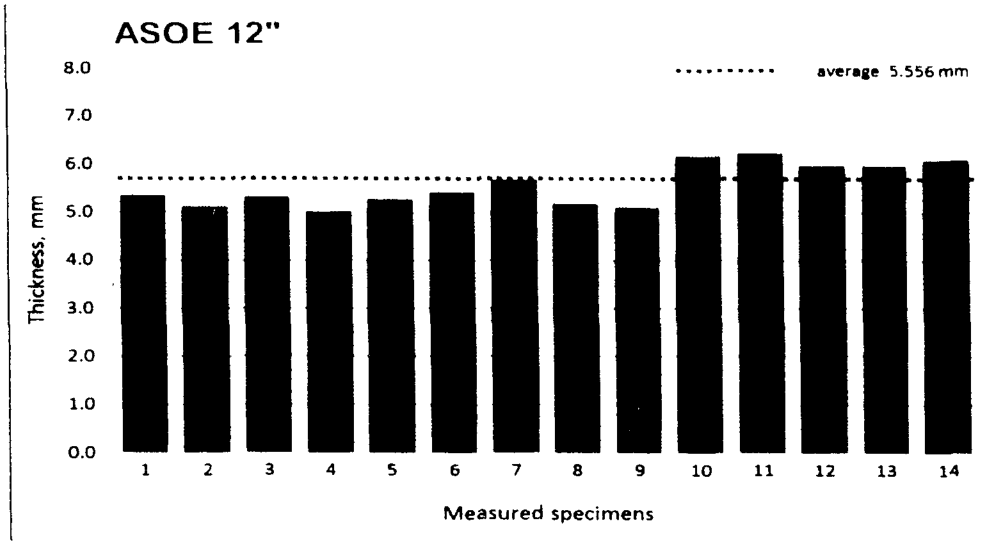


Figure 3-4: Average thickness of samples.

3.3 Surface Hardness of Hose

3.3.1 Testing Standards

This indentation test method allows for hardness measurement on a rubber specimen using a specified standard indenter. ASTM D2240 (International 2015) refers to several rubber hardness measurement scales (A, B, C, D, DO, O, OO, and M). It is used to evaluate the indentation hardness of materials such as elastomers, thermoplastic elastomers, vulcanized rubber, and plastics. The method consists of indenting the specimen using a hardened steel indenter with specific geometry and force, based on the chosen scale of measurements. The indenter tip displacement is measured for calculating the hardness of the material. A mathematical relation is used to convert the displacement data into hardness number, limited within a range of 0 to 100. Type D is one of the most commonly used scales (**Figure 3-5**).

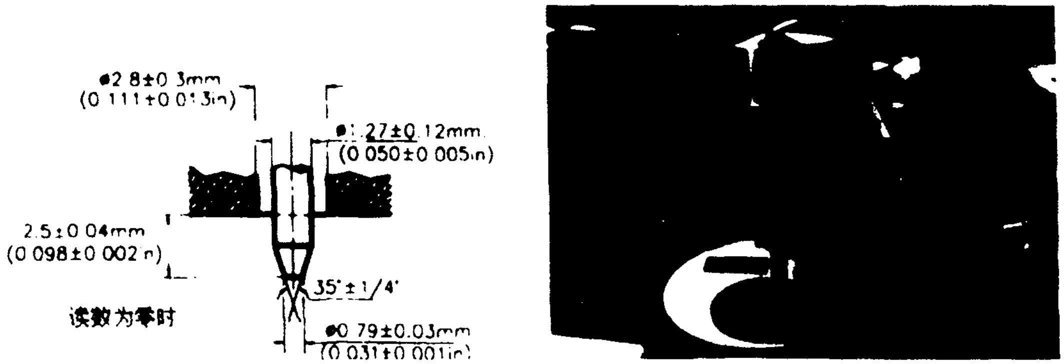


Figure 3-5: Type D head and hardness testing machine.

3.3.2 Testing Procedure and Results

According to ASTM D2440, Shore Type D Durometer was used to determine the hardness of the liner samples. The Shore D hardness scale utilizes a weight of 10 lb (4,536 g). The tip diameter and angle are 0.004" (0.1 mm) and 35°, respectively. Samples (2" × 2") ($50.8\ mm \times 50.8\ mm$) were cut from the Asoe hose by a water jet machine. A total of 100 readings were read on the inner and outer surfaces of the liner specimens (**Figure 3-6**).

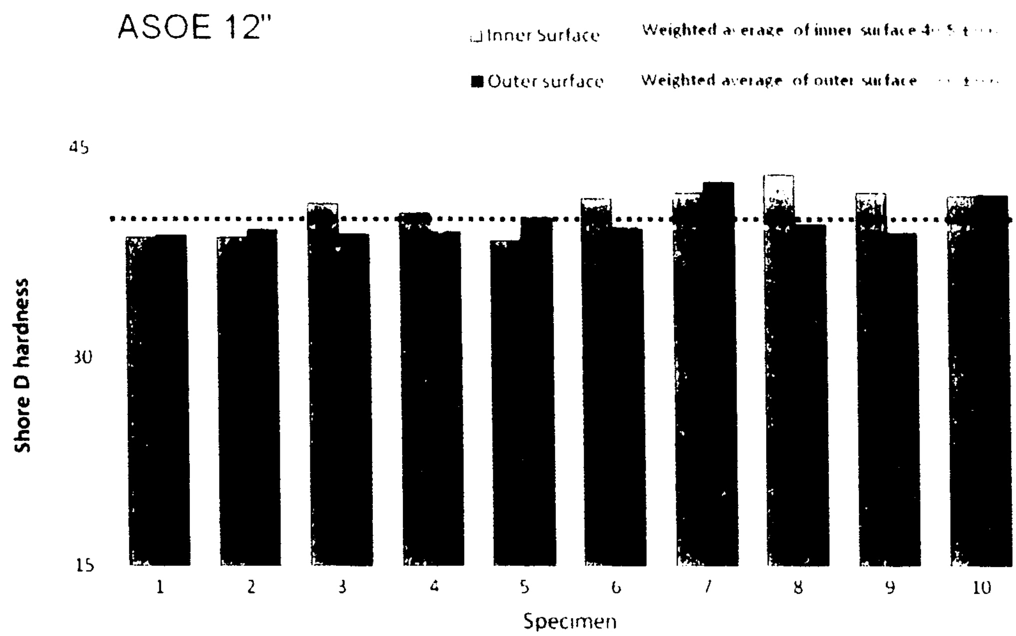


Figure 3-6: Shore D hardness readings from the inner and outer surfaces.

3.4 Tensile Testing

3.4.1 Testing Standards

Tensile strength testing is one of the most common physical property testing methods. ASTM D638 (International 2014) is a tensile testing standard designed to determine the tensile properties of unreinforced and reinforced plastics in the form of standard dumbbell (dog-bone) shaped test specimens. ASTM D638 can be adapted to this testing.

3.4.2 Sample Size

As the thickness is less than 0.3" (7.62 mm), the tensile specimen's shape should select Type I of ASTM D638. The specific specimen dimension of tensile testing is shown in **Figure 3-7** as ASTM D638 described. Dog-bone dimensions are similarly chosen to reflect the in situ applied thickness and an average thickness of 0.185" (6.2 mm) is selected. The length of the narrow section of the sample is also kept at 2.25" (7.5 mm) and the remaining dimensions follow the Type I specimen in ASTM D638. The sides of the specimens were smoothed using sharp scissors. A total of fifteen specimens were prepared and tested separately along circumferential, longitudinal and 45 degree directions. Marked tensile specimens and test setup are shown in **Figure 3-8**.

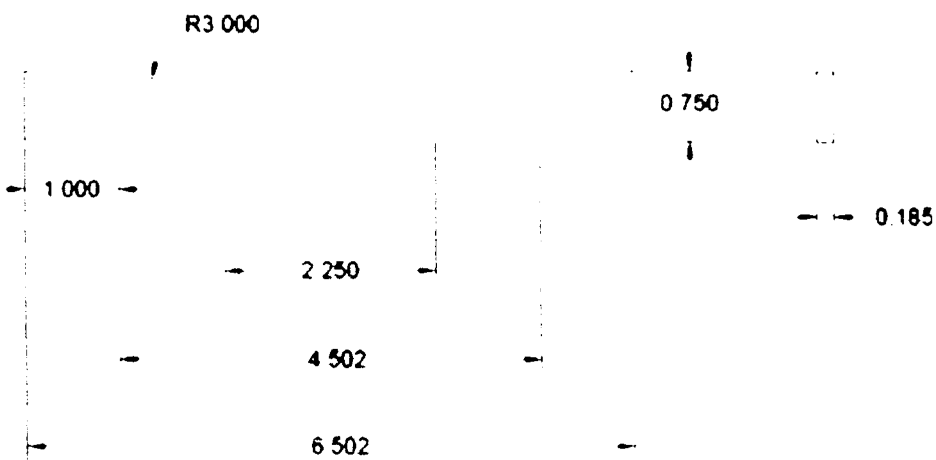


Figure 3-7: ASTM D638 Type I (Unit: in).

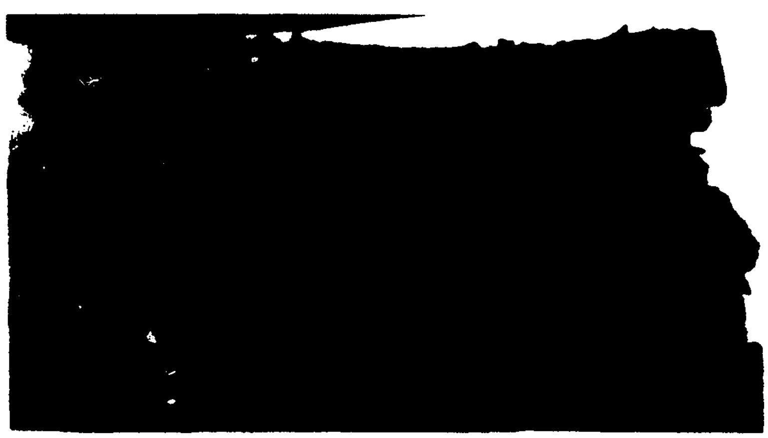


Figure 3-8: Specimens prepared for tensile testing.

3.4.3 Testing Procedure and Results

The suggested loading rates of 5 to 1.97"/minute (50 mm/minute) in the ASTM D638 (1998) Standard are intended for thin plastic sheets. Based on the material properties, the hose specimens have limited deformation range, and failure occurs in less than 0.04" (1 mm) of deformation. The use of 0.2 inch/minute (5 mm/minute) loading rate would imply that the testing would be completed in 12 seconds, which falls short of the minimum test duration recommendation of 30 seconds (Ozturk and Tannant 2010). The testing should ideally be completed in 3 minutes. Therefore, the loading rate should be flexible in such a way that failure is achieved within the recommended time limit, whether the rigid or yielding hose are tested (**Figure 3-9**).

Figure 3-9: Tensile testing in a 45 degree direction.

The tensile testing results are presented in **Figure 3-10** and in **Table 3-2**. The average tensile stress was around 583 psi (4 MPa), 3,680 psi (25 MPa) and 4,623 psi (32 MPa). They are automatically given and inputted into the PC side by ADMET eXperT-500 lbs Universal Testing Machine. The average tensile modulus was calculated as 9,750 psi (67 MPa), 25,922 psi (179 MPa) and 68,175 psi (470 MPa), respectively, in a 45 Degree Direction, Circumferential Direction (CD) and Longitudinal Direction (LD).

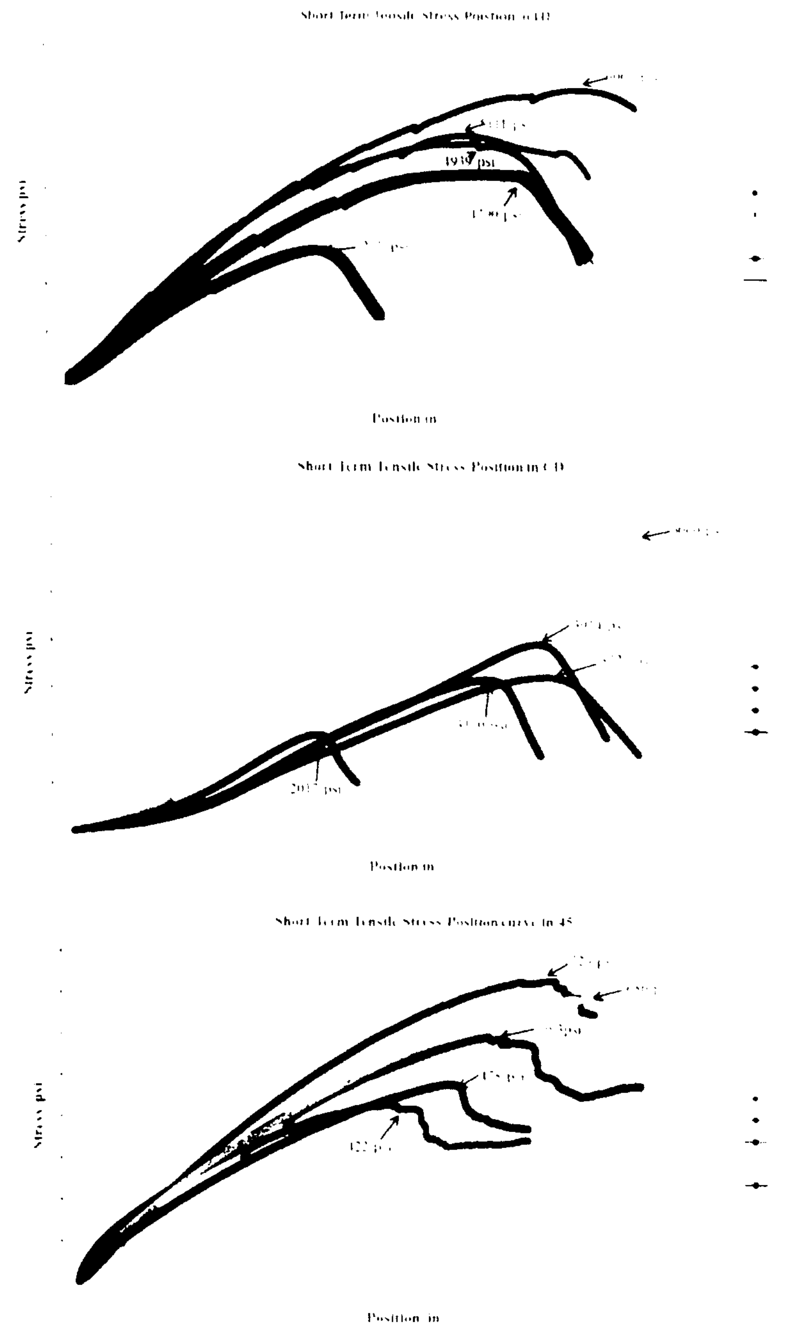


Figure 3-10: Stress – position curves of tensile testing of specimens in 45 degree, CD and LD.

Table 3-2: Tensile testing results.

Direction	Sample ID	Area (in^2)	Max load (lb)	Max stress (psi)	Strain (in)	Tensile modulus (psi)
45 Degree	1	0.1276	54.66	428	0.0182	16,597
	2	0.1279	93.25	729	0.075	4,882
	3	0.1236	73.32	593	0.0337	11,407
	4	0.1243	85.24	686	0.0538	6,207
	5	0.1255	59.98	478	0.0342	9,671
	Average		73.3	583	0.0430	**9,750**
	STDEV		16.3	130	0.0196	4,630
Circumferential Direction	1	0.1038	629.04	6,060	0.1987	40,812
	2	0.0961	193.81	2,017	0.1113	22,445
	3	0.1573	507.31	3,225	0.2795	13,112
	4	0.1051	411.35	3,914	0.2316	29,674
	5	0.0946	299.89	3,170	0.1922	23,568
	Average		408	3,680	0.2027	25,922
	STDEV		171	1,496	0.0557	**10,200**
Longitudinal Direction	1	0.1031	509.24	4,939	0.0517	77,519
	2	0.1084	293.83	2,711	0.0448	62,178
	3	0.1133	486.09	4,290	0.0505	62,177
	4	0.1028	525.41	5,111	0.0388	71,393
	5	0.0988	599.27	6,065	0.0536	76,952
	Average		482.77	4,623	0.0479	**68,175**
	STDEV		102	1,112	0.0054	6,311

3.4.4 Tensile Stress along LD

Hoop stress is the main factor to be considered for the composite hose. Combining the short-term tensile testing results in different directions and PIL construction characteristics, we would like to discuss the following situations when tensile strength occurs along the longitudinal direction.

3.4.4.1 *PIL installation method*

Composite hose repair is a kind of Pipe in Linear trenchless repair method. This process uses the hose that has been folded into a "U" shape, then pulled into the existing pipe. Using air or water pressure, the liner is reshaped to meet the existing pipe. Tensile force along the longitudinal direction will happen every time during production, storage and transportation and PIL installation (**Figure 3-11**).

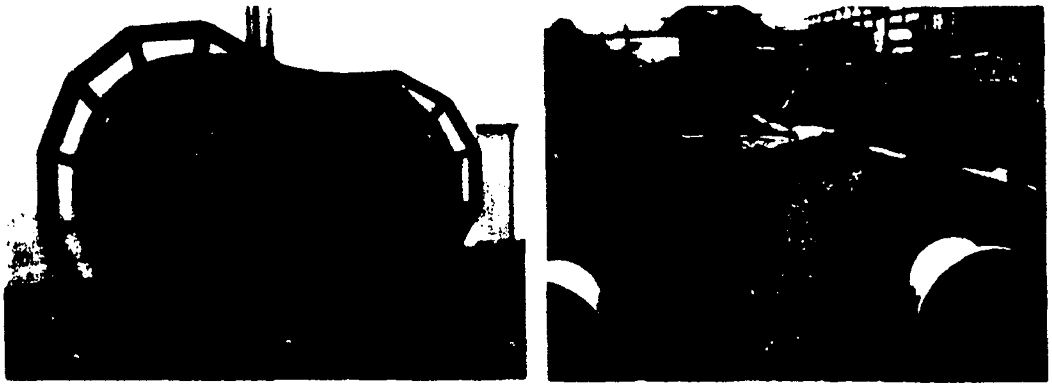


Figure 3-11: Tensile and bending in longitudinal direction.

3.4.4.2 *Out of service and contacting method*

The hose rehabilitation is a semi-class rehabilitation without any adhesive between the main pipes. It entirely relies on the special joints and internal pressure to squeeze the hose to conform tightly to the host pipe. When the new repaired pipe is out of service, the fatigue deformation and tensile strength will occur along the longitudinal direction (**Figure 3-12**).

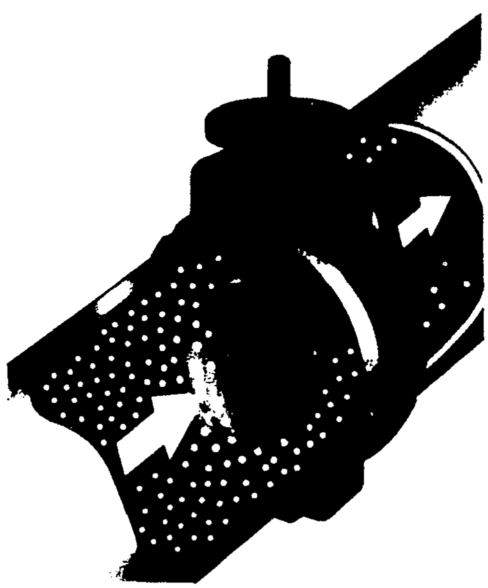


Figure 3-12: Tensile strength along the longitudinal direction.

3.4.4.3 *Hose structure*

The composite hose is a three-layer structure. The intermediate layer is for reinforcement, and its weaving direction is along the longitudinal direction. The testing results of longitudinal strength are strongest (**Table 3-2**). This design is consistent with its principle force.

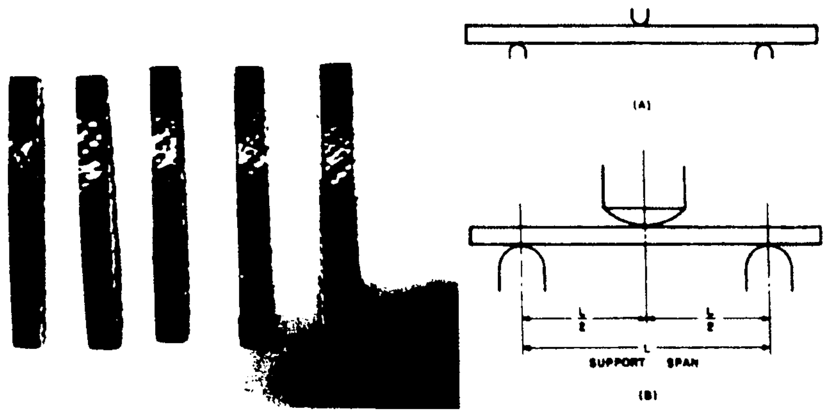
3.5 Bending Test

3.5.1 Testing Standards

Bending strength testing has been one of the most common physical property testing methods. ASTM has a bending test standard designed to determine the bending properties of unreinforced and reinforced plastics in the form of standard rectangular sheet shaped test specimens. ASTM D790 (International. 2015) can be adapted to this testing.

3.5.2 Sample Size

According to ASTM D790, where the hose's thickness is less than 0.3" (7.62 mm), five bending specimens were prepared along LD, the specific specimen dimension of the bending test is similarly chosen to reflect the in situ applied thickness and an average thickness of 0.185" (6.2 mm), the rectangular with 5" (127 mm) ×0.5" (12.7 mm) (**Figure 3-13 right**). A bar of rectangular cross section rests on two supports and is loaded by means of a loading nose midway between the supports (**Figure 3-13 left**). A support span-to-depth ratio of 10:1 is used for certain laminated materials. It is set up as 3" (76.2 mm) for this test. The specimen is deflected until rupture occurs in the outer surface of the test specimen or until a maximum strain of 5% is reached, whichever occurs first. The procedure employs a strain rate of 0.10 mm/mm*min (0.01 in/in*min).



Note: (A) minimum radius = 3.2 mm $\left(\frac{1}{8}\text{in.}\right)$. (B) maximum radius support 1.6 times specimen depth; maximum radius loading nose = 4 times specimen depth.

Figure 3-13: Bending test specimens (right) and allowable range of loading nose and support radii (left).

3.5.3 Testing Procedure and Results

The size and information of the specimen was inputted into the PC side by ADMET eXperT-500 lbs Universal Testing Machine (**Figure 3-14**). The load was applied from 0.1 lb at 1 lb/second loading rate. It automatically unloaded at the end of deformation. The testing should ideally be completed in 3 minutes.

Figure 3-14: Flexural testing.

The bending test results are presented in **Table 3-3**. The area values (Line 2 in **Table 3-3**) were automatically calculated by the software when the max load was reached. The 3rd test sample is negative (rounding). The ratio of the measured bending stress and strain is Young's flexural modulus. The average flexural modulus was 3,640 psi (25 MPa) and flexure strength was 578 psi (4 MPa).

Table 3-3: Original bending data collected and calculated by ADMET Machine.

Item (unit)	Sample1	Sample 2	Sample 3	Sample 4	Sample 5
Area (in^2)	0.0039	0.005	0.0043	0.0043	0.0044
Span (in)	3	3	3	3	3
Width (in)	0.5	0.536	0.51	0.493	0.48
Depth (in)	0.188	0.205	0.195	0.199	0.204
Peak Load (lb)	2.54	2.44	2.58	2.37	2.65
Peak Bending Stress (psi)	651	488	600	551	602
Flexural Modulus (psi)	5,008	3,997	N/A	4,627	4,583
Average Flexural Modulus (psi)			4,554		

CHAPTER 4

LONG-TERM CREEP BEHAVIOR TESTS

4.1 Long-term Experiments Preparation

The ASTM D2990 (International. 2009) tests were performed to evaluate the long-term creep behavior of specimens prepared following the ASTM D638 and ASTM D790 standards. A programmable air condition unit and a humidifier were utilized to ensure the following environmental requirement, shown in **Table 4-1**.

The strain over time and the creep modulus were obtained after 1,000 hours of testing. Long-term bending and tensile Young's Modulus were obtained. Long-term bending Young's Modulus was compared with short-term testing to predict the lifetime of the hose. According to ASTM D638 and ASTM D790 standards, it is the same as the short-term sample preparation process.

Table 4-1: Environmental requirement and testing duration.

Requirement item	Temperature	Humidity	Testing duration
Specific value	73 ± 4°F (23 ± 2°C)	40 ± 5%	1,000 hours

4.2 Long-term Tensile Strength Test and Analysis

The ASTM D2990 long-term tensile, compressive and flexible creep testing method (The left in **Figure 4-1**) designs and manufactures a long-term tensile testing instrument, taking advantage of a steel arm and hanging weights, applying a long-term load for the tensile sample fixed by two clips. The applied load and tensile strain are recorded by the strain gage. It is connected to the PC and records all real-time data. The ratio of the stress and the strain gauge meter is tensile strength. In order to get a successful test, a 15 days' continuous holding test for the 1,000 hours long-term tensile grip was carried out from June 8 to June 23 (The right in **Figure 4-1**).

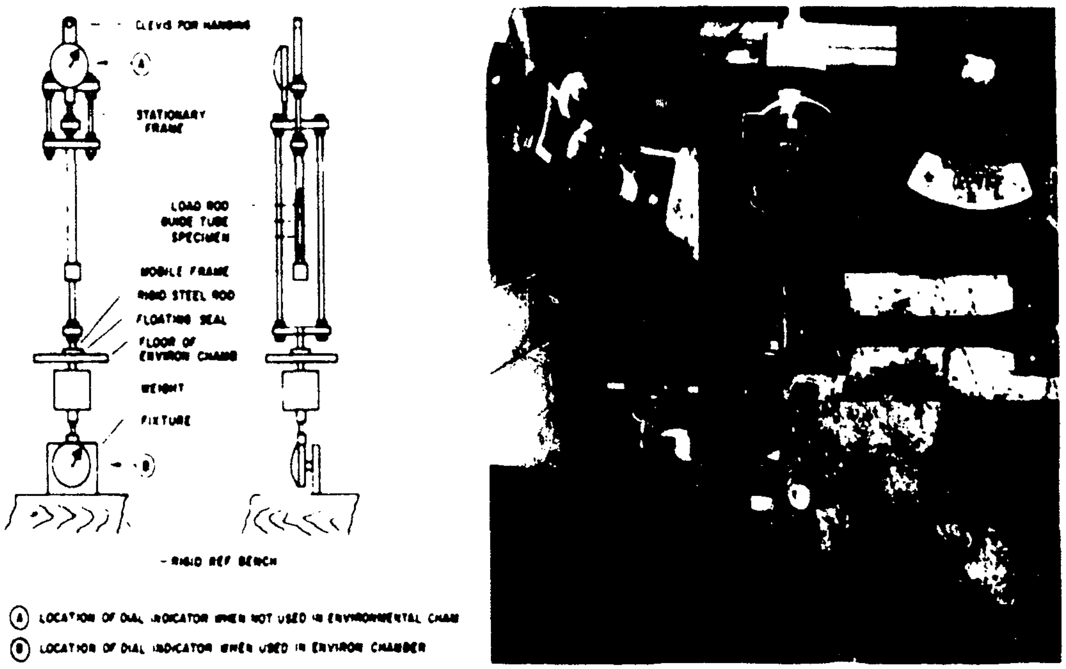


Figure 4-1: Long-term tensile creep testing procedures and a 15 day continuous holding test.

A constant temperature and humidity chamber was built at the south campus lab (**Figure 4-2**). It was equipped with a thermometer, hygrometer and voice facilities.

Figure 4-2: Environmental chamber with constant temperature and humidity.

Long-term tensile testing started on September 15, 2015 (**Figure 4-3**). It is still ongoing to make sure more than 1,000 hours continuous loads on testing samples are applied. Three different test loads were applied and each load was applied on three samples.

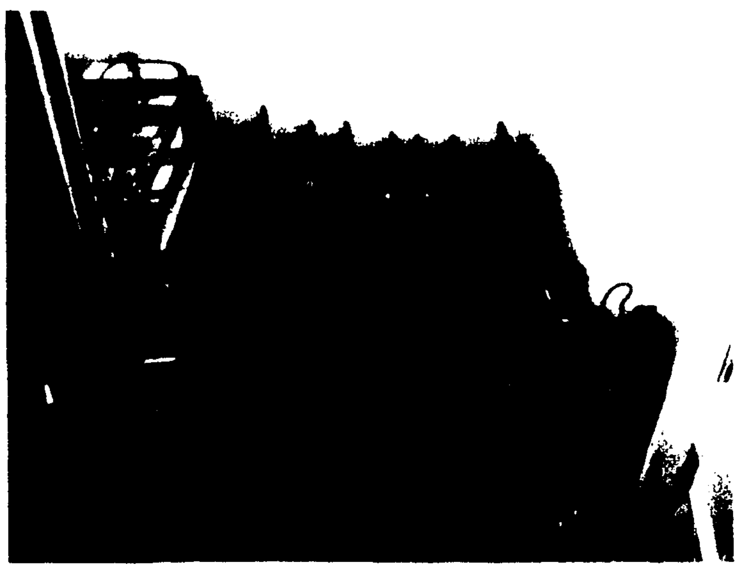


Figure 4-3: Tensile specimens in the environmental chamber.

According to ASTM D638 standard, the specimen size and preparation process were the same as the short-term tensile testing. We used the high-strength thin string to hang the homemade weights on the rear of the steel arm. The force diagram of long-term tensile testing is shown in **Figure 4-4**.

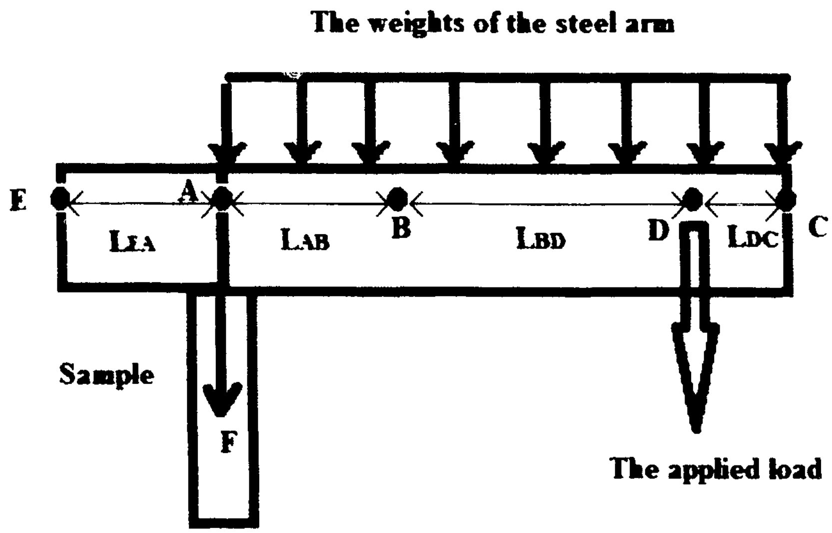


Figure 4-4: Force diagram of long-term tensile testing.

The calculated applied tensile stress load may be calculated from **Eq. 4-1** to **Eq. 4-7**. The physical map of the long-term tensile creep testing is in **Figure 4-5**.

$$q = \rho \times \frac{12"}{1ft} \qquad \textbf{Eq. 4-1}$$

$$M_A = F \times \left(L_{AB} \times \frac{1ft}{12"}\right) + \frac{1}{2}(L_{AB} \times \frac{1ft}{12"}) \times q \qquad \textbf{Eq. 4-2}$$

$$M_D = W \times L_{AB} \times \frac{1ft}{12"} \qquad \textbf{Eq. 4-3}$$

$$M_C = \frac{1}{2}(L_{BC} \times \frac{1ft}{12"})^2 \times q \qquad \textbf{Eq. 4-4}$$

$$\sum M_B = 0 = M_D + M_C - M_A \qquad \textbf{Eq. 4-5}$$

$$F = \frac{\left[W \times L_{BD} \times \frac{1ft}{12"} + \frac{1}{2} \times (L_{BC} \times \frac{1ft}{12"})^2 \times q - \frac{1}{2} \times (L_{AB} \times \frac{1ft}{12"})^2 \times q\right]}{L_{AB} \times \frac{1ft}{12"}} \quad \textbf{Eq. 4-6}$$

$$\sigma = \frac{F}{A} \quad \textbf{Eq. 4-7}$$

where:

ρ = density per unit length, $\frac{\text{lb}}{\text{in}}$,

q = density per unit length, $\frac{\text{lb}}{\text{ft}}$,

F = calculated load for the sample, lb,

L_{AB} = length of AB section in **Figure 4-4**, in,

L_{BC} = length of BC section in **Figure 4-4**, in,

L_{BD} = length of BD section in **Figure 4-4**, in,

W = weight of the applied load, lb,

M_A = moment at point A in **Figure 4-4**, $lb \times ft$,

M_B = moment at point B in **Figure 4-4**, $lb \times ft$,

M_C = moment at point C in **Figure 4-4**, $lb \times ft$,

M_D = moment at point D in **Figure 4-4**, $lb \times ft$,

σ = calculated tensile stress, psi,and

A = cross area of tensile sample.

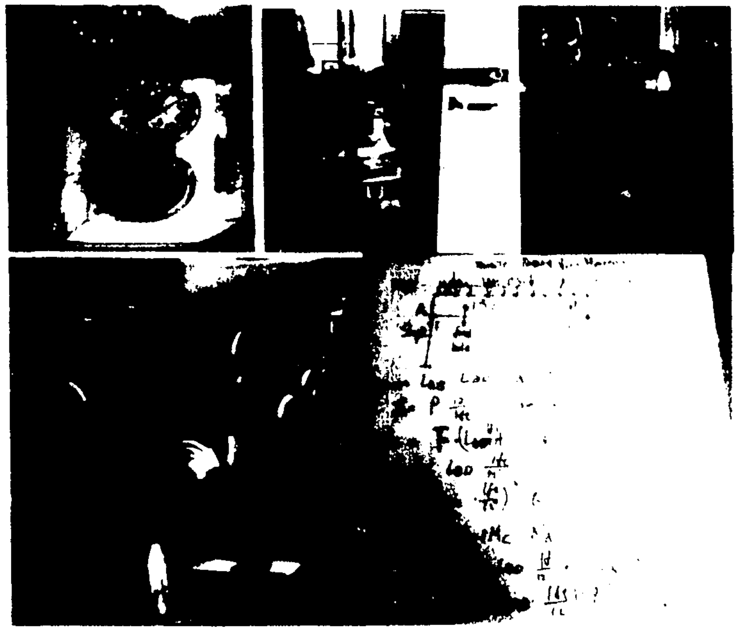


Figure 4-5: Physical map of long-term tensile creep testing.

Based on the sample sizes in **Table 4-2** and the parameters in **Table 4-3**, the tensile stress were calculated by **Eq. 4-1** and listed in the very left column of **Table 4-3**. The segment length in **Table 4-3** respectively corresponds to the arm conversion formulas manuscript in **Figure 4-4**, where EA is the corresponding arm length to the left of point A, and is used to calculate the density ρ (lb / in) of the steel arm. Other parameters are described in **Table 4-3**.

Table 4-2: Long-term tensile specimen size.

Unit: Inch	1	2	3	4	5	6	7	8	9
Sample width	0.489	0.486	0.489	0.456	0.463	0.486	0.485	0.485	0.493
	0.492	0.485	0.494	0.468	0.457	0.476	0.479	0.500	0.479
	0.501	0.488	0.496	0.481	0.464	0.473	0.501	0.486	0.499
Average	0.494	0.486	0.492	0.468	0.461	0.478	0.488	0.490	0.490
Sample thickness	0.184	0.224	0.188	0.217	0.205	0.189	0.181	0.226	0.185
	0.186	0.218	0.194	0.226	0.206	0.187	0.189	0.229	0.184
	0.181	0.220	0.191	0.217	0.207	0.193	0.190	0.225	0.190
Average	0.184	0.220	0.190	0.220	0.206	0.189	0.190	0.226	0.186

Table 4-3: Parameters in Eq. 4-1.

	L_{AB} (in)	L_{EA} (in)	L_{BD} (in)	L_{BC} (in)	Steel Arm Mass of unit length q (lb/ft)	The weight of the applied load W (lb)	Density of the steel arm ρ (lb/in)	L_{total} (in)	L_{DC} (in)	The calculated applied load (lb)	Sample cross-sectional area (in²)	Tensile load after calculating σ (psi)
NO.1	2	3.12	18.9	20.6	3.03	0.50	0.253	23.8	1.75	31.0	0.091	341.8
NO.2	2	3.13	18.8	20.8	2.98	0.50	0.250	23.9	2.00	30.9	0.107	289.2
NO.3	2	3.00	18.9	21.1	2.98	0.50	0.250	24.1	2.25	31.9	0.093	342.1
NO.4	2	3.13	19.1	21.4	2.94	0.75	0.250	24.5	2.25	34.6	0.103	335.9
NO.5	2	3.00	19.1	22.0	2.90	0.75	0.242	25.0	2.88	35.9	0.095	378.4
NO.6	2	3.30	19.0	20.5	3.03	0.75	0.253	23.8	1.50	33.0	0.091	364.6
NO.7	2	3.40	18.80	20.6	3.00	1.00	0.250	24.0	1.88	35.3	0.091	387.9
NO.8	2	3.25	18.80	20.9	3.00	1.00	0.250	24.0	2.00	35.6	0.111	321.2
NO.9	2	3.15	18.90	20.9	3.00	1.00	0.250	24.0	2.00	36.0	0.0913	394.2

A strain gauge was connected with the PC by the hexadecimal data processing box. Strain data was automatically saved, transferred and processed by the PC. Strain data was recorded every second by the PC-side in the first 100 hours. Then, the strain data was recorded every minute by the PC-side in 100-500 hours. After 500 hours, data was recorded every hour by the PC-side.

At the same time, data was recorded and pictures were taken manually and regularly. The strain data was manually recorded every two hours in the first 100 hours. After 100 hours, data was recorded every two days. Also, the strain values at critical points according to ASTM standards were recorded. These two recorded methods guaranteed the accuracy of the 1,000 hours long-term tensile strength test.

4.3 Long-term Bending Strength Testing and Analysis

According to ASTM D2990, we designed and manufactured a long-term bending test table, strain gauges and load weights (**Figure 4-6**), which was placed in the environmental chamber with constant temperature and humidity. Firstly, a 15 day continuous bending pre-test was carried out to verify the feasibility of the bending test table and strain gauges. The pre-test proved that the strain gauge can record data in real-time and the PC terminal can store and collect data automatically.

Three different loads were applied for bending Young's modulus test and each load was for three samples. According to ASTM D790 standard, the specimen's size and preparation process were consistent with short tensile testing.

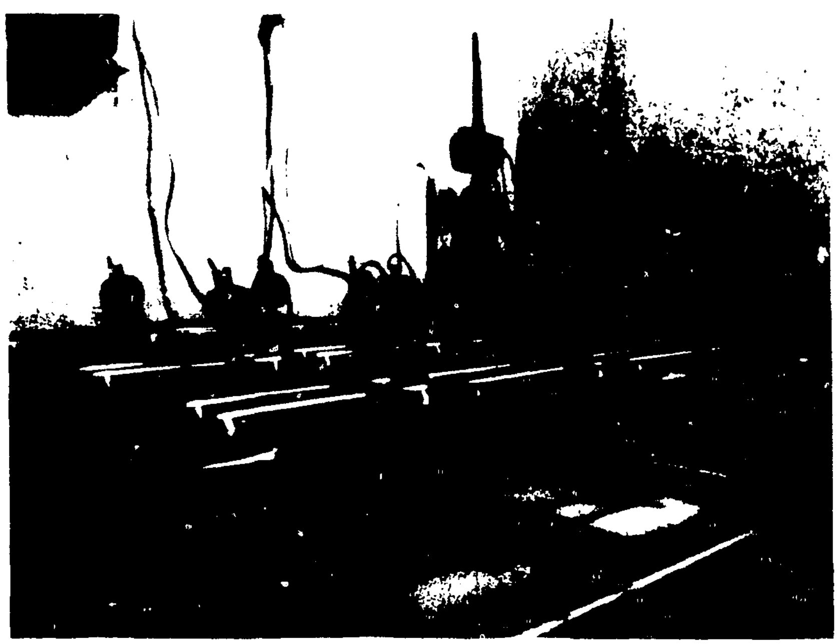


Figure 4-6: Long-term bending test tables, strain gauge and load weights.

Long-term bending testing principle and structure is the same as the short-term bending testing. The support span-to-depth ratio is still 10:1 for this laminated material. It was set up as 3" (76.2 mm) for this test. It is different that a homemade weight was hanged at the midpoint as the constant load. Strain gauge was fixed on the top of the center point. Bending deformation is recorded in real-time and collected in the PC. According to ASTM D790 standards, the long-term bending stress was calculated by **Eq. 4-8**.

$$\sigma_f = 3PL/2bd^2$$ **Eq. 4-8**

where:

σ = applied load in the center, MPa (psi),

P = applied weights in the center, N (lbf),

L= span, mm (in),

b = sample width, mm (in), and

d = sample thickness, mm (in).

Based on the sample sizes and applied weight in **Table 4-4,** the long-term bending stress were calculated and listed at the very end line in **Table 4-4**. Data storage, processing and collection for long-term bending test are the same as the methods for long-term tensile testing.

Table 4-4: Sample sizes, load and calculated stress of long-term bending samples.

Item	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9
Width (in)	0.50	0.49	0.51	0.49	0.54	0.51	0.50	0.51	0.54
	0.51	0.52	0.51	0.49	0.52	0.51	0.51	0.51	0.52
	0.51	0.52	0.50	0.51	0.51	0.51	0.51	0.52	0.51
	0.48	0.48	0.49	0.47	0.49	0.48	0.49	0.49	0.48
	0.49	0.48	0.48	0.47	0.48	0.49	0.49	0.49	0.48
	0.49	0.47	0.47	0.46	0.48	0.50	0.50	0.48	0.48
Average width (in)	0.50	0.49	0.49	0.48	0.50	0.50	0.50	0.50	0.50
Thickness (in)	0.18	0.18	0.18	0.19	0.21	0.19	0.20	0.21	0.20
	0.20	0.18	0.17	0.19	0.21	0.19	0.19	0.19	0.19
	0.19	0.19	0.19	0.19	0.21	0.19	0.20	0.19	0.19
Average thickness (in)	0.19	0.19	0.18	0.18	0.21	0.19	0.20	0.20	0.19
Loads (oz)	1	1.02	0.99	2.01	2.03	2.03	3.05	3.03	3.02
Loads (lb)	0.063	0.064	0.062	0.13	0.13	0.13	0.19	0.19	0.19
Span (in)	2	2	2	2	2	2	2	2	2
Stress (psi)	10.5	11.3	11.3	21.8	17.1	21	29	29	30

Based on hundreds of data, long-term bending Young's modulus VS Time curve figure was drawn by Excel in **Figure 4-7**. The ratio between the stress and strain is the long-term Young's modulus. One thousand hours' long-term bending Young's modulus were listed and compared with short-term Young's bending modulus in **Table 4-5**. The average value of 1,000 hours' long-term bending Young's modulus was 47% less than the short-term value. The reason may be that ASTM D790 Standard is suitable for plastic and rigid materials, but this is the hose material.

In order to establish suitable testing methods for the new composite pressure pipe, TTC and manufacturer jointly drafted the Engineering Design Guide for Rehabilitation with Pipe in Liner by Fiber Reinforced Hose in Chapter 8.

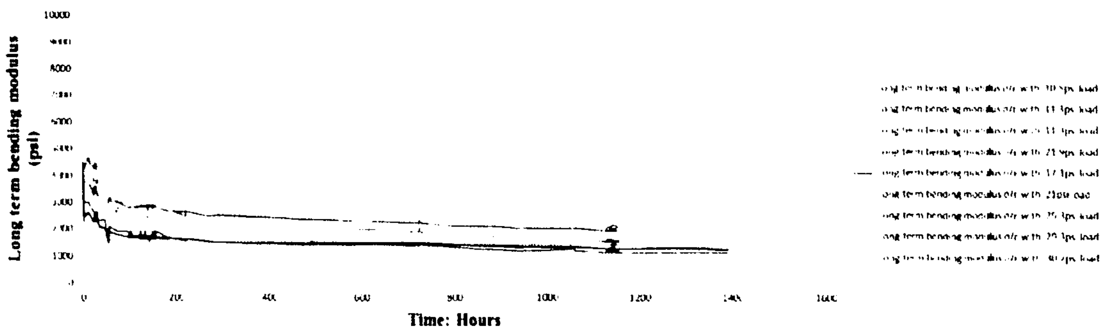


Figure 4-7: Long-term bending Young's modulus VS time.

Table 4-5: Bending Young's modulus comparison : long-term vs short-term.

Item	Short-term load applied (psi)	Short-term Young's Bending Modulus (psi)	Long-term load applied (psi)	Long-term Young's Bending Modulus(psi)
Sample one	651	5,008	30.2	3,020
Sample two	488	3,997	21	2,000
Sample three	600	N/A	29.3	2,254
Sample four	551	4,627	N/A	N/A
Sample five	602	4,583	N/A	N/A
Average	578	4,554	27	2,425
The difference between long-term and short-term%	(4554-2425) /4554*100% = 47%			

4.3.1 Prediction Curve

Based on the huge number of bending test results, a curve (**Figure 4-8**) and equation (**Eq. 4-9**) were created for prediction by Excel. It may predict Yong's bending Modulus in a hose's design life.

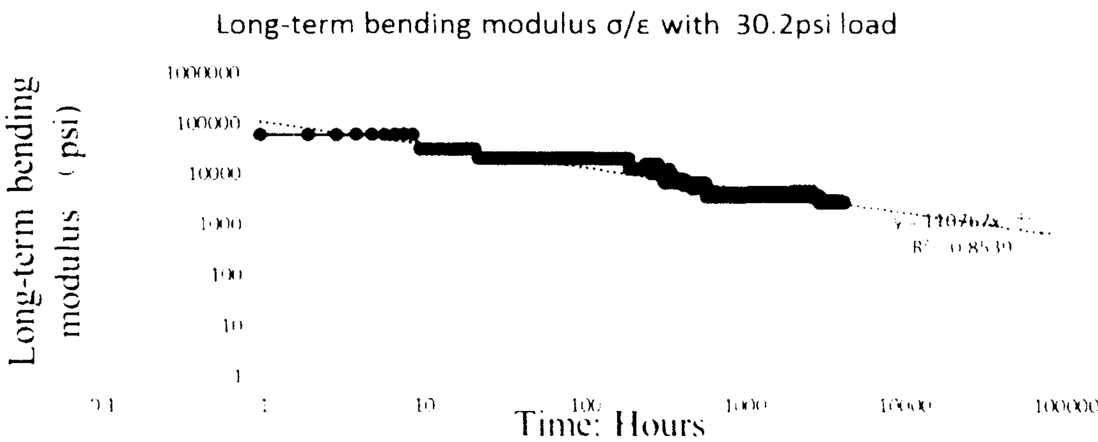


Figure 4-8: Bending Young's modulus prediction curve.

Theoretically, we can get the long-term bending modulus at a specific time by substituting the specific hour into the equation during the hose's lifetime.

$$y = 110767x^{-0.45} \qquad \textbf{Eq. 4-9}$$

where:

y = long-term bending modulus at specific time, psi,

x = specific time, hours.

4.3.2 Validation of Prediction Curve

The long-term bending testing is still ongoing in the environmental chamber. Based on the physical data, the bending Young's modulus is 2,727 psi testing at 10 AM, May 11, 2016.

The long-term bending test started at 10 AM, August 16th. The duration was calculated as 269 days (6,456 hours) **(Figure 4-9)**.

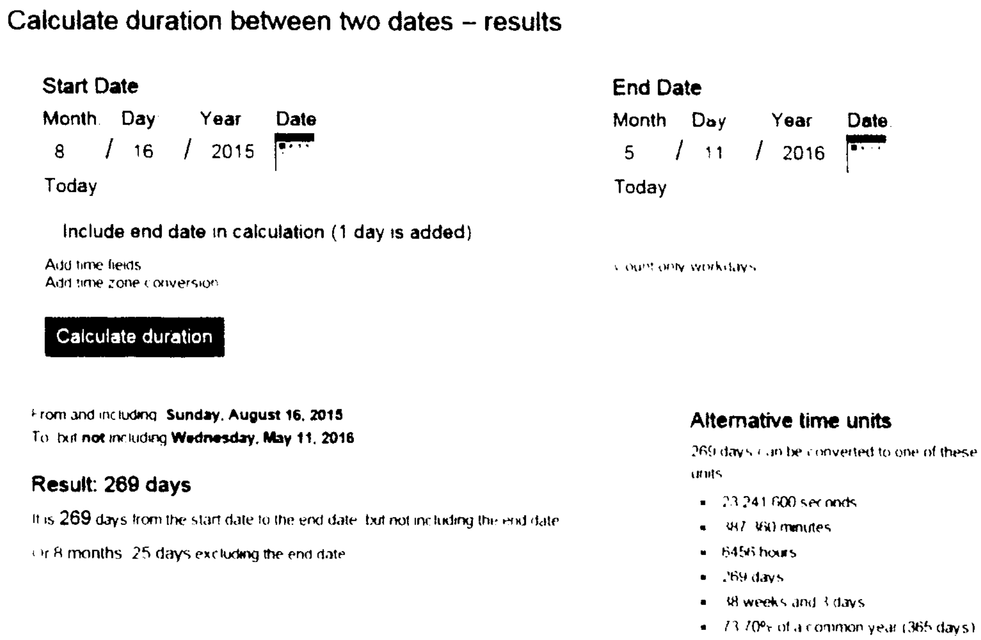


Figure 4-9: The duration calculation.

Then, 6,456 hours were substituted into **Eq. 4-9**, the calculated long-term bending Young's modulus is 2,138 psi. The physical testing value is 2,727 psi. There is a 10% difference between the actual value and prediction value (**Table 4-6**).

Table 4-6: Comparison between physical data and prediction of bending modulus.

Initial strain	The strain in 6456 hours	
0.0135	0.017	
The short-term bending Young's Modulus	The physical testing value	The prediction value
3640 psi	2727 psi	2138 psi
The different between actual value and prediction value	$\left\|\frac{1940-2138}{1940}\right\| \times 100\% = 10\%$	

4.3.3 Stages of Creep Theory

There are three creep stages (Wikipedia 2016). In the initial stage, or primary creep, the strain rate is relatively high, but slows with increasing time. This is due to work hardening. The strain rate eventually reaches a minimum and becomes near constant. This is due to the balance between work hardening and annealing (thermal softening). This stage is known as secondary or steady-state creep. This stage is the most understood. The characterized "creep strain rate" typically refers to the rate in this secondary stage. Stress dependence of this rate depends on the creep mechanism. In tertiary creep, the strain rate exponentially increases with stress because of necking phenomena (**Figure 4-10**). Fracture always occurs at the tertiary stage. Creep is a very important aspect of material science.

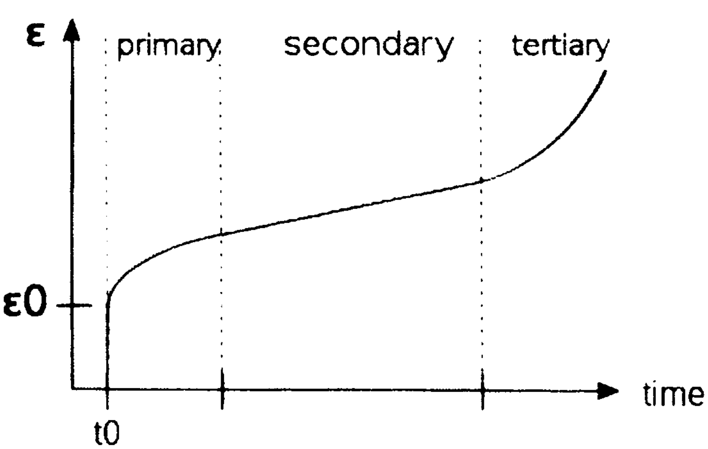


Figure 4-10: Strain as a function of time due to constant stress over an extended period for a viscoelastic material.

According to the stages of creep theory and the near constant strain rate, the prediction curve for the bending Young's Modulus is in secondary or steady-state creep. The curve and equation may be applied to predict the bending Young's Modulus during steady-state creep in the hose's lifetime design, but it is a bit overestimated.

CHAPTER 5

RESEARCH ON PERFORMANCE OF HOSE

5.1 Overview

Short-time hydraulic pressure tests, including the strength testing, flexibility testing and burst testing, were performed in the liners with the connectors of 12" diameter. It was based on the field performance test conducted by the CUG (Wuhan), China. The purpose of these tests was to verify the sealing and overall performance of the hose and the joints under the testing pressure (**Figure 5-1**). These tests can provide better insight of the pipe material performance when subjected to hydraulic pressure.

Figure 5-1: Specially designed connector for pressure pipe rehabilitation.

5.2 Testing Equipment

Short-time hydraulic pressure tests were performed in accordance with ASTM D1599 using the TTC's Elevated Pressure Application Device (EPAD) shown below in **Figure 5-2**.

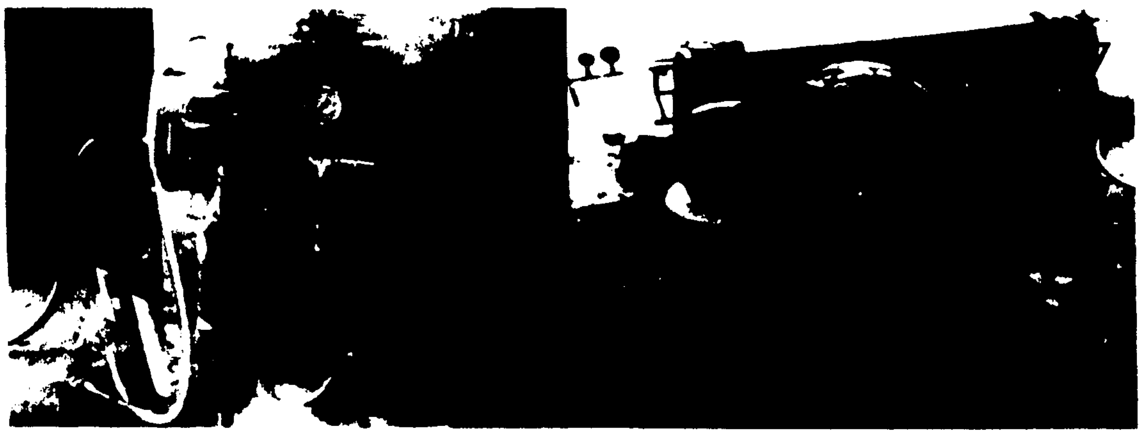


Figure 5-2: Elevated pressure application device and pressure test setup.

Water was injected into the hose with the connector in both ends by using pump with maximum pressure of 1000 psi. The gauge within the range of 2000 psi connected at both ends would show the maximum pressure value. The camera would record pressure values at real time.

5.3 Strength Testing

According to the hose manufacturer, the hose design working pressure is 87 psi (0.6 MPa). Strength testing was performed at pressure gradually increasing up to 130 psi (0.9 MPa), which is 150% of the system's design pressure. The 150% working pressure was kept for four hours. Strength testing should be stopped when leakage or burst happened.

In accordance with ASTM D1599, the strength testing of the composite hose with connectors was conducted from 11:00 to 15:00 on December 16, 2015. No leaks and cracks occurred on the hose itself and the connectors. No pressure drop occurred by gauge observations (**Figure 5-3**).

Figure 5-3: Strength testing.

5.4 Flexibility Testing

Then, gradually decrease the internal pressure to 100 psi (0.7 MPa), which is 120% of the system's design pressure. Flexibility testing was performed at 120% of the system's design pressure. The 120% working pressure was kept for twenty-four hours. Flexibility testing should be stopped when leakage or burst happens.

In accordance with ASTM D1599, flexibility testing was conducted from 15:00 on December 16 to 15:00 on December 17, 2015. A camera recorded the gauge reading. No leaks and cracks occurred on the hose or the connectors. No pressure drop occurred by gauge observations (**Figure 5-4**).

Figure 5-4: Flexibility testing.

5.5 Burst Testing

Burst testing was performed at pressures gradually increasing up to the crack or leakage happening on the surface of the hose. A camera was set up to record the whole procedure of the burst. The bursting pressure would be recorded when damage or leakage occurred. The first burst testing started at 2 PM, Dec. 18, 2015, and it lasted two hours. The internal pressure was gradually increased by a pressure pump with maximum pressure of 3000 psi (20.7 MPa).

However, the hose did not break, but it was estimated to break at 600 psi (4.2 MPa). We decided to stop the pressurizing pump. Then the video observation was checked. It found that the maximum pressure maintained at 200 psi (1.4 MPa) with no boosting trend.

The second burst testing started at 9 AM, Jan 15, 2016. The red connector collapsed from the hose at the pressure of 235 psi (1.6 MPa). The connecter was worn after the second burst testing. The inner diameter of the connector was changed from 12.125 " to 12.3125" with an expansion of 1.5% (**Figure 5-5**).

Figure 5-5: Second burst testing.

We contacted the hose manufacturer Asoe to check for the history testing data. There was a very good testing chamber, pressure equipment and electronic recording instruments in Asoe. According to the Chinese national standard GB/T 5563: Rubber and plastics hoses and assemblies, Hydrostatic testing, the Asoe carried out the burst testing on June, 2014. The burst testing result was 435 *psi* (3 *MPa*) for the same hose with a 12" (300 mm) diameter (**Figure 5-6**). Specific test parameters and results are shown in **Table 5-1**.

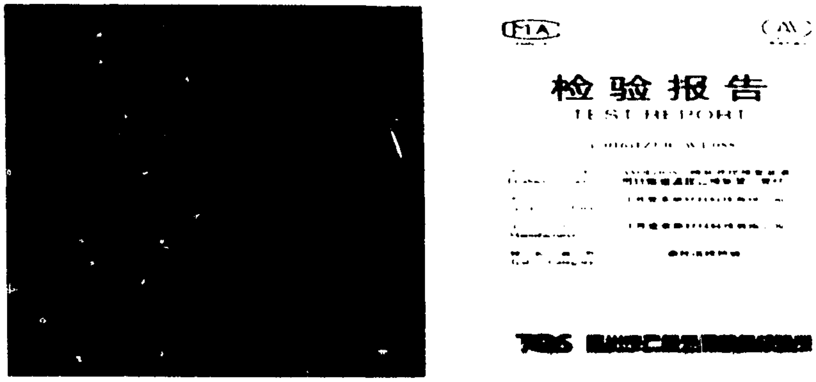


Figure 5-6: Burst testing results from the manufacturer.

Table 5-1: Burst testing table.

Burst sample	300 mm（12"）	Time: June 17th, 2014		
Burst pressure (MPa)	Actually measured circumference (mm)	Expansion (%)	The actual measuring length (mm)	Elongation (%)
0.10	970	N/A	1039	N/A
	968	N/A		
	969	N/A		
1.00	1050	8.25%	1045	0.58%
	1048	8.26%		
	1051	8.46%		
Ultimately burst pressure	435 psi (3.0 MPa)		Final expansion	Ultimate elongation
			8.3%	0.6%

5.6 Burst Testing in Manufacturer Plant

On November 2015, Dr. Iseley and Xuanchen visited the Asoe plant in Taizhou, Jiangsu, China. We discussed and helped them to improve the hose connector's design. It solved the problem of too less over-flow area.

Also, we witnessed and recorded the burst testing for a new composite pressure hose with a 6” diameter (**Figure 5-7**). This new composite pressure hose was designed for pressure water pipeline rehabilitation. According to ASTM D1599, the burst pressure was 5.5 MPa (797.5 psi). The working pressure should be 1/3 of the burst pressure, which was 1.8 MPa (266 psi). The working pressure could meet the requirements of medium and high-pressure gas pipeline, which is 0.4 MPa-4 MPa (56 psi-560 psi).

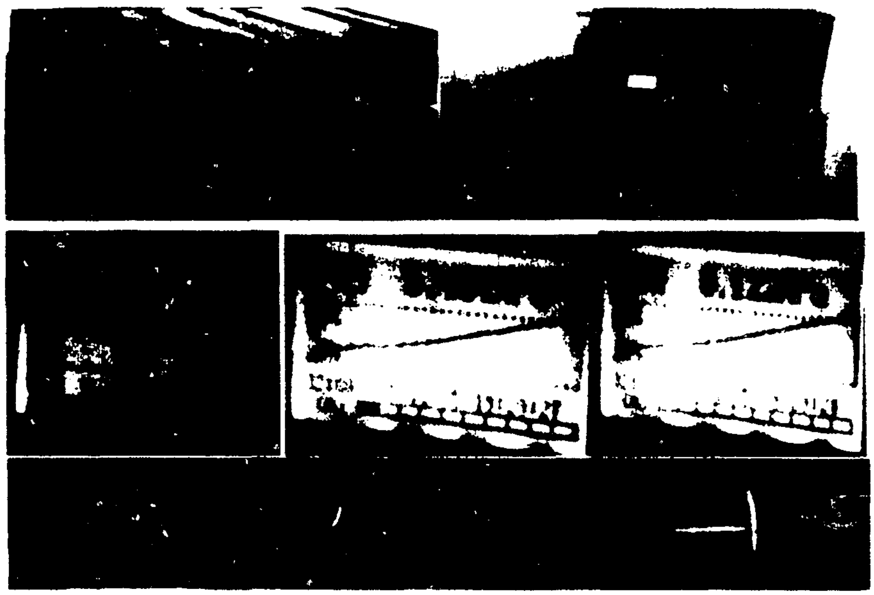


Figure 5-7: Burst testing in Asoc.

CHAPTER 6

FINITE ELEMENT ANALYSIS

6.1 Object and Purpose of FEA

The finite element analysis (FEA) is a numerical technique for finding approximate solutions to boundary value problems. The FEA model can analyze the stress and strain on each layer of the composite hose. We can better understand the structural information and function of each layer.

6.2 Material Properties and Parameters

Various material properties and parameters are needed for FEA. The ideal plastic stress-strain relationship and bilinear kinematic hardening guidelines are used for material non-linear VonMises yield criterion and associated flow rule calculation. For FEA nonlinear and large deformation calculation, accurate measurement of bilinear data of material properties is the premise for correct calculation.

Tensile mechanical properties in the longitude direction are one of the important parameters for the composite hose, which is explained in Section 3.4.4.

Short-term tensile stress-position curves was shown in **Figure 6-1**. The number marked in **Figure 6-1** is the maximum stress.

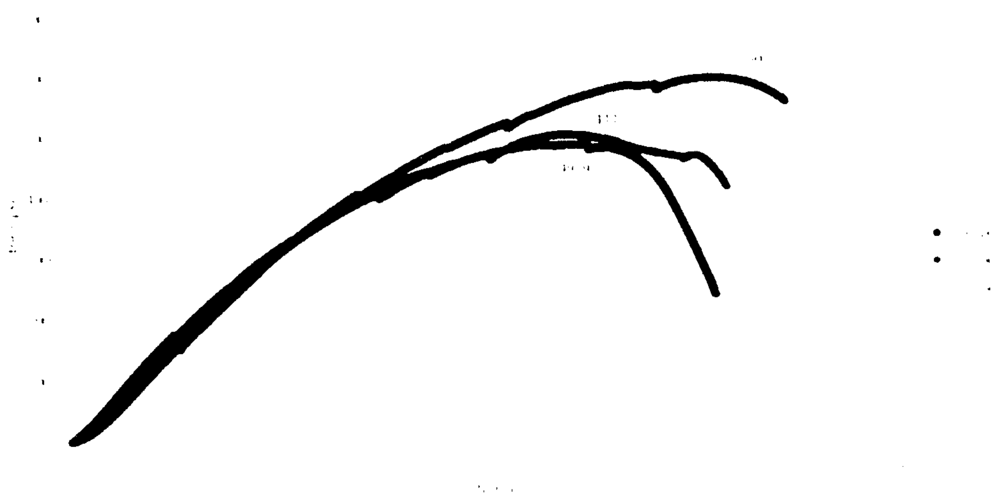


Figure 6-1: Tensile stress-position curve in LD.

Based on the specific sample size (**Table 4-1**), the long-term tensile stress is the divisor of applied load and heavy steel arm weights and the cross-sectional area of the sample. The specific long-term stress may be calculated by **Eq. 4-1**. Gauge readings are the strains. The ratio between the stress and strain is the long-term Young's modulus.

Based on hundreds of data, long-term tensile Young's modulus vs. Time curve figure was drawn by Excel in **Figure 6-2**.

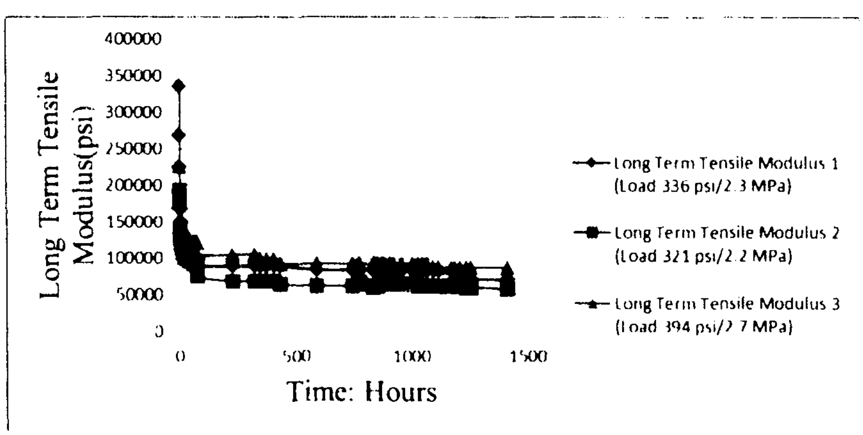


Figure 6-2: Long-term tensile Young's modulus.

One thousand hours' long-term tensile Young's modulus were listed and compared with short-term Young's tensile modulus in **Table 6-1**. The average value of 1,000 hours' long-term tensile Young's modulus was 3.5% less than the short-term value. The Young's modulus of similar common material Medium-Density PE was listed and compared. The testing was according to the ASTM specification.

Table 6-1: Tensile Young's Modulus comparison: long-term VS short-term.

Unit (psi)	Short-Term Test Applied Load	Short-Term Tensile Young's modulus	Long-Term Test Applied Load	Long-Term Tensile Young's Modulus	Medium-Density PE
	4,939	77,519	394	77,230	
	6,065	76,952	321	70,608	
	5,111	71,393	336	70,722	
Average Value	5,372	75,388	350	72,853	80,000
Difference between Long-term and short-term %	(75,388-72,583) /72,583*100% = 3.5%				

The manufacturer Asoe commissioned Taizhou Product Quality Supervision and Inspection Agency to carry out physical and mechanical tests of the hose materials (**Figure 6-3**). The test data (**Figure 6-4**) were used for mathematical equations and numerical simulation.

Figure 6-3: Testing in Taizhou Product Quality Supervision and Inspection Agency.

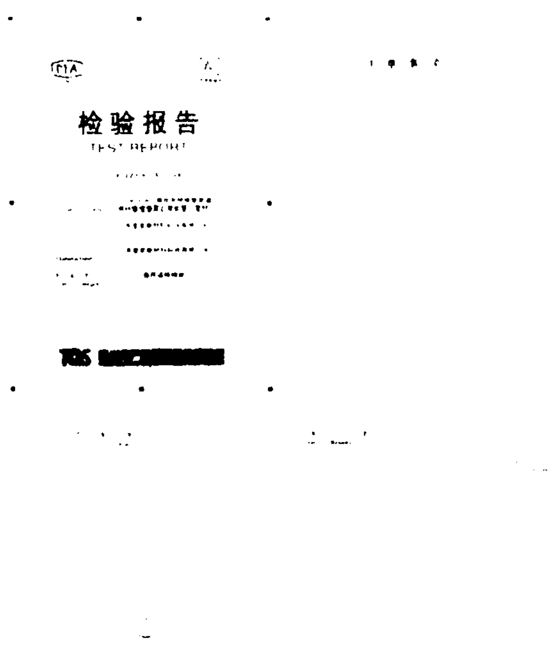


Figure 6-4: Testing reports for fiber reinforced polyethylene hose.

6.3 Finite Element Model and Test Results

The finite element model (FEM) is a numerical technique to find approximate solutions for the boundary value by the partial differential equations. It is also referred to as finite element analysis (FEA). Modeling is the key to the whole process of FEA. The reasonable model will directly affect the accuracy of the calculation results, process and time. The model established in this dissertation not only took into account the present analysis, but also considered the follow-up work, as well as quantitative calculations on similar cases. A parametric model, including the geometry, material properties, and applied load, was established. If re-modeling for each case, it will cost a lot of time. So the use of the parametric model is very important and can save time. Simply changing the value of part of the parameters can be available when re-modeling.

The model geometry, material properties, and load and other factors depended on the project and can be parameterized. The effect on the strength and deformation of the composite pipe by different parameters can be studied systematically and quantitatively. Primary and secondary factors that affect strength and deformation can be analyzed. The parameter model can lay the foundation for the design and optimization of the composite pipes.

The basic idea for modeling is to set up a mechanical model for a class of material issues firstly. Model the mechanical behavior in the working state by numerical methods and simulation.

By the comparison with the physical experimental, the "parametric" contained in models were prepared and calibrated. The variables were about the model's structure and properties. If the calculation does not match the physical experiment, the given initial value of "within the variable" needed to be adjusted until satisfied.

6.3.1 Modeling Preparation and Introduction

There are two methods to create a finite element model, direct generation and solid modeling. For nodes and elements needing special analysis, the direct generation is a simple and easy method, but it applies to a more regular shape. Solid modeling is to generate geometric entities firstly, if necessary, to control the unit and divide the parameters. Mesh nodes and unit are generated automatically by Solidworks (but sometimes not very regularly). Solid modeling method can create the model quickly and is more convenient when the model is larger and more complex. For the geometry model needed to study in this dissertation, we need to analyze the stress and strain distributions along the wall. The unit should be divided by the mapping method, so the obtained discrete units can be regular. If the unit is divided by the free method, it may be irregular in some places. There may be some bias. The stress design and analysis in this dissertation is to create a simple surface by the direct generation method firstly, then use the mapping division for the structural units to ensure the accuracy of the results.

The following points are needed to be taken into account when modeling:

(1) Take advantage of the symmetry properties of the structure to make the model as simple as possible. Using the simple modeling orders, including mirror, copy and rotate the functions to obtain complex structures modeling.

(2) Minimize the number of Boolean operations command and make the geometric structure as simple as possible.

6.3.1.1 *Simplify the model*

In order to highlight the main factors and to reduce computing time-consuming, there are these following principles:

(1) Generally, the actual ratio between the pipe diameter and the longitudinal length is large. Therefore, the hose can be considered infinitely long. Just one section needs to be analyzed.

(2) Do not consider the friction between the fibrous layer and the plastic layer.

(3) Ignore the diameter reduction caused by stretching and winding.

(4) Do not count composite pipe weight.

6.3.1.2 *Selection of unit type*

When we use the FEM to analyze the problem, it is very important to select the appropriate unit type for the calculation. SOLID45 unit is selected as the plastic deformation unit. The links unit is selected as the fiber deformation unit. The auxiliary unit is used during the modeling (only used for graphic unit and deleted when pulled out of the body's unit). The spring unit COMBNI14 is used as boundary constraints.

The characteristics of each unit are described as follows. SOILD45 unit is mainly utilized to simulate a three-dimensional solid structure. It is defined by eight nodes. Each node has three degrees of freedom (namely, UX, UY, UZ). This unit is suitable for elastic, creep, swelling, hardening stress, and large deformation analysis. It has a degraded function and can degenerate into pentahedral and tetrahedron, which is easy to generate a complex structural grid of cells.

6.3.2 Modeling

In theory, either section of a hose along the infinite length can simulate the stress state of the entire hose. In order to save calculation time, computer memory and hard disk space, a pipe section with 36 mm length is used for FEA. In this dissertation, a fiber reinforced plastic composite with a three-layer hose with 12" (304.8 mm) diameter is studied. According to the actual structure, the thickness of each layer of the composite pipe is 2 mm, 2 mm and 2 mm, from the inner to the outer layer, respectively. Plastic Unit width is divided into 36 equal portions in the circumferential direction.

6.3.2.1 *Flat unit*

Firstly, the annular surface of the hose was made. As the hose was axially symmetric along its longitudinal cross section, it was possible to take advantage of a quarter arc surface.

6.3.2.2 *Unit model and material properties*

According to the manufacturer, the hose is a three-layer structure and composed by the hot extrusion molding processing technology. The inner liner is TPU (thermoplastic polyurethane). The intermediate layer is the reinforcing fabric and the material is polyester filament fabric nets. The overcoat layer is PE (polyethylene). The hose can be flat and coiled and the structure diagram is shown in **Figure 6-5** (left).

The So1id45 unit and Links unit were selected. The length of the plastic element along the longitudinal direction was 2 mm and the total length of the stretch was 36 mm. The hose diameter was 12". Take advantage of the Extruder Command to stretch the planar element along the longitudinal. The finite element model (FEM) was drawn in **Figure 6-5** (right).

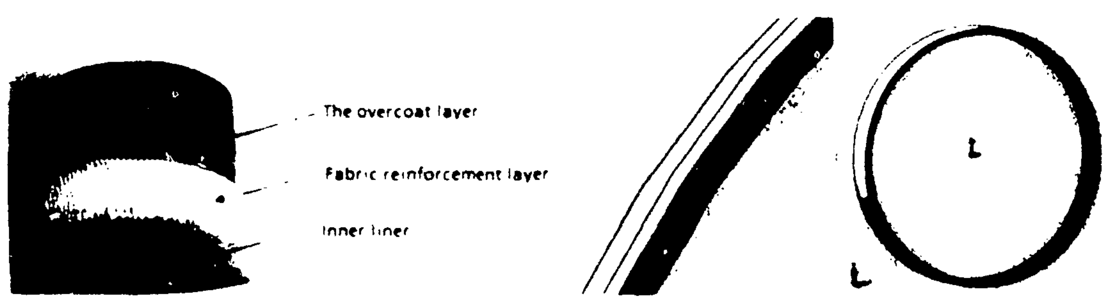


Figure 6-5: The structure and FEM of the three-layer hose.

The overall physical and mechanical properties of the three-layer hose were tested in TTC. However, the physical properties of each layer cannot be tested separately.

Material mechanical properties, including the elastic modulus, the Poisson's ratio and the thickness of each layer used in FEM simulation and Numerical Analysis Calculation (Chapter 7) were shown in **Table 6-2**. They were from the reference of materials providers so that the results may be more accurate.

Table 6-2: Elasticity properties, Poisson's ratio, and thickness of each layer.

Material	Elastic Modulus (MPa)	Poisson's ratio	Thickness (mm)
Inner layer: TPU	100	0.48	2
Middle layer: Polyester Filament	15,000	0.35	2
Outer layer: PE	1,070	0.41	2

The final simulation and calculation results were compared and analyzed with the overall physical and mechanical properties obtained by TTC. The operation of material selection and definition are shown in **Figure 6-6**. PE High Density in the Solidworks material library was chosen as the material definition for the outer layer material.

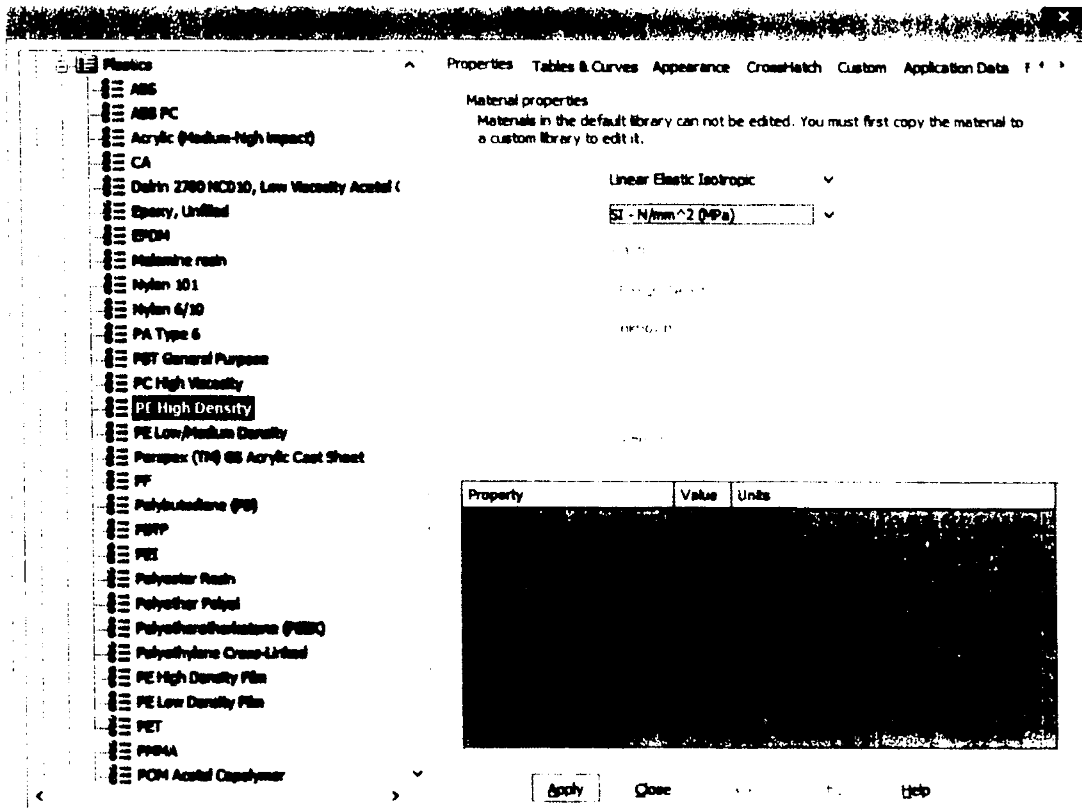


Figure 6-6: Applied material properties of outer layer material in Solidworks.

According to the manufacturer Asoe (Mortensen 2006), the definition of intermediate layer, polyester filament properties, was defined as a new material in Solidworks. The specific parameters are shown in **Figure 6-7**.

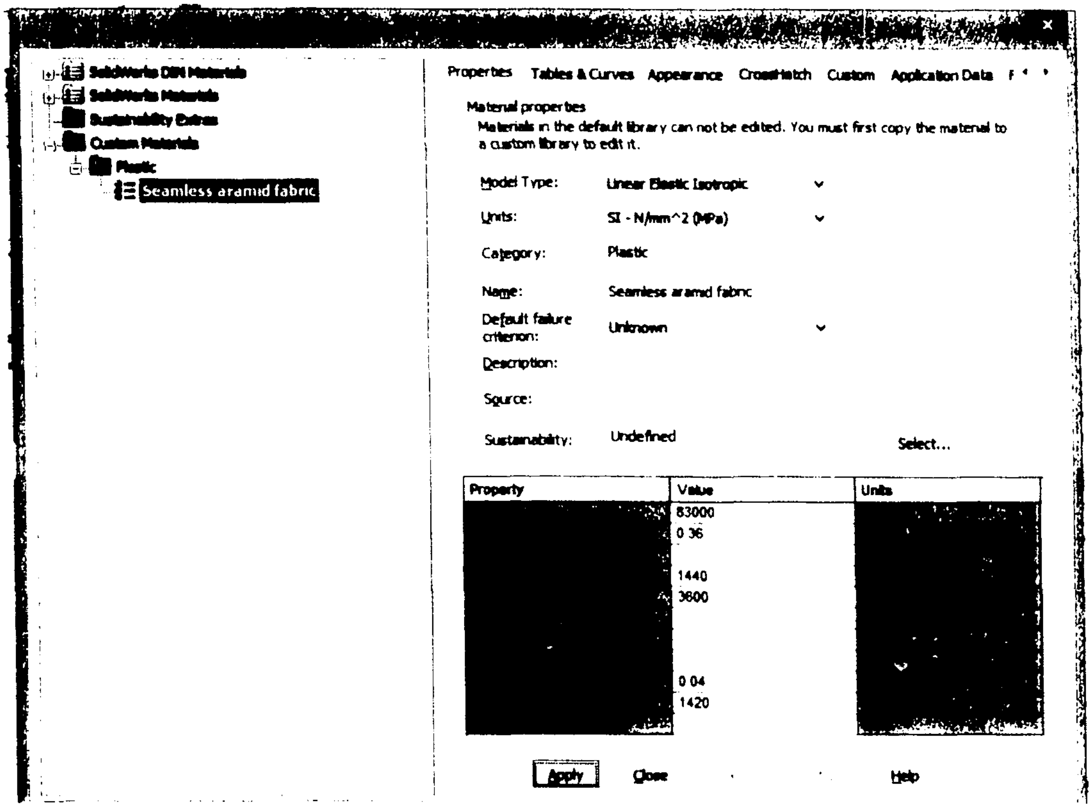


Figure 6-7: Applied material properties of fabric material in Solidworks.

The definition of inner layer thermoplastic polyurethane (TPU) is according to the material supplier (BASF 2011) and (Qi and Boyce 2004). A new material was defined in Solidworks and the specific parameters were shown in **Figure 6-8**.

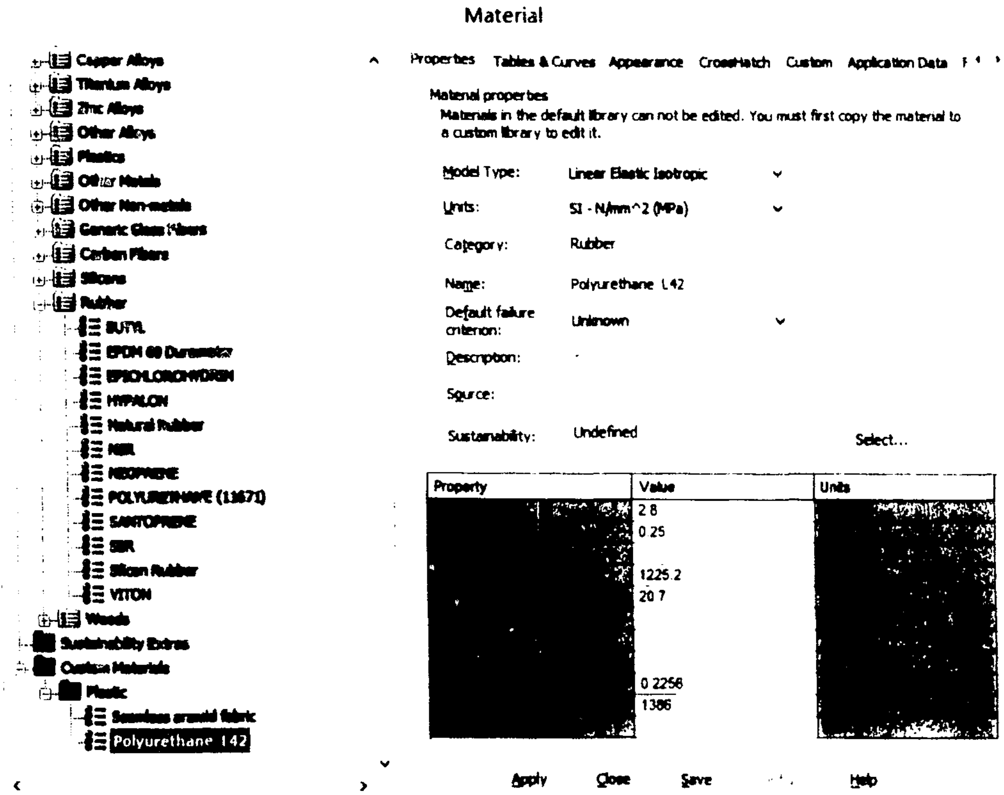


Figure 6-8: Applied material properties of inner layer of TPU in Solidworks.

6.3.2.3 *Boundary conditions*

For calculation accuracy, the boundary conditions should be similar to the actual working conditions of the pipeline. Boundary conditions for the composite hose were established as follows:

1. The longitudinal support

Since the whole pipe segment should be numerically analyzed, it inevitably resulted in the pipe suspension. In order to solve this problem, there are two treatments.

(1) At the edges of the composite hose (i.e., $z = 0$ mm, $z = 36$ mm), the spring supports with stiffness K (K take .05) were set to limit the displacement of the spring ends in X, Y, Z-direction. The spring supports were in the circumferential angles of 0°,

90°, 180° and 270°. This treatment was appropriate because the weight of the hose was not considered. The selection principle of the spring's stiffness K followed the Hooke's law (**Eq. 6-1**).

$$F = KX \qquad \textbf{Eq. 6-1}$$

Eq. 6-2 was assumed and has fully met the simulation accuracy requirements. **Eq. 6-1** was substituted into **Eq. 6-2** and it got K < 3.5. Different K values were calculated for comparison and the results show that the K value had little effect on the calculation results. K was determined to be 0.5.

$$F/(P \times A) \approx 10^{-3} \qquad \textbf{Eq. 6-2}$$

where:

F- the force on the spring when the composite hose under internal pressure, MPa,

P- the internal pressure with the value 3MPa,

X- the spring deformation during burst testing and taking 0.01mm-20 mm,

A- the unit area of the outer surface of the composite hose, mm.

(2) An imaginary outermost supporting sleeve was made for the composite hose. Elastic modulus of the sleeve was taken as .05. Then the constraint was applied in the normal direction on the outer surface of the sleeve.

FEA was respectively simulated by these two restrictions. The calculations were the same by these two different boundary conditions. When eight springs were symmetrically built at the edge of the composite hose (and then limiting the constraints the displacement along x, y, z direction at spring end), it can minimum the impact of additional constraints on the deformation and stress. This boundary condition was similar with the free boundary of composite hoses and guaranteed the authenticity of the simulation. Compared with the imaginary outermost supporting sleeve, the spring support greatly reduced the number of units. The corresponding calculation time-consuming was greatly reduced. So the spring support was selected to solve the suspension problem. The elastic support from Solidworks was chosen as the constraints (**Figure 6-9**).

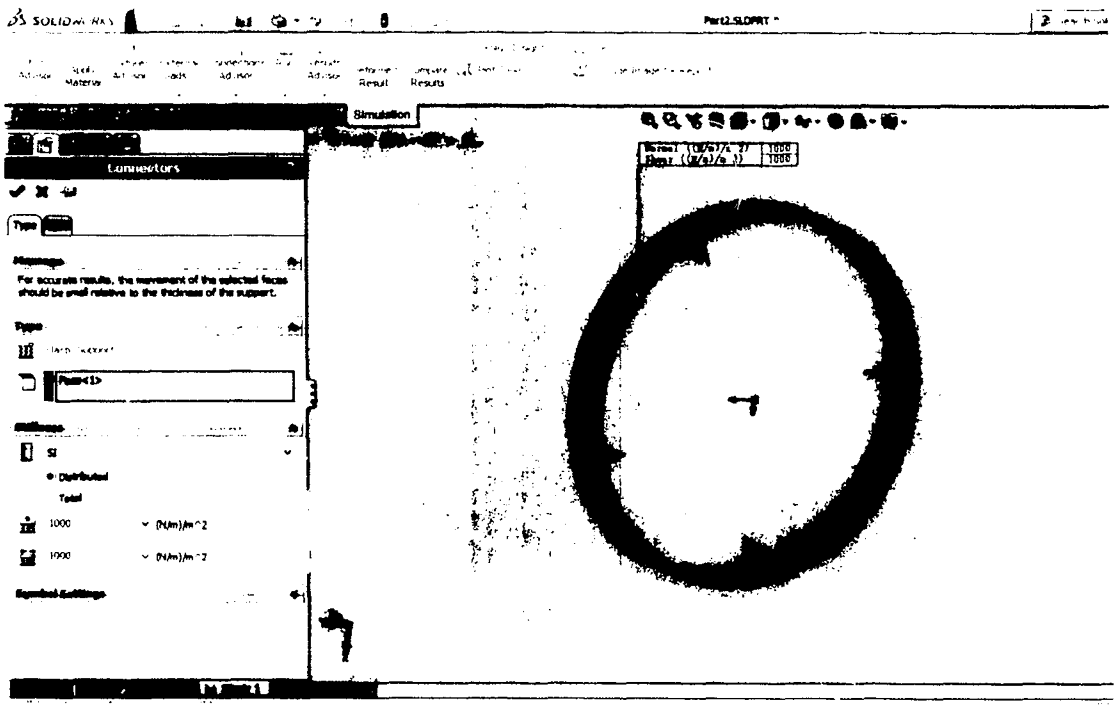


Figure 6-9: Elastic support and constraint in Solidworks.

2. Contact settings between each layer

As the hose was composed by the hot extrusion molding processing technology, bonded is selected as the contact type for the three layers connection (**Figure 6-10**).

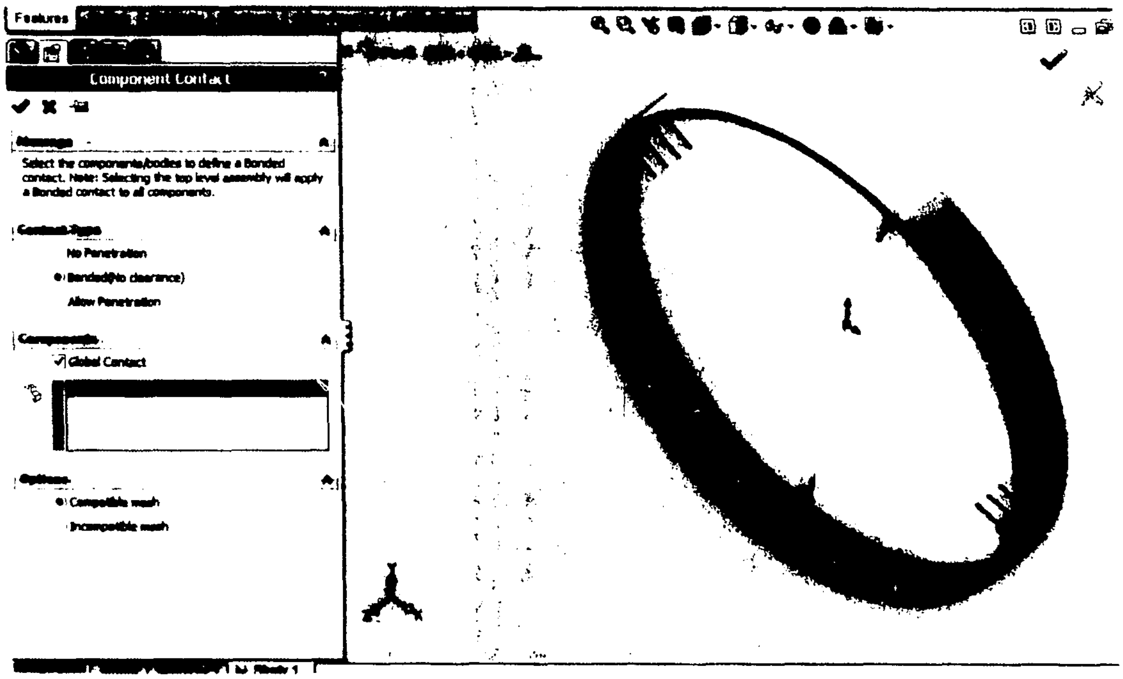


Figure 6-10: Contact type of each layer in Solidworks.

6.3.2.4 *Mesh*

Many grid problems can be solved by using a small unit, but it may lead to longer solving time. In order to find the maximum working unit, automatic loop function (ALF), in COSMOSWorks options window, was used. ALF required the meshing program to reclassify the model with smaller global cell size. Fine mesh density was set in Solidworks. Meshing was automatically generated as shown in **Figure 6-11** by the following three steps:

- Geometric model assessment,
- Borders processing, and
- Grids creation.

The parameters of the grids are shown in **Figure 6-12**.

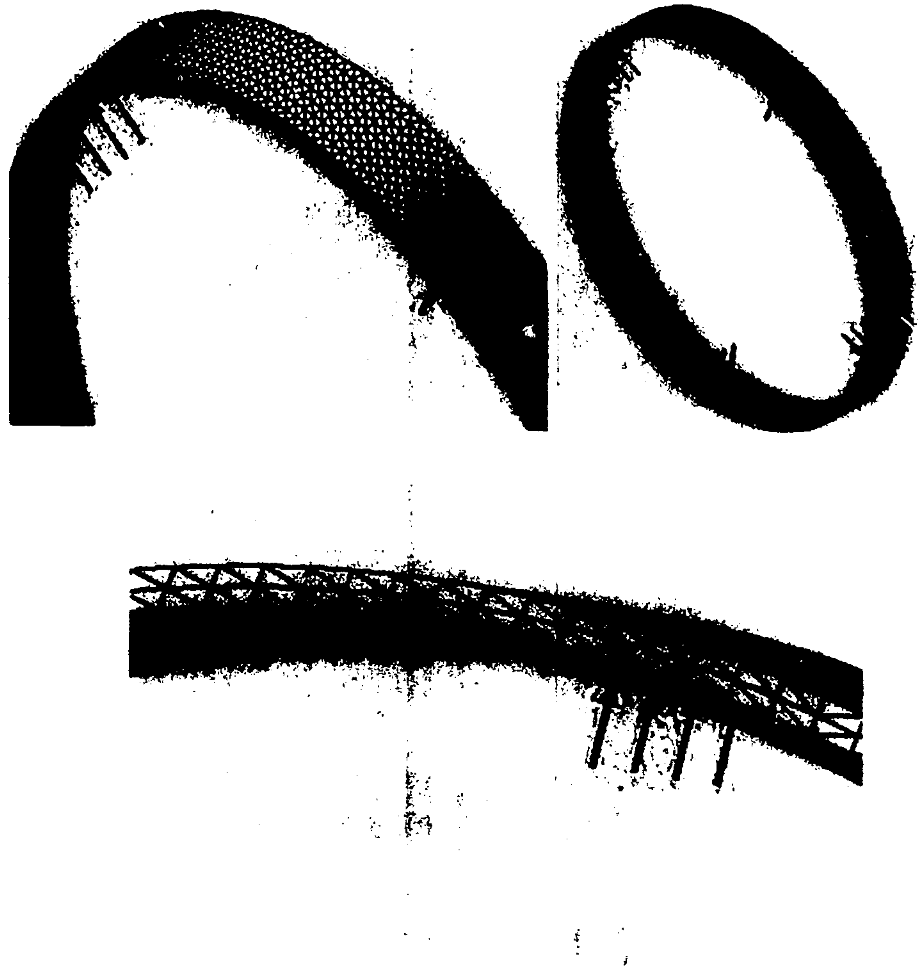


Figure 6-11: Mesh generation in Solidworks.

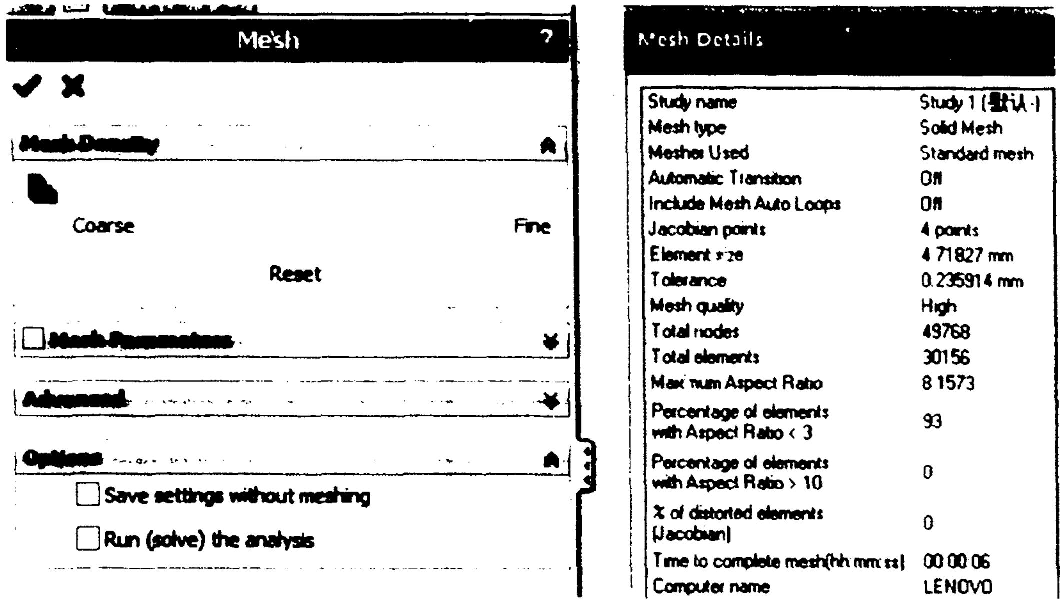


Figure 6-12: Grid Parameters in Solidworks.

6.3.2.5 *Load*

It was difficult to determine the operating pressure of the hose accurately. So the load applied to the FEM was greater than the actual operating pressure and was uniformly applied to the inner wall surface of the composite hose. We set up the internal pressure of FEM as 3 MPa (435 psi) obtained by bursting (**Figure 6-13**).

When the program reached the burst pressure value, the calculation would stop automatically. The internal pressure was applied to simulate the hose under normal operation.

Also, we set up the longitudinal pressure as 3 MPa (435 psi) (**Figure 6-14**). The longitudinal pressure was applied to simulate the hose when it was out of service. As it was explained in Section 3.4.4, the fatigue deformation and tensile strength would occur along the longitudinal direction.

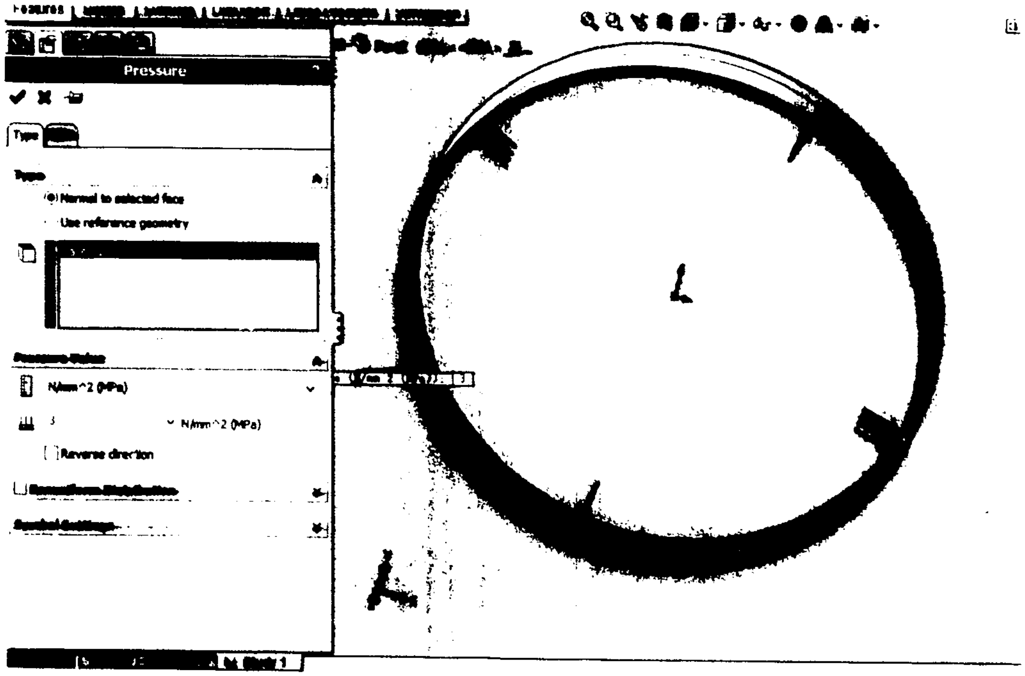


Figure 6-13: Applied internal load in Solidworks.

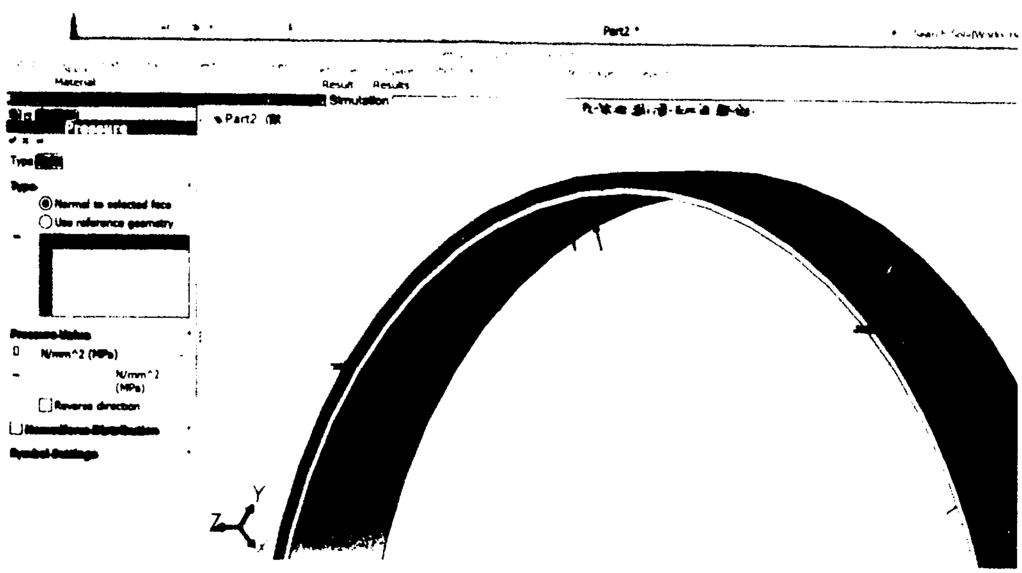


Figure 6-14: Applied longitudinal load in Solidworks.

6.3.3 Results of Finite Element Analysis

6.3.3.1 *Mises equivalent stress distribution of different units*

Solidworks software has powerful post-processing capabilities. According to different unit types, it gives contours of Mises equivalent stress at maximum loads for different unit types using different data processing methods. Analysis principles for Solidworks maximum stress (vonMise) by FMA software are in **Eq. 6-3.**

$$vonMise = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \quad \textbf{Eq. 6-3}$$

where:

$\sigma_1, \sigma_2,$ and σ_3 are the uniaxial stress separately in the X,Y, and Z direction, MPa.

The FEA simulation result was consistent with the physical burst testing. The maximum stress occurs in the intermediate fiber layer (230 MPa) (**Figure 6-15**), which fits the tensile yield strength (200 MPa) of polyester filament given by material suppliers (**Table 6-3**) (Mortensen 2006). That is, when the inner pressure reached 3 MPa (435 psi), the maximum stress in intermediate layer will reach 230 MPa, exceeding the tensile yield strength (200 MPa) of the polyester filament. So the hose break. This is the role that fiber-reinforced layer should play. FEA simulation results also show the maximum tensile stress for each layer (**Figure 6-16**).

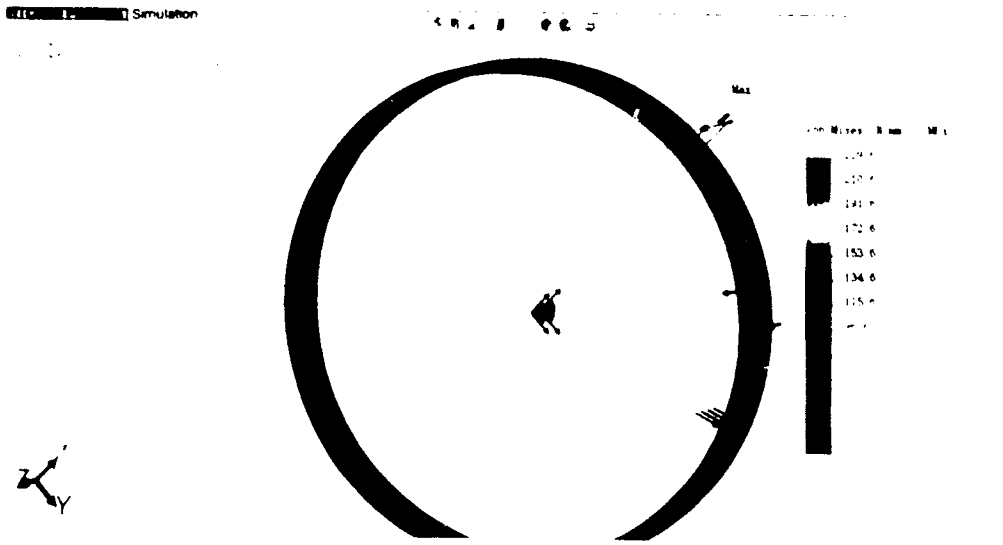


Figure 6-15: Maximum stress occurred in the fiber reinforcement layer.

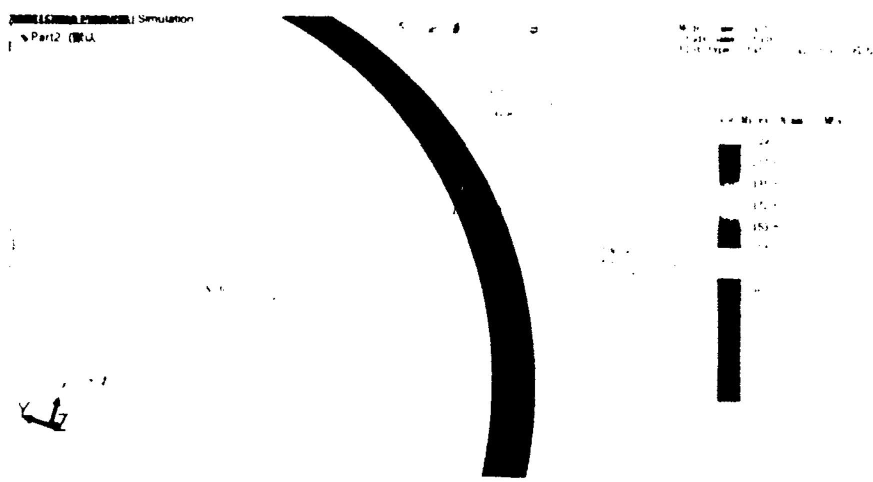


Figure 6-16: Maximum stress of each layer.

Table 6-3: Material properties of polyester filament.

Properties	Value
Yield Tensile Strength, MPa (psi) (ASTM D412-61T)	200 (29,000)
100% Modulus, MPa (psi) (ASTM D412-61T)	150 (21,750)
Mass Density Kg/m^3 lb/in^3	1,440 0.052
Possion ratio	0.35
Thermal Conductivity [W/(m*K)]	0.04
Special heat (J/Kg*K)	1,420

6.3.3.2 *Displacement and deformation results analysis*

To better understand the overall deformation of the composite hose during burst testing, strain (ESTRN) and displacement figures were shown from **Figure 6-17** to **Figure 6-19**. Maximum strain was 3% and occurred on the inner surface. Strain results of FEM were comparatively analyzed with the results of the Approximate Analytical Calculation in Chapter 7.

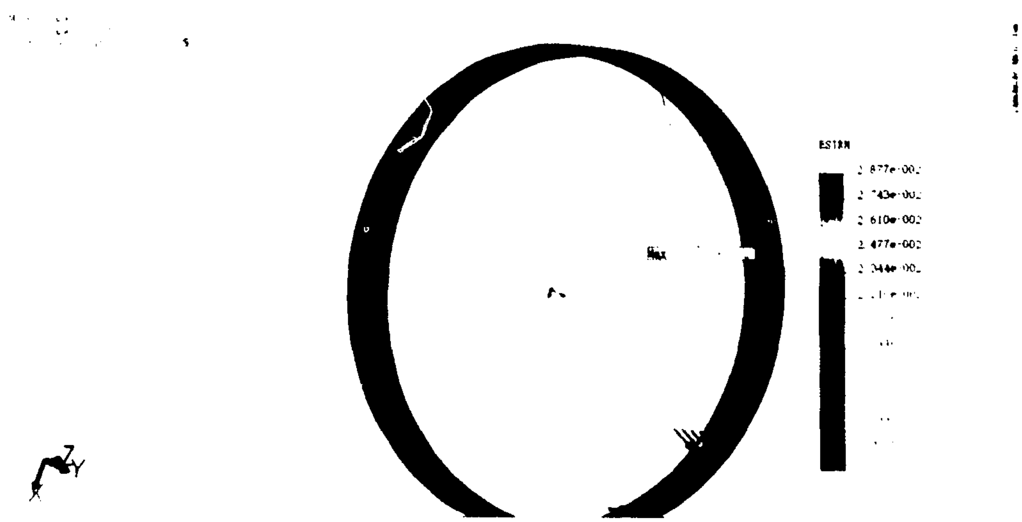


Figure 6-17: Maximum strain and strain results of composite hose.

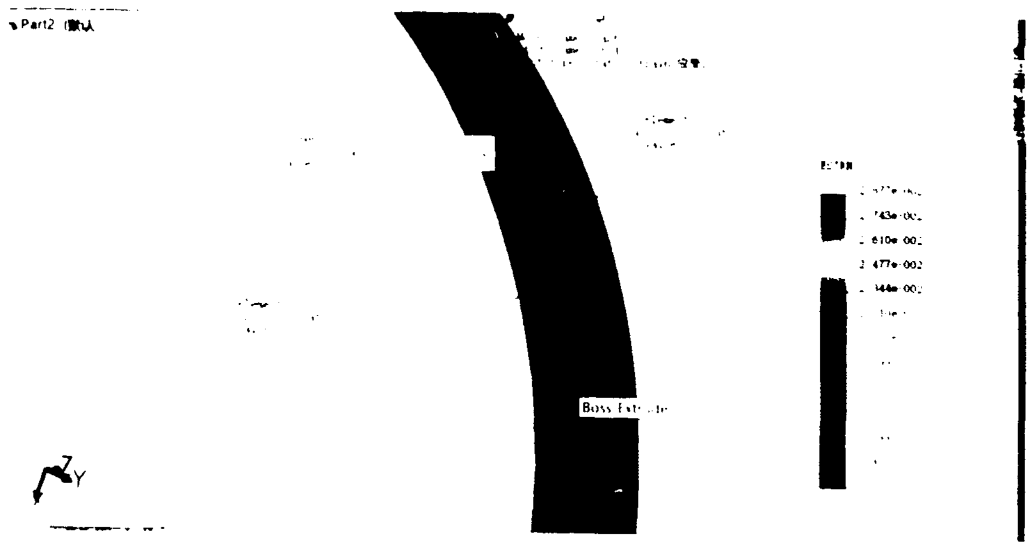


Figure 6-18: Maximum strain of each layer.

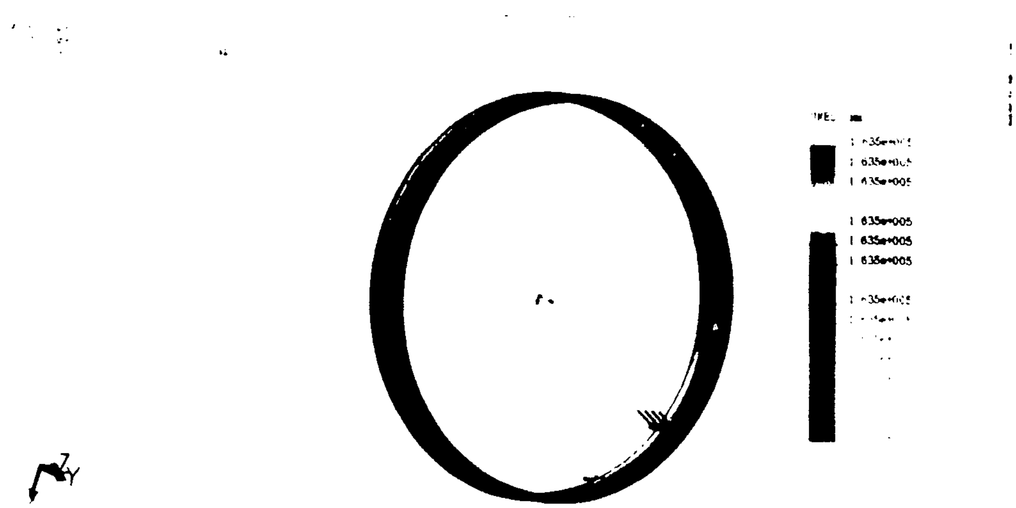


Figure 6-19: Displacement results of composite hose.

It was clearly shown that the longitudinal displacement as the color went from dark to light in **Figure 6-19**. So the material longitudinal properties were important when the repaired pipe was out of service.

We should pay attention to the increasing of deformation and stress during pipe installation and when the repaired pipe was out of service. It is also recommended to make the pipe joint long enough to avoid the burst area occurring in these parts. The working pressure for the composite pipe was determined by the maximum stress and safety factor in Chapter 8.

CHAPTER 7

MATHEMATICAL MODEL OF COMPOSITE HOSE

7.1 Approximate Analytic Solution

In order to compare with FEA, the regional balance analytical method in material mechanics was applied to do AAC for the composite hose. A pipe section was taken by two imaginary planes with spacing 12", perpendicular to the hose axis, then using the plane parallel to the axis to split the pipe section and get a local area, as shown in **Figure 7-1**. AAC method was used to calculate the stress and strain for each layer of the composite pipe under bursting test pressure.

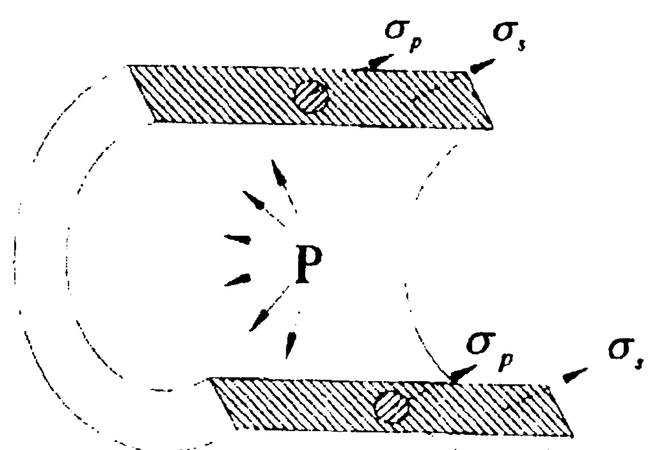


Figure 7-1: Stress analysis of composite hose.

The size of the internal forces in two longitudinal end surfaces in **Figure 7-1** is equal but in the opposite direction, so they cancel each other and will not be considered for stress analysis. σ_s is the sum of all the internal forces perpendicular to the cross-section, and σ_p is the fluid pressure acting on the inner surface.

7.1.1 AAC Equations

This methodology (**Figure 7-2**) proposed aims at the long-term extrapolation of multilayer plastic pipes with thermoplastics, fiber reinforced layers, and metallic layers (Farshed 2005). The steps to be followed in this procedure are:

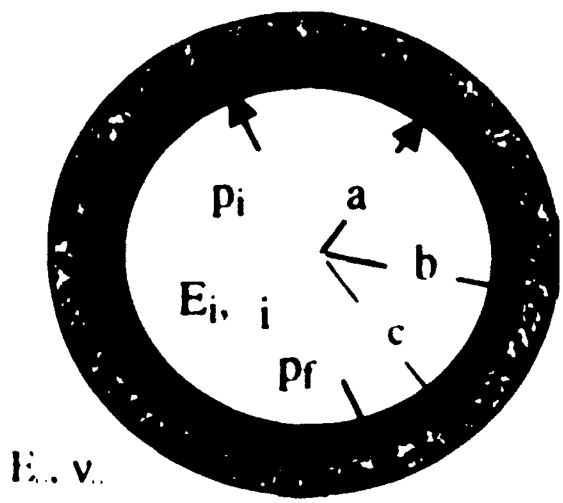


Figure 7-2: Parameters of two-layer composite hose.

Consider a two-layer hose made of two bonded layers under internal hydrostatic pressure, 435 psi (3MPa). Then the internal radius of the internal layer is designated by a. The internal radius of the external layer is designated by b, and the external radius of the external layer is designated by c. The material of each layer is assumed to be linearly elastic and isotropic. The elasticity material parameters of the internal and the external layer are designated by E_i, V_i and E_o, V_o, respectively.

With the effect of the internal pressure p_i, an interface radial stress P_f is produced by the interaction of the two layers. Using the classical elasticity theory for multilayer thin-walled cylinders, the interface pressure can be obtained by the following relation from **Eq. 7-1**.

$$P_f = \frac{2P_i}{\left\{E_i(R_i^2 - 1)\left[\frac{1}{E_i}\left(\frac{R_i^2+1}{R_i^2-1} - V_i\right) + \frac{1}{E_o}\left(\frac{R_o^2+1}{R_o^2-1} + V_o\right)\right]\right\}} \qquad \textbf{Eq. 7-1}$$

where:

P_f = radial stress, MPa,

P_i = internal pressure, MPa,

E_i = elastic modulus of internal layer, MPa,

E_o = elastic modulus of outer layer, MPa,

V_i = Poisson's ratio of internal layer,

V_o = Poisson's ratio of outer layer,

$R_i = b/a$, and

$R_o = c/b$.

The hoop stresses between the internal and the external layer can be obtained by the following relations (**Eq. 7-2**, **Eq. 7-3** and **Eq. 7-4**):

$$\sigma_{hi} = \frac{P_i}{(R_i^2 - 1)}\left(1 + \frac{b^2}{a^2}\right) - \frac{P_f R_o^2}{(R_i^2 - 1)}(1 + \frac{a^2}{a^2}) \qquad \textbf{Eq. 7-2}$$

$$\varepsilon = \frac{1 + V_i}{E_i}[(1 - V_i)\sigma_\theta - V_i\sigma_r] \qquad \textbf{Eq. 7-3}$$

$$\sigma_\theta = \sigma_{hi}, \sigma_r = P_f \qquad \textbf{Eq. 7-4}$$

where:

σ_{hi} =hoop stress of the internal layer, MPa,

P_i = internal pressure MPa,

P_f = radial stress, MPa,

E_i = elastic modulus of the internal layer, MPa,

E_o = elastic modulus of the outer layer, MPa,

V_i = Poisson's ratio of the internal layer,

V_o = Poisson's ratio of the outer layer,

$R_i = b/a$,

$R_o = c/b$, and

ε = strain.

7.2 Hoop Stress Equation for Middle Layer of Hose

Since the three-layer hose is a thin-walled cylinder and the fiber carried all the internal pressure, so we would like to take advantage of the hoop stress equation to calculate the stress of the middle layer.

Then the maximum stress of the middle layer calculated by the hoop stress equation would be compared with FEM and AAC results. It was important to verify the result of hoop stress was closed to the FEM and AAC results. Then we can determine if the hoop stress equation can be the design principle for the hose.

7.2.1 Introduction of Hoop Stress Equation

The hoop stress is the force exerted circumferentially (perpendicular both to the axis and to the radius of the object) in both directions on every particle in the cylinder wall (**Figure 7-3**).

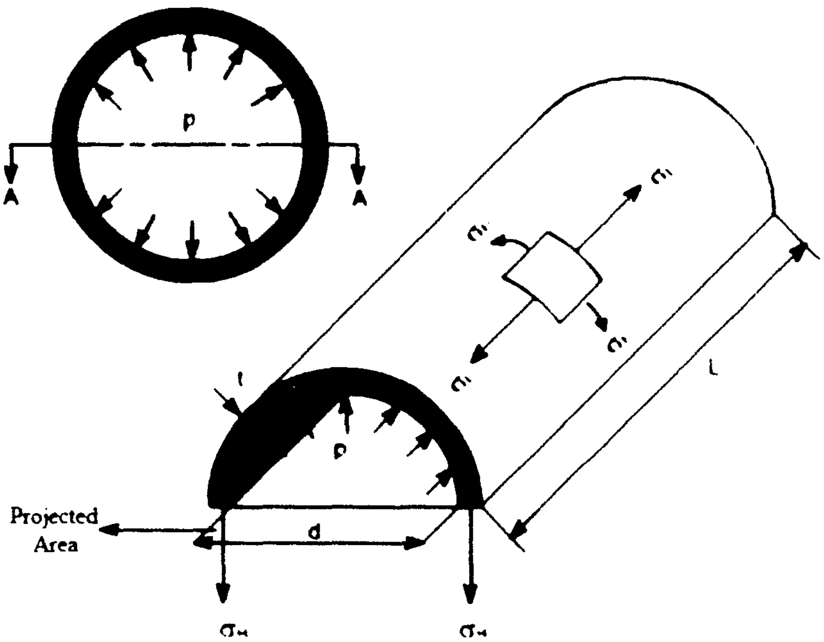


Figure 7-3: Schematic diagram of hoop stress.

For the thin-walled assumption to be valid, the vessel must have a wall thickness of no more than about one-tenth (often cited as one twentieth) of its radius ($\frac{r}{t} \geq 10$). This allows for treating the wall as a surface, and subsequently using the Young-Laplace equation **Eq. 7-5** for estimating the hoop stress created by an internal pressure on a thin-walled cylindrical pressure vessel (Wikipedia 2016):

$$\sigma_h = \frac{p \times r}{t}, \qquad \textbf{Eq. 7-5}$$

where:

P = internal pressure, MPa,

t = wall thickness, mm,

r = mean radius of the cylinder, mm,

σ_h = hoop stress, MPa.

7.3 Two Calculation Process

According to burst testing results of 12" fiber-reinforced hose, it took 435 psi (3 MPa) as the maximum working pressure. The parameters of the mathematic model were determined prior to calculation and are shown in **Table 7-1**. They were from material suppliers and are the same as the ones from the FEA modeling.

Principal stress and strain for each layer were obtained by AAC. Maximum stress of the fiber layer was obtained by the hoop stress equation.

Table 7-1: Parameter table for mathematic model.

Inner radius a	Inner radius of first layer b	Inner radius of second layer c	Inner radius of third layer d	Pi
152.4 mm	154.4 mm	156.4 mm	158.4 mm	3 MPa
Material	Elastic Modulus	Poisson's Ratio	Thickness (mm)	Diameter ratio
Inner TPU	100 MPa	0.48	2	$R_i = \frac{b}{a} = 1.013$
Middle layer Polyester filament	15,000 MPa	0.35	2	$R_o = \frac{c}{b} = 1.013$
Outer PE	1,070 MPa	0.41	2	$R_{o1} = \frac{d}{c} = 1.013$

7.3.1 AAC Method

7.3.1.1 *Calculation for inner TPU material*

The parameters in **Table 7-1** for the inner layer were substituted into the interface pressure **Eq. 7-1**. The calculation process was as follows. The radial stress of the inner layer was 3 MPa:

$$|P_f| = \frac{2p_i}{\left\{E_i(R_i^2-1)\left[\frac{1}{E_i}\left(\frac{R_i^2+1}{R_i^2-1}-V_i\right)+\frac{1}{E_o}\left(\frac{R_o^2+1}{R_o^2-1}+V_o\right)\right]\right\}} \quad \textbf{Eq. 7-1}$$

$$= \frac{2\times 3\,MPa}{\left\{100\,MPa(1.013^2-1)\left[\frac{1}{100\,MPa}\left(\frac{1.013^2+1}{1.013^2-1}-0.48\right)+\frac{1}{15000\,MPa}\left(\frac{1.013^2+1}{1.013^2-1}+0.35\right)\right]\right\}}$$

$$= \frac{6\,MPa}{\left\{100MPa(0.026169)\left[\frac{1}{100\,MPa}\left(\frac{2.026169}{0.026169}-0.48\right)+\frac{1}{15000\,MPa}\left(\frac{2.026169}{0.026169}+0.35\right)\right]\right\}}$$

$$= \frac{6\,MPa}{\left\{2.6\,MPa\left[\frac{1}{100\,MPa}(77.4)+\frac{1}{15000\,MPa}(78.3)\right]\right\}}$$

$$= 3\,MPa$$

$$\sigma_r = P_f = -\,3\,MPa. \quad \textbf{Eq. 7-4}$$

It is clear that the radius stress should be negative, as the internal pressure is outward. Then the hoop stress for the first layer was calculated by **Eq. 7-2**. The calculation process was as follows and the hoop stress of the inner layer was 3 MPa:

$$\sigma_{hi} = \frac{P_i}{(R_i^2-1)}\left(1+\frac{b^2}{r^2}\right)-\frac{P_f R_o^2}{(R_i^2-1)}\left(1+\frac{a^2}{r^2}\right) \quad \textbf{Eq. 7-2}$$

$$\sigma_{hi} = \frac{3MPa}{0.026}(1+1.026)-\frac{3MPa\times 1.026}{0.026}(1+1)$$

$$\sigma_{hi} = 3\text{ MPa}$$

Finally, the hoop stress and radial stress were substituted into **Eq. 7-3.** The strain of the inner layer was 0.045.

$$\varepsilon = \frac{1+V}{E}[(1-V)\sigma_\theta - V\sigma_r] \qquad \textbf{Eq. 7-3}$$

$$= \frac{1+0.48}{100\ MPa}[(1-0.48)\times(3\ MPa) - 0.48\times(-3\ MPa)]$$

$$\varepsilon = 0.0444$$

7.3.1.2 *Calculation for middle fabric material*

At this point, the parameters of the middle layer and the outermost layer were substituted into **Eq. 7-1**. The value of P_{i1} was the calculated P_f value of the TPU layer.

The parameters shown below for the middle layer were substituted into the interface pressure of **Eq. 7-1**.

$$P_{i1} = -3\ MPa, \qquad \textbf{Eq. 7-1}$$

$$b = 154.4\ \text{mm},\ c = 156.4\ \text{mm},\ d = 158.4\ \text{mm},$$

$$R_{i1} = \frac{c}{b} = 1.013,\ R_{o1} = \frac{d}{c} = 1.013,\ E_{i1} = 15000\ MPa,$$

$$V_{i1} = 0.35,\ E_{O1} = 1070MPa,\ V_{o1} = 0.41.$$

The calculation process was as follows: The radial stress of the middle layer was $-0.2\ MPa$.

$$P_{f1} = \frac{-2p_{i1}}{\left\{E_{i1}(R_{i1}^2-1)\left[\frac{1}{E_{i1}}\left(\frac{R_{i1}^2+1}{R_{i1}^2-1}-V_{i1}\right)+\frac{1}{E_{o1}}\left(\frac{R_{o1}^2+1}{R_{o1}^2-1}+V_{o1}\right)\right]\right\}}$$ **Eq. 7-1**

$$= \frac{-2 \times 3\,MPa}{\left\{15000\,MPa(1.013^2-1)\left[\frac{1}{15000\,MPa}\left(\frac{1.013^2+1}{1.013^2-1}-0.35\right)+\frac{1}{1070\,MPa}\left(\frac{1.013^2+1}{1.013^2-1}+0.41\right)\right]\right\}}$$

$$= \frac{6\,MPa}{\left\{15000\,MPa(0.026169)\left[\frac{1}{15000\,MPa}\left(\frac{2.026169}{0.026169}-0.35\right)+\frac{1}{1070\,MPa}\left(\frac{2.026169}{0.026169}+0.41\right)\right]\right\}}$$

$$= \frac{-6\,MPa}{\left\{390\,MPa\left[\frac{1}{15000\,MPa}(77.6)+\frac{1}{1070\,MPa}(78.3)\right]\right\}}$$

$$= -0.2\,MPa$$

Then the hoop stress for the fiber layer was calculated by **Eq. 7-2.** The calculation process was as follows and the hoop stress of the inner layer was 218 MPa:

$$\sigma_{hi1} = \frac{P_{i1}}{(R_{i1}^2-1)}\left(1+\frac{c^2}{b^2}\right) - \frac{P_{f1}R_o^2}{(R_{i1}^2-1)}\left(1+\frac{b^2}{b^2}\right)$$ **Eq. 7-2**

$$\sigma_{r1} = P_{f1} = -0.2\,MP$$

$$\sigma_{hi1} = \frac{3MPa}{0.026}(1+1.026) - \frac{-0.2\text{MPa} \times 1.026}{0.026}(1+1)$$

$$\sigma_{hi1} = 250\text{MPa}$$

Thirdly, the hoop stress and radial stress were substituted into **Eq. 7-3.** The strain of the middle layer was 0.013.

$$\varepsilon = \frac{1+v}{E}[(1-\text{v})\sigma_\theta - v\sigma_r]$$ **Eq. 7-3**

$$= \frac{1+0.35}{15000\,MPa}[(1-0.35) \times 250\text{ MPa} - 0.35 \times (-0.2\text{ MPa})]$$

$$\varepsilon = 0.015$$

7.3.1.3 *Calculation for outer PE material*

The hose was considered as a single layer and the value of the radial stress was equal to P_{f1} in this case. Parameters from **Table 7-1** were substituted into **Eq. 7-6** to calculate the hoop stress of the outer layer. The stress of the outer layer was 15.6 MPa:

$$\sigma_\theta = \frac{P_{f1}}{(R_{o1}^2 - 1)}(1 + \frac{d^2}{c^2}) \qquad \textbf{Eq. 7-6}$$

$$\sigma_{r2} = P_{f1} = -0.2\, MPa$$

$$\sigma = \frac{P_{f1}}{(R_{o1}^2 - 1)}(1 + \frac{d^2}{c^2})$$

$$= 15.6 \text{ MPa}$$

The hoop stress and radial stress were substituted into **Eq. 7-3** and the strain of the inner layer was 0.012.

7.3.2 Hoop Stress Equation

Based on FEA simulation and AAC mathematic model, the maximum stress occurred in the intermediate layer.

The stress of the fiber reinforced intermediate layer may be calculated by **Eq. 7-5**. For the middle layer, the internal pressure *P* was equal to 3 MPa. The radius of the middle layer was 154.4 mm and the thickness was 2 mm. The hoop stress for the middle layer was 232 MPa.

$$\sigma_r = \frac{P \times r}{t}$$

$$= \frac{3\, MPa \times 154.4\, mm}{2\, mm}$$

$$= 231.6\, MPa$$

7.4 Results Comparison and Analysis

The results of the theoretical analysis were compared in **Table 7-2**, including the simulation results of FEA, calculation results of AAC and hoop stress equation, and the fatigue tensile strength of the middle layer.

Table 7-2: Comparision between the theoretical analysis.

Burst testing	3 MPa (Load applied for numerical calculation)					
	Inner TPU		Fiber layer		Outer PE	
	Maximum stress	Maximum strain	Maximum stress	Maximum strain	Maximum stress	Maximum strain
FEA	3 MPa	0.03	230 MPa	0.014	16	0.014
AAC	3 MPa	0.04	250 MPa	0.015	15.6	0.012
Hoop stress equation	N/A	N/A	232 MPa	N/A	N/A	N/A
Material properties of polyester filament	Fatigue tensile strength, 200 MPa (29,000 psi) (ASTM D412-61T)					

According to the strain and stress value of each layer by FEA model and AAC equation (**Table 7-2**), it is clear to state each layer's function as follows. For the outer layer, its main function is wear resistance. For the inner layer, its main function is leakage proof. For the middle layer, its main function is structural reinforcement.

The radial stress σ_r is equal to P on inside surface and the P value is working pressure, σ_r is equal to zero on the outside surface as the host pipe withstands the soil load and surface load. The radial stress σ_r is quite small when compared to hoop stress σ_h.

When we compared the stress of the middle layer of the hoop stress with the value of the FEA model and AAC equations in **Table 7-2**, the calculated value by the hoop stress equation was the same as the result of the FEA, but 5% more than the value of AAC.

Since the fibers carry all the internal pressure, the hoop stress equation can be used as a simple and practical design principle and equation for the composite pipe with the PIL method. Basic design for the hose should be depended on the hoop stress. Hoop stress is validated and set up as the hose design principle.

CHAPTER 8

INNOVATION: ENGINEERING DESIGN GUIDE

8.1 Technical Advantages and Construction Scope

8.1.1 Technical Advantages

Fiber Reinforced Polyethylene Hose (hereinafter referred to as "hose") is a trenchless technology for the rehabilitation of pressure pipelines for different media such as water, gas and oil. The process is based on a flexible high-pressure hose and a specially developed connection technique (ASOE 2016).

Due to its multi-layer structure and thin thickness, the hose provides both flexibility and ultra high strength material. The inner layer of the hose can be selected for the specific media. The outer layer - regardless of medium - is made of wear-resistant PE. Polyester filament is between the inner and outer layers, functioning as a static load-bearing layer (Primus Line 2016).

The hose is produced in nominal diameters from DN 75 to DN 200 (6 to 12 inch). It is inserted into the host pipe from small construction pits, thus avoiding large road works. The hose is not attached to the host pipe and is self-supporting. An annulus remains between the hose and the host pipe. Via a specially developed high-pressure connector on each end, the hose is connected to the host pipe (steel, iron cast, PE, or other materials), and thus to the pipe network.

The PIL method has short rehabilitation times and rapid recommissioning, and thus represents not only an inexpensive alternative to open rehabilitation, but also a high-quality method for the renewal of the pressure pipes.

For both the gravity flow and the internal pressure design, equations have been divided into categories of "partially deteriorated" and "fully deteriorated" conditions of the existing pipe to be rehabilitated (Lanzo Lining Services, 2010). These piping conditions are defined as follows:

8.1.2 Partially Deteriorated Piping Condition

A partially deteriorated internal pressure design pipe is one in which the existing pipe may have displaced joints, cracks or corrosion, but is structurally able to support all soil and surface loads. In this case, the existing pipe is intended to provide structural support over the full circumference of the linear. When assuming a pipe is partially deteriorated, the linear will be designed to withstand uniform hydrostatic pressure over the full circumference of the linear. In addition, as a conservative approach, this design does not assume that the linear is attached to the existing pipe in any way.

A partially deteriorated pressure pipe is one in which the existing pipe may also have minor corrosion, leaking joints, and/or small holes, and should be free of any longitudinal cracks. In this case, the existing pipe is assumed to be able to withstand the specified internal design pressure over the expected lifetime of the pipe. When assuming a pressure pipe is partially deteriorated, it is assumed that the linear will conform tightly against the host pipe everywhere (i.e. in bends or diameter changes, etc.) and uses the strength of the existing pipe to support the stresses. The thickness of the linear can be compensated to span small holes or leaking joints, but will not be of sufficient thickness to withstand design pressures. In addition, if the partially deteriorated pressure pipe is assumed to be leaking, the designer must also be aware of external hydrostatic pressure to ensure that the minimum linear thickness is sufficient to withstand these forces over the design life of the product.

8.1.3 Fully Deteriorated Piping Condition

A fully deteriorated gravity flow pipe is one in which the existing pipe has insufficient strength to support all soil and surface loads. A fully deteriorated pipe is characterized by severe corrosion, missing pipe, crushed pipe, longitudinal cracks, and severely deformed pipe. When assuming a pipe is fully deteriorated, the liner is designed as a pipe able to withstand all hydrostatic, soil, and live loads that may exist in the linear-soil system with adequate soil support.

An alternative strategy for fully deteriorated gravity flow pipes is available to the designer in areas where there are isolated sections of missing or severely offset pipe that would otherwise cause it to be classified as fully deteriorated. In these areas, it may be possible to carry out point repairs, and rehabilitate the pipe as a partially deteriorated classification. However, each situation must be considered separately.

A fully deteriorated pressure pipe is one in which the existing pipe has failed and/or has insufficient strength to operate at specified design pressures. A pipe may also be classified as fully deteriorated if it is determined that it will not be able to withstand design pressures at some point during the expected lifetime. A fully deteriorated pressure pipe is characterized by significant loss of wall thickness due to severe corrosion, large holes, missing sections of pipe, and leaking longitudinal cracks. When assuming a pipe is fully deteriorated, the linear is designed as a stand alone pipe able to withstand all internal pressure. In addition, the designer must also be aware that fully deteriorated linear pressure pipe must be capable of withstanding external hydrostatic pressure.

8.1.4 Rehabilitation Scope of PIL

According to Infrastructure asset management (RF 2003), TRT applications have been divided into categories of four classes based on the conditions of the existing pipe to be rehabilitated.

Class I is the non-structure rehabilitation for "partially deteriorated" conditions of the gravity flow pipelines. The thickness of the linear can be compensated to span small holes or leaking joints, but will not be of sufficient thickness to withstand soil and surface loads.

Class II and III are the semi-structure rehabilitation for "partially deteriorated" conditions of pressure pipelines. The linear conforms tightly against the host pipe everywhere and as a stand alone hose able to withstand all internal pressure, but will not be of sufficient thickness to withstand soil and surface loads.

Class IV is the full-structure rehabilitation for "fully deteriorated" conditions of gravity flow pipe and pressure pipelines. The linear is designed as a stand alone pipe able to withstand all internal pressure. In addition, the designer must also be aware that a fully deteriorated linear pressure pipe must be capable of withstanding external hydrostatic pressure.

Based on this standard and TRT categories, PIL methods belong to Class II and III semi-structure rehabilitation for pressure pipelines. The product can be used in urban water and gas pipe repair and temporary long-distance pipeline transportation.

8.2 Installation Details and Technical Parameters

8.2.1 PIL Installation Details

A general description of the installation steps will be described for PIL techniques. The descriptions and figures detailed are not intended to encompass all aspects of any given installation. Variable job site, underground piping, and climatic conditions may necessitate a variety of modifications to these descriptions that are intended to produce the same installed product.

The basic categories involved with PIL installation involve the following steps:

8.2.1.1 *Pipe and job site preparation*

Operational stops the pipe service to be renewed. Shut down the host pipe, establish the construction pit, cut and the drain pipe (**Figure 8-1**) (Tonisco 2016).

Figure 8-1: Service stop.

8.2.1.2 *Inspection*

Initially, before any lining tubes are prepared, the existing pipe must be CCTV inspected for debris, roots, damage, offset joints, or any other anomaly that does not allow for proper PIL installation. Inspection also involves measurement of the pipe diameter, pipe length, manhole depths and records of pipe location and other job site conditions (i.e. overhead power lines, or railway, backyard easement, excessive sewerage flows, etc.) that can be properly planned for to help the project proceed efficiently. PIL will not eliminate existing pipe defects, but rather it will contour the configuration of the host pipe being lined. It must be determined that later inspection with CCTV or water jet cleaning may occur and that bumps or fins in the liner will not disallow the equipment from passing through the rehabilitated pipeline (**Figure 8-2**) (SMS 2016).

Figure 8-2: Pipe inspection.

8.2.1.3 *Insertion of an auxiliary rope*

An auxiliary rope will be inserted into the host pipe for testing and later pulling back (**Figure 8-3**) (Iplex 2009).

Figure 8-3: Insertion of an auxiliary rope .

8.2.1.4 *Pipe preparation*

Preparation for lining may involve internal mechanical cleaning and grinding to remove roots, protruding laterals, or other obstructions in the pipe. Collapsed pipe or severely offset joints (i.e. 40% of the diameter) typically require point excavations at those locations. Loose dirt, debris, or tuberculation may require high pressure water or mechanical cleaning with a final pre-lining inspection showing the full circumference of the pipe. Using scraper pigs and pull through pigs to do mechanical coarse cleaning of the pipe interior (**Figure 8-4**) (Apachepipe 2013).

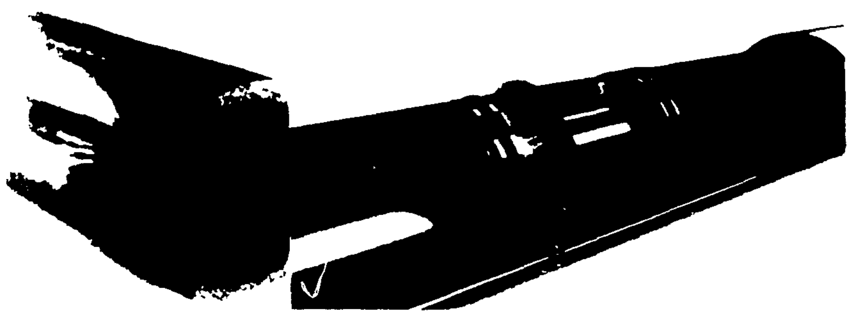


Figure 8-4: Pipe cleaning.

8.2.1.5 *Hose preparation*

Position the coiled hose at the start the pit and the pulling winch at the destination pit (**Figure 8-5**) (Asoe 2016).

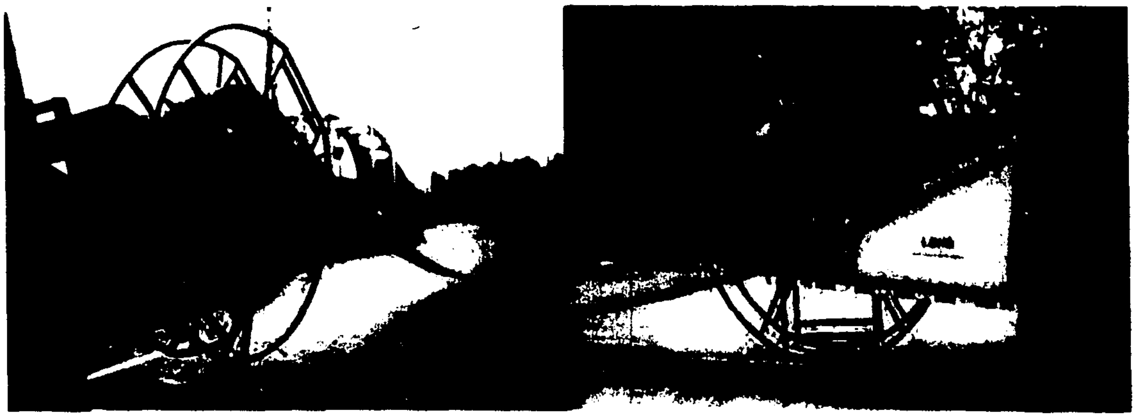


Figure 8-5: Position and pulling winch.

8.2.1.6 *Hose installation*

The following installation descriptions are intended to be a generalized overview of common PIL hose installations. Since there are so many variables associated with each project and the job site conditions of the projects, an overview is provided here to familiarize the reader with the general knowledge of this technology.

Firstly, install the pulling head, hose guides and feeder cable (**Figure 8-6**) (Primus Line 2016).

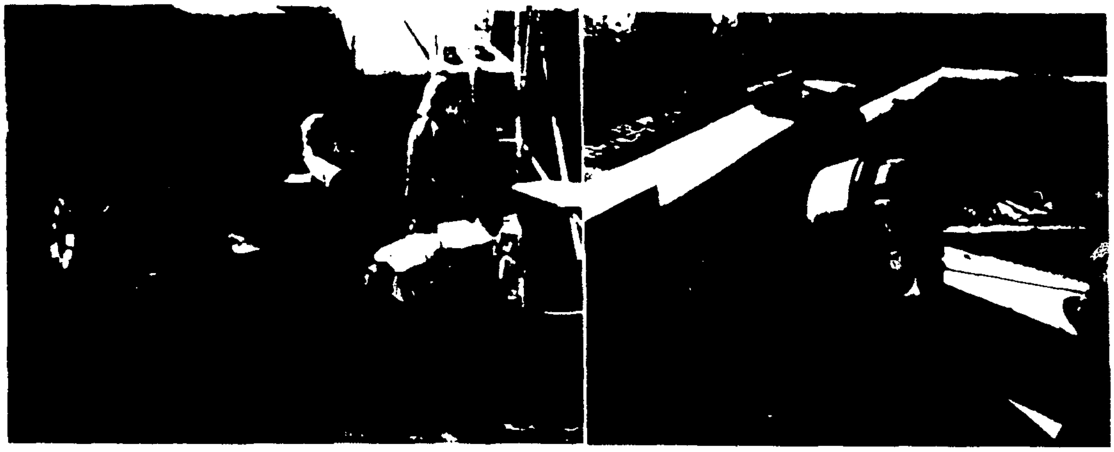


Figure 8-6: Installation of pulling head, hose guides and feeder cable.

Then insert the hose (folded or unfolded) (**Figure 8-7**) (Renos 2016). This process uses the hose that has been folded into a "U" shape then pulled into the existing pipe. Using air or water pressure, the liner is reshaped to meet the existing pipe. Fold and form has been attempted in diameters ranging from 6" to 12".

Figure 8-7: Hose insertion (folded or unfolded).

8.2.1.7 *Assembly of transition connector*

The hose is connected to the existing pipe using special connectors. The high-pressure connector consists of a contoured internal core and external sleeve. The external sleeve has a malleable steel jacket on the inside. A resin, which is injected through a valve on the external sleeve, forces the external steel sleeve and the hose into the contours of the connector's core. So it is a durable, pull-proof connection.
After pressure-resistant sealing of the connector on the rehabilitated pipe section, a leak test will be performed (Primus Line 2016).

Depending on the requirements, the specially designed connector can be fitted either with a flange or welded ends. In this way, it is also possible to join bends, tees or other fittings and fixtures (made of different materials).

Figure 8-8: Specially designed connector.

8.2.1.8 *Pressure tests and integration*

A pressure test will be performed in the liners with connectors in working pressure to see if any leakage or crack occurred before the integration (**Figure 8-9**).

Figure 8-9: Pressure tests.

After testing, integrate the renewed pipe in the pipeline network and commissioning with flange as shown in **Figure 8-10** (Nortechtrinity 2016).

Figure 8-10: Integration and commissioning.

8.2.1.9 *Final inspection and pit closure*

As with any project, final CCTV (**Figure 8-11**) inspection provides the documentation for the project engineer that the PIL was properly installed. Ideally, PIL is free crack throughout the length of the installation (Mocke 2016).

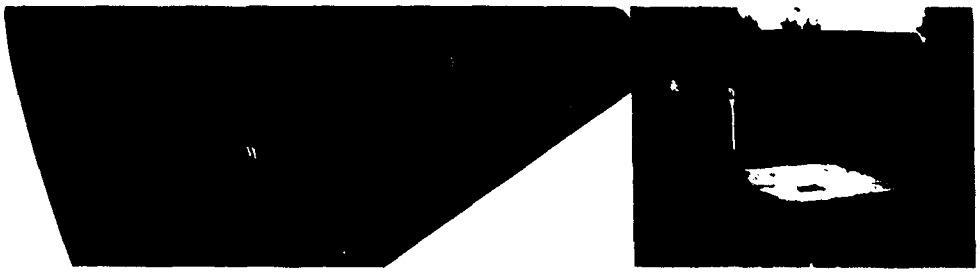


Figure 8-11: Final inspection and pit closure.

8.2.2 Technical Parameters for Lowest LCC

Consulting the technical department of the manufacturer, combined with physical and mechanical properties and Burst testing performed by TTC, as well as FEA and numerical simulation results, the medium layer material of Fiber Reinforced Polyethylene Hose is one of several key elements of the PIL process. The proposed technical parameters for fiber reinforcement hose are given in **Table 8-1** and **Table 8-2**.

Table 8-1: Technical details of composite hoses with different diameters.

Description	Fiber Reinforced Polyethylene Hose*				
The inner diameter	Each layer thickness t mm	Potable water** psi	Density lbs/ft	Gas** psi	Density lbs/ft
8 inch	2	840	1.87	460	2.00
10 inch	2	580	2.42	350	2.66
12 inch	2	400	2.90	290	3.12

* Technical feasibility of different diameters after consulting the technical department of Asoe.

** The indicated maximum working pressure is valid for a straight course of the pipe without bends. Maximum working pressure according to declaration of the technical department of Asoe.

Table 8-2: Technical details summary for fiber reinforced polyethylene hose.

Nominal size	150 - 500 DN 6 - 20 in
Maximum operating pressure (Potable water)	840 psi
Maximum operating pressure (Gas)	460 psi
The maximum Burst pressure	1260 psi
Single-layer wall thickness	2 mm
Density Varied with radius	3 - 4.7 kg/m 1.87 - 3.12 lbs/ft
Abrasion resistance (DIN53516)	10.5 mm^3 0.00064 in^3
The maximum insertion length	2.5 m 8.2 ft
Hose length per drum max Depends on diameter	6 m 19 ft
Bendability	Max 45°
Bending radius	5
Continuous working temperature	Max 50°C Max 122°F
Life	50 years

8.3 Introduction of Industry Standard

This standard applies as the basis for the production and testing. It should also comply with the provisions of the relevant national product laws and regulations.

This standard followed Engineering Design Manual ASTM specifications F1216 and F1743 and China's National Standard GB / T 1.1-2009 "Standardization Guide Part 1: Structure and drafting for the Standard."

Please note that some contents of this document may involve patents. The issuing authority and filing institutions of this document do not assume the responsibility to identify these patents.

This standard is jointly proposed by TTC and Jiangsu Asoe Materials Co., Ltd. The drafters of this standard are Dr. Tom Iseley, Xuanchen Yan, Xihui Zhao, Hua Zou and Zhou Lei. *APPENDIX B* is the Industry Standard for Fiber Reinforced Hose Application in Trenchless Rehabilitation Technology.

CHAPTER 9

CONCLUSION AND FUTURE STUDY

9.1 Conclusion

This dissertation is focused on semi-structural rehabilitation for medium and high pressure urban gas pipeline with the Pipe-in liner method by a fiber-reinforced composite hose. It provided the advice and technical support for gas pipelines rehabilitation in Yunnan.

This dissertation increased the awareness of global emerging TRT for gas pipeline. It provided a strategy for transferring TRT into China. The Design Principle and Equation and Engineering Manuals were established and can be applied in the real case.

These are following accomplishments:

9.1.1 <u>Literature Review</u>

The aim of this study was to learn about, compare, and analyze the application of TRT for gas pipelines in different countries in the 21st century. An introduction of TRT for Gas Pipelines were provided, including Cured-in-place pipe (CIPP), Sliplining (SL), Sprayed in Place Pipe (SIPP), Close-Fit Pipe, Coating and Linings(CL), Pipe bursting and replacement using HDD, etc. Also, an overview of international and China's TRT for gas pipeline was provided, including various TRT applications utilized in different countries and years of application. TTC at Louisiana Tech University was a subcontractor to China University of Geosciences (CUG) in Wuhan, China on a research project to evaluate various TRT for gas pipelines in China and select a suitable candidate to transfer into China's market. The TRT applied in China will play an exemplary role in China's global leadership in managing underground infrastructure assets (Yan, Iseley *et al.* 2015).

9.1.2 International Research and Selection

We developed the evaluation process for their technology, including contacting the company to learn about the previous tests and history data, specifications and field performance evaluation. Also, we contacted the owners, designers, contractors, installers, and operators to collect related information about their technology.

Before lab testing, TTC completed a set of written criteria to evaluate candidate technologies. A flowchart of the selection was established. Selection criteria were the qualification for the rehabilitation technology performance in China. Finally, we selected a fiber reinforcement composite hose as the specific TRT for China.

9.1.3 Short-Term and Long-Term Testing

The mechanical properties testing were performed on the fiber reinforced hose from Asoe, Shanghai, China. These tests are for the project research on the Application of Trenchless Technology in Medium and High Pressure Gas Pipeline Rehabilitation, which is funded by China University of Geosciences (Wuhan) (CUG).

Based on ASTM standards, TTC performed the mechanical and material property tests on this new composite pressure hose. These tests included a thickness test, hardness test, bending test, tensile strength test, and long-term creep behavior test for the 12" (305 mm) fiber reinforcement hose from Asoe. Then these experimental data and results were recorded, collated and analyzed. The thickness, shore hardness, tensile stress and

Young's modulus separately along 45 degrees, the longitudinal and circumferential directions, the longitudinal bending stress and Young's modulus, and other important parameters of the hose were obtained.

One thousand hours of long-term bending and tensile testing were completed. The strain over time and the creep modulus were obtained after 1,000 hours of testing. Long-term bending and tensile Young's Modulus were obtained. Long-term bending Young's Modulus was compared with short-term testing to predict the lifetime of the hose.

9.1.4 Burst, Flexibility and Strength Testing

Short-time hydraulic pressure tests, including the strength testing, flexibility testing and buıst testing, were performed in the liners with connectors with 12" diameter. It was based on the field performance test conducted by the CUG (Wuhan), China.

The sealing and overall performance of the hose and the joints under the testing pressure were verified. The bursting pressure was obtained and applied as the internal pressure in the theoretical analysis. These tests provided better insight of the pipe material performance when subjected to hydraulic pressure.

9.1.5 Numerical Simulation

In order to take quantitative calculations on similar composite pipes and to better understand the overall stress and deformation during composite hose bursting, parametric models and formula were created.

The purpose of theoretical analysis is to find a simple and practical design principle and equation for the composite pipe with the PIL method.

In order to get this design principle, the FEA model and multilayer equations were built and compared with each other. All parameters, including elasticity properties, Poisson's ratio and the thickness of each layer, as well as working pressure, were from TTC and the manufacturer's testing results and material suppliers. Stress and displacement data and figures of the composite hose by FEA after bursting were shown in Chapter 6.

The regional balance analytical method in material mechanics to do approximate analytical calculation (AAC) for the composite pipe was carried out. They proved and validated that the max stress occurred at the middle layer.

For the outer layer, its main function is wear resistance. For the inner layer, its main function is to be leakage proof. For the middle layer, its main function is structural reinforcement.

Since the three-layer hose is a thin-walled cylinder and the fiber carried all the internal pressure, we took advantage of the hoop stress equation to calculate the stress of the middle layer. The accuracy of the hoop stress equation with the thin-walled assumption to calculate the max stress of the multilayer hose was compared and validated by the FEA model and multilayer equations AAC in Chapter 7. Their results were closed. It was verified that the stress of the middle layer calculated by the hoop stress equation can on behalf of the max stress of the three-layer hose.

So the hoop stress equation was selected as the principle design for the hose.

9.1.6 Engineering Design Guide

TTC has developed a living lab program to assist with moving technical solutions into the user community. The living lab and Asoe co-authored the following engineering design guide for PIL promotion.

Technical advantages of the hose were systems proposed. According to Infrastructure asset management (RF 2003), the PIL method was first identified as Class II and III semi-structure rehabilitation for pressure pipelines.

A general description of the installation steps were described for PIL techniques. The basic categories of PIL installation involved the following steps:

- Pipe and job site preparation
- Inspection by CCTV
- Insertion of an auxiliary rope
- Pipe preparation and cleaning
- Hose preparation
- Hose installation
- Assembly of the transition connector fixed to the host pipe
- Pressure tests and Integration of the renewed pipe in the pipeline network and commissioning
- Final inspection and pit closure

Specific technical parameters for the hose were given and validated based on the theoretical analysis. Industry Standards for Fiber Reinforced Hose Application in Trenchless Rehabilitation Technology were drafted by TTC and the manufacturer. There are following deliverables.

- Two papers have been published in International Conference on Pipelines and Trenchless Technology (ICPTT) and CHKSTT International Conference and Exhibition – Trenchless Asia for Smart City 2016.
- This is a template project that could support the official agreement between Louisiana Tech University and Wuhan Industrial Technology Research Institute of Geo-resources and Environment Co.,Ltd (IGE).
- This is a success case and ongoing example for TTC's Living Lab idea.

Also, there are the following innovations.

- The hoop stress was firstly proposed and used as the design principle and equation for the composite pipe.
- Engineering Manuals were established.
- The technical advantages were systems proposed firstly.
- The PIL method was first identified as Class II and III semi-structure rehabilitation for pressure pipelines.
- The PIL installation details were determined and illustrated shown.
- PIL technical parameters for the lowest Life Cycle Cost were optimized.
- Industry Standards and Testing Requirements for Fiber Reinforced Polyethylene Hose for Trenchless Rehabilitation in English and Chinese versions were drafted by TTC and the manufacturer.

9.2 Future Study

We are developing a deeper cooperation between CUG and IGE by pilot projects. A demonstration project of gas pipeline rehabilitation with 1 mile (1.6 kilometer) long and 12" (300 mm) diameter is ongoing. We are applying the Design Principle and Equation and Engineering Manuals of the PIL method in this real case.

Combined with the project data from the job site, we will verify and optimize the Design Principle and Equation and Engineering Manuals with the manufacturer. The manufacturing, production and experimental process will be improved. The better and suitable composite hose for pressure pipeline rehabilitation will be designed and produced. The living lab program of TTC will be utilized to assist with moving this new composite pipe into the gas and water pipeline rehabilitation market.

APPENDIX A

EXPERIMENTAL DATA OF LONG-TERM

In order to guarantee the accuracy of the 1,000 hours' long-term tensile and bending strength test, data was recorded and pictures were taken manually and regularly. Some manual recorded data of long-term tensile testing are listed in **Table A-1**.

Also, according to ASTM standards, the strain values at critical points of long-term tensile testing were recorded and listed in **Table A-2**. These value of critical points were used to justify the creep stage of the sample.

Table A-1: Tensile strain by manual record.

Sample No.	10/30/2015 4:30 PM	11/5/2015 4:30 PM	11/12/2015 4:30 PM	11/19/2015 4:30 PM	12/3/2015 4:30 PM	12/11/2015 4:30 PM
Sample 1	0.0730	0.0730	0.0735	0.0735	0.0740	0.0740
Sample 2	0.0810	0.0810	0.0810	0.0810	0.0825	0.0825
Sample 3	0.0325	0.0385	0.0385	0.0405	0.0410	0.0410
Sample 4	0.0080	0.0095	0.0095	0.0095	0.0105	0.0100
Sample 5	0.0705	0.0715	0.0720	0.0720	0.0725	0.0725
Sample 6	0.0865	0.0860	0.0885	0.0885	0.0890	0.0890
Sample 7	0.0130	0.0135	0.0135	0.0135	0.0145	0.0150
Sample 8	0.0155	0.0160	0.0165	0.0165	0.0165	0.0160
Sample 9	0.0085	0.0090	0.0090	0.0095	0.0095	0.0095

Table A-2: Tensile strain values at key points.

Time	Data	T1	T2	T3	T4	T5	T6	T7	T8	T9
First second	2015/09/15 14:10:46	0.051	0.0635	0.0215	0.001	0	0.074	0.0115	0.005	0.0035
First minute	2015/09/15 14:11:06	0.062	0.0635	0.0215	0.0013	0	0.075	0.0115	0.0055	0.0035
Second minute	2015/09/15 14:11:46	0.0625	0.0635	0.022	0.003	0	0.0755	0.0115	0.0055	0.0035
Sixth minute	2015/09/15 14:17:42	0.0635	0.064	0.022	0.003	0.012	0.0765	0.0115	0.0055	0.0045
Twelfth minute	2015/09/15 14:23:42	0.064	0.064	0.022	0.0035	0.012	0.077	0.0115	0.0055	0.006
Thirtieth minute	2015/09/15 14:40:50	0.064	0.065	0.0225	0.0035	0.012	0.0775	0.0115	0.0075	0.006
First hour	2015/09/15 15:10:42	0.065	0.0655	0.023	0.004	0.012	0.078	0.0115	0.0075	0.006
Second hour	2015/09/15 16:10:43	0.065	0.0655	0.0235	0.0045	0.0625	0.0785	0.012	0.008	0.006
Fifth hour	2015/09/15 19:10:56	0.066	0.0685	0.024	0.005	0.063	0.079	0.012	0.008	0.006
Twentieth hour	2015/09/16 10:02:57	0.0675	0.0685	0.026	0.0055	0.0635	0.0795	0.012	0.0095	0.0065
Fiftieth Hour	2015/09/17 15:03:56	0.0675	0.0725	0.026	0.006	0.0635	0.0815	0.012	0.0095	0.0065
Hundredth hour	2015/09/18 15:47:10	0.069	0.0795	0.028	0.007	0.065	0.082	0.0125	0.011	0.0065
Five hundredth hour	2015/10/03 13:04:22	0.0715	0.081	0.0315	0.0075	0.0685	0.0835	0.013	0.014	0.008
Seventh hundredth hour	2015/10/21 18:55:19	0.0725	0.081	0.0325	0.008	0.0705	0.087	0.014	0.015	0.0085
Thousandth hour	2015/10/27 10:09:58	0.0725	0.081	0.0325	0.008	0.0705	0.089	0.014	0.015	0.0085

Also, the manually recorded bending data of 1,000 hours is listed in **Table A-3**. Bending strain values at critical points according to ASTM standards are recorded and listed in **Table A-4**.

Table A-3: Long-term bending strain by manual record.

No.	10/30/2015 4:30 PM	11/5/2015 4:30 PM	11/12/2015 4:30 PM	11/19/2015 4:30 PM	12/3/2015 4:30 PM	12/11/2015 4:30 PM
CB1	0.0100	0.0100	0.0105	0.0100	0.0110	0.0110
CB2	0.0090	0.0090	0.0160	0.0095	0.0095	0.0095
CB3	0.0075	0.0075	0.0105	0.0080	0.0085	0.0085
CB4	0.0155	0.0115	0.0160	0.0160	0.0165	0.0165
CB5	0.0145	0.0140	0.0150	0.0145	0.0155	0.0150
CB6	0.0120	0.0115	0.0095	0.0120	0.0125	0.0125
CB7	0.0150	0.0150	0.0155	0.0150	0.0160	0.0155
CB8	0.0200	0.0200	0.0120	0.0205	0.0215	0.0215
CB9	0.0115	0.0115	0.0080	0.0120	0.0130	0.0125

Table A-4: Bending strain at key point.

Key point	Date	T1	T2	T3	T4	T5	T6	T7	T8	T9
First second	8/16/15 8:29 AM	0.0005	0.0005	0.0005	0.0005	0.001	0.001	0.0005	0.001	0.0005
First minute	8/16/15 8:30 AM	0.0005	0.001	0.0005	0.0005	0.0015	0.0015	0.001	0.001	0.0005
Sixth minute	8/16/15 8:35 AM	0.0015	0.003	0.0015	0.002	0.003	0.0025	0.003	0.002	0.0015
Twelfth minute	8/16/15 8:41 AM	0.0015	0.003	0.0015	0.002	0.004	0.003	0.0035	0.0025	0.0015
Thirtieth minute	8/16/15 8:59 AM	0.0015	0.003	0.0015	0.002	0.004	0.003	0.003	0.0025	0.0015
First Hour	8/16/15 9:29 AM	0.002	0.0035	0.002	0.003	0.0045	0.0035	0.0035	0.0035	0.002
Second Hour	8/16/15 10:29AM	0.003	0.004	0.002	0.004	0.0055	0.004	0.0055	0.0045	0.0035
Fifth Hour	8/16/15 12:52 PM	0.0035	0.005	0.003	0.0055	0.007	0.005	0.006	0.0065	0.0045
Twentieth Hour	8/17/15 9:23 AM	0.004	0.005	0.0035	0.0065	0.0075	0.0055	0.007	0.0075	0.005
Fiftieth Hour	8/20/15 12:47 PM	0.0055	0.007	0.0045	0.009	0.01	0.0075	0.01	0.012	0.0075
Hundredth Hour	8/24/15 1:32 PM	0.0065	0.007	0.005	0.01	0.0105	0.008	0.011	0.013	0.0085
Five hundredth hour	9/5/15 10:51 PM	0.0075	0.0075	0.0055	0.0115	0.0115	0.009	0.0115	0.0145	0.0085
Seventh hundredth hour	9/15/15 2:06 PM	0.0075	0.0085	0.006	0.012	0.0115	0.0095	0.0115	0.0165	0.009
Thousandth hour	9/29/15 11:55 AM	0.0085	0.008	0.007	0.0135	0.013	0.0105	0.013	0.0175	0.01

APPENDIX B

INDUSTRY STANDARD

This proposed industry standard is based on the working pressure, material properties of each layer and hose diameter and thickness. The design principle is the hoop stress equation for the middle layer material.

B.1 Scope

This standard specifies the product structure, requirements, test methods and rules, packaging, transportation and storage of the TRT fiber reinforced polyethylene hose.

B.2 Referenced Documents

For referenced China's National Standards (GB), visit China's National Standards website (http://cx.spsp.gov.cn/index.aspx?Token=$Token$&First=First). All the GB can be checked in ISO website.

GB/T 2918: Plastics-Standard atmospheres for conditioning and testing,

GB/T 1040.1: Plastics-Determination of tensile properties Part 1: General,

GB/T 9573: Rubber and plastic hoses and hose assemblies-Methods of measurement of dimensions,

GB/T 5563: Rubber and plastics hoses and assemblies-Hydrostatic testing,

GB/T 14905: Rubber and plastics hoses-Determination of adhesion between components,

GB/T 5478: Plastics-Test method for wear by rolling,

GB/T 17219: Standard for safety evaluation of equipment and protective materials in the drinking water system.

B.3 Terms, Definitions and Symbols

B.3.1 Terms and Definitions

The following terms and definitions apply to this document.

1) Trenchless rehabilitation

Trenchless rehabilitation includes such construction methods as sliplining, thermoformed pipe, pipe Burst, shotcrete, gunite, cured-in-place pipe (CIPP), grout-in-place pipe, mechanical spot repair, and other methods for the repair, rehabilitation, or replacement of existing buried pipes and structures without excavation, or at least with minimal excavation (https://en.wikipedia.org/wiki/Trenchless_technology#Trenchless_rehabilitation).

2) The host and old pipe

Pipelines need to be replaced or repaired.

3) The new pipe and hose

It refers to fiber polyethylene reinforced hose applied for TRT in this standard.

B.3.2 Symbol

d_{min} is the minimum inner diameter of the old pipe, in millimeters.

$d_{em,min}$ is the minimum average outer diameter of the new pipe, in millimeters.

$d_{em,max}$ is maximum average outer diameter of the new pipe, in millimeters.

B.4 Product Structure and Model

B.4.1 Product Structure

The hose is a three-layer structure and composed by the hot extrusion molding processing technology. The inner liner is TPU (thermoplastic polyurethane). The intermediate layer is the reinforcing fabric and the material is polyester filament. The overcoat layer is PE (polyethylene). The hose can be flat and coiled and the structure diagram is shown in **Figure B-1**.

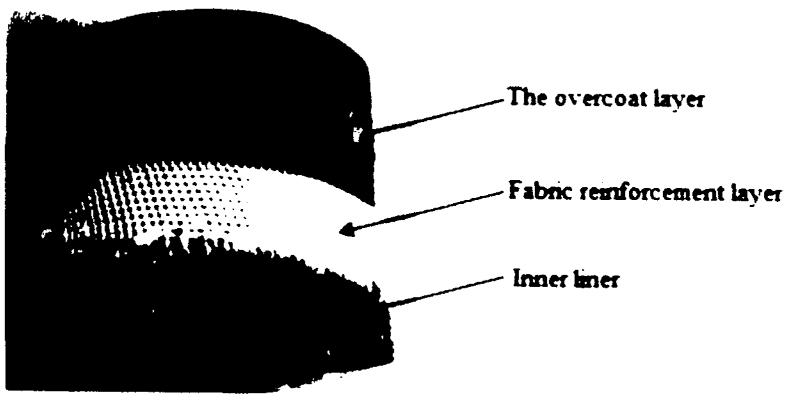


Figure B-1: Hose structure.

B.4.2 Model

Product model consists of the design working pressure, maximum average diameter, and length (**Figure B-2**).

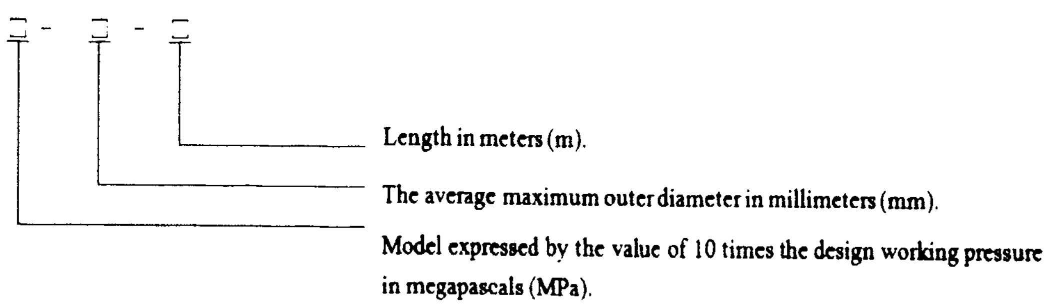


Figure B-2: The product model expression.

Example 1: The design working pressure is 0.3 MPa, the average maximum outer diameter is 100 mm and the length is 100 m. The model specification should be 3-100-100.

Example 2: The design working pressure is 1.0 MPa, the average maximum outer diameter is 150 mm and the length is 200 m. The model specification should be 10-150-200.

B.5 Requirements

B.5.1 The main material requirements

1) Reinforcement layer

Enhancement layer of the hose is a high-strength fiber woven braid and complied with the relevant technical documents. High-strength fiber woven braid should be uniform, with a clean surface, no hole or puncture, no scratches, and no delamination.

2) Adhesives

The adhesives used for the hose should conform to the appropriate product standards, tensile strength, and elongation at break. Performance indicators should be consistent with the provisions in **Table B-1** and along with product quality certificates. Check and verify the supplier's product certification reports prior to use.

Table B-1: Performance indicators for the adhesives.

No.	Item	Performance	
		Inner	Outer
1	Tensile strength/MPa ≥	11.0	11.0
2	Elongation at break/ % ≥	400	400

B.5.2 Appearance

1) The hose's inner and outer surfaces should be clean, smooth and not allowed to have pinhole, bubble, obvious scratches, irregularities, impurities, cracks, exposed reinforcement layer, uneven color, and other defects. Pipe ends should be cut flat and perpendicular to the hose's axis.

2) The hose's color is generally blue, but other colors may be discussed between supply and demand.

B.5.3 Length

The hose's length should be agreed by both parties which does not allow negative bias.

B.5.4 The Maximum and Tolerance of Outer Diameter

Average maximum outer diameter of the hose under normal circumstances should be in accordance with **Table B-2**. The outer diameter also can be determined in accordance with user requirements.

Table B-2: Average maximum outer diameter of hose (unit:mm).

The minimum nominal diameter of the old pipe d_{min}	The difference between the maximum outer average diameter of new pipe and the minimum inside diameter of old pipe $\Delta d = d_{min} - d_{em,max}$	Tolerance for new pipe outer diameter
$80 \leq d_{min} \leq 100$	4.0	0~2.0
$100 \leq d_{min} \leq 250$	6.0	
$250 \leq d_{min} \leq 400$	8.0	0~3.0
$400 \leq d_{min} \leq 600$	10.0	

B.5.5 Thickness and Allowable Tolerance

The wall's thickness and tolerances shall comply with the provisions in **Table B-3**.

Table B-3: Thickness and allow tolerance (unit:mm).

The maximum average outside diameter $d_{em,max}$	Wall thickness	Tolerance
$80 \leq d_{em,max} < 100$	3.0	+0.8
$100 \leq d_{em,max} < 250$	4.0	
$250 \leq d_{em,max} < 400$	5.0	
$400 \leq d_{em,max} \leq 600$	6.0	

B.5.6 Design and Burst Pressure

There should be no leakage, bubbling, cracks, sharp deformation or other signs of destruction in the hose's wall within one hour of the testing pressure (**Table B-4**). Minimum burst pressure shall not be less than the value specified in **Table B-4**.

Table B-4: The testing pressure (unit: MPa).

The maximum average outside diameter $d_{em,max}$	Design working pressure	Testing pressure	Minimum Burst pressure
$80 \leq d_{em,max} < 100$	0.28	1.5	3.0
$100 \leq d_{em,max} < 250$	0.28	1.0	2.0
$250 \leq d_{em,max} < 400$	0.28	0.8	1.5
$400 \leq d_{em,max} \leq 600$	0.28	0.8	1.0

B.5.7 Axial Elongation

The rate of the axial length change of the hose should not exceed 2% in the design working pressure.

B.5.8 Diameter Expansion

The hose's diameter expansion rate should not exceed 10% in the design working pressure.

B.5.9 Twisting

1) The hose twisting should be less than $5° / m$ when the nominal outside diameter is less than or equal to $\Phi 150\ mm$ in the maximum working pressure.

2) The hose twisting should be less than $10° / m$ when the nominal outside diameter is greater than $\Phi 150\ mm$ in the maximum working pressure.

B.5.10 Adhesion Strength

The adhesion strength between the inner layer (cover layer) and the reinforcement layer should be not less than $40\ N / 25mm$.

B.5.11 Wear Strength

Rolling by the No. H22 wheel without additional weights, the rotation should not be less than 6,000 rpm when the reinforcement layer is exposed.

B.5.12 Connector

According to the method listed in *Hose and Connector Performance Test*, carry out the hydrostatic test for the connector between the hose and fittings. In the corresponding testing pressure in Section B.5.6, hose connections and joints should not shift, leak, burst, or slip.

B.5.13 Low Temperature Performance

At -55 ℃ $\pm$ 2 ℃, there should be no cracks, nicks, sharp deformation, or other signs of damage. Then, carry out pressure testing at the normal temperature. There should be no leakage or bubbling.

B.5.14 Aging Properties in Hot Air

1) After the aging test in hot air, there should be no cracks, nicks, sharp deformation, or other signs of damage. Then, carry out pressure testing at the normal temperature. There should be no leakage or bubbling.

2) The adhesion strength between the inner layer (cover layer) and the reinforcement layer should not be less than 75% of the value measured before aging test.

B.5.15 Sanitary Properties

Hoses used in the drinking water transportation should be consistent with the GB / T 17219 and NSF 61 Standards.

B.6 Material Inspection Methods

B.6.1 Sample Pretreatment

According to GB / T 2918 Standards, the testing temperature was set up as 23 ℃ ± 2 ℃ and the conditioning time is 24 hours. The specific inspection method should be in accordance with GB / T 2918 standards.

B.6.2 Reinforcement layer

It is by the visual inspection method.

B.6.3 Adhesives

1) Tensile strength test method should be carried out according to GB / T 1040.1.

2) Elongation at the break was tested in accordance with GB / T 1040.1.

B.6.4 Visual Inspection

The inside of the hose can be visually inspected by a light source.

B.6.5 Length Measurement

Expand and pave the hose to be measured with the tape. When the hose is greater than the tape range, it can be segmentally measured. The minimum accuracy of tape should be 1 mm. The hose can also be placed on a fixed table and measured by the certified scale on the table.

B.6.6 The average outer diameter measurement

1) Intercept a section sample with the length not less than one meter from the same species, the same size, and the same material.

2) One end of the testing sample is connected with the water resource and the other end is closed by a sealing device with the exhaust valve. Hold the sample flat, make the sample filled with water and drain the air. Then close the exhaust valve. Pressurize to 0.1 MPa (14.5 psi) and make the water pressure change between 0.08 MPa ~ 0.12 MPa (11.6 psi ~17.4 psi).

3) Take three reference markers (A, B and C) in the outer surface of the sample. The middle mark B should be as close as possible to the midpoint of the hose. The minimum distance between both ends (A and C) and the point B should be 250 mm **(Figure B-3)**.

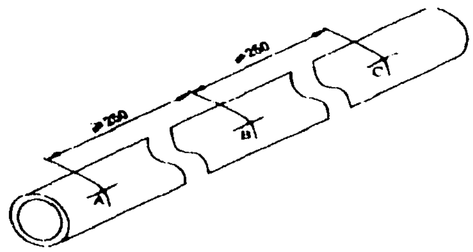


Figure B-3: Three reference markers in the outer surface (unit: mm).

4) When holding pressure, measure the circumferential length of points A, B and C by a tape with the accuracy of $\pm$ 1 mm.

5) The outer diameters A, B and C were calculated using **Eq. B-1** and the arithmetic mean to determine whether the results meet the requirement in Section B.6.6.

$$\text{Perimeter} = \text{outer diameter} \times \pi. \qquad \textbf{Eq. B-1}$$

B.6.7 Wall Thickness Measurement

Measure the wall's thickness in accordance with Test Method GB / T 9573.

B.6.8 Strength Testing

Pressurize the hose in accordance with the test method in GB / T 5563 in Section B.5.6 and maintain the testing pressure for one hour. We should check if leakages, bubbling, cracks, sharp deformation, and other signs of damage happened during this period.

Note: The hose cannot be bent during the test.

B.6.9 Burst Testing

The burst testing should be in accordance with GB / T 5563 and ASTM D1599.

B.6.10 Axial Elongation, Diameter Expansion Rate and Reversing

Carry out the testing at the design pressure according to GB / T 5563.

B.6.11 Adhesion Strength Test

The adhesion strength test should be in accordance with Test Method GB / T 14905.

B.6.12 Wear Resistance Test

The wear resistance test should be according to GB / T 5478.

B.6.13 Hose and Connector Performance Test

1) The two ends of the sample with a length of 1 meter were fitted with the connectors. They were separately in contact with the water and sealed connection with the exhaust valve.

2) Hold the specimen straight and drain the sample hose. Close the exhaust valve after the air drained. Increase the appropriate test pressure uniformly. Hold pressure for 5 minutes. Then, determine whether the testing results meet the requirements in Section B.5.12 and drainage and relief.

B.6.14 Low Temperature Testing

1) Place the tightly rolled testing sample (not less than 2 m) into the cold box at 55 ℃ ± 2 ℃ for 72 hours. Flatten the hose within 3 min and check whether there are cracks or breaks occurring at the outer cover by visual inspection at room temperature.

2) Take a section sample with one meter long after low temperature testing and place at room temperature for one hour. Then pressurize the sample hose at the testing pressure and keep the pressure for one hour in accordance with GB / T 5663. Inspect for

any leaks, bubbling, cracks, a sharp deformation, or other signs of damage in the sample during this period.

B.6.15 Aging Test in Hot Air

1) The sample for aging test and the comparison sample should be taken from the adjacent portion of the hose.

2) Place the tightly rolled testing sample (no less than 2 m) in the hot air tank. The distance between the tank wall and sample should not be less than 70 mm (2.75"). Hold the sample hose at the testing temperature (60 ± 1) ℃ for 168 hours. Observe and confirm if blocking or deformation phenomena happened between inner layer or the outer layer after removing.

3) Take a section sample with one meter long after hot air testing and place at room temperature for one hour. Then, pressurize the sample hose at testing pressure and keep the pressure for one hour in accordance with GB / T 5663. Inspect for any leaks, bubbling, cracks, a sharp deformation, or other signs of damage occurring during this period.

4) Adjust the aged samples at standard laboratory temperature for at least 24 hours. Measure the interlayer adhesion strength according to the method in Section B.6.11 and compare with a sample without aging testing. Determine whether or not the testing results comply with the provisions in Section B.5.4.

B.6.16 Sanitary Performance Test

According to GB / T 17219, carry out the testing by using the hose with a minimum diameter.

B.7 Inspection Rules

B.7.1 Inspection Classification

Inspection includes factory inspection and type inspection.

B.7.2 Factory Inspection

1) Each batch of products shall be qualified along with product certification subject to the enterprise quality inspection department before entering the market.

2) Factory inspection follows the items from Section B.5.2 to Section B.5.10 in this standard.

3) Take the same type product as a test batch with the same raw materials, formulations and processes for continuous production. Random sample, three test samples for the testing from Section B.5.2 to Section B.5.5 and one test sample for the testing from Section B.5.6 to Section B.5.10. The sample section extract from the sample hose.

4) The product batches are qualified only when all the testing results are satisfactory.

5) If the testing results fail to meet, double the sample and retest unqualified items. If it still fails, then it is determined that the product is defective.

B.7.3 Type Inspection

1) Type inspection should be carried out with one of the following conditions:

- Setting new product trial and putting stereotypes into operation,
- Major changes happening after officially production, such as structure, materials, process changes that may affect product performance,

- At least once a year for normal production (at intervals of no more than 12 months),
- Product discontinuation in six months or more and the production recovery,
- A slight difference between the factory inspection results and the last type inspection,
- The request from national quality supervision departments for type inspection.

2) Type inspection follows all the testing requirements in Section B.3.5.

3) Type inspection sample should be a random sample from qualified samples from factory inspection. Three hoses are selected randomly each time. Testing pieces are extracted from the sample hose.

4) If the testing results fail to meet the requirement, double the sample and retests the unqualified items. If it still fails, it is determined that the product is defective.

B.8 Marks, Packaging, Transportation and Storage

B.8.1 Marks

1) Each end of the hose should include the following marks:

- The product name,
- Model specifications,
- Main technical parameters like the nominal pressure,
- The production date / batch number,
- Product standards Number,
- The company name, and,

- Sanitary permit approval number.

2) The product shall be accompanied by the following documents:

- Product certification,
- The product manual, and
- Sanitary inspection reports.

B.8.2 Packaging

Package should be according to user requirements.

B.8.3 Transportation

1) Select the appropriate transport equipment. Tie to real pad level and comply with the relevant provisions of the transport department.

2) Handle with care, no throw, no roll, and no drag. Use non-metallic rope (belt) for lifting.

3) Non-metallic rope (belt) bundle is used and the hoses are fixed during transportation. Prevent the weight and mechanical damage during transportation, Handle gently. Avoid sunlight, rain and snow shower and prevent breakage. The product should not be mixed with toxic and hazardous substances during transportation.

4) Transportation and stacking places should be clean and sanitary. No sharp projections to damage the hose material and there should be protective measures.

B.8.4 Storage

1) The product should be stored in dry, clean and ventilated warehouse. Expose to the weather with protective measures. Do not store with oil, acid, alkali, and other corrosive chemicals. Equip with fire safety and fire-fighting measures in the storage area.

2) Whenever possible, the storage temperature should be around 0 ℃ ~ 35 ℃, preferably at about 15 ℃. The temperature should not fall below 55 ℃ and exceed 70 ℃ during storage.

3) Stack horizontally on a flat surface or support with anti-collapse and deformation measures.

4) Different sizes and types should be stored in a different place and comply with the FIFO principle.

5) The storage life is 5 years. If more than the storage period, it should be re-inspected.

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