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USE OF SPOOLABLE PIPE TECHNOLOGIES AS A MEANS FOR REHABILITATING SMALL DIAMETER HIGH PRESSURE PIPELINE SYSTEMS

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ABSTRACT

The aging infrastructure of pipeline systems around the world requires operators to explore novel and innovative methods for rehabilitating pipelines. Conventional repair methods involve the installation of steel sleeves or composite repair systems. While these repair methods are reliable and provide operators with options for pipeline repair, a major drawback is the requirement that pipelines must be excavated. Activities related to excavation have inherent risk in the form of personnel and environment safety along with the applicable cost of excavation activities. If extensive flaws are present in a pipeline system, efforts associated with a comprehensive pipeline repair system can be cost-prohibitive. Additionally, the rehabilitation of pipelines that were installed via horizontal direction drilling, using current repair methods, is near to impossible.

This paper provides an in-depth presentation on a comprehensive study completed to evaluate the use of a spoolable pipeline technology as a means for rehabilitating pipelines. Results are included from an industry survey with responses from 15 pipeline operators on the use of spoolable pipe technologies. One outcome from the survey was the lack of full-scale test data associated with combined loading, which was a central feature in the current study. The combined loads considered in the year-long study included burst testing and cyclic pressure testing utilizing torsion, axial tension, and axial compression loads. More than 30 full-scale test samples were destructively tested in combined loading scenarios, utilizing up to 100,000 pressure cycles to the full operating pressure of the pipeline system. The approach employed in this study, and the associated test results, provides a model for evaluating a spoolable pipeline technology prior to implementation for rehabilitating pipelines. This approach is in addition to the required product qualification standards accepted by industry.

Keywords: spoolable pipe, rehabilitation, non-metallic, testing

INTRODUCTION

Historically, carbon steel pipelines have been the primary material selected for transporting large volumes of liquid and gas products. However, spoolable pipeline technologies were developed to address corrosive products and simplify the process of installing small diameter (typically 8-inch or less) pipeline systems. The rapid-deployment advantage of spoolable pipe technologies also makes them a viable option for insertion into an existing high-pressure pipeline for rehabilitation.

Past research and experience have shown that combined loadings (e.g., bending, internal pressure, and operation at elevated temperatures) can be problematic for some spoolable pipe systems [1]. Spoolable pipe manufacturers are currently the best resource for design information and limit loads; however, the information available with respect to performance of their systems, when considering combined loading scenarios, can be limited. API 15S [2] specifies the design, manufacture, and testing requirements of spoolable pipe systems. This standard uses performance testing to establish operating limits but is primarily focused on single loading and static operating conditions. The performance testing does not include an extensive assessment of combined loading conditions that can be experienced in actual pipeline installation and operation scenarios. These comments are not intended to be a criticism of those responsible for the early development of standards such as API 15S. As is often the case when introducing new technologies, it is sometimes necessary for a technology to be utilized before both users and manufacturers can properly identify potential limitations of a system. Based on these limitations, the applicable standards can then be evolved to mitigate these limitations.

The contents of this paper provide details on the full-scale test program designed to evaluate the performance of a spoolable pipe technology for rehabilitation projects. The test program included combined loading conditions in conjunction with static and cyclic pressure loading. Also included are results from an industry survey taken from operators experienced in using spoolable pipe technologies for onshore applications.

Industry Survey

Surveys are an effective method for gathering information from industry on topics, technologies, and other areas of interest. A survey was developed by subject matter experts, spoolable pipe manufacturers, and pipeline operators. The survey was distributed in the Fall of 2017 to a select group of pipeline operators with experience using spoolable pipe technologies. Provided below are several general observations from the survey that included a total of 18 responses:

- 47% of responders said they had experienced failures in spoolable pipe systems.
- 89% of responders said using a technology per a performance-based standard such as API 15S was important.
- 50% of the respondents have a Quality Program related to spoolable pipe technology.
- The top three critical issues that need to be addressed:
    - Performance at elevated temperatures
    - Accepted QA / QC methods
    - Need to develop inspection technology

Listed below are three questions from among ten questions posed to survey responders and the corresponding figure number showing the respective data.

- Figure 1: Survey question – With what manufacturers are you familiar?
- Figure 2: Survey question – Have you had failures and if so, how many?
- Figure 3: Survey question – What concerns do you have in using spoolable pipe?

Technology Assessment Roadmap

Members of the Spoolable Pipe Users Group (SPUG) and the API SC15 committee conducted a Technology Assessment Roadmap (hereafter referred to as the "Roadmap") in Austin, Texas in January 2017. The development of roadmaps provides Subject Matter Experts (SMEs) with a vehicle for evaluating industry's understanding of topics based on a list of identified / related areas of interest. These areas of interest are then evaluated based on pre-determined metrics that assist SMEs in the assessment and grading process. A primary aim in conducting roadmaps is identification of knowledge gaps.

The purpose in developing the SPUG Roadmap was to identify knowledge gaps and lay the foundation for future research efforts, including the formation of future Joint Industry Programs (JIPs). Provided below are the five steps used in developing the Roadmap:

1. List topics that impact the use of spoolable pipelines, including those related to categories such as manufacturing, construction, and operation. Group the topics based on categories of interest if appropriate. These are listed as ROWS in the Roadmap. For most roadmaps, the number of topics (rows) is at least 15.
2. Select metrics for assessment, also commonly known as key performance indicators (KPIs), to evaluate the "technical readiness" of the topics developed in Step #1. These are listed as COLUMNS in the Roadmap. For most roadmaps, the number of KPIs (columns) is no more than 5.
3. Using the KPIs developed in Step #2, grade each topic developed in Step #1 using a pre-selected scale based on the level of technical readiness (e.g., "1" for the least developed to "3" for the most developed).
4. The scores assigned to each metric are averaged to generate a single number for each topic. If appropriate, weighting factors can be assigned to a metric if one is deemed more critical than another.
5. Once a single number has been developed for each topic, the list can be ranked (i.e., sorted) to allow users to identify the topics / areas of interest that are the most important and/or least developed. Subject matter experts can then identify knowledge gaps through the ranking process.

Table 1 includes the numerical assessments assigned to the Roadmap topics based on the SPUG group's feedback during the Austin meeting. Listed below are several high-level observations made in reviewing the Roadmap:

- Installer qualification is a concern, along with QA/QC of installation practices
- Inspection and NDT of spoolable pipes is a gap
- There is a need for the development of a fitness for service approach
- Combined loading continues to be a concern

It should be noted that the Roadmap only includes U.S. regulations as a weighting category in Column 4 (i.e., the "US Regulations" column). However, the Canadian regulators have a broad acceptance of spoolable composite pipe as referenced in CSA Z662 [3] that were not considered in the Roadmap assessment.

Operator's Perspective

From the perspective of a pipeline operator, there are multiple advantages in using spoolable pipe technologies for the rehabilitation of existing pipelines. Upon inspection of an existing pipeline, it may be identified that numerous excavations are required to safely manage the integrity of the pipeline. The completion of any pipeline excavation has inherent risk associated with personnel and environment safety, along with the applicable cost of excavation. The use of spoolable pipe as an internal rehabilitation technique can be a preferred alternative to a pipeline operator, as the rehabilitation can be completed with a reduced number of excavations, therefore reducing the risk and associated impacts. Additionally, excavations in environmentally sensitive areas can be potentially avoided.

Recognizing the advantages that spoolable pipe technologies can provide to high pressure transmission operators, it is imperative that their performance be completely validated before they are utilized in this capacity. The installation of a spoolable pipeline through an existing pipeline can generate additional loads that would not be experienced in a typical "in-ditch" or above ground installation. These additional loads will depend on the layout of the existing pipeline (i.e. bends and elevation changes), but could include tension, compression, torsion and/or bending. It is important that operators know the design limitations of the spoolable technology in these combined load situations prior to deployment. Depending on the spoolable technology provider, this information may or may not be available, or provided numerically. Cyclic performance with combined loads is not a requirement of API 15S and was of special interest in this test program. For these reasons TC Energy elected to fund the study that is the subject of this paper.

TEST METHODS

The test program for this study included 31 individual samples. In addition to combined loads, the study included damage mechanisms and three sample configurations. Table 2 provides a summary of the different test variations utilized. Each sample was tested with internal pressure as either static (pressurized to failure) or cyclic (pressure cycles to either failure or runout). The combined loads included axial tension, axial compression, bending, and torsion. Each combined load was tested with both static and cyclic pressure conditions. The test program also examined different levels of pipe damage that included wall loss on the outer cover, damage to the reinforcement layer, and the annulus pressure capacity with outer cover wall loss. All damage mechanism samples were only tested with static pressure (no cyclic pressure testing). Three different sample configurations were also tested with static/cyclic pressure and combined loads. This included the standard pipe (baseline pipe), pipe with internal welds, and pipe with a midline fitting. The purpose of these load combinations was to simulate several potential combined loading cases that could be experienced in a pipeline rehabilitation or damage to the pipeline during the installation.

The focus of this study was the FlexSteel® spoolable pipe technology available from FlexSteel Pipeline Technologies, Inc. (Houston, Texas). The product consists of an HDPE liner, helically wrapped steel strip reinforcement, and an HDPE cover. Provided in Figure 4 is a schematic diagram showing a cut-away of the FlexSteel® spoolable pipe technology. All test samples were 4-inch diameter 1,500 psig (10,340 kPa) rated pipe with 600# ANSI flanges. The test methods presented below are potentially applicable to any spoolable technology.

Sample Configuration

Table 3 lists abbreviations for the combined loading and pipe damage samples that are used for the test descriptions throughout this paper. Table 4 and Table 5 form a comprehensive list of all performed tests, including the test description. Additional details and background are provided for each set of tests addressed in the sections that follow.

An initial hydrostatic burst test with no combined loading or damage was performed as a baseline. Then five tests were performed to characterize damage to either the HDPE cover, the steel reinforcing strips, and the annulus pressure integrity (Samples S2 through S6). Four hydrostatic burst tests were completed that included axial tension, axial compression, bending, and torsion. A static test was also performed with an internal weld sample, and a midline fitting while in bending. One static test used nitrogen gas as the test fluid which was completed to characterize pipe behavior in the event of a gas failure. All other tests were completed with water. To initiate failure in a predetermined location, the gas test sample included damage to a steel reinforcement strip so that any propagation mechanism could be assessed.

Several different types of test fixtures applied the secondary loads. As a reminder, static tests were pressurized to failure while holding the secondary load (e.g., tension) constant. Cyclic tests cycled the internal pressure between 150 and 1,500 psig (1,035 to 10,340 kPa), while holding the secondary load constant. All testing took place at ambient temperature conditions. The sections below document the test setup and procedures for each phase of testing.

Axial Tension and Compression Test Fixtures

The axial tension and compression test fixture, shown in Figure 5 and Figure 6, used a hydraulic cylinder to apply load through the sample's flange. Hydraulic pressure was locked into the cylinders at the desired load. The cylinder and sample were mounted to an I-beam that acted as the strongback (i.e., reaction member). To prevent buckling during compression, anti-buckling supports were placed around the test sample as shown in Figure 6. A 20-kip (89.0 kN) load cell and pressure transducer, shown in Figure 7, continuously monitored load and internal pressure respectively throughout testing. The target axial tension and compression forces for the test program were 6,000 lbf and -6000 lbf, respectively (±26.7 kN). The 6,000 lbf (26.7 kN) load represents 50% of FlexSteel's 4-inch 1,500 psig (10,340 kPa) pipe axial tension load capacity.

Bend Fixtures

The bending fixtures were designed to hold the pipe samples at the operating MBR for the test duration. The operating MBR for the FlexSteel 4-inch diameter 1,500 psig (10,340 kPa) pipe was 3.6 feet (1.1 meters). The bend fixtures for this test program were fabricated at 4 feet (1.2 meters). Figure 8 illustrates the bend fixture for the baseline pipe samples that were approximately 2 meters in length. The sample was bolted to the frame at the steel end connections using U-bolts. The internal weld samples in Figure 9 had the same bending radius as the baseline pipe but required larger fixtures due to their 6-meter length.

The test program included one (1) midline fitting sample that was designated for static testing at the MBR. Aligning with FlexSteel installation and operating requirements, the operating MBR was applied to the baseline pipe on either side of the midline fitting as shown in Figure 10. The end connections of the sample were connected using a strap to prevent the sample from straightening during testing.

Torsion Fixtures

Additional fixtures were fabricated to apply a secondary torsion load to the static and cyclic pressure samples. The torsion test fixtures, shown in Figure 11 and Figure 12, fixed one end of the FlexSteel sample to the frame and allowed the other end to rotate in a bushing. Since the as-received FlexSteel samples had a residual curvature from storage on the reel, they were pulled straight using a hydraulic cylinder. A tensile load was not actively maintained in the sample prior to application of torsion.

Once the samples were installed into the frame, torque was applied to rotate the samples 7° as measured by an inclinometer. The samples were welded to the frame in this position. Following welding and removal of the applied torque the resulting rotation of each sample was approximately 6°.

Mechanical Damage

The test program included five static tests to characterize the effect different damage mechanisms had on the short-term burst pressure of the pipe. The static tests were abbreviated S2 through S6 as listed in Table 3 and included wall loss to the outer HDPE cover and damage to the internal steel reinforcement. Shown in Figure 13 is an intentionally damaged test sample that included a 100% cover wall loss of the cover. Testing also included damage to the steel reinforcement layer.

TEST RESULTS

Figure 14 illustrates a typical test setup for a static burst with no secondary load. Static tests were performed in a test chamber or a cordoned off area located a safe distance from test personnel. Water was the test fluid for all samples, except for one specific static test that used nitrogen gas. A pressure transducer monitored internal pressure throughout each test. All tests were completed at ambient temperature. The static burst tests were conducted per API 15S requirements.

Figure 15 shows one of the cyclic pressure test setups from the test program that included a combined axial tension load. Water was the test fluid for the cyclic tests and a pressure transducer monitored internal pressure throughout testing. Typically, samples were plumbed in parallel to allow for simultaneous cycling. The pressure range for the cycles was R=0.1, 150 to 1,500 psig (1,030 to 10,340 kPa). All cyclic tests ran until either failure or a runout condition of 100,000 cycles was reached. A typical cycle rate over the course of the test program was 6-8 cycles per minute.

The overall results of this test program indicate that the FlexSteel spoolable technology performs well in both static and cyclic combined loading conditions. The next two sections discuss observations from the static and cyclic tests, respectively.

Static Test Results

All static samples in this test program burst above the 3,000 psig (20,680 kPa) requirement of API 15S Section 5.2.5., which was established as a minimum benchmark burst pressure for the current study. Figure 16 plots the failure pressures of the "combined load" and "static samples" for comparison purposes. The burst pressures between the two groups were similar in both the average and standard deviation as listed below. From comparison of these results, it is evident that the combined loads had minimal effect on the static failure pressures.

- Static Only (No Secondary Load)
  - Average 3,245 psig (22,370 kPa)
  - Standard Deviation 150 psig (1,040 kPa)
- Combined Loading
  - Average 3,320 psig (22,890 kPa)
  - Standard Deviation 122 psig (840 kPa)

The static pressure test performed with nitrogen gas showed no evidence of longitudinal propagation, with the failure location limited to the pre-existing damage location (to initiate a failure).

Cyclic Test Results

Like the performance of the static load cases, most of the cyclic samples reached the runout condition of 100,000 cycles without failure, regardless of the secondary load. The combined loading scenario where this was not true was the axial compression. The three axial compression samples failed below 53,000 cycles. It is important to note that the approximate 6000 lbf (26.7 kN) compressive load applied to these samples exceeds what would normally be experienced in the field and was applied to establish a limit load case. In the field, flexibility will move the pipe out of the plane of loading and thus relieve the force (i.e. pushing a rope). Analysis of the loads on the steel strip confirmed that the combined cyclic and compression load exceeded the yield strength of the steel, thus failure was not unexpected.

CONCLUSIONS

This paper has included details on the test setup, procedure, and results of TC Energy's assessment of the FlexSteel spoolable pipe technology. The goal of this test program was to validate that the FlexSteel technology was suited for TC Energy's rehabilitation needs in gas transmission service. Several important findings of the test program are summarized in the bullets that follow.

- Combined loadings did not have a noticeable effect on the static failure pressures of the samples in this test program. There was little difference between the average failure pressures of samples with a secondary load to those without.
- The FlexSteel product performed well in cyclic loading conditions, with many of the combined loading samples reaching the runout condition of 100,000 cycles. Axial compression loading had the most noticeable effect on fatigue life with all samples failing in less than 53,000 cycles but it was noted that this is an atypical loading condition.
- Simulated damage to the outer HDPE cover of the pipe had no noticeable effect on the static failure pressure.

The results of the testing program provide added assurance, additional to the API 15S qualification requirements, towards the ability of the FlexSteel spoolable technology to operate safely in gas transmission service. Considering the uniqueness of every spoolable pipe technology, the API 15S qualification requirements can only address the broad failure mechanisms and cannot fully address specific testing for each technology. The completion of a product specific testing program can address specific potential failure mechanisms, minimizing risk in a rehabilitation application.

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3. CAN/CSA-Z662-19, Oil and Gas Pipeline Systems, published by the Standards Council of Canada, 2010.

Table 1: Spoolable Pipe Users Group Technology Assessment Roadmap

Technical Performance Criteria	Actual Service Installation	Standards	Independent Research (Mfg - Operators)	US Regulations	Joint Industry Research	Average
Design						
Long-term performance	3	3	2	1	1	2
Combined loading: Pressure + Tension	3	2	2	1	1	1.8
Combined loading: Pressure + Bending	3	3	3	1	1	2.2
Combined loading: Pressure + Temperature	3	3	3	1	1	2.2
Combined loading: Torsion	3	1	2	1	1	1.6
Cyclic Loading	3	2	2	1	2	2
External Loads	3	3	2	1	1	2
Fittings / Connections loading (same as combined loading)	3	3	3	1	1	2.2
Impact resistance	3	3	2	1	1	2
Thermally induced loads (global)	3	2	2	1	1	1.8
Offshore collapse	3	1	3	1	1	1.8
Surge loads	3	1	2	1	1	1.6
Annular pressure build up (liner collapse/cover blow-off)	3	3	3	1	1	2.2
Post construction / FFS / Inspection						
Inspectability	1	1	1	1	1	1
Inspection Technology (NDT)	1	1	1	1	1	1
Monitoring	2	1	2	1	1	1.4
FFS	2	1	2	1	1	1.4
Third party damage	3	1	2	1	1	1.6
Hot tapping	1	1	1	1	1	1
Repair methods	3	1	2	1	1	1.6
Internal cleaning durability	3	1	2	1	1	1.6
Road crossing	3	2	2	2	2	2.2
Installation / QC						
Installation /construction practices (including HDD)	3	1	2	1	1	1.6
Installer qualifications (training)	2	1	2	1	1	1.4
QA / QC of Installation Practices	2	2	1	1	1	1.4
QA / QC of manufacturerd product	3	3	3	1	1	2.2
Inspection of fittings and connections	3	2	3	1	1	2
Service Conditions / Environment						
Product content (e.g. H2S)	3	3	3	1	1	2.2
External environment (soil type, climate)	3	2	2	1	1	1.8
Toxic release / permeation	3	2	2	1	1	1.8
UV Resistance	3	3	3	1	1	2.2
Corrosion resistance of fittings (coatings and cp)	3	3	3	1	1	2.2
Wear / erosion	3	1	2	1	1	1.6

Color Code	
3	Work performed in this area
2	Moderate/limited experience
1	Minimal to no experience

Table 2: Summary of test variations

Internal Pressure	Combined Loads	Damage Mechanisms	Sample Configuration
Static Cyclic	Axial Tension Axial Compression Bending Torsion	Outer Cover Wall Loss Steel Reinforcement Damage Wall Loss Effect on Annulus Pressure	Baseline Pipe Internal Welds Midline fittings

Table 3: Sample abbreviations for combined loading sample configurations and damage mechanisms

Abbreviation	Test Description
S	Static Burst
CP	Cyclic Pressure
AC	Axial Compression
AT	Axial Tension
B	Bending
T	Torsion
IW	Internal Weld
MC	Midline Fitting
S2	50% Wall Loss in HDPE Cover
S3	100% Wall Loss in HDPE Cover
S4	100% Wall Loss in HDPE Cover + Damage to Steel Strips
S5	25% Wall Loss in HDPE Cover, Pressurized Annulus Only
S6	50% Wall Loss in HDPE Cover, Pressurized Annulus Only

Table 4: Static test sample listing
(Nomenclature shown in **BLUE** corresponds to labels used in Figure 16)

Test Description	Secondary Loading
Static Pressure – **S**	None
Static Pressure Test #2 (Cover 50% Wall Loss) – **S2**	
Static Pressure Test #3 (Cover 100% Wall Loss) – **S3**	
Static Pressure Test #4 (Cover 100% Wall Loss plus Strip Damage)	
Static Pressure Test #5 (Annulus 25% Wall Loss)	
Static Pressure Test #6 (Annulus 50% Wall Loss)	
Static Pressure with Internal Weld– **S + IW**	
Static Pressure + Axial Tension– **S + AT**	6,000 lbf or 26.7 kN
Static Pressure + Axial Compression– **S + AC**	-6,000 lbf or -26.7 kN
Static Pressure + Bending– **S + B**	Bend Radius 4-feet or 1.22-meters
Static Pressure + Bending with Mid-line Connector– **S + B (MC)**	
Static Pressure + Torsion– **S + T**	600 ft·lbf or 813 N·m
Gas Burst Test (100% Cover Wall Loss with Reinforcement Damage) (16 meter length sample)	None

Table 5: Cyclic pressure test sample listing

Test Description	Secondary Loading
Cyclic Pressure	No Secondary Loading
Cyclic Pressure	
Cyclic Pressure	
Cyclic Pressure + Axial Tension	6,000 lbf or 26.7 kN
Cyclic Pressure + Axial Tension	
Cyclic Pressure + Axial Tension	
Cyclic Pressure + Axial Compression	-6,000 lbf or -26.7 kN
Cyclic Pressure + Axial Compression	
Cyclic Pressure + Axial Compression	
Cyclic Pressure + Bending	Bend Radius 4-feet or 1.22-meters
Cyclic Pressure + Bending	
Cyclic Pressure + Bending	
Cyclic Pressure + Bending with Internal Weld	Bend Radius 4-feet or 1.22-meters
Cyclic Pressure + Bending with Internal Weld	
Cyclic Pressure + Bending with Internal Weld	
Cyclic Pressure + Torsion	Torque to achieve 6° Rotation
Cyclic Pressure + Torsion	
Cyclic Pressure + Torsion	

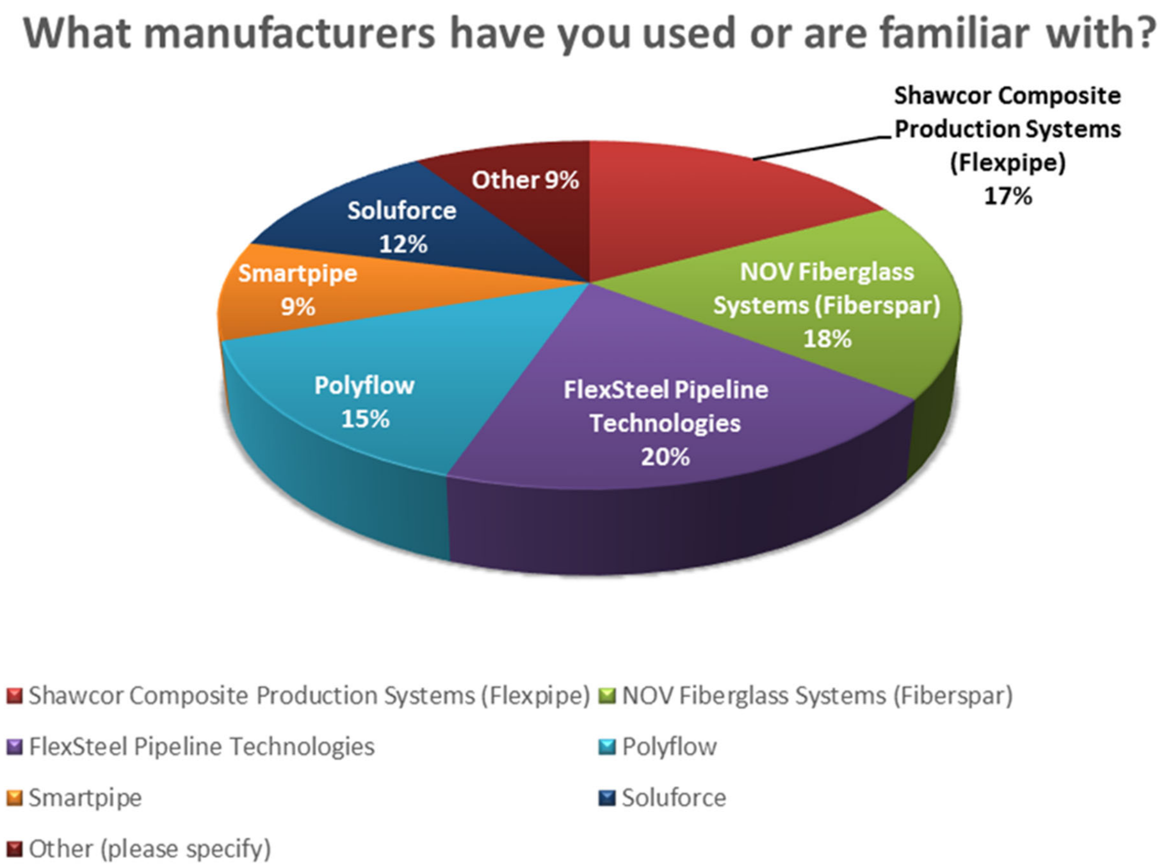

Figure 1: Survey question – ***With what manufacturers are you familiar?***

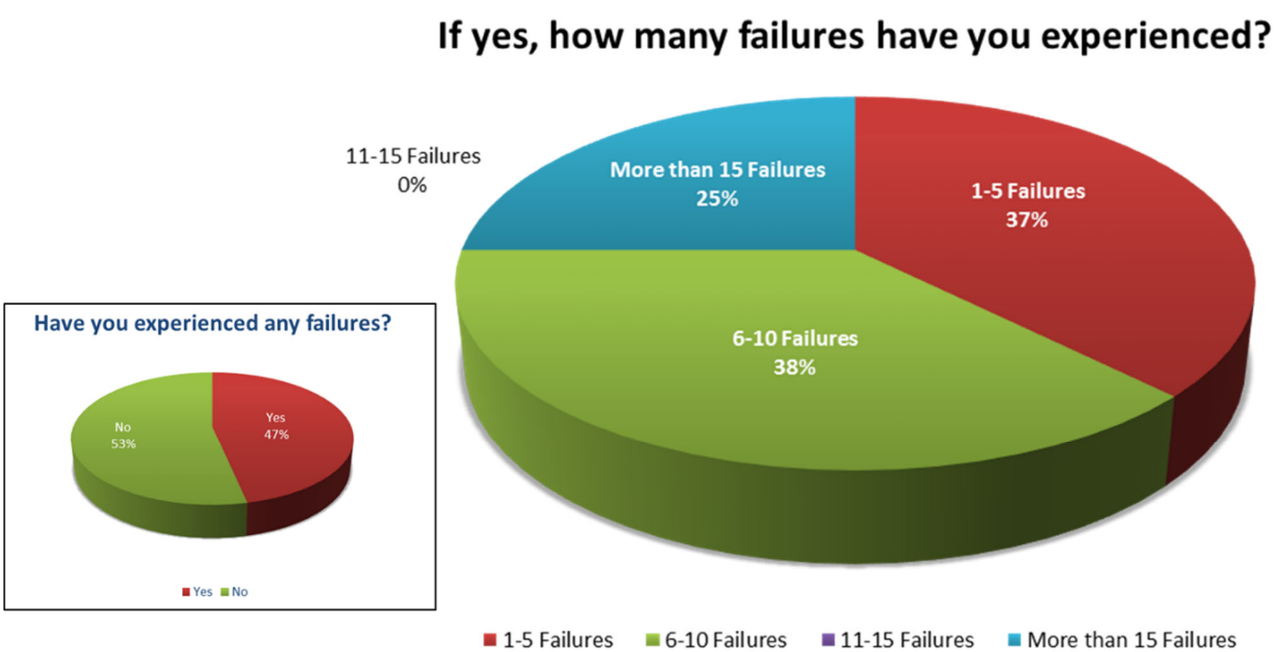

Figure 2: Survey question – ***Have you had failures and if so, how many?***

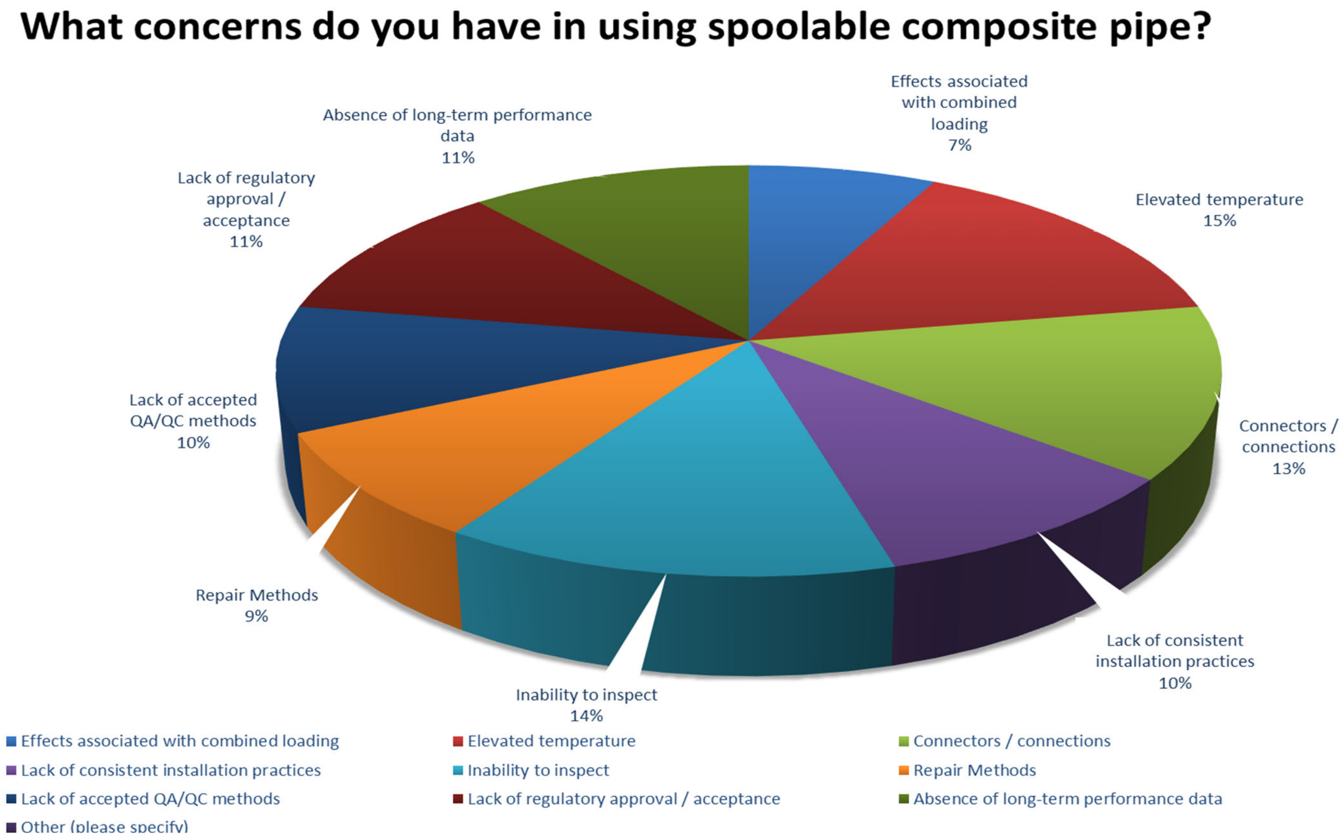

Figure 3: Survey question – What concerns do you have in using spoolable pipe?

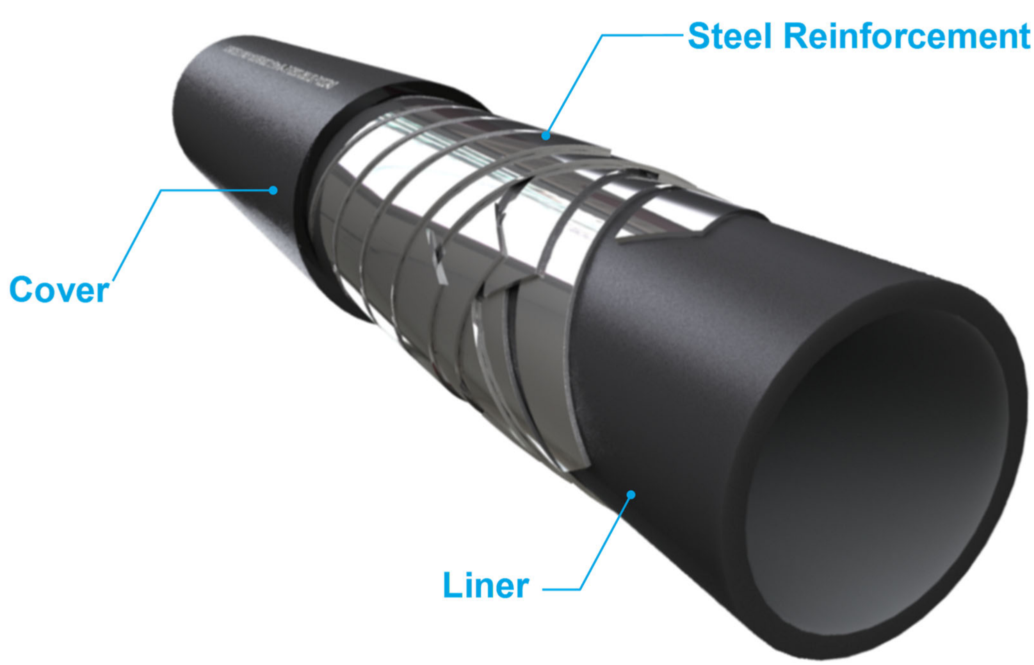

Figure 4: Schematic diagram showing a cut-away of the FlexSteel® spoolable pipe technology

Figure 5: Axial tension / compression test fixture

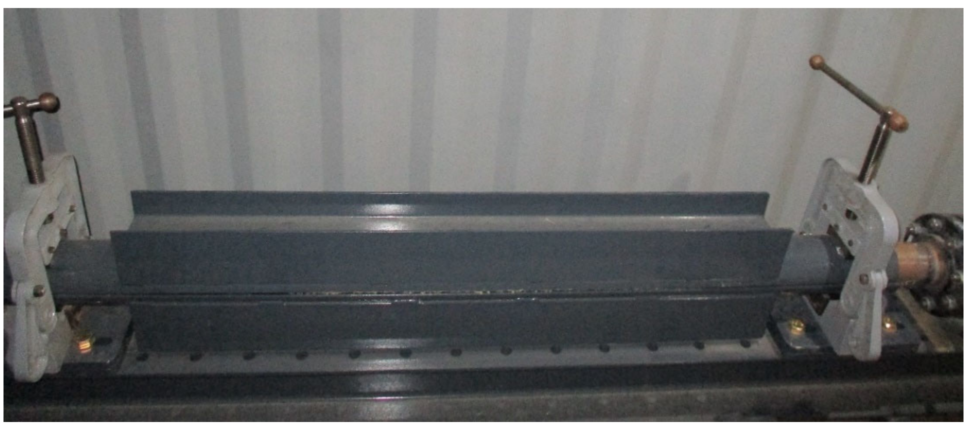

Figure 6: Axial compression test fixture with anti-buckling supports

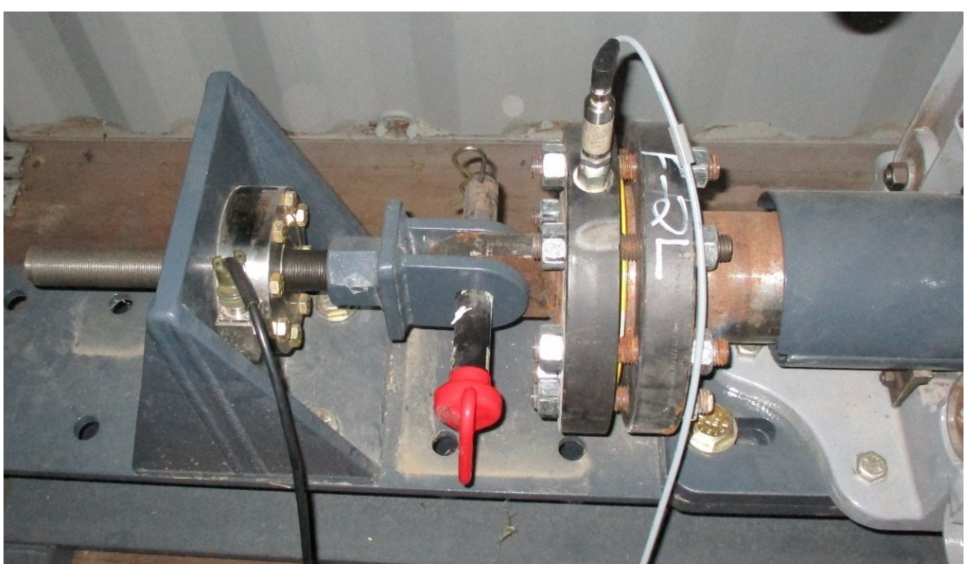

Figure 7: Tension/compression load cell and pressure transducer

Figure 8: Minimum bend radius fixture for standard samples

Figure 9: Minimum bend radius fixture for internal weld samples

Figure 10: Bending fixture for midline fitting sample

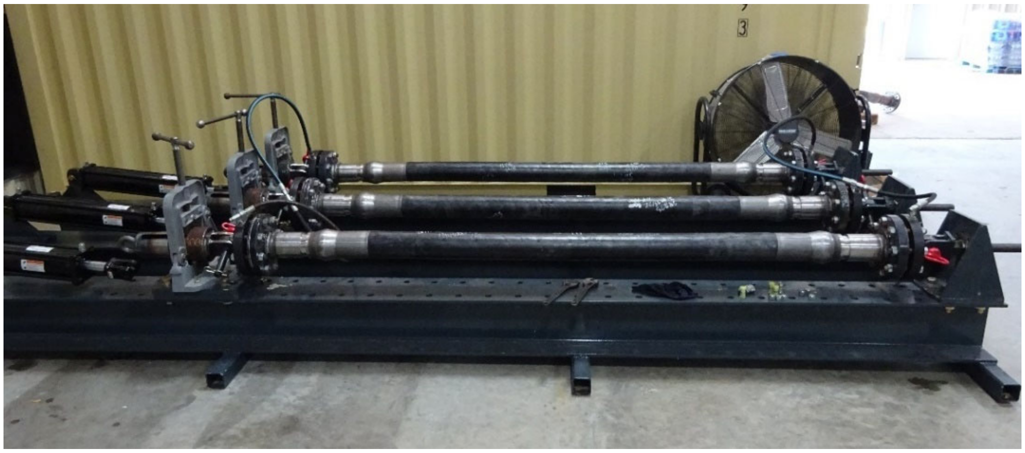

Figure 11: Torsion fixtures for static and cyclic testing

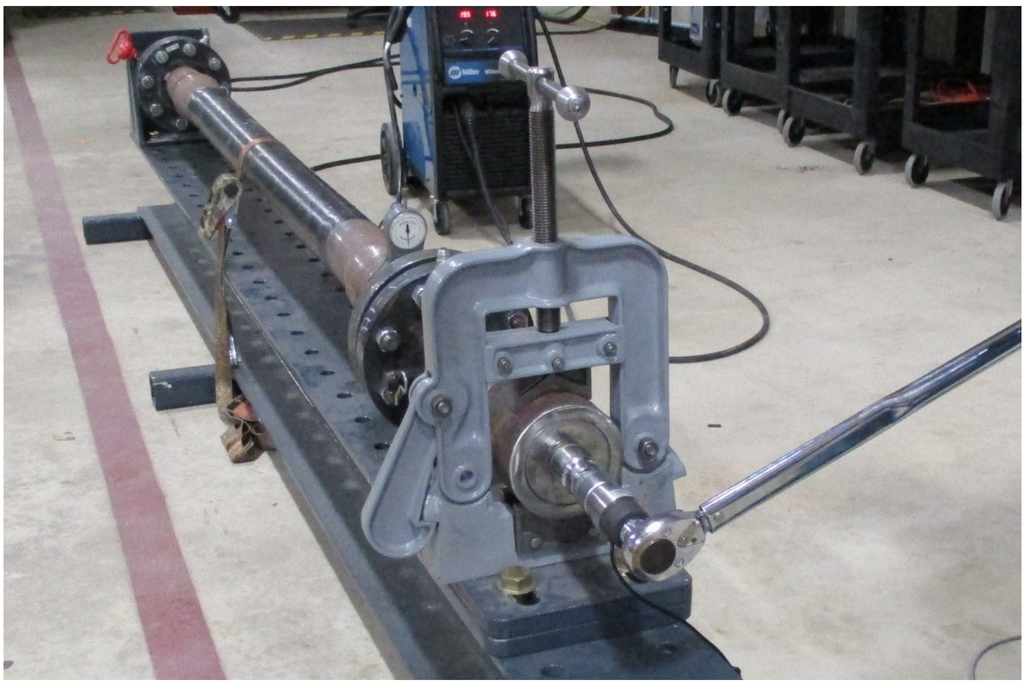

Figure 12: Torsion measurement with torque cell and torque wrench

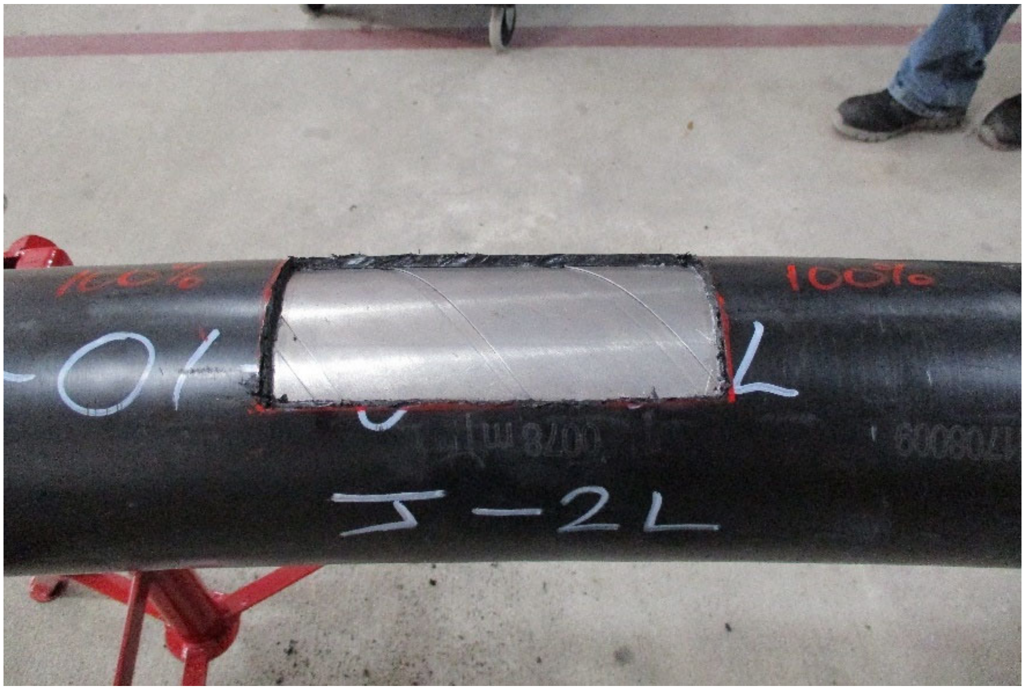

Figure 13: 100% wall loss to HDPE outer cover

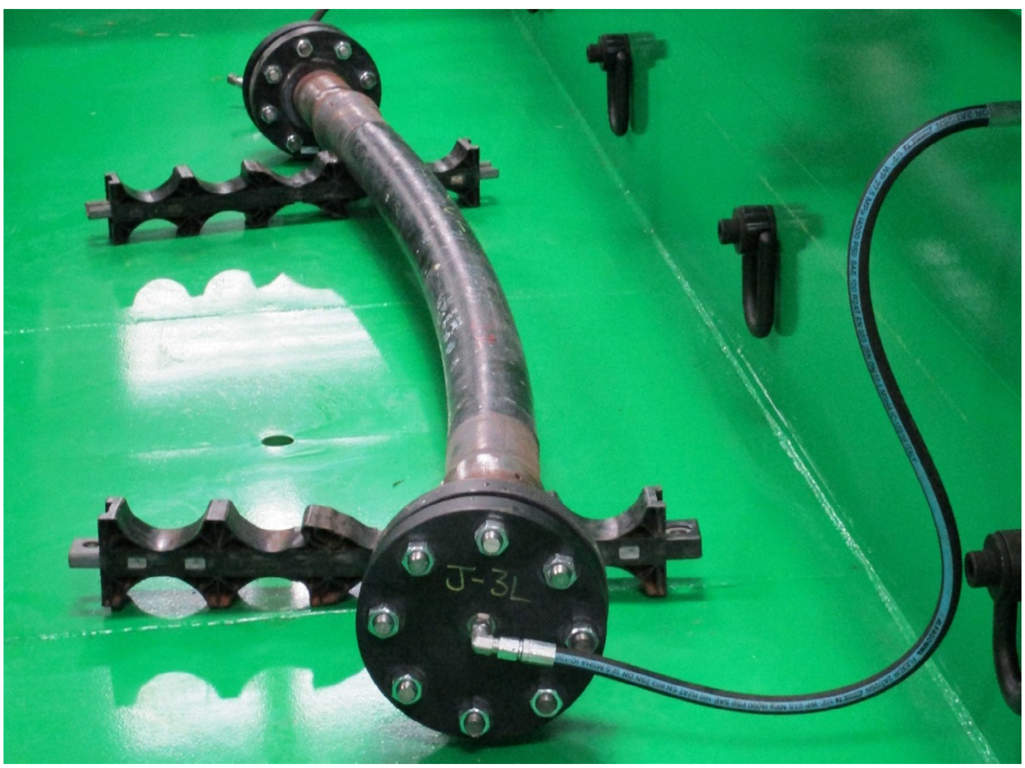

Figure 14: Example static test setup

Figure 15: Example cyclic pressure test setup (cyclic pressure with tension)

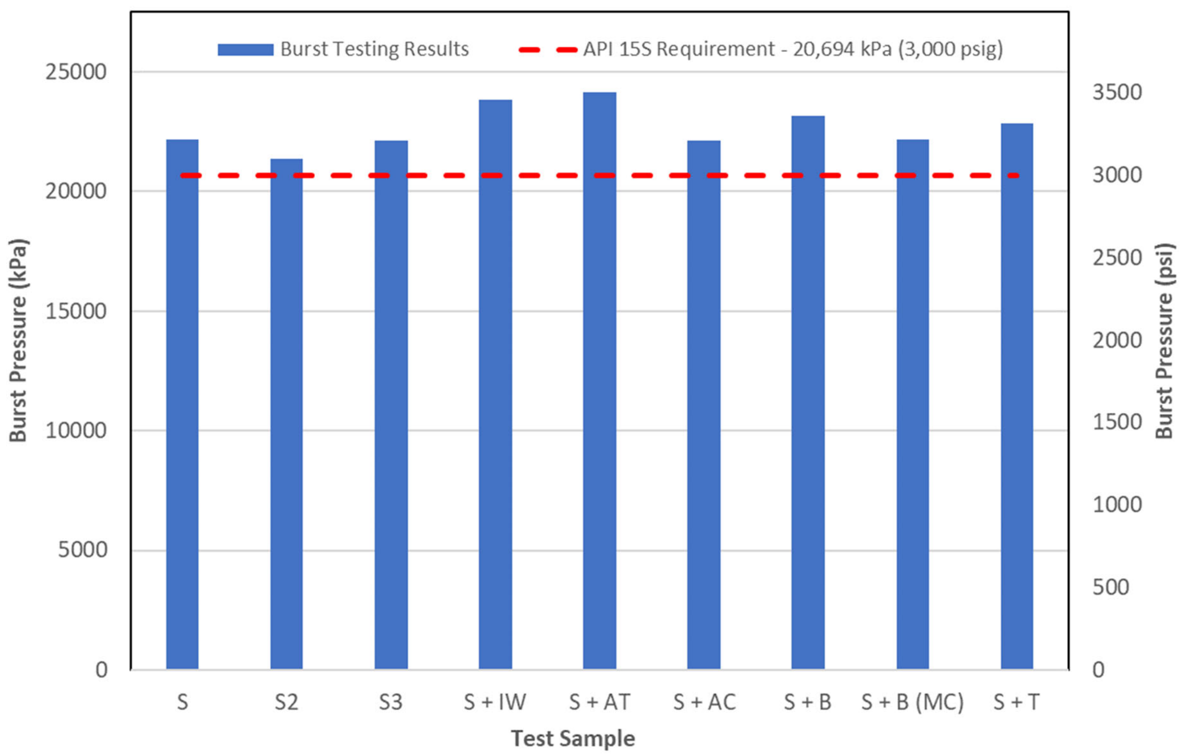

Figure 16: Comparison of static sample burst pressures for combined loading vs. static