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Experimental Evaluation of Newly Developed InfinitPipe®

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Executive Summary

This report presents results of controlled laboratory tests performed on newly developed *InfinitPipe*®, consisting of a 3-D glass fabric saturated with resin and sandwiched between layers of resin-saturated carbon fiber plastic. The report is comprised of two (2) sections as follows:

- Evaluation of Short-Term Behavior
- Numerical Modeling

Tests conducted for evaluating the short-term performance of the *InfinitPipe*® and the numerical simulation, are listed in Table 1.

Table 1: Test Matrix for Short-Term Evaluation of *InfinitPipe*®

Test Series	Description	Standard	No. of Specimen
Short-Term Tests (STT)			
1	Parallel Plate Test	ASTM D2412	5
2	Impact Resistance Test	ASTM D2444	10
3	Deflection Test under Applied Over Burden Pressure	-	1
4	Buckling Test		2
5	Static Burst Test	ASTM D1598	3
6	Tensile Test	ASTM D638	5
7	Bending Test	ASTM D790	10
8	Hardness Test	ASTM D2240	10
Numerical Simulation (NS)			
-	Numerical model was developed using SolidWorks®	-	-

Overall the *InfinitPipe*® product was found to perform well under mechanical loading, either monolithically applied or impact load. Furthermore, the overall response of the pipe to external soil loads during a direct buried test under simulated 25 ft of overburden pressure was found to be satisfactory, demonstrating the ability of the product to serve as a stand-alone pipe. The testing program revealed the need for a 0.25" impervious layer on the inside of the carbon and glass fibers envelop to enhance the pressure retaining capabilities of the pipe. Other modifications undertaken by QuakeWrap, including moving from a honeycomb structure to a 3-D fabric and switching to a heat cure resin resulted in significant improvement in the ability of the product to withstand loads. Another benefit of adding the HDPE inner core is simplifying connection to standard HDPE flanges, utilizing standard buff-fusion practices.

Additional testing recommended for Phase II include long-term static and cyclic pressure tests (following ASTM D2992), additional burst pressure tests on specimens fabricated using the newly developed automatically welded HDPE inner core technology (following ASTM D1599) and long-term creep test of the composite material (following ASTM D2990).

Materials Tested and Numerical Simulation Performed

Development of the *InfinitPipe*® was an evolving process to obtain a better pipe product. Therefore, pipe materials were modified to tackle challenges during the short-term tests and later continued with the same material until a new challenge rise.

Samples made of three (3) different combinations of materials (see Table 2) were received based on which numerical model was developed and short term tests were performed. Numerical simulation was performed based on the first sample (Type-1) received and continued. During the short term tests it was found that InfinitPipe® constructed of material combinations Type-2 had leaks when subjected to buckling test (STT-4) although the samples exhibited good results during STT-1,-2, and -3. Therefore, a HDPE sheet was introduced at the inner side of the pipe which was named as Type-3. This type was subjected to STT-5. Again, for STT-6,-7, and -8 samples were prepared from the panel made as Type-2 and later tested.

Table 2: *InfinitPipe*® Materials Type and Tests Performed

***InfinitPipe®* Material**	**Description**	**STT / NS**
Type-1 (see Figure 1)	*InfinitPipe®* embedded with honey comb structure inside layers of carbon fiber and glass fiber.	NS
Type-2 (see Figure 2 and Figure 3)	*InfinitPipe®* manufactured using 3D fabrics and which consists of the following layers from inside towards the outside: • Two (2) layers of veil • Single layer of QuakeWrap TU27C Unidirectional Carbon Fabric • Single Layer of QuakeWrap TB20C Biaxial Carbon Fabric • Single Layer of 8mm thick 3D Glass Fabric cut in a 6-inch wide band and helically wrapped around the pipe • Two (2) Layers of QuakeWrap VB26G Glass Fabric	STT-1 STT-2 STT-3 STT-4 STT-6 STT-7 STT-8
Type-3 (see Figure 4)	*InfinitPipe®* manufactured using 3D fabrics and which consists of the following layers from inside towards the outside: • A 1/8" thick HDPE sheet heat-welded along the seam to create a 12" diameter x 4-ft long tube • 1 layer of QuakeWrap TU27C Unidirectional Carbon Fabric • 1 Layer of QuakeWrap TB20C Biaxial Carbon Fabric • 1 Layer of 8mm thick 3D Glass Fabric cut in a 6-inch wide band and helically wrapped around the pipe (was this included? Shaurav: please verify.) • 2 Layers of QuakeWrap VB26G Glass Fabric	STT-5




Figure 1: Specimen Type-1 Honey Comb Structure

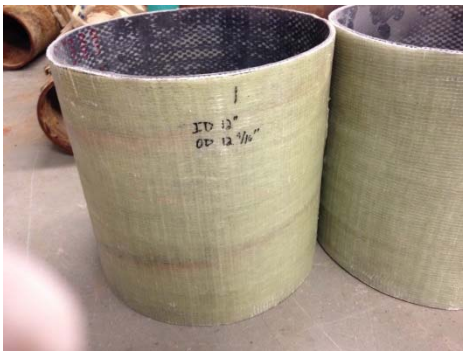



Figure 2: Specimen Type-2 3D Fabric Pipe




Figure 3: Specimen Type-2 3D Fabric Flat Panel




Figure 4: Specimen Type-3 3D Fabric HDPE Lining Inside

Short-Term Tests

STT-1: ASTM D2412 – Parallel Plate Test

Five (5) 1'-0" long specimens were cut from 12" ID *InfinitPipe*®. Average thickness was calculated based on the thickness measured using a slide caliper at ten (10) locations along the perimeter. The diameter of the pipe product was measured using a Pi Tape® (see Figure 5).



Figure 5: Measurement of Specimen Thickness (left) and Diameter (right)

Next, the length of each specimen was measured and recorded (see Figure 6). On the odd-numbered specimens, the seam was located at the crown–invert plane while on even-numbered specimen the seam was located at the spring line plane.



Figure 6: Measurement of Length of the Specimen (left) and Marked Specimens (right)

The specimens were placed inside the parallel plate and loaded at a rate of 0.50 in/min (see Figure 7). Final deflection value was set to 30% of the inner diameter (3.60 in.) of the pipe.

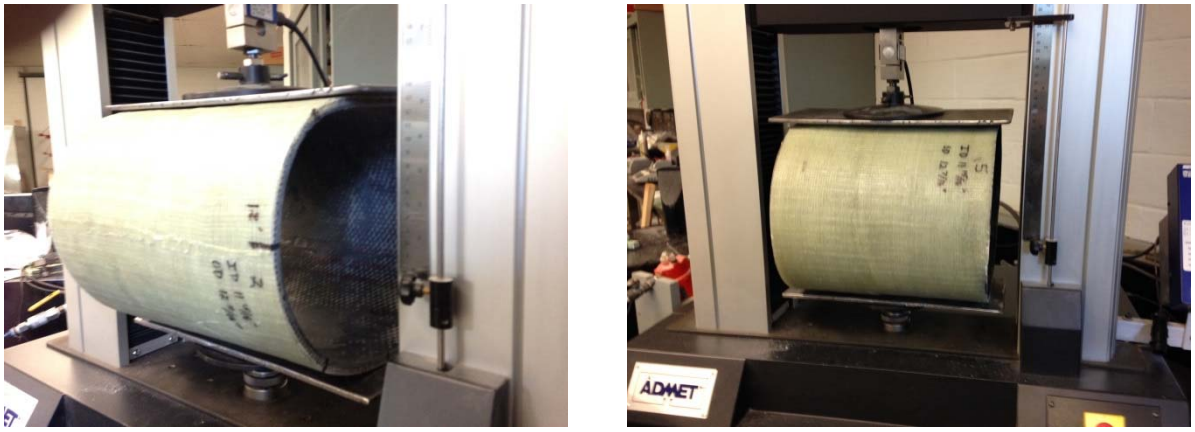


Figure 7: Application of Load on Specimen # 2 (left) and Specimen # 5 (right)

ASTM D2412 test results are shown in Figure 8, Table 3, and Figure 9. Load vs. Deflection curves for all the specimens are shown in Figure 8. The curves are divided into three segments. The moderate slope at the beginning (up to around 0.15 in. deflection) of the curve may be due to the result of initial adjustment of the load application mechanism. In the second segment, steep slope from around 0.15 in. to 0.75 in. shows elastic behavior of the sample. It was observed that for all the specimens the elastic relation exists between 1000 lbf to 1400 lbf. After that, flat slope indicated failure and cracks in the specimen.

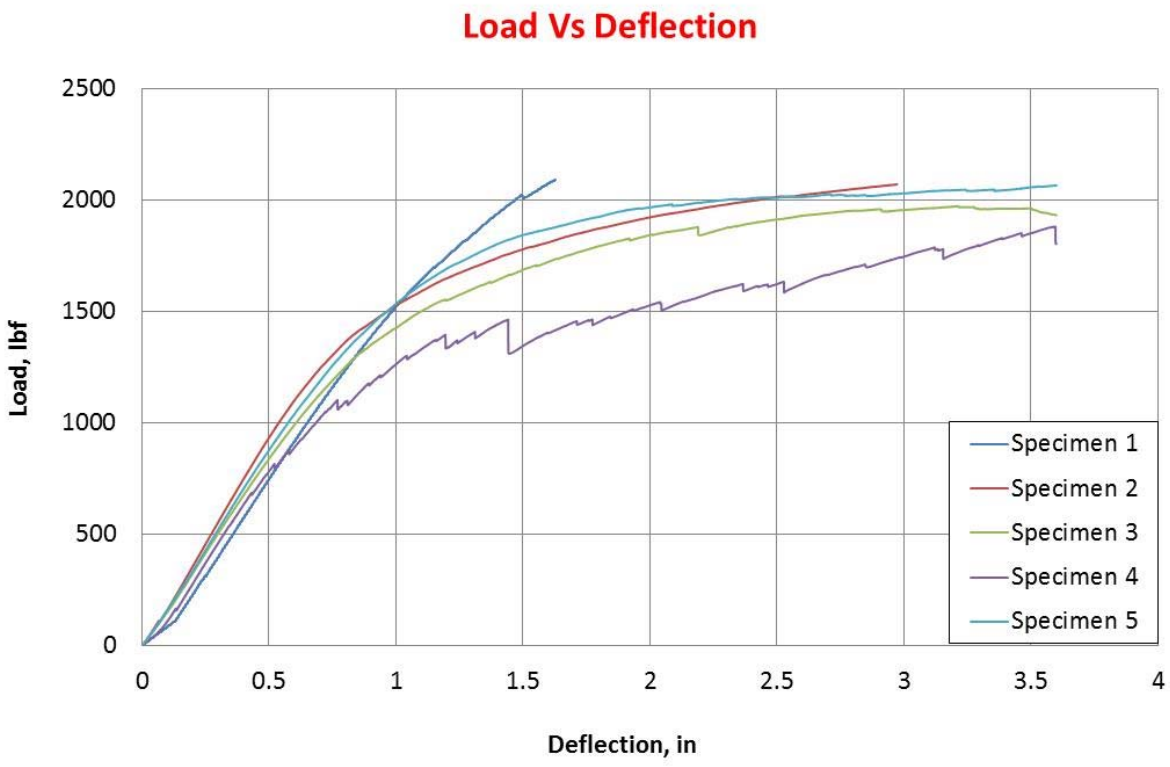


Figure 8: Load - Deflection Curve of the Five (5) Specimens

The average stiffness factor and modulus of elasticity were calculated based on the 5% deflection, which means 5% change of the inside diameter (see Table 3). Average stiffness factor was found to be around 4500 lbf-in and modulus of elasticity was above 1,000,000 psi. Crack propagation was observed along the seam for most specimens at full deflection and the average modulus of elasticity value was calculated close to 800,000 psi (see Table 4). Average stiffness at 5% deflection was found around 140 psi while it reduced around 57% for full deflection. Ability of the specimens tested to resist overburden load is considered adequate for a wide range of practical applications.

Table 3: ASTM D2412 Test Results at 5% Deflection

Parameter	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Average
Outer Diameter, in	12.45	12.73	12.74	12.75	12.70	12.68
Length, in	12.17	12.04	12.09	12.09	12.19	12.12
Thickness, in	0.30	0.38	0.38	0.40	0.35	0.36
Load, lb	930.25	1,118.90	1,017.98	915.88	1,067.87	1,010.18
Load, lb/in	76.44	92.93	84.20	75.76	87.60	83.39
Deflection, in	0.59	0.60	0.60	0.60	0.60	0.60
Stiffness, psi	129.56	154.89	140.33	126.26	146.00	139.41
Correction Factor	1.08	1.08	1.08	1.08	1.08	1.08
Stiffness Factor, lbf-in	4,017	4,948	4,495	4,022	4,704	4,437.14
Modulus of Elasticity	1,905,501	1,160,879	1,045,145	840,357	1,423,808	1,275,138

Table 4: ASTM D2412 Test Results at Full Deflection

Parameter	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Average
Outer Diameter, in	12.45	12.73	12.74	12.75	12.70	12.68
Length, in	12.17	12.04	12.09	12.09	12.19	12.12
Thickness, in	0.30	0.38	0.38	0.40	0.35	0.36
Load, lb	2,090.52	2,071.14	1,973.47	1,881.83	2,066.67	2,016.73
Load, lb/in	171.78	172.02	163.23	155.65	169.54	166.44
Deflection, in	1.63	2.97	3.21	3.59	3.60	3.00
Stiffness, psi	105.57	57.89	50.83	43.38	47.10	60.95
Correction Factor	1.22	1.42	1.46	1.52	1.52	1.43
Stiffness Factor, lbf-in	3,273.76	1,849.20	1,627.81	1,381.73	1,517.53	1,930.01
Modulus of Elasticity	1,760,214	572,201	512,570	407,657	648,603	780,249

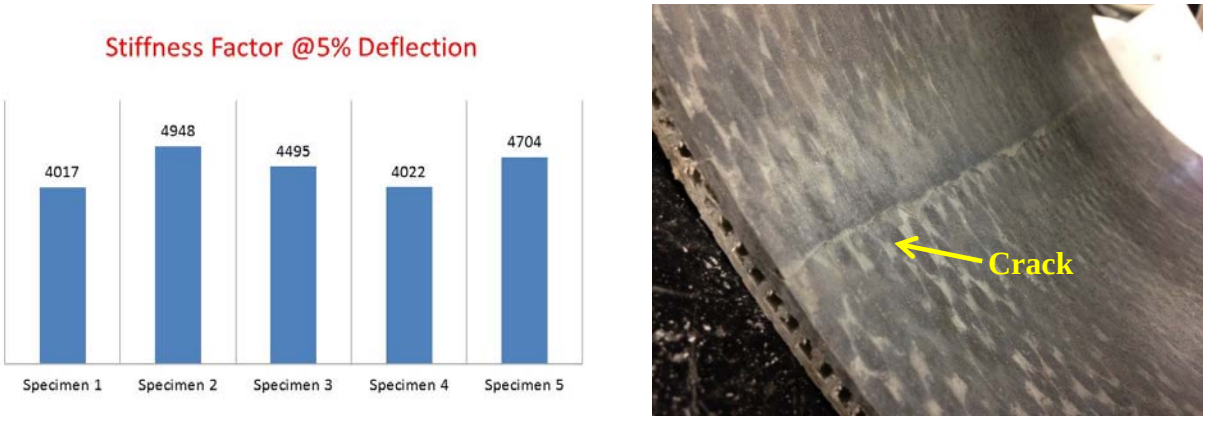


Figure 9: Stiffness Factor of Tested Specimens (left) and Crack along the Seam (right)

STT-2: ASTM D2444 – Impact Test

Ten (10) 1'-0" long specimens were cut from a 12" ID *InfinitPipe*®. Average thickness, length, and outer diameter (OD) were calculated. Room temperature was also monitored and found to be 72°F. A Charpy impact test device, capable of measuring the energy absorbed by the pipe's wall when subjected to an impact load, was utilized. The impact head was replaced by a Tup Type B, as mentioned in ASTM D2444 (see Figure 10).



Figure 10: Head of the Charpy – Before Modification (left) and After Modification (right)

The scale on the instrument was calibrated to measure the energy imparted upon the pipe's wall as a free swinging weight (pendulum) positioned at 120° to the pipe's wall, was released. The specimen was positioned and securely clamped or strapped to a platform bolted to the base of the Charpy. The weight was positioned at an angle of 120°, locked, and released. As the Tup hit the specimen, the gauge on the dial moved from 120 ft-lb to a reading which was interpreted as the energy absorbing capacity of the material (see Figure 11).



Figure 11: Impact head swung to 120° (left); Reading on the Gauge (right)

The energy absorbed by the specimens is shown in Table 5. The average absorbed energy was found 119.50 ft-lb (162 Joules) which is close to anneal steel. For anneal steel similar tests produced around 119 ft-lb of energy. ASTM D2444 suggests testing a minimum of 110 specimens, but only ten (10) specimens were tested due to the limited number of available samples.

Table 5: ASTM D2444 Test Results

Sample	Thickness, in	Energy Absorbed, ft-lb
1	0.38	119.6
2	0.38	119.5
3	0.39	119.5
4	0.37	119.5
5	0.36	119.5
6	0.34	119.5
7	0.36	119.5
8	0.37	119.5
9	0.35	119.4
10	0.33	119.3
Average	*0.36*	*119.5*

STT-3: Deflection Test Under Applied Over Burden Pressure

Soil Chamber

The soil testing apparatus used in this test was 6'-0" wide × 12'-0" long and 5'-0" deep. On the opposite short walls of the soil box, two steel plates with 16 in. diameter circular openings were fabricated and slid through a pair of collars (see Figure 12).



Figure 12: 16 in. dia. Openings Enable Ease of Placement of the Pipe Product in the Soil Box

Next, the peripheral walls and the bottom of the soil box were covered with three layers of polyethylene sheets. Lubrication (AC Delco – Automotive Axle Grease) was applied in between the layers to ensure minimum friction between the soil and the chamber's walls (see Figure 13). Then, the soil box was filled with a 12 in. layer of SB2 soil (hard small rocks usually used for non-paved driveways), compacted (see Figure 13) each time using a single direction plate compactor at 6 in. layer, and covered with 6 in. of compacted silty-sand which reached the invert of the *InfinitPipe*®. Thus, minimum vertical global movement due to the applied over burden load was ensured, while a smooth surface at the invert of the pipe was provided.



Figure 13: Polyethylene Sheet on the Sidewalls of the Soil box (left) and Compaction of SB2 Type Soil (right)

Placement of EPCs

Five earth pressure cells (EPCs) were placed in the vicinity of the pipe specimen; one located at 2" above the crown, another 2" beneath the invert, and another 2" from the pipe's surface at the haunch. Two more EPCs were placed at 2" from the spring line – one vertically and one horizontally. The positions of the EPCs are shown in Figure 14. The placement of EPCs ensured uniform contact area with the surrounding bedding material. This process lowers the risk of

developing concentrated stress on the EPCs. After the EPCs were placed, the soil box was filled with a 6 in. layer of silty-sand and compacted each time using the same plate compactor up to the inner edge of the soil box.

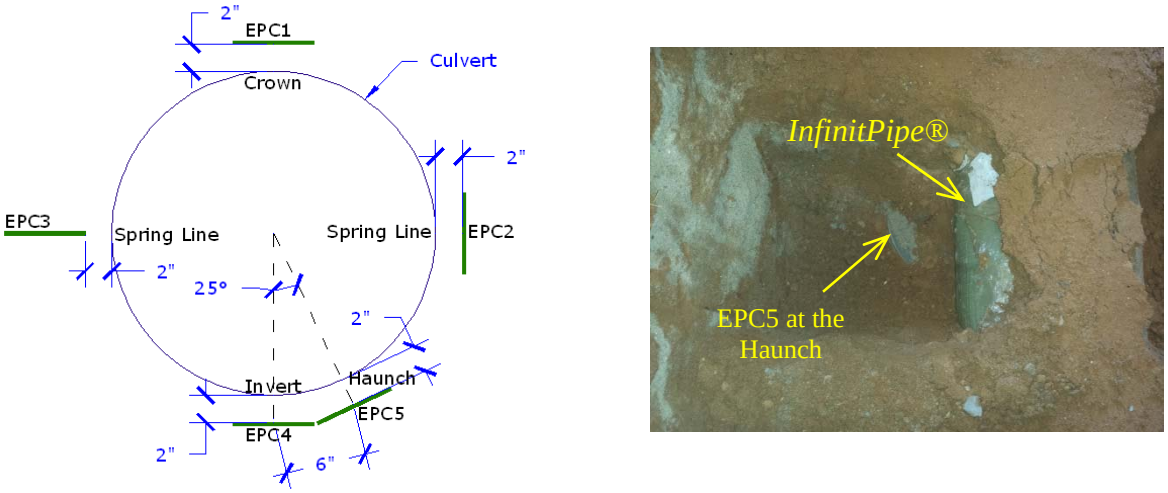


Figure 14: Arrangement of Earth Pressure Cells (EPCs) (left) and EPC5 at the Haunch (right)

Placement of the Lid

After the soil box was filled to the top, a ½" x ½" rectangular seal was glued to the top edge of the soil box, and a rubber bladder covering the seal was placed on top of the soil surface to ensure uniform pressure (see Figure 15) before the lead was placed.



Figure 15: Soil Chamber Filled with Bedding Soil (left) and Rubber Bladder Positioned on Top of the Soil Surface (right)

The lid of the soil box was comprised of two parts – a rigid top part and hollow bottom part. The bottom surface of the top part was coated using polyurea (SPI Aquaseal) to ensure a smooth surface and prevent air leakage through the top part. A ½" x ½" rectangular seal was glued on the top edge of the bottom part and both parts were bolted together. Thus, the lid was assembled with a polyurea coated inner surface. Provisions were kept to apply air pressure and record the applied pressure data using a pressure transducer in this part (see Figure 16).



Figure 16: Bottom Surface of the Top Part – Inverted (left), Top Edge of Bottom Part (middle), and Assembled Lid (right)

Next, a ½" x ½" rectangular seal was glued to the bottom of the assembled lid, which was placed on top of the soil box while aligning the holes used to connect the lid to the chamber's main body. The lid was then bolted using twenty-two ½" 13 TPI bolts. A low level of air pressure was applied to the soil inside the chamber, and soap water was applied along the seal to check for any leakages. The step by step setup is shown in Figure 17 and Figure 18.



Figure 17: Rectangular Seal Glued to Bottom of the Lid (left) and Lid being Placed on Top of Soil Chamber (right)

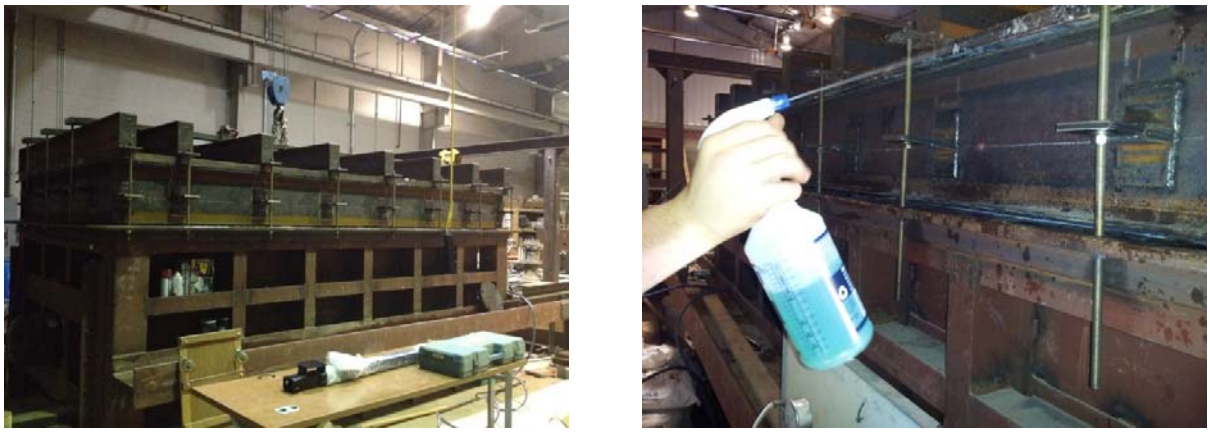


Figure 18: Lid Placed and Bolted on the Soil Chamber (left) and Check for Leakages (right)

Placement of LVDTs

A frame with four (4) LVDTs installed on it (see Figure 19) was positioned inside the pipe. The LVDTs provided continuous information regarding the displacement of the *InfinitPipe*® pipe specimen at the invert, crown, and spring-line regions at the center location along the length of the pipe specimens. The planned layout of LVDTs is shown in Figure 20.



Figure 19: LVDTs Installed on a Rigid Frame

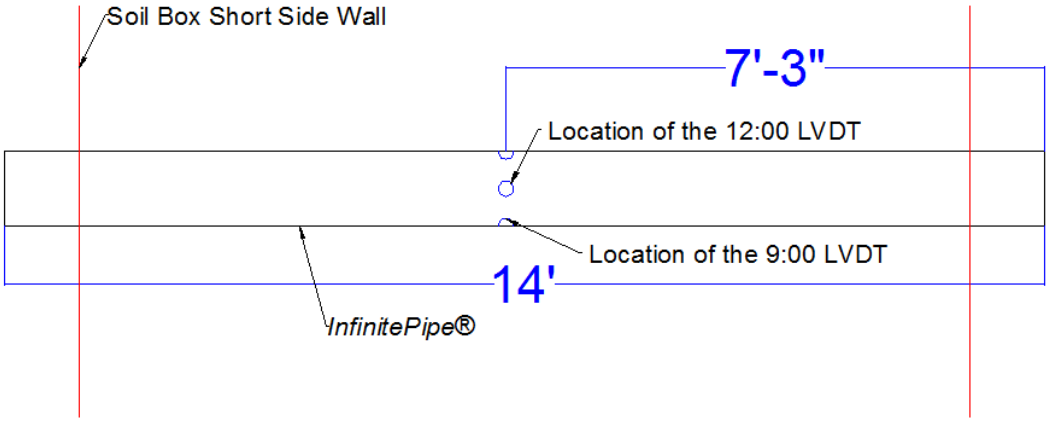


Figure 20: Planned location of LVDTs inside the *InfinitPipe*® pipe

Results

Air pressure was applied to the bladder which transferred the uniform stress on the surface of the soil located inside the soil box. Stress in soil is shown in Figure 21. Earth pressure cells in all five locations were recording similar stress for up to around 10 psi of applied over burden load. Later, EPC1 located 2 in. above the crown recorded higher stress in comparison to the others, indicating minimum or zero arching affect as the EPC3 located on the spring line (SL) positioned on the horizontal plane recorded lower value. Lower values recorded by the EPC4 and EPC5 indicated global movement (if any) absorbed by the silty-sand at the invert. Lowest value recorded by the EPC2 revealed no lateral stress produced by the side walls.

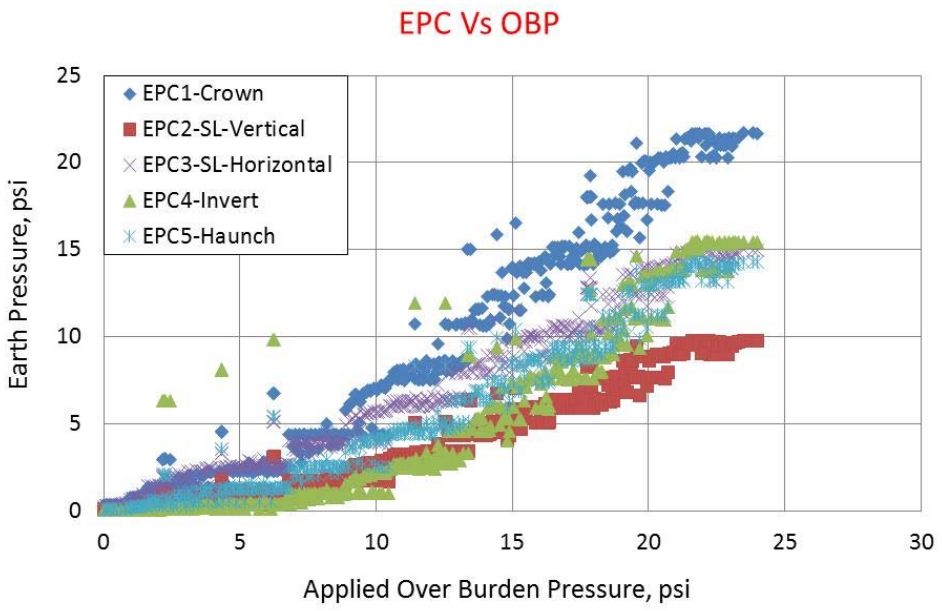


Figure 21: Stress Recorded by the EPCs

Deflection and vertical movement of the *InfinitPipe*® was measured using the LVDTs positioned inside around the center of the pipe. Analyzed data recorded by the LVDTs are shown in Figure 22. The data recorded by the LVDTs at positions 3 and 9 O'clock reveals no lateral expansion at the spring line of the *InfinitPipe*®. LVDT1 located at the crown showed maximum deflection at the crown was around 0.10 in, approximately 16% of the inner diameter. Readings obtained from LVDT1 were subtracted from those collected by LVDT4 located at the invert and showed around 0.25 in of global settlement or rigid body movement of the pipe (see Figure 23). Drop of the deflection readings after 0.10 in deflection by LVDT1 and 0.35 in deflection by LVDT4 are attributed to depressurization of the air bladder.

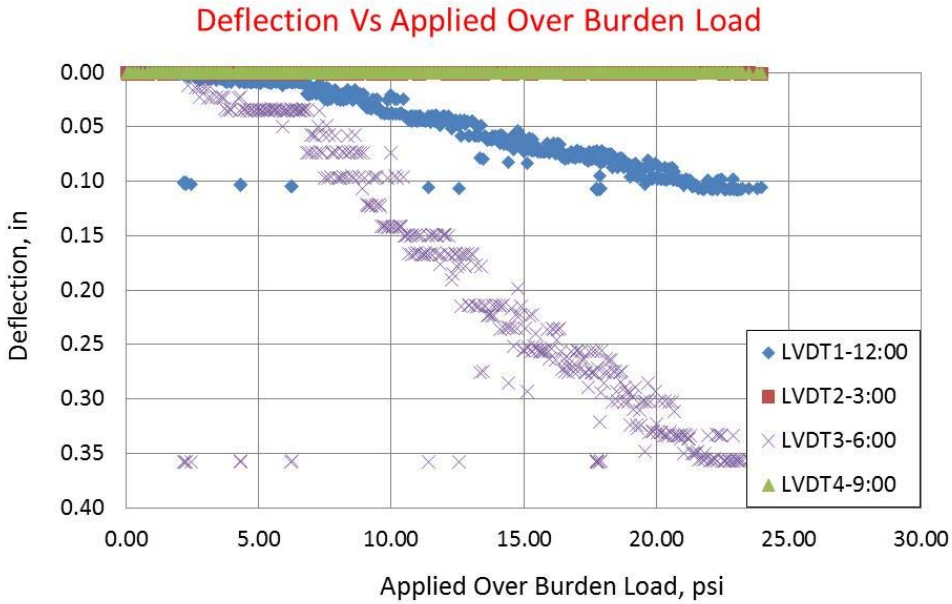


Figure 22: Displacement Recorded by the LVDTs

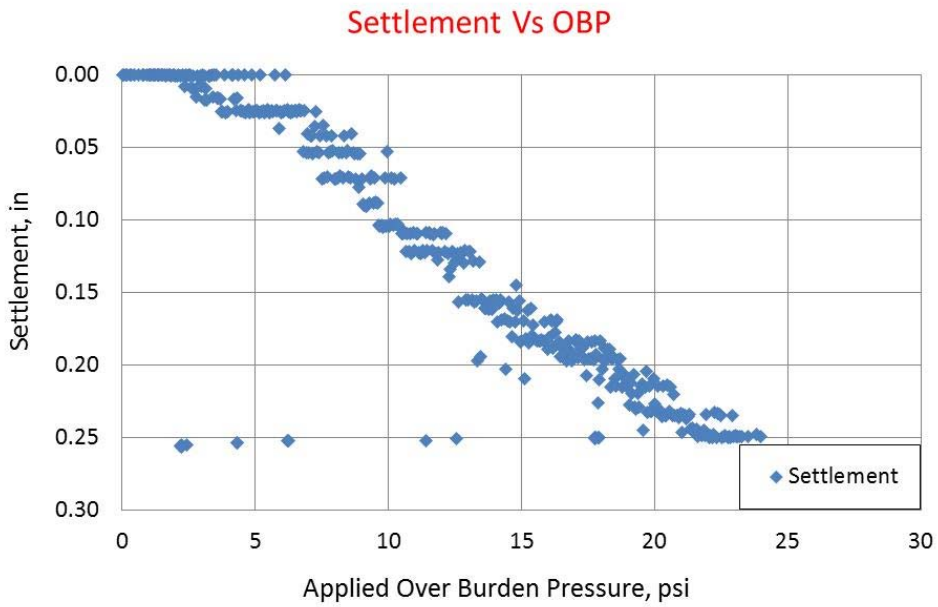


Figure 23: Settlement or Rigid Body Movement of the Pipe Recorded by the LVDT1 and LVDT4

Following the load test the *InfinitPipe*® was exhumed from the soil chamber and no evidence of physical damage was found on the surface of the pipe (see Figure 24).



Figure 24: *InfinitPipe*® Pipe Specimen Exhumed following the Over Burden Load Test

STT-4: Buckling Test

Three 4'-0" long 12" ID *InfinitPipe*® specimens were prepared for the buckling test. A steel pipe 18” ID was machined and prepped to serve as the host pipe. Holes were drilled and tapped on opposite sides, one at the crown and the other at the invert of the host pipe. Appropriate connections were used to enable connecting the pressure tap at the invert while an air bleeding connection was installed at the crown.

Two (2) caps were prepared for each sample. Each cap consisted of a hollow circular plate 22" OD and 10.75" ID. Two steel rings – one 22" ID and the other 10.75" ID were centered and welded on the plate (see Figure 25). Thus, a circular channel was formed which the steel host pipe and the *InfinitPipe*® were inserted into. A leak test was performed to ensure the caps were leak free.



Figure 25: Prepared Cap (left) and Leak Test of the Cap (right)

After the caps were prepared, the *InfinitPipe*® specimen was attached to the steel pipe using quick grips. The arrangement was then positioned 1" above the cap and polyurea was poured to seal the ends of the pipe (see Figure 26).



Figure 26: Specimen and Pipe Holding Together (left) and Arrangement Positioned on Top of the Cap (right)

Next, the steel host pipe and the *InfinitPipe*® were positioned on a horizontal frame (see Figure 26), and the annular space between the specimen and host-pipe was filled to the air bleeding valve at the crown, purging the air. Finally, the valve was shut.





Figure 27: Specimen Positioned on the Frame (left) and Supply Water Connected via Elevated Pressure Device (right)

Powder was applied to the inner wall of the specimen to assist in identifying leakage through the wall of the specimen. Next, the water in the annulus was pressurized gradually. Water was observed to start weeping under an external pressure of approximately 15 psi at different locations along the inner wall of the pipe (see Figure 28).





Figure 28: Powder sprayed Inside the Specimen (left) and Weeping of Water Inside the Specimen's Inner Wall (right)

The process was repeated with a 2nd specimen. Powder was applied to the inner wall of the specimen and the water in the annulus was pressurized gradually. Water was observed to start weeping at an external pressure of approximately 19 psi at various locations along the inner wall of the pipe. While any pipes are buried at relatively shallow depths, placement below the ground water table is not uncommon. Therefore, it is recommended to remedy this issue by adding a thin impervious layer (polyethylene, polypropylene, etc.) to serve as the innermost surface of the pipe. Implementing 2nd thin impervious coating on the outermost surface of the *InfinitPipe*® should also be given a consideration. Also, it is expected that moving from ambient cure resin to heat cure resin will assist in reducing the permeability of the matrix.

STT-5: Burst Pressure Test

Two pipe specimens, each 4'-0" long and 12 in. ID were prepared for the internal pressure test. First, solid caps were fabricated with an inner and an outer circular flange, each 3 in. tall. Next, the specimens were suspended and positioned over the flange 0.5 in. to ensure free flow of polyurea. Polyurea was poured in between the outer flange and the pipe's outer wall, and filled the gap between the inner flange and the pipe's inner wall (see Figure 30).

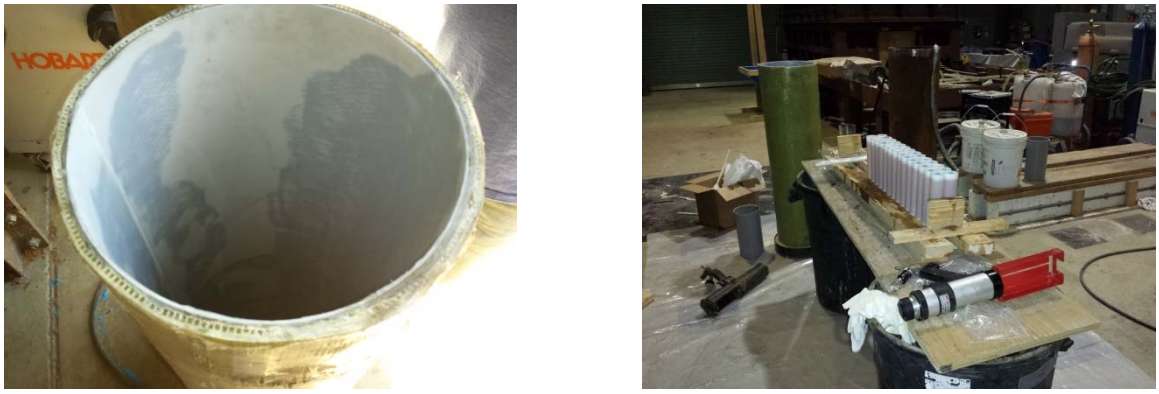


Figure 29: Pipe Specimen (left) and Batch of Polyurea Prepared to Pour (right)



Figure 30: Polyurea Poured in between the Pipe & Inner Flange (left) and Pipe & Outer Flange (right)

Next, the specimen was positioned on a metal frame and two ball valves were attached on the caps. The specimen was filled with water to bleed the inside air out. Two pressure gauges – one 0-100 psi and the other 0-3000 psi were attached to the outlet (see Figure 31).



Figure 31: Valve attached to Caps' Outlet with Pressure Gauge (left) and Inlet Valve (right)

Pressure was applied on the specimen using the TTC's Elevated Pressure Application Device (EPAD). The specimen began leaking when the internal pressure reached 80 psi (see Figure 32 through Figure 34) and water was visible, as it flew between the fiberglass and carbon fiber layers. This could be potentially attributed to a manufacturing defect as all specimens at this early stage of the technology development process are produced manually.



Figure 32: Elevated Pressure Application Device (left) and Bursting Pressure Test Setup (right)

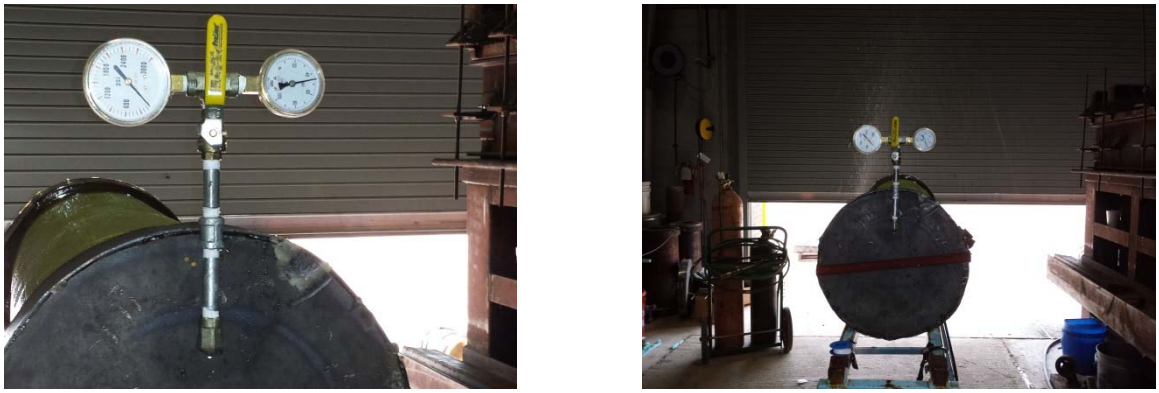


Figure 33: Pressure Applied on the Pipe – 40 psi (left) and 80 psi (right)



Figure 34: Water Dripping through the Cracked Specimen

STT-6: ASTM D638 – Tensile Test

Tensile test was performed following the standard ASTM D638. The samples were cut along the transverse and longitudinal direction (see Figure 35). All the samples' strength was found reaching or exceeding the capacity of the universal testing machine and therefore, they could not be elongated all the way to breaking point and no ultimate strength was calculated. However, the average tensile modulus was found to be above one million psi and average peak stress was found 7,285 psi.

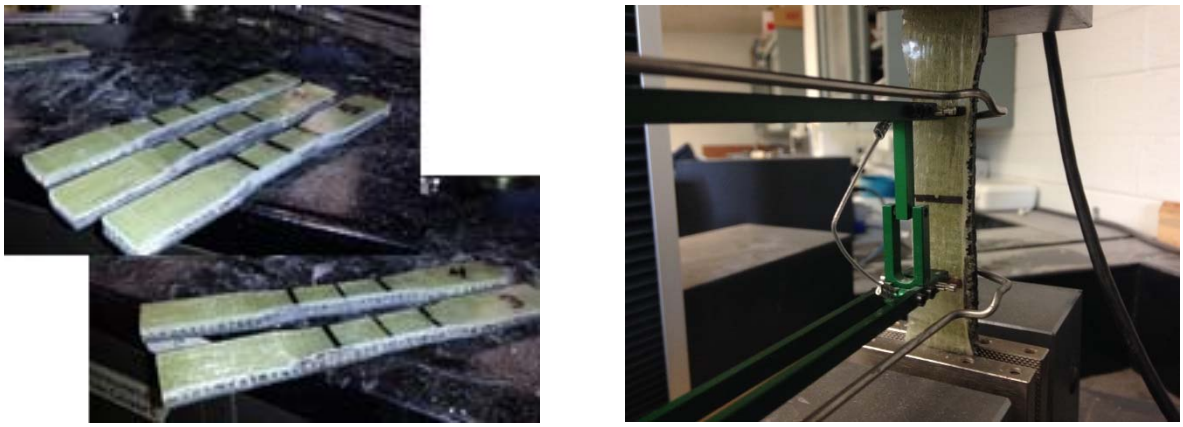


Figure 35: Samples Cut in Longitudinal and Transverse Direction (left) and Testing of a Sample (right)

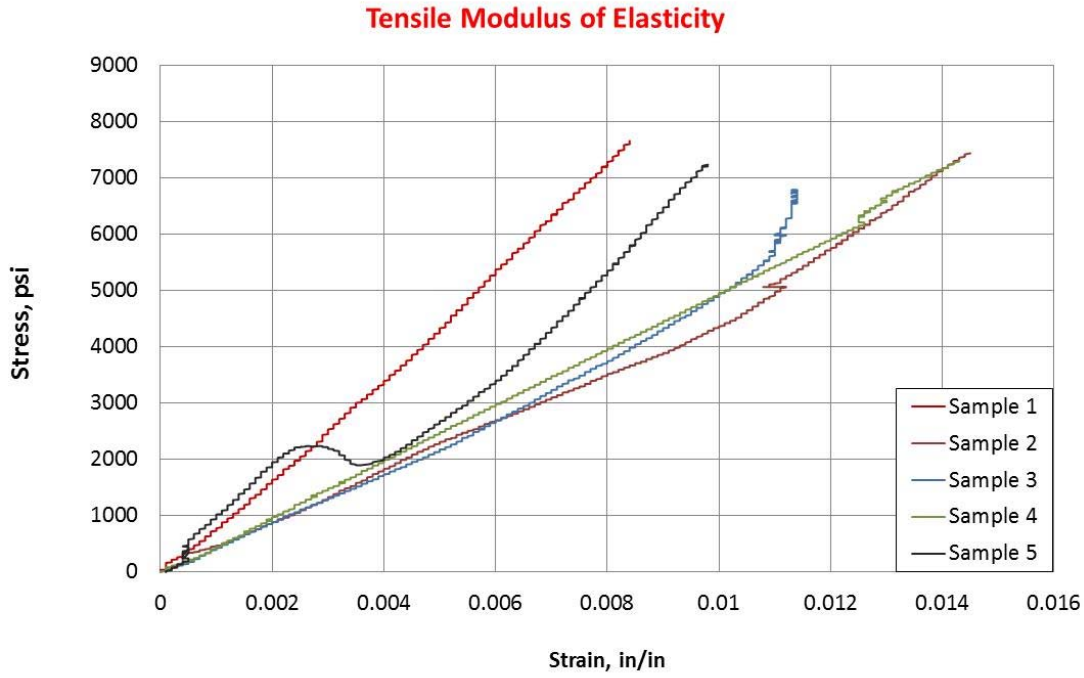


Figure 36: Stress-Strain Curve from Tensile Testing of the Specimens

Table 6: ASTM D638 Test Results

Sample ID	Area (in^2)	Direction	Peak load (lb)	Peak stress (psi)	Tensile modulus (psi)
1	0.2608	Longitudinal	1,996	7,657	1,660,217
2	0.2687	Longitudinal	1,997	7,437	790,111
3	0.2944	Transverse	1,997	6,785	1,009,531
4	0.2734	Transverse	1,998	7,311	995,786
5	0.2757	Longitudinal	1,994	7,235	2,029,874
Average			1,997	7,285	1,297,104
Std. Dev.			1.55	322	524,246

STT-7: ASTM D790 – Flexure Test

Flexure test was performed following the standard ASTM D790. Ten (10) samples were cut – five (5) along the transverse and five (5) along the longitudinal direction. For the samples cut along the transverse direction (see Figure 37) the average flexure modulus was found to be above 455,000 psi and average peak stress was found around 7,500 psi.

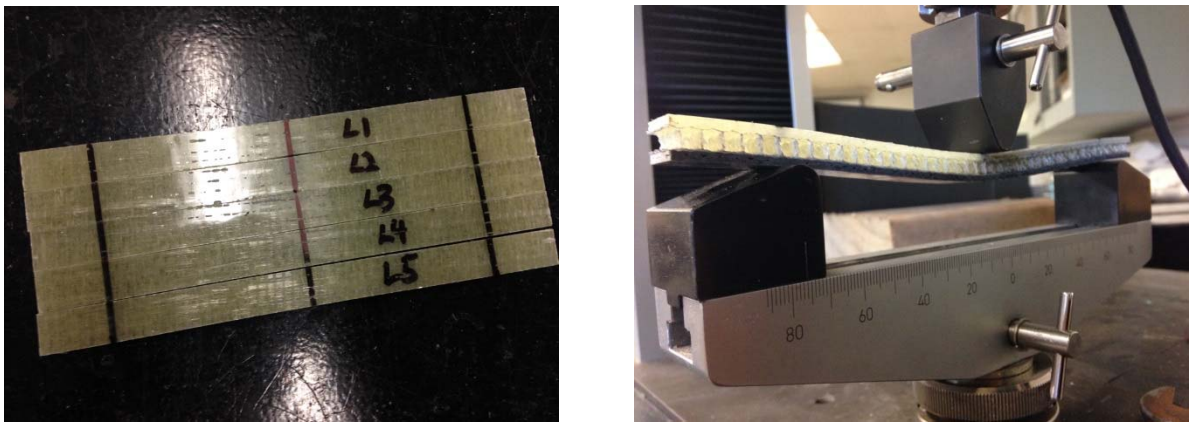


Figure 37: Samples Cut in Transverse Direction (left) and Testing of a Sample (right)

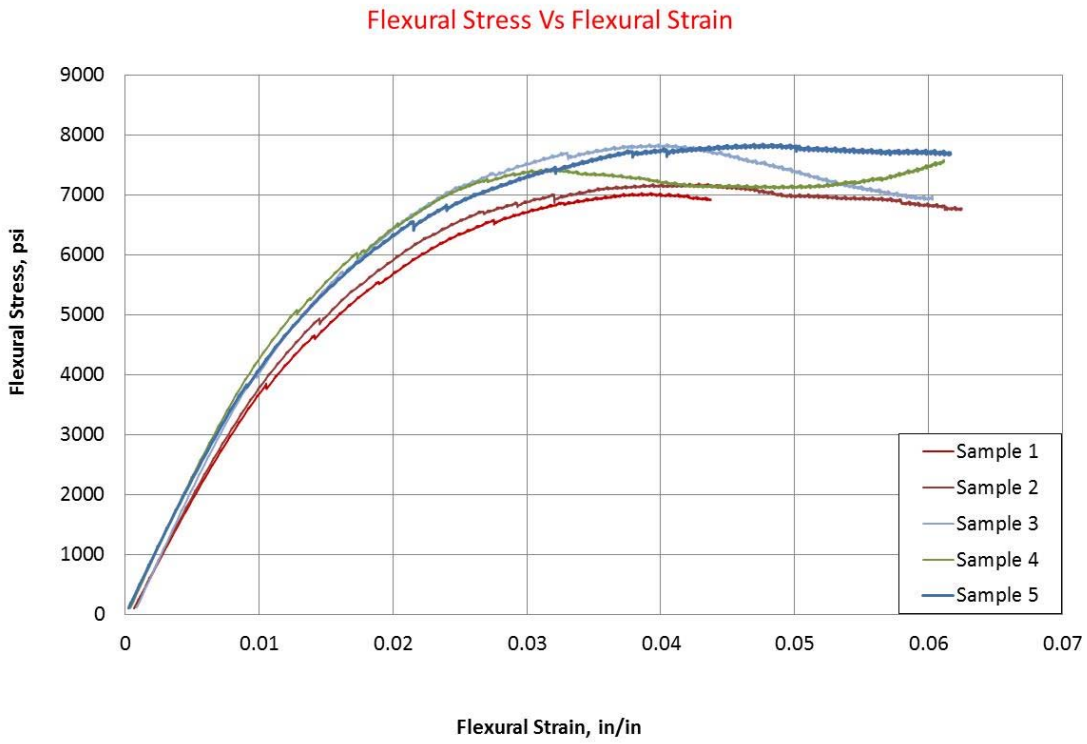


Figure 38: Stress-Strain Curve-Flexure Testing of Specimens Cut in Transverse Direction

Table 7: ASTM D790 Test Results – Samples cut in Transverse Direction

Sample ID	Area (in^2)	Peak load (lb)	Peak stress (psi)	Flexure modulus (psi)
1	0.01	63.33	7,037	420,685
2	0.01	64.96	7,218	434,250
3	0.01	65.94	7,850	481,880
4	0.01	65.28	7,591	480,260
5	0.01	69.74	7,836	458,479
Average		65.85	7,506	455,111
St. Dev		2.38	366.53	27,298.01

For the samples cut along the longitudinal direction (see Figure 39) the average flexure modulus was found to be above 2 million psi and average peak stress was found around 16,000 psi (see Table 8). The stress strain plot is shown in Figure 40. All of the samples had an average flexural modulus and flexural stress test values which met the ASTM requirement of 250,000 psi and 4,500 psi respectively.



Figure 39: Samples Cut in Longitudinal Direction (left) and Testing of a Sample (right)

Table 8: ASTM D790 Test Results – Samples cut in Longitudinal Direction

Sample ID	Area (in^2)	Peak load (lb)	Peak stress (psi)	Flexure modulus (psi)
1	0.0089	119.28	13,402	1,939,062
2	0.0093	142.00	15,269	2,181,531
3	0.0102	170.45	16,711	1,845,636
4	0.0093	146.62	15,766	2,228,061
5	0.0100	180.35	18,035	2,090,724
Average		151.74	15,837	2,057,003
St. Dev		24.20	1,721	161,625

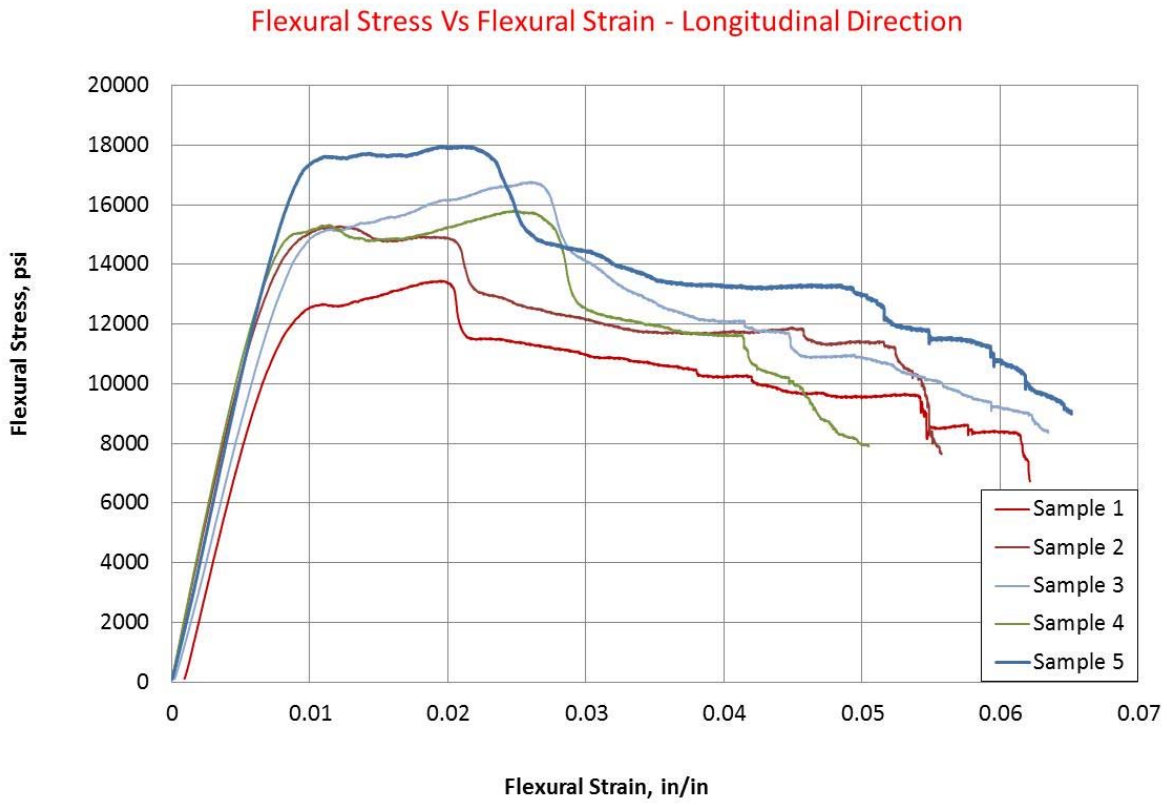


Figure 40: Stress-Strain Curve - Flexure Testing of Specimens Cut in Longitudinal Direction

STT-8: ASTM D2240 – Hardness Test

A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Twenty (20) samples (1 in. × 1 in.) were cut from the panel with a band saw (see Figure 41). A total of 400 readings were taken on the inner and outer surfaces of the specimens. The average recorded hardness values are shown in Figure 42. The hardness of the outer surface was found to be slightly lower than that of the inner surface may be due improper impregnation of resin.



Figure 41: Samples Prepared for ASTM D2240 Test (left) and Testing of a Sample (right)

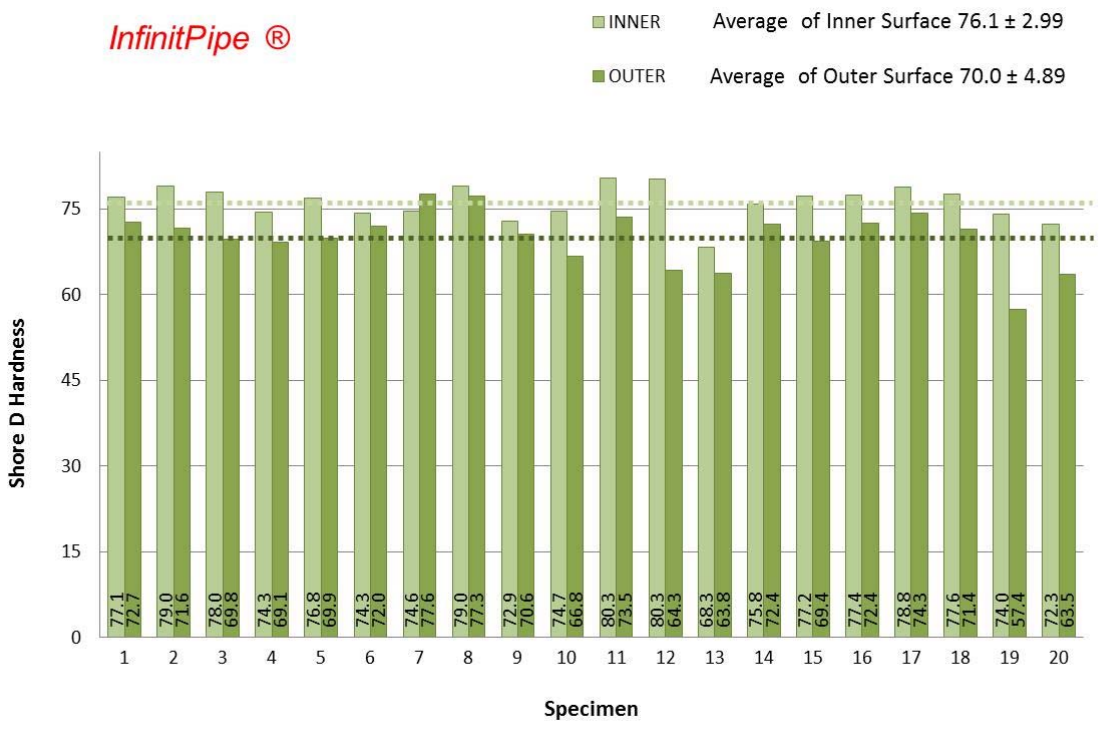


Figure 42: Shore D Hardness Readings for the Inner and Outer Surfaces of the *InfinitPipe*®

Numerical Simulation

A 3D Numerical simulation effort was commenced based on the initial concept of the *InfinitPipe*® pipe, namely the use of an interior honey-comb structure (see Figure 43) which was received first. The model was intended to be developed based on the shapes and actual dimensions of the *InfinitPipe*®. Development of this model using ANSYS Parametric Design Language (APDL) was found to be highly complex and therefore, the initial model was developed using SolidWorks.

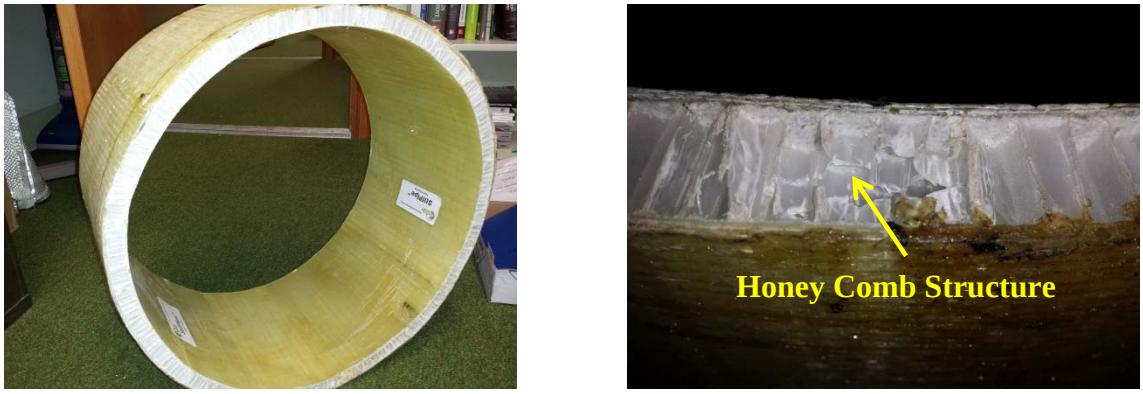


Figure 43: Early concept of the *InfinitPipe*® Sample (left) and Interior Honeycomb Structure (right)

Honeycomb structures exhibits high out-of-plane compression and shear strength with minimum thickness. Therefore, honeycombs embedded in two thin layers were modeled using Shell elements to form a plate-like assembly.

Dimensions of the honeycomb structure were measured on a physical specimen using a micrometer, and were used to develop the 3D model in SolidWorks (see Figure 44). The plane of rotation was fixed and the 3D model was generated based on that plane (see Figure 45 and Figure 46).

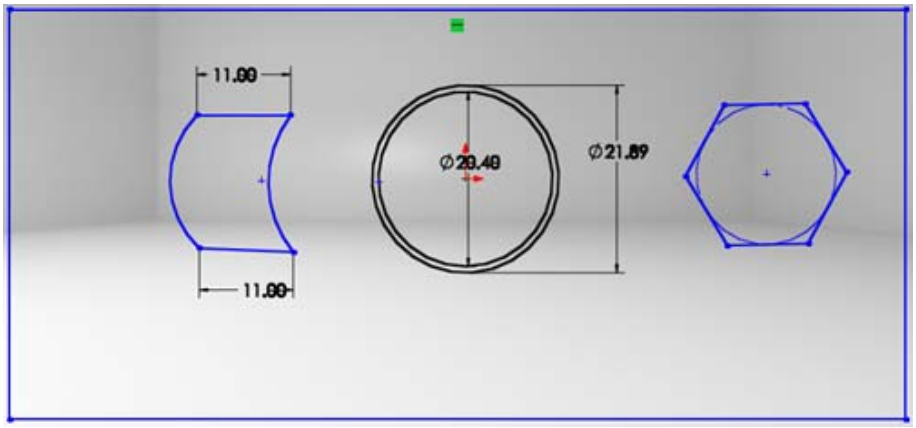


Figure 44: Dimensions Inserted in SolidWorks

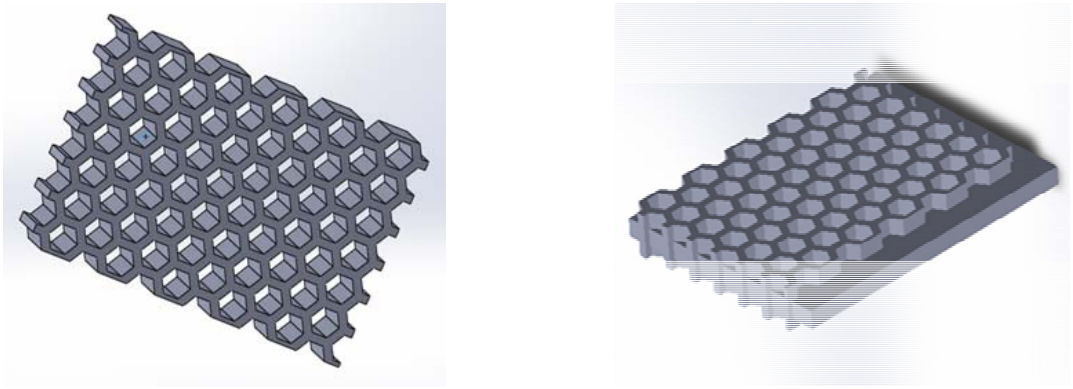


Figure 45: Development of Honeycomb based on the Plane of Rotation

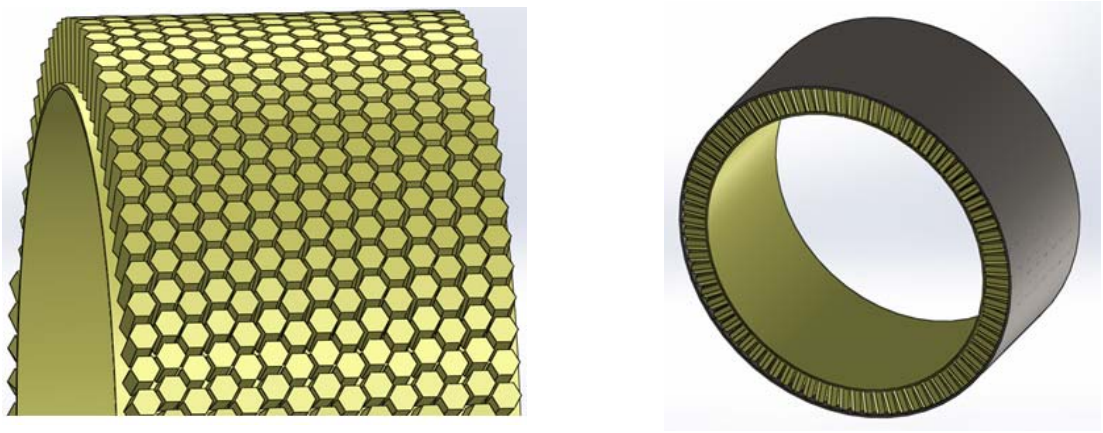


Figure 46: Model Developed using SolidWorks

The model was meshed and tested by applying a load at the crown, spring-line, and invert (see Figure 47). In the numerical model developed using SolidWorks® material properties of steel were used, as a provision for providing custom material properties was not available in the SolidWorks® version Deflection at the crown of the numerical model was found close to the readings obtained by LVDT1 during the Deflection Test Under Applied Overburden Pressure (see Figure 48). Moreover, the results revealed that the strength of the pipe was in close proximity to a pipe made of steel, which was also found in the impact test (ASTM D2444)

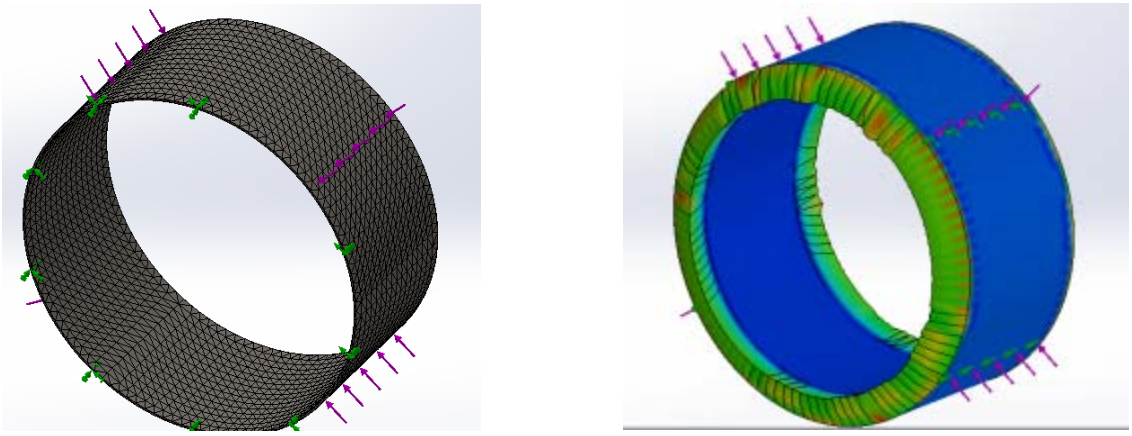


Figure 47: Analysis using SolidWorks

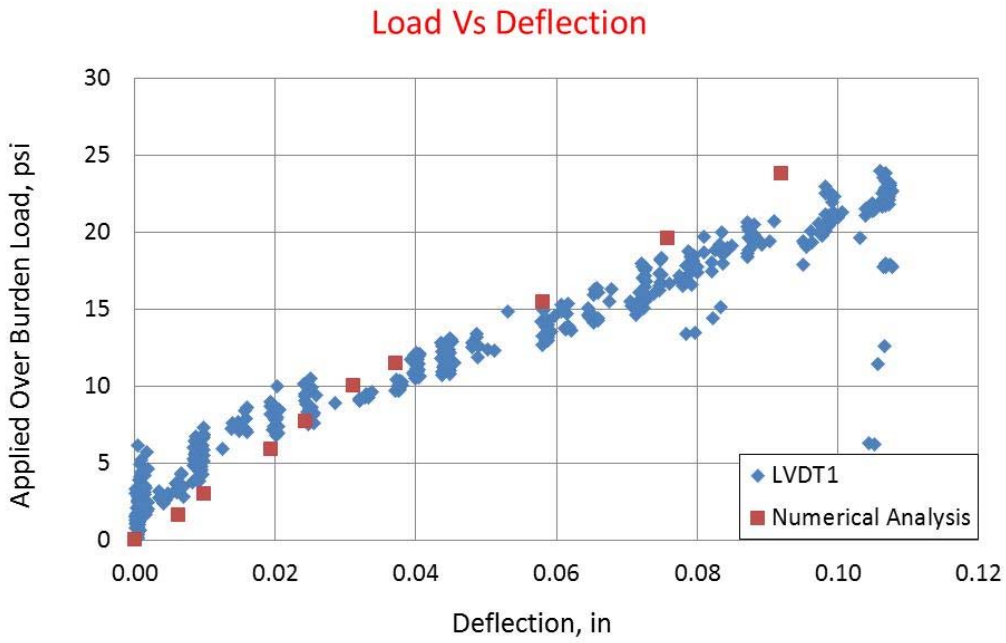


Figure 48: Comparison of Deflection Obtained by Test and Numerical Analysis

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