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# Evaluation of Mechanical Properties of Sandwich Construction FRP Pipe

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## 1. ABSTRACT

In pipeline construction operation, transportation, handling, storage and welding/butt fusion of individual pipe segments involve a significant cost. This paper describes an innovative, in-situ pipeline manufacturing technology, where the pipe's structure consists of a 3-D glass fabric saturated with resin and sandwiched between layers of resin-saturated carbon or glass fabrics. This manufacturing process enables the pipe to be manufactured in a continuous manner at the job site to the desired length, and hence was coined '*InfinitPipe*®'. Benefits associated with this technology include lower project costs, reduced probability of pipe/coating damage during transportation and handling, enhanced safety, as well as added flexibility in addressing changes that arise in the field 'on-the-run'. The Trenchless Technology Center (TTC) at the Louisiana Tech University undertook a battery of controlled laboratory tests to evaluate the mechanical performance of this newly developed pipe under external and internal mechanical and hydraulic loads. Short-term performance of the pipe was evaluated by conducting standard ASTM tests. Overall response of the pipe-soil system was examined via a full-scale direct buried test. Pressure testing was also performed, to evaluate the internal burst pressure of the product as well as its ability to withstand external hydrostatic pressure. The pipe product was found to perform well under mechanical loading. Observations made during the testing program were incorporated into the pipe's development process, resulting in continuous improvements towards the high performance objectives expected of this new class of pipeline technology. The work was performed with financial support through National Science Foundation's (NSF's) Small Business Innovation Research (SBIR) program.

## 2. INTRODUCTION

Sandwich panel technology provides outstanding stiffness and strength for low weight. Thin, high strength skins are separated by, and bonded to, thick lightweight 3D fabric fiber reinforced polymer (FRP) core; the thicker the core, the higher the stiffness and strength of the panel. Sandwich panels are an important composite structure in aerospace applications as well as in high performance automobiles, boats and wind turbines. The technology is extended to pipeline industry through *InfinitPipe*® (Ehsani 2015) technology. *InfinitPipe*® combines the high structural performance of sandwich panels with the innovative pipe onsite continuous production technology and the high performance Fiber Reinforced polymer fabrics. TTC at the Louisiana Tech University undertook controlled laboratory tests to evaluate the mechanical performance of this newly developed pipe under external and internal mechanical and hydraulic loads. This paper presents results of controlled laboratory tests (see Table 1) performed on the newly developed *InfinitPipe*® pipe material and sections.

## 3. MATERIALS TTESTED AS PART OF THE PROGRAM

Development of the *InfinitPipe*® was an evolving process to obtain a better pipe product (Ehsani 2012). Therefore, pipe materials were modified to tackle challenges during the short-term tests (STT) and later continued with the same material until a new challenge arises. During the short term tests it was found that *InfinitPipe*® constructed of material combinations Type-1 started leaking slowly when subjected to buckling test (STT-4) although the samples exhibited good results during STT-1,-2, and -3. Therefore, a layer of HDPE was introduced at the inner side of the pipe which was named as Type-2. This type was subjected to STT-5. Again, for STT-6,-7, and -8 samples were prepared from the panels made as Type-1 and later tested (see Figure 1 and Figure 2).

Table 1. Matrix of short-term tests (STT) performed on *InfinitPipe*®

| STT | Description | Standard | No. of Specimen |
|---|---|---|---|
| **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 |

Table 2. Tests performed on *InfinitPipe*® materials

| ***InfinitPipe*® Material** | **Description** | **STT** |
|---|---|---|
| **Type-1 (see Figure 1)** | *InfinitPipe*® manufactured using 3D fabrics and which consists of the following layers from inside towards the outside:<br>• Two (2) layers of veil<br>• Single layer of QuakeWrap® TU27C Unidirectional Carbon Fabric<br>• Single Layer of QuakeWrap® TB20C Biaxial Carbon Fabric<br>• Single Layer of 8mm thick 3D Glass Fabric cut in a 6-inch wide band and helically wrapped around the mandrel<br>• Two (2) Layers of QuakeWrap® VB26G Glass Fabric | 1,2,3,4,6,7,8 |
| **Type-2 (see Figure 2)** | *InfinitPipe*® manufactured using 3D fabrics and which consists of the following layers from inside towards the outside:<br>• A 1/8" thick HDPE sheet heat-welded along the seam to create a 12" diameter x 4-ft long tube<br>• 1 layer of QuakeWrap® TU27C Unidirectional Carbon Fabric<br>• 1 Layer of QuakeWrap® TB20C Biaxial Carbon Fabric<br>• 1 Layer of 8mm thick 3D Glass Fabric cut in a 6-inch wide band and helically wrapped around the mandrel<br>• 2 Layers of QuakeWrap® VB26G Glass Fabric | 5 |

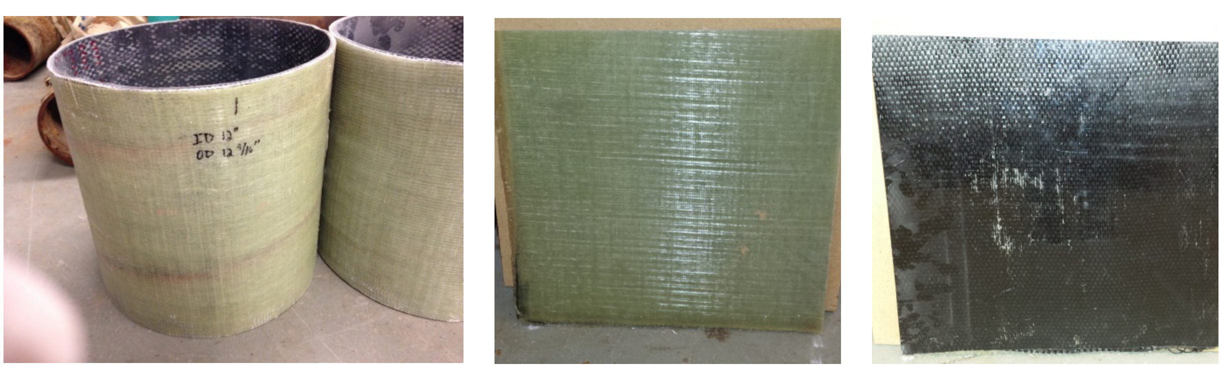


Figure 1. Specimen Type-1 3D fabric pipe (left); fabric flat panel (middle) and (right)

Figure 2: Specimen Type-2 3D fabric HDPE lining inside

## 4. 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®. Next, the length of each specimen was measured and recorded. 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. The specimens were placed inside the parallel plate and loaded at a rate of 0.50 in/min as shown in Figure 3. Final deflection value was set to 3.60 in., i.e. 30% of the inner diameter of the pipe.

Figure 3: Application of load on specimens

Load vs. Deflection curves for all the specimens are shown in Figure 4. 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.

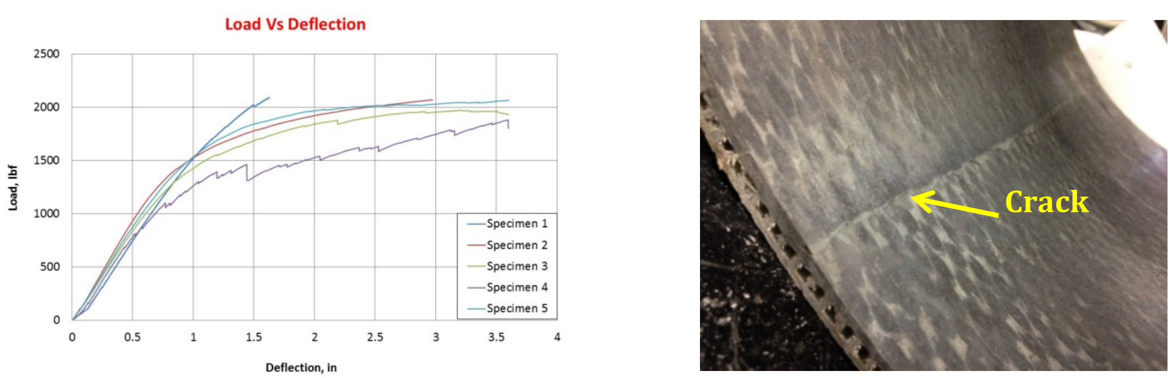



Figure 4: Load-deflection curve of tested specimens (left) and crack propagated along the seam (right)

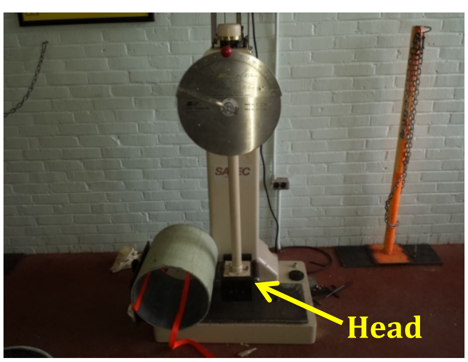
The flat slope at the end was not observed on Specimen 1 indicating it failed at a lower deflection (at ultimate); possible reason might be low thickness value resulted in high resin concentration leading to a brittle behavior of the pipe material. The average stiffness factor and modulus of elasticity 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 at 5% deflection and around 2000 lbf-in at full deflection. Propagation of crack was observed along the seam for most specimens at full deflection and average stiffness at 5% deflection was found around 140 psi while it reduced by 57% for full deflection. Although permanent deformation was observed at full deflection, ability of the specimens tested to resist overburden load at 5% deflection is considered adequate for a wide range of practical applications.

Table 3: ASTM D2412 test results at 5% deflection and at full deflection

| **Parameter** | **Deflection** | **Specimen** | | | | | **Average** |
|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** | |
| **OD, in** | | 12.45 | 12.73 | 12.74 | 12.75 | 12.70 | 12.67 |
| **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** | **5%** | 930.25 | 1,118.90 | 1,017.98 | 915.88 | 1,067.87 | 1,010.18 |
| | **Full** | 2,090.52 | 2,071.14 | 1,973.47 | 1,881.83 | 2,066.67 | 2,016.73 |
| **Load, lb/in** | **5%** | 76.44 | 92.93 | 84.20 | 75.76 | 87.60 | 83.39 |
| | **Full** | 171.78 | 172.02 | 163.23 | 155.65 | 169.54 | 166.44 |
| **Deflection, in** | **5%** | 0.59 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 |
| | **Full** | 1.63 | 2.97 | 3.21 | 3.59 | 3.60 | 3.00 |
| **Stiffness, psi** | **5%** | 129.56 | 154.89 | 140.33 | 126.26 | 146.00 | 139.41 |
| | **Full** | 105.57 | 57.89 | 50.83 | 43.38 | 47.10 | 60.95 |
| **Correction Factor** | **5%** | 1.08 | 1.08 | 1.08 | 1.08 | 1.08 | 1.08 |
| | **Full** | 1.22 | 1.42 | 1.46 | 1.52 | 1.52 | 1.43 |
| **Stiffness Factor, lbf-in** | **5%** | 4,017 | 4,948 | 4,495 | 4,022 | 4,704 | 4,437 |
| | **Full** | 3,273 | 1,849 | 1,627 | 1,381 | 1,517 | 1,929 |

## 5. 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 at 72°F. A modified Izod impact testing 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 5).



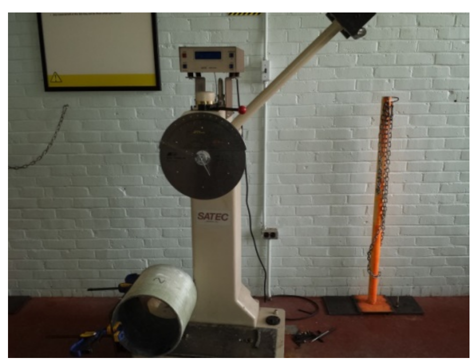



Figure 5: Modified head of the Izod impact tester (left) and specimen ready to test (right)

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 tester. 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 to be the energy absorbing capacity of the material (see Figure 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 and average energy absorbed was found to be 119.50 ft-lb.

## 6. STT-3: DEFLECTION TEST UNDER APPLIED OVER BURDEN PRESSURE

The testing apparatus used in this test was 6’-0” wide × 12’-0” long and 5’-0” deep soil chamber. The chamber was modified by adding two steel plates with 16 in. diameter circular openings slid through a pair of collars located on the opposite short walls (see Figure 6). The 16 in diameter openings enabled ease of pipe placement inside 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 6). 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 6) 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.

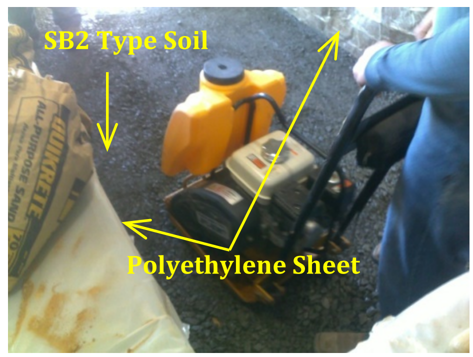
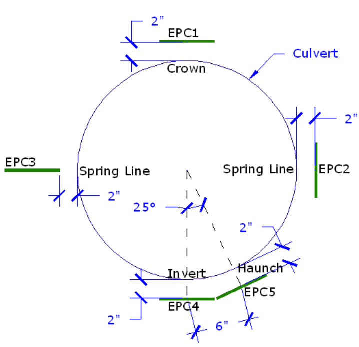



Figure 6: 16 in. dia. openings (left) and polyethylene sheet on the sidewalls and compaction of soil (right)

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 7. 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.



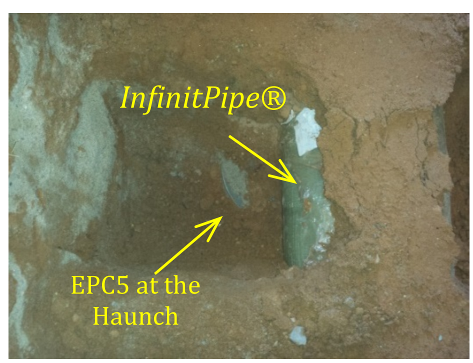




Figure 7: Arrangement of earth pressure cells (EPCs) (left) and EPC5 at the haunch (right)

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 8) before the lead was placed. 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. 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. A frame with four (4) Linear Voltage Displacement Transducers (LVDTs) installed on it 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.

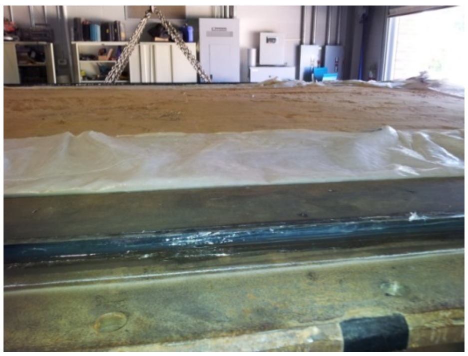


Figure 8: Soil box filled with bedding soil (left) and lid positioned on top of the soil surface (right)

Figure 9: Rectangular seal glued to bottom of the lid (left) and lid being placed on top of soil chamber (right)

**RESULT**

Air pressure was applied to the bladder which transferred the uniform stress on the soil surface inside the soil box. 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 (see Figure 10).

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 10. The data recorded by the LVDTs at positions 3 and 9 O’clock reveals no lateral deformation at the spring line of the *InfinitPipe*®. LVDT1 located at the crown showed maximum deflection at the crown was around 0.10 in, approximately 0.8% of the inner diameter.

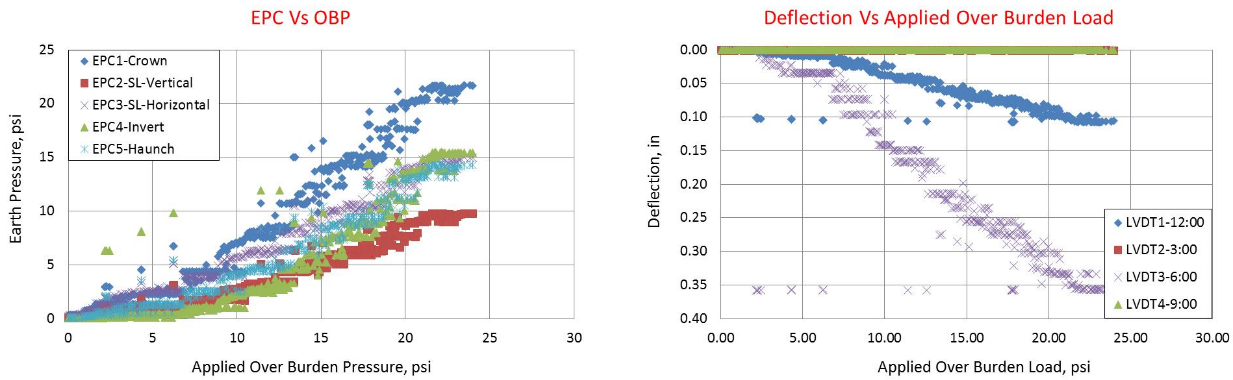



Figure 10: Stress recorded by the EPCs (left) and displacement recorded by the LVDTs (right)

Readings obtained from LVDT1 were subtracted from those collected by LVDT3 located at the invert and showed around 0.25 in of global settlement or rigid body movement of the pipe (see Figure 11). 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. 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.

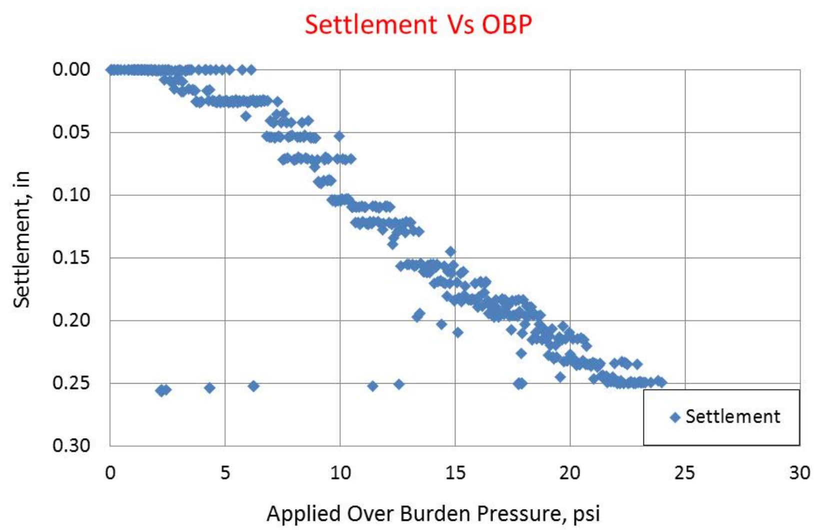



Figure 11: Rigid body movement (Settlement) of the pipe specimen

## 7. STT-4: BUCKLING TEST

Two 4'-0" long 12" ID *InfinitPipe®* specimens were prepared for the buckling test. The specimens were encapsulated inside 18” ID steel pipe and the annular space between the specimen and host-pipe was filled with water to bleed the air out through the valve located at the crown of the steel pipe. Finally, the valve was shut and external pressure was applied on the pipe’s surface using the TTC’s EPAD. Powder was applied to the inner wall of the specimen to assist in identifying any leakage through the wall of the specimen and the pipe started weeping at around 15 psi of external pressure. 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 many 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 a 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.

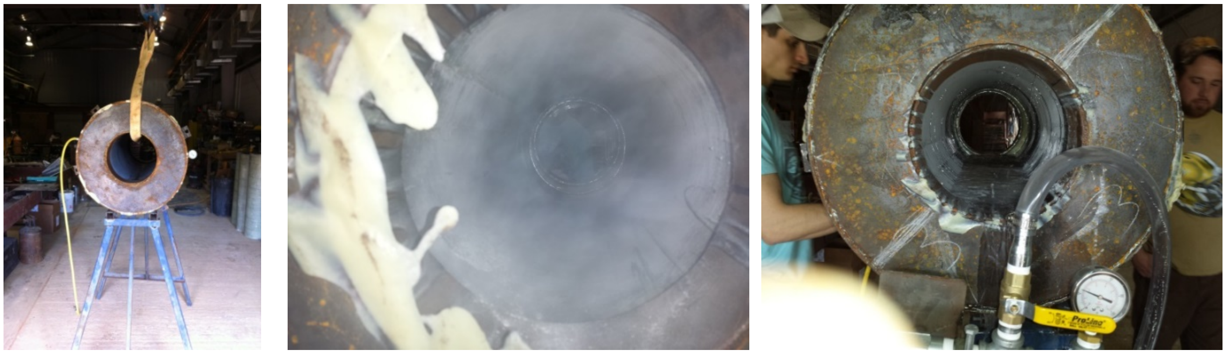


Figure 12: Buckling test specimen positioned on the frame (left and middle) and specimen weeping inside (right)

## 8. STT-5: BURST PRESSURE TEST

In this test, the specimens were pressurized internally. Three specimens each 4’-0” long and 12 in. ID were prepared using Type 2 material for the test. The specimens were sealed using two solid steel caps attached to the ends using polyurea. 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 13). Pressure was applied on the specimen using the TTC’s Elevated Pressure Application Device (EPAD). The specimen began leaking when the internal pressure reached at 80 psi (see Figure 13) and water was visible, as it spread 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.

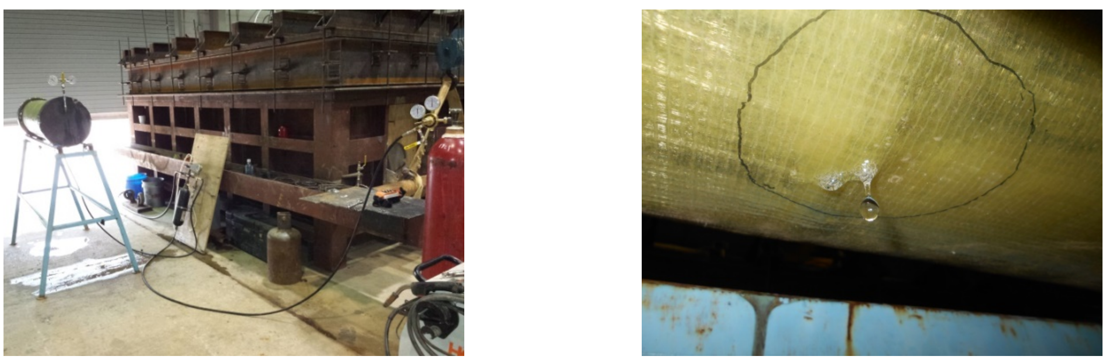


Figure 13: Valve attached to caps’ outlet with pressure gauge connected (left) and specimen leaking (right)

## 9. STT-6: ASTM D638 – TENSILE TEST

Tensile test was performed following the ASTM D638 standard. The samples were cut along the transverse and longitudinal direction (see Figure 14). Peak tensile load for all the samples reached the safe capacity of the testing equipment and therefore, terminated at around 2000 lbf. So, the specimens could not be elongated all the way to the breaking point and no ultimate strength was obtained. The average tensile modulus for both longitudinal and transverse direction was found to be above one million psi and average peak stress was found more than 7000 psi.

Table 4: 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 |

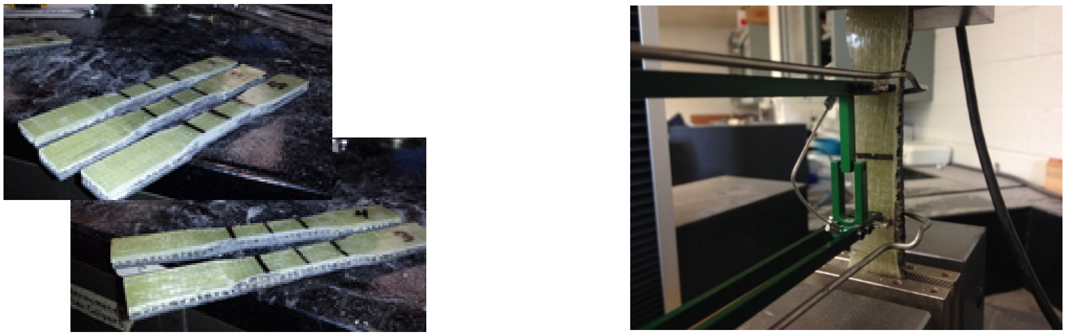


Figure 14: Samples cut in longitudinal and transverse direction (left) and testing of a sample (right)

## 10. STT-7: ASTM D790 – FLEXURE TEST

Flexure test (see Figure 15) was performed following the standard ASTM D790. Ten (10) samples were cut – five (5) along the transverse and five (5) along the longitudinal direction and subjected to ASTM D790 loading. For the samples cut along the transverse direction (see Figure 15) the average flexure modulus was found to be above 455,000 psi and average peak stress was found around 7,500 psi. For the samples cut along the longitudinal direction the average flexure modulus was found to be above 2 million psi and average peak stress was found around 16,000 psi. 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.

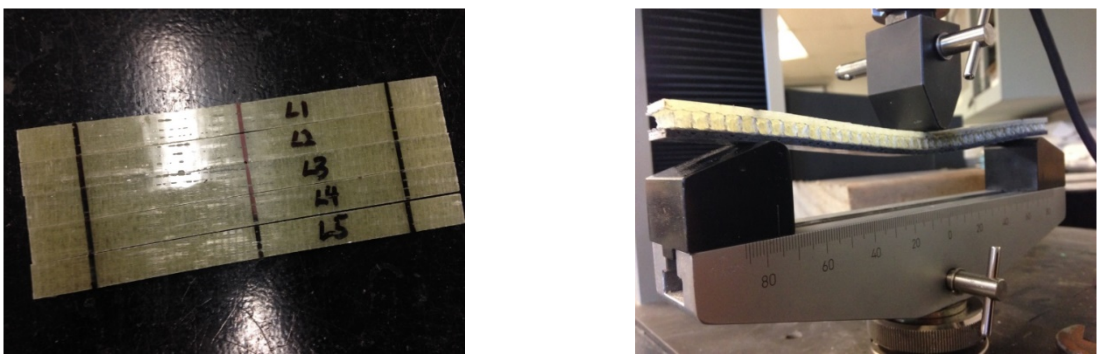



Figure 15: Samples cut in transverse direction (left) and testing of a sample (right)

Table 5: ASTM D790 test results

| Sample ID | Transverse Direction | | | Longitudinal Direction | | |
|---|---|---|---|---|---|---|
| | Peak load (lb) | Peak stress (psi) | Flexure modulus (psi) | Peak load (lb) | Peak stress (psi) | Flexure modulus (psi) |
| **1** | 63.33 | 7,037 | 420,685 | 119.28 | 13,402 | 1,939,062 |
| **2** | 64.96 | 7,218 | 434,250 | 142.00 | 15,269 | 2,181,531 |
| **3** | 65.94 | 7,850 | 481,880 | 170.45 | 16,711 | 1,845,636 |
| **4** | 65.28 | 7,591 | 480,260 | 146.62 | 15,766 | 2,228,061 |
| **5** | 69.74 | 7,836 | 458,479 | 180.35 | 18,035 | 2,090,724 |

## 11. 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 and total of 400 readings were taken on the inner and outer surfaces of the specimens. The average recorded hardness values were found to be 76 on the inner surface and 70 on the outer surface. The slightly lower hardness value obtained at the outer surface may have resulted from an improper impregnation of resin as the flat panels were prepared manually.

Figure 16: Samples prepared for ASTM D2240 test (left) and testing of a sample (right)

## 12. CONCLUSION

The structural performance of *InfinitPipe®* was evaluated by the TTC at the Louisiana Tech University through a battery of short-term performance evaluation of the evolving *InfinitPipe®* by conducting standard ASTM tests. Overall response of the pipe-soil system was examined via a full-scale direct buried test. Pressure testing was also performed, to evaluate the internal burst pressure capacity of the product as well as its ability to withstand external hydrostatic pressure. Overall the *InfinitPipe®* product was found to perform well under mechanical loading, either monolithically applied or impact load with some localized limitations attributed to manual preparation of the specimens. 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. Observations made during the testing program were incorporated into the pipe's development process, resulting in continuous improvements towards the high performance objectives expected of this new class of pipeline technology.

## 13. ACKNOWLEDGEMENT

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