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Laboratory testing of invert-cut corrugated metal pipes renewed with polymeric spray applied pipe lining

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A B S T R A C T

Buried culverts are important components of highway infrastructure. Most large culverts are built decades ago from corrugated metal or reinforced concrete materials and now have reached their design life. A variety of renewal techniques can be utilized to enhance load carrying capacity of the existing deteriorated culverts and extend their design life. Spray applied pipe lining (SAPL) is a trenchless renewal methodology that applies layers of liner on the interior surface of the deteriorated host culvert. The SAPL’s substances generally fall into two categories: cementitious and polymeric materials. Currently, there is no standard method available for structural design of SAPLs that resulting in various methods being applied by SAPL vendors. To provide the essentials for development of a design methodology for SAPLs, the objective of this paper is to examine the structural performance of full scale soil box testing of 60 in. (1.5 m) diameter circular invert deteriorated host culvert. The SAPL’s substances generally fall into two categories: cementitious and polymeric materials. The performances of SAPL renewed CMPs were compared with a same size invert-cut bare CMP under the same testing configuration. The results indicated that depending on thickness of the polymeric SAPL, application of this method could improve the structural capacity of a fully deteriorated invert CMP culverts up to 80%.

Introduction

Drainage infrastructure systems (culverts, storm sewers pipes, outfall, etc.) represent an integral portion of Departments of Transportation (DOTs) assets that routinely require inspection, maintenance, repair, and renewal. According to the American Society of Civil Engineers (ASCE) Infrastructure Report Card, the condition of the United States infrastructure, including drainage infrastructure, is in a poor quality (D + ) and needs further investments and improvements [1]. According to the U.S. department of homeland security’s memorandum on “identification of essential critical infrastructure workers during COVID-19 response,” maintaining and repairing drainage infrastructure systems are essentials to continue infrastructure viability, which has significant impact on people lives, economy and national security [2]. Federal highway administration (FHWA) reports that the United States has approximately 4.12 million miles (6.63 million kilometers) of roadways, making it the largest in the world with millions of drainage pipes, including culverts, hidden underneath [3,4]. Culverts are important structural components of roadways that convey water or form a passageway through an embankment and are designed to support a superimposed earth load or other fill material as well as live load [5,48]. Many culverts in the United States have reached their service life and they need to be repaired, renewed, or replaced [6,7]. For many decades, Corrugated Metal Pipes (CMPs) have been used as culverts in the United States [19]. However, CMPs may expose to invert abrasion and corrosion damages [8].

Conventional open-cut replacement methods for the deteriorated culverts are expensive as they are associated with social and indirect costs [9]. As an alternative, trenchless technology renewal methods are cost-effective and environmentally friendly with minimized surface
Fig. 1. Trenchless Technology Renewal Solution: (a) trenchless renewal methods [9], (b) cementitious SAPL installation using spin casting machine (source: CentriPipe), and (c) hand spray installation of polymeric SAPL application (source: Sprayroq).
disruption that can improve the current condition of culverts and extend their design life [9,10]. Generally, the main objective of a trenchless structural renewal is to delay further deterioration and to structurally renew severely damaged culverts and drainage structures [7]. Trenchless technology culvert renewal methods include sliplining (SL), cured-in-place pipe (CIPP), spiral wound lining, close-fit pipe, and spray applied pipe lining (SAPL) [11,12].

Several researchers have investigated structural capacity of a lined pipe using different trenchless renewal applications. Smith et al. [13] conducted a laboratory testing to determine the effect of grout lining on sliplined pipes. Simpson et al. [14] conducted a series of experiments on a deteriorated CMPs rehabilitated with high-density polyethylene (HDPE) slipliner application under two different burial configurations (600 and 900 mm). Falter [15] conducted a soil-pipe stability analysis and studied the cross-section forces and deformation parameters of concrete sewer systems renewed with close-fit pipe method. Zhao et al. [16] studied the design and reliability of CIPP liners by examining the scatter in applied pressure versus buckling time plots, for the partially deteriorated host pipe condition, as specified in the ASTM F1216 [17,49]. However, the performance of a fully invert deteriorated CMP renewed with SAPL is not yet investigated.

Spray applied pipe lining (SAPL) is a pipe renewal methodology that provides corrosion resistance, structural support, and hydraulic improvement to severely damaged storm water conveyance conduits, culverts and manholes [18,19]. Compared with other trenchless renewal methods, SAPL is cost effective, environmentally friendly, and compatible with complex geometries [11,20]. The primary SAPL's substances, generally fall into two broad categories of cementitious, such as a mixture of Portland cement or geopolymer mortar, and polymeric materials including polyurethanes, polyurea, and epoxy, as illustrated in Fig. 1(a). SAPLs are commonly installed either using hand spray or with utilization of a spin casting machine, as shown in Fig. 1(b) and (c).

Walker and Guan [21] conducted a set of material property tests in accordance with ASTM standards and reviewed the performance of five primary materials of sprayed liners used in North America, including 100% solids rigid polyurethane, 100% solids epoxy, solvent amine based epoxy, 100% solids elastomeric polyurethane and cement mortar lining for the internal renewal of potable water steel pipelines. The study stated the 100% solids polyurethane had a better performance to be used in potable water steel pipelines. Ha et al. [22] conducted a series of laboratory testing to investigate the applicability of the fast-setting polyurea-urethane (PUU) lining as a structural lining material, applied inside of small diameter (5.91 in. (150 mm)) water pipes. Their study included pull off bond test, hole or gap spanning test, angular displacement test, transverse shear test and fatigue cyclic tests. It was concluded the fast-setting PUU lining could be used as a structural lining material for water pipelines. Szafrań and Matusiak [23] studied the structural behavior of reinforced concrete rings renewed from both inside and outside surfaces with polyurea SAPL, through the three-edge bearing test. They concluded the used polyurea SAPL membrane for standard application in two layers on both surfaces increased the compressive capacity of concrete rings by 21.9%. Authors stated further research is needed to explore the performance of polyurea SAPL in the existence of soil-pipe interaction system.

Table 1
Details of pipe samples.

| Test Type                  | Test Number | CMP | SAPL |
|----------------------------|-------------|-----|------|
|                           |             |     | Label | Shape and Diameter, in. (m) | Invert Condition | Length, ft (m) | Material | Thickness, in. (mm) |
| Bare CMP (Control Test)    | 1           | Circular 60 (1.5) | Fully Deteriorated Invert (Invert-cut) | 6 (1.8) | N/A | Polyurethane | 0.25 (6.35) |
|                           | 2           |     |       |       |     |       |         |           |
|                           | 3           |     |       |       |     |       |         |           |
|                           | 4           |     |       |       |     |       |         | 1.00 (25.4) |
| Polymeric SAPL             |             |     |       |       |     |       |         |           |

Entezarnahdi [24] conducted laboratory testing according to the ASTM standards C39, C76 and C497 to examine the structural capabilities of renewed reinforced concrete pipe (RCP) samples with different SAPL materials including epoxy, multi structural liners with modified polyurea and foam, polyurethane, and cement mortar. It was concluded that compared with the bare pipe sample, all of the tested lining materials enhanced the structural capacity of RCPs in different degrees, ranging from 45 to 133%. Royer and Isley [25] conducted a series of laboratory D-Load testing on rehabilitated pipe samples, including CMP, RCP and cardboard tubes, using geopolymer SAPLs in different thicknesses to investigate the externally applied load that yields the D-Load crack of 0.01 in. (0.2 mm). The authors concluded that a minimum thickness of 1 in (25.4 mm) cementitious SAPL for pipes less than 54 in. (1371 mm) in diameter and a minimum thickness of 1.5 in. cementitious SAPL (38.1 mm) for larger diameter pipes are required to improve the structural integrity of the pipes. Moore and García [26] conducted a series of large-scale laboratory testing to examine the performance of two deteriorated CMP culverts renewed with 2 and 3 in. (50.8 and 76.2 mm) cementitious SAPLs buried under 2 ft (609.6 mm) of soil cover. The CMP diameters were 47 in. (1,193.8 mm) and both were corroded at the invert locations with some perforations at hunch areas. The soil-pipe systems were subjected to single and tandem axle Canadian design truck loading configurations. The results showed that the cementitious SAPL enhanced the culvert response to the applied load.

Additionally, Moore and García studied the ultimate strength of the renewed CMPs from their previous study [26] under the same testing configurations and presented the results in another publication [27]. In this study, a static load-control regime was applied to obtain the SAPL’s ultimate load bearing capacity. The 2 in. (50.8 mm) SAPL renewed CMP sample cracked at 145 kips (650 kN) and the sample with 3 in. (76.2 mm) of SAPL cracked at 180 kips (800 kN) of load in the tandem axle configuration. It was noted that the thicknesses of the applied SAPLs were not uniform, and their variation at some locations were almost two times greater than the designed thicknesses.

Currently authors are not aware of any research studies that investigated the structural capacity and performance of a renewed metal culvert using polymeric SAPL that simulates the actual soil-pipe interaction system.

Objectives

The objectives of this paper are:

1. To examine the performance of invert-cut corrugated metal pipe culverts renewed with a commercially available polymeric SAPL material through a series of full-scale laboratory soil box testing,
2. To compare the results of SAPL renewed CMPs with a same size invert-cut bare (unlined) circular CMP,
3. To observe failure modes of CMPs renewed with polymeric SAPL, and
4. To investigate the feasibility of polymeric SAPL application as a fully structural renewal method.
Methodology

Since December 2017, a group of researchers at the Center for Underground Infrastructure Research and Education (CUIRE) at the University of Texas at Arlington have been conducting a comprehensive study to develop structural design methodologies for polymeric and cementitious spray applied pipe linings (SAPLs). The research program is sponsored by seven US DOTs of DelDOT, FDOT, MnDOT, NCDOT, NYSDOT, Ohio DOT (lead of the project), and PennDOT. The program includes five sets of full-scale soil-pipe structural testing [11,28]. To investigate the soil-pipe structural capacity, the pipes were backfilled with SP soil and buried under 2 ft (610 mm) of soil cover. A monotonic displacement-control static load was applied through a rigid 20 × 40 in. (25.4 × 101.6 cm) steel load pad over the crown of the pipes.

The first set of the experiments included the control tests (i.e., unlined/bare pipes) that investigated the behavior and load carrying capacity of invert-cut arch and circular CMPs, which the results were presented previously in another study [29]. This article presents the results of the second set of tests, which examines structural capacity of three fully invert deteriorated circular CMPs, renewed with polymeric SAPL.

Experimental setup

Host pipe samples

Four annular corrugated metal pipes (CMPs) were selected for this study including one unlined (bare) CMP and three SAPL renewed CMPs, as presented in Table 1. The pipe samples had an internal diameter of 60 in. (1.5 m) and a length of 6 ft (1.8 m). The CMP samples had a corrugation profile of 2 × ⅔ in. (6.8 cm) and gauge 12 (2.657 mm) thickness, as illustrated in Fig. 2(a), fabricated from bent hot-dip galvanized sheets along their edges fastened by rivets, as shown in Fig. 2. To simulate a culvert in a fully deteriorated invert condition, an 18 in. (45.7 cm) wide strip of CMPs at the invert location was entirely cut. The 18 in. (45.7 cm) value was selected based on observations that usually one-third of wetted perimeter of the pipe is more vulnerable to severe corrosion [30]. Furthermore, this value is in conformity with the middle bedding section as specified in AASHTO LRFD bridge design specifications [31]. Since the invert corrosion of culverts in field is a slow process and occurs in several years, the soil-pipe system is usually stabilized. Therefore, the invert-cut sections of the CMP samples were bolted to the main body of CMPs to maintain the pipes' original geometry during the backfilling. For the control test CMP sample, once the backfill was placed and the soil-pipe system was stabilized, the invert-cut section was unbolted and detached from the main body of CMP. Fig. 2(b) and (c) illustrate the detachable invert details of the bare CMP (i.e., control test).

However, after the invert-cut section detachment, the movement of CMPs due to the soil load was a major concern, and in that case, the CMP would not have the exact same geometry at the time of SAPL installation. Therefore, in order to have the same CMP geometry for all SAPL renewed pipe samples; two narrow strips with a 3 in. (76.2 mm) width at both ends of the invert section were kept bolted to the main body of CMP to hold the pipe's geometry. Once the SAPL was installed and cured, the 3 in. (76.2 mm) end-strips were removed to eliminate ring stiffness of the host pipe. This was essentially needed to maximize the applied load on the liner as the objective of the presented study was to investigate whether the polymeric SAPL is structural or not. Fig. 3 illustrates the detachable invert mechanism for SAPL renewed CMP samples, where at the stage (1) the invert is bolted to the CMP’s body during backfilling. Once the backfilling task was completed, in the stage (2) the middle detachable invert section was removed. In the stage (3) the polymeric SAPL was installed inside the pipe, and in the stage (4) the remaining invert section was unbolted to eliminate the ring stiffness of the host pipe.

Burial configuration

To minimize the experiment setup time, three CMPs were placed next to each other and separated by wooden partition walls for each set of tests in a soil box of 25 ft (7.62 m) long, 12 ft (3.65 m) wide, and 10 ft...
Fig. 3. Detachable invert mechanism for SAPL renewed pipe samples during the SAPL installation.

(3.05 m) deep. Fig. 4 illustrates the CUIRE’s laboratory facility at the University of Texas at Arlington. The CMPs were buried under 2 ft (609.6 mm) of soil cover. To prevent soil-wall friction, lubrication was used on wooden walls and a layer of plastic sheet was placed in between the soil and walls [32]. The gap between the CMPs and partition walls were sealed with Styrofoam.

The burial configuration included foundation, loose bedding, backfill and cover, as illustrated in Fig. 5. Poorly graded sandy (SP) soil, known as concrete sand, with a negligible amount of silt and clay was used for the foundation, bedding and backfill layers according to the unified soil classification system (USCS). The maximum Standard Proctor Dry Density (SPDD) of the soil was obtained by conducting the standard Proctor compaction test. The Proctor test showed the maximum unit weight of the soil was approximately 115 pcf (1842 kg/m³). It is noteworthy that the density of this type of soil was not significantly affected with the alteration of moisture content [33].

Two passes of a plate vibratory compactor with a 4496 lbs (20 kN) compaction force were utilized at every 8 in. (203.2 mm) lift of foundation to achieve approximately 96% of the SPDD, which was measured using a nuclear density gauge meter.

A 4-in. (101.6 m) bedding layer of loose SP soil was placed on top of the foundation at each cell as specified by AASHTO LRFD Bridge Construction Specification [34]. This loose bedding layer would allow the pipe sample to settle properly and to provide even bedding conditions [35]. In addition, this layer could represent the loosened soil under a pipe’s invert in the actual field condition as a result of stream passage in the absence of the invert section (i.e., fully corroded invert). The CMPs were placed on the bedding layer and were backfilled with SP soil up to one ft (304.8 mm) above top of the pipe sample. No attempt was made to compact the embedment and backfill to simulate poor conditions of pipe installation in field. The soil was dumped and spread out at 8 in. (203.2 mm) lifts. The water content and the compaction rate of the soil was measured at each layer using a nuclear density meter at two locations in both sides of the CMPs. The averaged water content and compaction rate for all three cells (lined CMPs) at the same lifts from foundation to the top level of the backfill are calculated and counterplotted in Fig. 6. A one-foot (304.8 mm) layer of aggregates with maximum particle size of 1.75 in. (44.5 mm), known as TxDOT 247 grade 1 type D aggregates, was placed on top of the backfill layer to prevent immature soil failure prior to the pipe sample failure. This layer is representative of the base course as a part of culvert’s cover in the field [32]. The burial configuration of the control test on the bare fully deteriorated invert CMP was in a similar manner as the SAPL renewed CMP test setup.

Surface preparation and polymeric SAPL installation

Once the CMPs were backfilled, they were renewed with different thicknesses of a commercially available polymeric SAPL material. Prior to the pipe installation in the soil box, the CMPs were power washed using pressurized water jet to be cleaned and to remove the dust and dirt attached to the inside surface of the CMPs, similar to the pipe

Fig. 4. CMP installation: (a) longitudinal configuration of CMPs in the soil box (25 ft × 12 ft × 10 ft) at CUIRE, (b) circular CMP sample, and (c) detachable invert and end-strip configuration for SAPL renewed CMP samples.
preparation procedure for lining in field recommended by SAPL vendors. In this study, SprayWall® polymeric SAPL material was selected to renew the CMPs. SprayWall® is a self-priming polyurethane lining by Sprayroq Protecting Lining System Company for pipe and manhole renewal that reinstates structural integrity, provides infiltration control and corrosion resistance. Its quick curing time allows the newly protected structure to be returned to service shortly after the completion of the application, which makes it ideal for utilization in water, wastewater and stormwater pipe renewal. Sprayroq recommends cleaning the host pipe from oil, and other contaminants, which may cause formation of blisters, pinholes, foamed material, debonding, cracking, or delamination of the SAPL from the host pipe.

The SAPL was applied up to 0.25 in. (6.35 mm) thick in a single application or lift with solidifying in approximately 8 seconds to complete curing process in 60 minutes. In the invert section, since it was not possible to spray the SprayWall directly on the soil, the fully detached

Fig. 5. The CMPs’ burial configuration: (a) plan view, (b) profile view of the aligned CMPs in the soil-box, and (c) cross sectional view of the circular CMP.

Fig. 6. The counterplot for averaged values of water content and compaction rate in every 8 in. (203.2 mm) lifts measurement.

Fig. 7. SAPL installation of invert-cut CMPs: (a) before SAPL installation (stage 2 of Fig. 3), (b) after SAPL installation (stage 3 of Fig. 3), and (c) end-strips detachment (stage 4 of Fig. 3).
Invert section was left in place and the 2-in. (50.8 mm) gaps between the invert section and the CMP’s main body were filled with Styrofoam, as shown in Fig. 7(a).

In this study, the vendor utilized a hand spray installation. In order to control the thickness during the installation, with respect to the volume of the sprayed material coming out of the nozzle per unit of time (i.e., second), the installer could estimate the amount of material that was sprayed on the CMP’s inside surface. In addition, by knowing the total volume of the required SAPL, the installer could estimate the number of passes required to reach the designed thickness. However, this type of installation requires the high proficiency and experience of the SAPL installer. The Sprayroq vendor calculated approximated amounts of 179.08 lb (81.22 kg), 358.16 lb (162.45 kg), and 716.33 lb (324.92 kg) of SprayWall® material that were required, respectively, to apply the 0.25 in. (6.35 mm), 0.5 in. (12.7 mm), and 1 in. (25.4 mm) thicknesses, each on the inside surface of a 6 ft (1.8 m) long, 60 in. (1.52 m) diameter CMP.

Prior to the SAPL installation, four plate samples with about 0.125 in. (3.175 mm) thickness were sprayed and collected from the same batch to examine the flexural and tensile properties of the installed SAPL material, as shown in Fig. 8(a). Once the plate samples were cured, they were cut into the required plaques for flexural and tensile tests as specified by the corresponding ASTM standards. The plaques were precision machined to exact dimensions to minimize edge effects, as shown in Table 2.

### Instrumentation

The pipe samples were instrumented with uniaxial strain gauges, cable displacement sensors (CDSs), linear variable differential transformers (LVDTs), earth pressure cells, digital image correlation (DIC) targets, and digital cameras. All the sensors used in this study were calibrated and certified by their own manufacturers.

### Strain gauges

Before backfilling, the bare CMP sample (control test) was instrumented with a total of 16 uniaxial strain gauges (Micro Measurement C2A-06-250LW-120) circumferentially at 45° intervals at the middle section of the pipe in two layers (i.e., one layer on the crests, and one layer in the valleys), as illustrated in Fig. 9(a). For each SAPL renewed CMP sample, 8 strain gauges were installed on the outer surface of the CMP and eight gauges on the inner surface of the installed SAPL, as illustrated in Fig. 9(b). Once the gauges were installed, the Micro Measurement air-drying M-Coat D was applied to protect gauges from moisture and electrical leakage. Two layers of physical protection were provided by attaching M-Coat FA Aluminum foil tape and M-Coat FN Neoprene rubber sheets to protect gauges form abrasive soil particles movement, as illustrated in Fig. 9(c) and (d).

### Earth pressure cells

To monitor the applied pressure at different layers of the soil, four Geokon 4800 series earth pressure cells were embedded around each CMP on top, bottom, and both sides of the pipe samples within a 4 in. (10.16 cm) distance away from the outer surface of the CMP, as shown in Fig. 5(c). The earth pressure cells were wired to a Geokon data acquisition system (DAQ) to digitalize the transmitted analog signals from the sensors during the test [37]. According to the sensors manufacturer, the accuracy of the pressures cells were ± 0.1% of the sensors’ full-scale range (i.e., 3 psi (21 kPa)).

### LVDT and CDS

LVDT and CDS sensors are commonly used to measure pipe deflection in laboratory condition experimental testing [38]. Two Micro-Epsilon WPS-500-MK30-P10 CDSs were attached vertically and horizontally on the inside surface of each pipe sample to measure crown and springline deflections at the mid-length of the CMPs (Micro-Epsilon 2019). Three Omega LD650 LVDTs were installed on a wooden frame, cantilevered to the middle of the pipe sample, to measure the crown, springline, and shoulder deflections during the loading application [39]. It should be noted that the sensors, wooden frame and the steel beam were not attached to the pipe samples and had a clear distance of 10 in. (254 mm) from the inverts of the pipes.

### DIC measurement and pipe monitoring

A DSLR Canon Rebel T5i camera was used to capture the pipe

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### Table 2

**Mechanical property test’s specimen dimensions.**

| Test                  | Specimen Replicate Number | Width in. (mm) | Thickness in. (mm) | Specimen Shape |
|-----------------------|---------------------------|----------------|--------------------|----------------|
| Flexural Test         | 1                         | 0.495 (12.57)  | 0.140 (3.55)       | Full-profile   |
| D790                  | 2                         | 0.495 (12.57)  | 0.137 (3.47)       | Full-profile   |
|                       | 3                         | 0.495 (12.57)  | 0.140 (3.55)       | Full-profile   |
|                       | 4                         | 0.495 (12.57)  | 0.145 (3.68)       | Full-profile   |

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Fig. 8. SAPL sampling: (a) sample plates prior to the cut into required shapes for flexural and tensile tests, and (b) the sampling site with Sprayroq installation truck.
samples profile changes during the tests. Multiple targets were designed and fabricated using high contrast colors such as black and white. They were placed on the inside crest of the CMP samples. The targets were installed circumferentially in the middle section of the CMPs. Two-dimensional digital image correlation (DIC) technique was implemented using commercially available software GOM Correlate and a developed MATLAB code. 2D DIC is a powerful technique that enable the multi point deflection measurement in a 2D plane at any stage of loading [40].

In addition, two same model cameras were installed inside the pipe samples to monitor the crack initiation on the SAPL in the crown and springline locations during the test. The LVDTs, CDSs, DIC targets set up and cameras inside the pipe sample are depicted in Fig. 10(a).

**SAPL thickness measurement**

The thickness of the installed polymeric SAPL was measured longitudinally at three locations along the pipe length and in circumferential direction with 45° intervals. The measurements were conducted using an OLYMPUS 38DL PLUS® Ultrasonic Thickness Gauge with a measuring thickness range of 0.003 in. (0.08 mm) to 25 in. (635 mm). The device was calibrated with two same SAPL material samples with the thicknesses of 0.25 in. (6.35 mm) and 1 in. (25.4 mm). All the measurements were conducted on top of the corrugation’s crest, since the probe was too large to be perfectly fitted in the valley location. For each point, three measurements were conducted and the averaged values were recorded. The measuring locations and the calibration samples are illustrated in Fig. 11.

**SAPL mechanical property testing, test samples and procedure**

Eight SAPL sample plaques were prepared for the tensile and flexural material property testing (four beam and four dog-bone samples). The tensile property of the dog-bone sample plaques were tested according to the ASTM D638, Test Method for Tensile Properties of Plastics, type I [41]. For this test the gauge length of 2 in. (50.8 mm), grip distance of 4.5 in (114.3 mm), and the load rate of 0.2 in/min (5.08 mm/min) were selected.

The flexural property of beam samples were tested in compliance with the ASTM D790, Test Method for Flexural Properties of Unreinforced Plastics.
and Reinforced Plastics and Electrical Insulating Materials, Method I procedure A [42]. The three-point bending configuration was used with the load rate of 0.053 in/min (1.34 mm/min) and a support Span-to-Depth ratio of 16 to 1 as specified by the ASTM standard. Table 2 lists the specimens’ dimensions for both mechanical property tests.

**Loading configurations and testing operation**

The CMPs were loaded using a 330-kip (1467 kN) MTS hydraulic actuator attached to a reaction frame located at the CUIRE Laboratory at the University of Texas at Arlington. The load was applied through a rigid 20 × 40 in. (25.4 × 101.6 cm) steel load pad in a static regime. Static loading regime was selected since it causes higher deformation on the pipe sample in compare with dynamic loading [43]. In this study, a monotonic displacement-control loading method was chosen due to its advantage for obtaining the post-peak softening behavior of the pipe samples with the loading rate of 0.03 in./min (0.762 mm/min) [47]. The reason of selecting a monotonic loading rather than incremental loading regime was due to the insensitivity of the selected SP soil to the delayed deformation and settlement [30,44].

**Results and discussions**

**SAPL mechanical property result**

The SAPL dog-bone and beam sample plaques were tested according to the related ASTM standards, discussed in the “SAPL mechanical property testing, test samples and procedure” section. The SAPL mechanical property test results are presented in Fig. 12. The averaged maximum force resisted by the polymeric SAPL samples under the 3-point bending flexural test configuration was 53.99 lb (240.16 N) with the standard deviation of 2.23 lb (9.92 N). Consequently, the calculated averaged flexural modulus was 855,639 psi (5899.42 MPa). The SAPL uniaxial tensile test showed the maximum averaged tensile stress for the specimens was 8670.78 psi (59.78 MPa) with the standard deviation of 623.94 psi (4.3 MPa). The averaged maximum tensile strain was 0.0443 with the standard deviation of 0.0031. With respect to the recorded tensile stress and its respective strain, the averaged elastic modulus of 329,209.9 psi (2269.82 MPa) and standard deviation of 12,152.16 psi (83.78 MPa) were obtained. The results of the tests are close to the manufacturers specifications [36,45].

**SAPL thickness survey**

The thickness measurement of the SAPL was conducted at three locations of approximately 1/3, 1/2, and 2/3 of the pipe sample’s length. In comparison with the design thickness, the measurement results showed that the applied thickness is usually higher at springline (i.e., locations W2 and E2 in Fig. 13) and lower at the crown locations (i.e., location C in Fig. 13). This alteration is more evident for thicker SAPL and could be due to sagging and movement of the sprayed material because of downward gravity force. The thickness variation of SAPL on the 1.0 in. (25.4 mm) SAPL renewed CMP sample, as presented in Fig. 13(c), shows that the thickness was more uniformly applied at the center of the pipe in compare with the both ends of the pipe. The same trend was observed for the 0.5 in. (12.7 mm) and 0.25 in.
SAPL renewed CMP samples. This can be because the polymeric SAPL was installed through a hand sprayed technique and probably the installer had more space and ease of movement at the center of the pipe in compare with both ends of the pipes, where the partition walls were located.

Manual thickness measurements using a digital caliper were conducted after the structural testing and failure of SAPL liners to verify the ultrasonic thickness measurement. The results comparison showed an excellent agreement between both measuring methods, especially for thicker liners. In case of 0.25 in. (6.35 mm) thick SAPL, the ultrasonic device was not able to accurately measure the thickness at the 2/3 of the pipe’s length, which was located towards the end wall at south location, as illustrated in Fig. 5(a). One possible reason could be due to the received higher volume of backscattered waves in low thickness

Fig. 13. Polymeric SAPL thickness measurement results: (a) 0.25 in. (6.35 mm) thick SAPL, (b) 0.5 in. (12.7 mm) thick SAPL, (c) 1 in. (25.4 mm) thick SAPL, and (d) measured locations in circumferential and longitudinal direction.

Fig. 14. Pipe profiling using DIC results for the invert-cut circular pipe sample movement due to the invert section detachment: (a) the CMP picture after detachment, and (b) the DIC results.
such as 0.25 in. (6.35 mm) that made the device unable to calculate the thickness accurately. Therefore, for this location (i.e., 0.25 in. at 2/3) the results of manual thickness measurements are reported in Fig. 13(a).

The visual observation on 0.25 in. (6.35 mm) SAPL renewed CMP showed the applied SAPL thickness on the seams of CMP was not sufficient and, in many sections, there were discontinuities on the liner at the seams’ locations. However, this issue was completely resolved on the 0.5 in. (12.7 mm) and 1.0 in. (25.4 mm) thick SAPL pipe samples, which implies the quarter inch thickness may not be sufficient or requires additional installation consideration on the seams’ locations.

Invert detachment

The invert section of the bare CMP (control test) was removed prior to the loading. Once the invert section was detached, due to the soil weight, the pipe moved circumferentially and squeezed. The CMP profile was measured using DIC technique before and after the invert detachment and diameter changes of almost 3.0 in. (76.2 mm) were observed in both horizontal and vertical directions, as illustrated in Fig. 14. The diameter of the CMP was also measured using a laser distance meter device, which recorded 3.1 in. (78.74 mm) vertically and 3 in. (76.2 mm) horizontally diameter changes. It should be noted that for safety of the researchers, the utilization of CDSs and LVDTs during the invert detachment process in such a confined area was not possible.

For the renewed CMPs, where the two end-strips were bolted to the main body of the pipes, no movement was registered due to the main invert section detachment. Once the liner was installed, the both end-strips were removed completely. At this stage, no sign of pipe movement, SAPL crack or damage was observed.

Fig. 15. Load vs. displacement results for CMP samples and soil: (a) bare invert-cut CMP, (b) 0.25 in. SAPL renewed CMP, (c) 0.5 in. SAPL renewed CMP, and (d) 1 in. SAPL renewed CMP.

Fig. 16. Formation of the first structural crack: (a) 0.25 in. SAPL renewed CMP at 39 kips, (b) 0.5 in. SAPL renewed CMP at 42.78 kips and (c) 1 in. SAPL renewed CMP at 66.26 kips.
Table 3
The CMPs' load bearing capacity, crown deflection and the soil displacement at initial crack and failure.

| Test Setup | Initial Structural Cracking Stage | Failure Stage |
|------------|-----------------------------------|---------------|
|            | Pipe load bearing capacity, crown deflection and the soil displacement at initial crack and failure. |               |
| Bare Invert-cut CMP | – | – |
| Bare Invert-cut CMP | 39.9 (177.48 kN) | 5.8 (147.23 mm) |
| Bare Invert-cut CMP | 7.27 (184.65 mm) | 2.12 in. (53.85 mm) |
| Bare Invert-cut CMP | 46.38 (206.20 kN) | 4.83 (122.68 mm) |
| Bare Invert-cut CMP | 52.43 (233.22 kN) | 4.43 (112.52 mm) |
| Bare Invert-cut CMP | 66.26 (294.73 kN) | 4.17 (105.92 mm) |
| Bare Invert-cut CMP | 72.15 (320.93 kN) | 4.17 (105.92 mm) |
| SAPL Renewed CMP | 0.25 in. (6.35 mm) | 5.8 (147.23 mm) |
| SAPL Renewed CMP | 42.78 kips (190.29 kN) | 1.75 in. (44.45 mm) |
| SAPL Renewed CMP | 3.06 (77.72 mm) | 4.58 (116.33 mm) |
| SAPL Renewed CMP | 5.16 (131.12 mm) | 5.61 (142.49 mm) |
| SAPL Renewed CMP | 4.83 (122.68 mm) | 4.17 (105.92 mm) |
| SAPL Renewed CMP | 12 in. (25.4 mm) | 6.69 (169.92 mm) |

Pipe load bearing capacity

The load was applied through a 20 × 40 in. (25.4 × 101.6 cm) steel load pad with a load rate of 0.03 in./min (0.762 mm/min) on the soil surface at the middle section of the pipe. The results of soil-pipe settlement due to the applied load for the bare invert-cut CMP, and all three SAPL renewed CMPs are presented in Fig. 15. The invert-cut bare CMP, in the absence of invert section and ring stiffness, initially resisted the applied load until approximately 5 kips (22.2 kN), which is believed to be due to the friction resistance force of the soil-pipe system. Once this limit was reached, since there was no other resisting force to prevent the pipe sample circumferential movement, the CMP moved continuously with the load progression until both sides of the cut sections contacted each other and recovered the ring stiffness. After this point, the system showed a significant stiffer response to the load until the failure at the load of 39.9 kips (177.48 kN) with almost 7.22 in. (183.38 mm) of soil displacement and 5.8 in. (147.23 mm) of pipe's crown deflection.

In contrast with the bare CMP sample, the SAPL renewed CMPs were able to resist the applied load without any sign of cracking or fracture at the invert location, which indicates the structural capability of polymeric SAPL, was sufficient to withstand the applied ring compression. The first structural crack of the 0.25 in. (6.35 mm) SAPL renewed CMP testing was observed at the load of 39 kips (173.48 kN) with 2.12 in. (53.85 mm) of pipe deflection at the crown. The crack initiated and propagated in the longitudinal direction, as shown in Fig. 16 (a). However, once the crack reached the CMP's interlocking seams, it diverted towards the circumferential direction in several branches. This can be due to the fact that the applied SAPL on the seams locations was not sufficient to cover the seams as discussed earlier in the “SAPL thickness survey” section. The 0.25 in SAPL renewed pipe sample failed at the load of 46.38 kips (206.30 kN), as illustrated in Fig. 15(b).

The 0.5 in. (12.7 mm) SAPL renewed CMP showed a similar response as the 0.25 in. (6.35 mm) SAPL to the load. The 0.5 in. (12.7 mm) SAPL cracked longitudinally at the crown at the load of 42.78 kips (190.29 kN) with 1.75 in. (44.45 mm) of pipe deflection and reached its ultimate load bearing capacity at the load of 52.43 kips (233.22 kN). Although it was expected to observe larger enhancement from 0.25 in. (6.35 mm) SAPL to 0.5 in. (12.7 mm) SAPL, the ultimate load bearing capacity was improved only 6.05 kips (26.91 kN). This can be due to the relative small difference between the applied SAPL thicknesses for both CMPs at the crown locations, as discussed in the “SAPL thickness survey” section. Fig. 15(c) illustrates the 0.5 in. (12.7 mm) SAPL renewed CMP response to the applied load. It should be noted the initial drop in Fig. 15(c) between the loads 25–35 kips (111.2–155.68 kN) was due to the detachment of the CMPs from the end partition walls, as the over-sprayed SAPL residues provided a minor contact between the SAPL and the partition walls at some locations. Although exercises were made to keep the pipe fully disconnected form the partition walls, such as making a notch or installation of plastic sheets at the edges prior to the SAPL installation, however, a few points were remained connected at the shoulder area. Due to the existence of a gap between the host pipe and the walls, which were filled with Styrofoam, a deep cut would tear the Styrofoam and raise the concern of soil ingress to the pipes. Therefore, it was decided to make notches instead of a full cut at those locations.

The 1 in. (25.4 mm) SAPL renewed CMP showed relatively stiffer response in compare with the other renewed CMP samples. The 1 in. (25.4 mm) SAPL cracked at the load of 66.26 kips (294.73 kN) with the 2.12 in. (53.84 mm) of pipe deflection and released a relative larger amount of energy. This is evident in Fig. 15(d), where a large drop in the load displacement graph at the time of the first structural crack initiation was registered by the LVDT. This can be related to the more rigidity of thicker SAPL in compare the flexible nature of the lower...
tested thicknesses, where the crack propagated throughout the crown instantly. While in the quarter and half an inch SAPL samples a small crack initiated at the center of the pipe at the crown and propagated with the increase of the load, as shown in the Fig. 16. The 1 in. (25.4 mm) SAPL renewed CMP eventually failed at the load of 72.15 kips (320.93 kN), which was about 20 kips (88.96 kN) higher than the load corresponding to the 0.5 in. SAPL renewed sample. The CMPs’ load bearing capacity, crown deflection at initial crack and failure as well as the soil displacement in both initial crack and failure stages are summarized in Table 3.

Ultimate load comparisons between the SAPL renewed CMPs and the bare CMP showed that the application of SAPL increased the

Fig. 17. Load improvement by SAPL application: (a) Ultimate load comparison of renewed SAPL CMPs with bare CMP, and (b) Load carrying capacity comparison of renewed SAPL CMPs with the bare CMP at the 2 in. of pipe deflection.

Fig. 18. Earth pressure cells’ results: (a) bare CMP, (b) 0.25 in. SAPL renewed CMP (c) 0.5 in. SAPL renewed CMP, and (d) 1 in. SAPL renewed CMP.
null
the invert of all three SAPL renewed samples was observed. In addition to that, the SAPL renewed samples had horizontal expansion at the springline and shoulder areas as well as vertical deflection and fracture at the crown, as illustrated in Fig. 20 (d), (f), and (h). The pipe profiling using DIC results implied that for all CMP samples the mode of failure was local buckling at the crown location, where in case of bare CMP the buckling caused CMP deformation and in case of SAPL samples it caused cracking and fracture of the liner at the crown. It should be noted that, due to the existence of the instrumentation frame’s beam and wires, illustration of a full ring of pipe sample was not possible.

Summary and conclusions

Three invert-cut corrugated metal pipes (CMPs) renewed with
polymeric spray applied pipe lining (SAPL) and one invert-cut bare CMP (simulating a fully invert deteriorated CMP) were buried under 2 ft (610 mm) of soil cover including layers of poorly graded sand (SP), and TxDOT 247 grade 1 type D aggregates. A static load with a displacement-control regime was continuously applied with a load rate of 0.03 in./min (0.762 mm/min) through a rigid 20 × 40 in. (254 × 102 mm) steel load pad on the soil surface over crown of the pipe. The results and discussions were presented in this paper and the conclusions are summarized as follows:

- The mechanical property test results showed that the polymeric SAPL had the flexural modulus of 855,639 psi (5899.42 MPa), the averaged maximum tensile stress of 8670.78 psi (59.78 MPa), and the elastic modulus of 329,209.9 psi (2269.82 MPa).
- The results of thickness measurement showed that the utilization of hand spray installation of the polymeric SAPL resulted in a thicker liner at the springline for all renewed CMPs than the designated thickness. However, the SAPL was installed closer to the required thickness at crown and both shoulders. One of the possible reasons for the inconsistent thickness installation could be due to the sagging and movement of the SAPL material at the initial stage (i.e., before hardening) of installation due to gravity.
- The invert-cut bare CMP in the absence of the ring stiffness was not able to resist the applied load beyond its frictional resistance limit. The CMP continuously squeezed until both sides of the invert-cut sections contacted the main body of the CMP and retrieved the ring stiffness. The invert-cut bare CMP structurally failed at the load of 39.9 kips (177.48 kN).
- All SAPL renewed pipes cracked at about 3% of pipe deflection, where at this deflection the application of 0.25 in. (6.35 mm), 0.5 in. (12.7 mm), and 1 in. (25.4 mm) polymeric SAPLs increased the load carrying capacity for 471.7, 482.8, and 802.7% respectively.
- Application of the polymeric SAPL increased the stiffness of the invert-cut CMP. The SAPL renewed CMPs with the thicknesses of 0.25 in. (6.35 mm), 0.5 in. (12.7 mm), and 1 in. (25.4 mm) increased the ultimate load bearing capacity of the fully invert deteriorated CMPs for 16.24, 31.4, and 80.82%, respectively.
- The CMP with the thinner liner (i.e., 0.25 in.) was susceptible to crack at the seam’s locations, where the thickness of liner was not sufficient to prevent cracking. Although the first crack was initiated in the longitudinal direction, once it reached the seam locations, it diverted towards the circumferential direction. Therefore, for this thickness additional installation consideration at the seams locations is suggested.
- The CMP with 1 in. (25.4 mm) thick SAPL showed a stiffer response to the applied load compared with the other SAPL renewed pipe tests. In contrast with the other samples, no circumferential crack was observed in the pipe sample.
- In the absence of the host pipe’s ring stiffness, the SAPL was able to resist the ring compression solely. Therefore, the polymeric SAPL can be considered structurally sufficient to withstand the applied load and improve the overall load bearing capacity of the fully invert deteriorated host pipe.

CRediT authorship contribution statement

Zahra Kohankar Kouchesfahani: Writing - original draft, Conceptualization, Formal analysis, Methodology, Investigation. Amin Darabnoush Tehrani: Writing - original draft, Software, Formal analysis, Methodology, Visualization, Data curation. Mohammd Najafi: Writing - review & editing, Supervision, Project administration. Jeffrey Syar: Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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