Achieving a 100-Year Design Service Life on Wastewater Projects

James P. Eng. Teppan

Abstract The primary cause of premature deterioration on wastewater infrastructure is due to the lack of or improperly installed protective measures, not the structures themselves. Using newly developed design, manufacturing and installation protocols, Engineered Containment has pioneered a 100-year design service life guarantee. The concrete protective lining protocol eliminates the failure modes of traditional lining systems (both epoxy and embedment liner) while reducing costs at the front end and through the lifecycle of the structure(s). This cradle-to-grave approach, which is currently being implemented on strategic projects across Canada, provides owners and stakeholders tangible assurances regarding service life and warranty. Innovations are based upon the results of an in-depth review of current industry modalities and a mechanical and chemical review of various products utilized for concrete protection.

Keywords Wastewater infrastructure · Engineered Containment · Protective lining · Service life guarantee · Concrete protection innovations

1 Introduction

The use of internal concrete protective lining systems for new infrastructure is prevalent around the world and can generally be placed into two categories; epoxy coatings or concrete protective liner (CPL) typically made with high-density polyethylene (HDPE). These coatings/linings are utilized to protect concrete from hydrogen sulfide gas and the subsequent and destructive sulfuric acid that is produced at the gas-to-concrete interface.

Given the relatively high cost of 3–4 mm thick epoxy coatings as compared to 2–3 mm thick HDPE CPL along with the difficulties associated with epoxy's mid- to long-term adhesion to concrete in high groundwater environments, only anchor/embedment CPL will be addressed. Note that epoxy coatings are a more expensive

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polymer than HDPE and are also more expensive to apply to the concrete when troweled on with thickness inconsistencies. Sprayed epoxy is more cost-effective, but the 3–4 mm thickness necessary to avoid pinholes/holidays is also expensive and must be done in a factory setting to maximize quality. Both epoxy and CPL require proper installation techniques for the system to be successful and maintain its integrity. A final note with epoxy is its relatively brittle nature as compared to HDPE CPL. Movement/settlement of manhole barrels or trunkline/pipeline segments could result in cracks at joints exposing the concrete to gas/fluids and/or water ingress. HDPE has elongation properties that allow for settlement without joint failures.

With any polymeric coating/liner, the correct application of the material is imperative for the creation of a system that has containment integrity as well as a long lifespan (the target of the developments discussed herein is 100 years). This paper will now delve into the study of how to create a CPL system within either a precast or cast-in-place structure. The study is a cradle-to-grave analysis that starts with the use of H2S-resistant HDPE which has a 446 year half-life at 20 °C in non-UV-exposed applications [4, 5] and ends with the on-going surveillance and maintenance of the system. All aspects of the system from start to finish are critical in achieving a 100-year service life. The cradle-to-grave analysis steps are as follows:

1. HDPE CPL manufacturer's embedment/anchor liner (CPL) design and quality.
2. Accessory availability and quality.
3. Precast design, production techniques, handling techniques, and quality.
4. Cast-in-place formwork design, cladding techniques, gapping, and the use of accessories to minimize inferior welds.
5. In-plant and in-situ extrusion welding quantity.
6. In-plant and in-situ extrusion welding quality.
7. QA/QC techniques including the ability to follow ASTM holiday testing protocols.
8. On-going surveillance of the system to ensure small operating problems are resolved early via maintenance such as patching and welding holes, scratches, or failed components.

2 CPL Manufacturer's Design and Quality

To assure a long life, it is imperative that one uses a manufacturer with experience and a solid track record. There are two such companies that manufacture quality CPL globally: AGRU and Solmax (previously GSE). AGRU is third party certified by South Carolina Manufacturing Extension Partnership (SCMEP) and has been in business since 1948. They pioneered the use of their Suregrip/ultra-grip V-anchor that is made as one piece in one step and has over 30 years of in-service Suregrip installations. Solmax/GSE has been in business since 1981 and produces their Studliner which is made as one piece in two steps with over 20 years of in-service Studliner installations (Fig. 1).

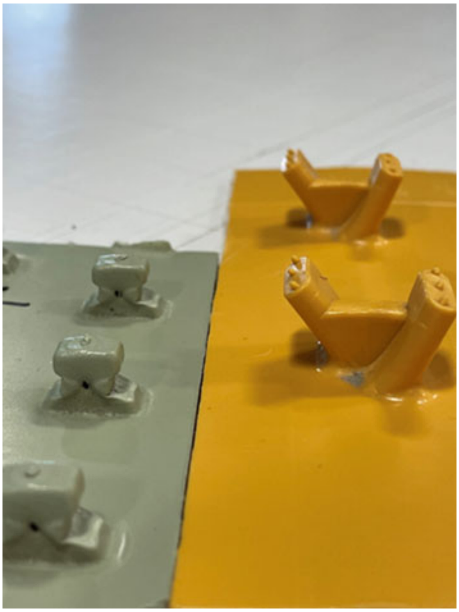

Fig. 1 Solmax/GSE Studliner on left and AGRU Suregrip/ultra-grip on right

Neither of the aforementioned CPL sheets can be considered better than the other except to make your own judgment on anchor design, anchor density, and/or sheet width availability. Suregrip has 13–19 mm V-anchors at 420 anchors per square meter [2], while Studliner has 8 mm head-type anchors at 1200 anchors per square meter [6].

Suregrip is available in sheet widths up to 5 m (16.4′), and Solmax is available in sheet widths up to 2.44 m (8′). The wider width is important when producing precast pipe as it minimizes longitudinal welds on 3 m (10′) and greater lengths of pipe. As an example, 3 m (10′) Suregrip requires only 1 long weld on 3 m (10′) long precast jacking pipe, whereas 8′ wide sheet requires 2 longitudinal welds on 1350 mm diameter pipe and 3 welds on 1800 mm diameter pipe. The goal to reduce potential failure modes by minimizing welds will be discussed at length in the quality section (Fig. 2).

A signal layer option is available with AGRU's Suregrip material that allows for easier visual detection and inspection of construction and in-service mechanical damage that must be repaired. This is created by coextruding multiple layers for 3 mm CPL, creating a 1 mm thick "signal" layer on the inside surface of the structure. While not a necessity, it is a value-added in the consideration of a 100-year design service life analysis.

Fig. 2 10′ width CPL on left allowing one longitudinal weld on 10′ jacking pipe in the invert. The 8′ width CPL on right requiring 2–3 longitudinal welds on 10′ jacking pipe (3 welds are shown in the picture of 1800 mm jacking pipe)

3 Accessory Availability and Quality

To assure excellent fit and finish as well as the minimization of inside and outside corner welds, accessories are key. Accessories will vary between the manufacturers and installers and may include:

- Conductive tear-off profiles
- End-profiles for terminations away from another intersecting CPL panel
- Fabric-backed material for penetrations
- Thermoformed inside/outside corners made from smooth or anchor sheet.

Corner pieces are generally bent by hand or by heating with a torch which are both detrimental to the lifespan of the polymer/sheet from a 100-year design service life. Corners should only be produced under specific temp/time conditions such as extrusion or thermoforming. Engineered Containment has developed an accessory line (included in the list above) to supplement the manufacturers' lines and aid in 100-year design service life (Figs. 3 and 4).

The use of these accessories significantly improves welding and system quality by:

1. Keeping CPL panels aligned during concrete pours (tear-off profiles)
2. Allowing proper gaps between panels, so wrinkles do not occur (tear-off profiles)
3. Allowing proper ASTM protocol spark testing (tear-off profiles)
4. Minimizing nail/staple holes, so a single weld bead can be utilized (tear-off profiles with Engineered Containment floating panel procedures)

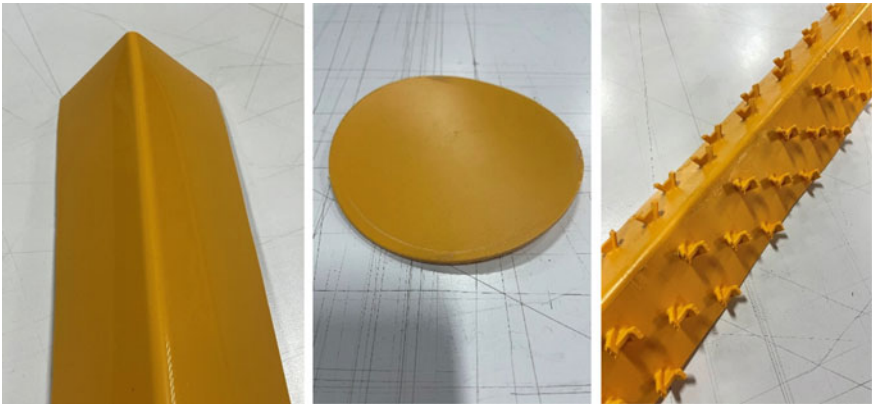

Fig. 3 Corner and patch accessories (Engineered Containment EC-FIT100 accessories)

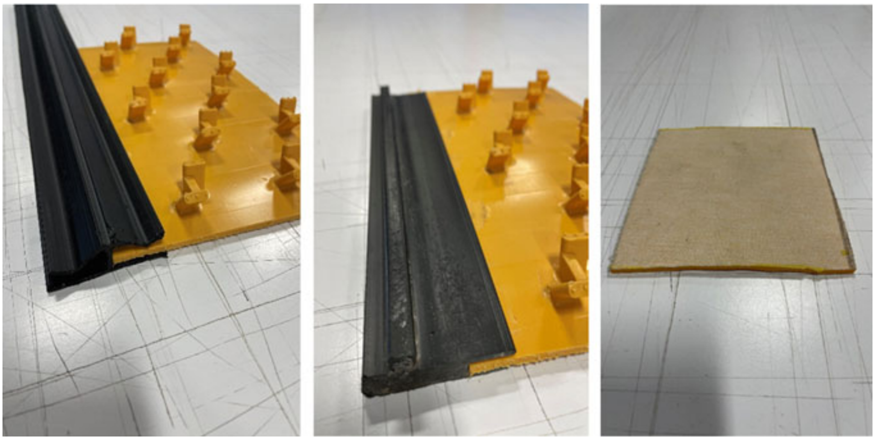

Fig. 4 Tear-off, end, and fabric-back accessories (AGRU accessories)

5. Keeping process gases from propagating behind the CPL (end-profiles)
6. Keeping welds on a flat area instead of difficult to achieve high-quality inside/outside corner welds (thermoformed corners)
7. Maintaining a proper seal at all pipe/steel penetrations (fabric-back CPL).

4 Precast Design, Production, Handling, and QA/QC Procedures

The precast stage of CPL lined trunk line and manhole systems is key. The quality of each precast piece (i.e., wet cast jacking pipe, wet or dry cast open cut pipe, manhole barrels, cones, etc.) is paramount as poor fit and finish from a precasting standpoint and/or poor in-plant finishing welding cascades to unnecessary and serious issues for the in-field welding phase and overall quality of the project.

Quality starts with the CPL panel or tube being utilized for the precast piece. Panels are either wrapped around molds, or tubes are inserted on molds with both techniques problematic if due care and attention is not taken in the production of the panels or tube. The production accuracy for these pieces should be aligned with finishing carpentry (i.e., ± 1/8″) not general formwork accuracy. Unfortunately, many precasters do not have carpentry tools/systems or the technician to achieve this. If the precast production accuracy is not ± 1/8″, problems arise in panel sizing for wrapping molds and major problems in the case of CPL tube fabrication. An example of this need for precision is detailed below.

During panel production/wrapping, two cuts are required to produce a 4′ (1.22 m) manhole barrel if using 8′ wide 2 or 3 mm CPL. The 8′ length/circumference cut can be a little less accurate given the overlap used for wrapping the mold, but the center cut must be precise, so two 4′ (1.22 m) pieces are produced. (For a 1200 mm manhole, this is 12.66′ (3858 mm)). From a practical standpoint, this is an extremely difficult cut to complete without the proper cutting system that can hold that line. Without a panel that is 4′ (1.22 m) end-to-end, a manhole barrel with a single weld bead cannot be achieved. Instead, capstrip with 2 welds must be utilized significantly increasing the cost and decreasing the containment quality of the barrel because the gap will exceed the maximum allowable of 10 mm at the barrel-to-barrel joint.

In addition to panel sizing issues, panel wrapping and lacing techniques by precaster technicians must be administered with precision to prevent/reduce the risk of liner failure either during the initial QA/QC testing or in the future service life of the system. Robust and special lacing to ensure the overlapped panel does not move up the mold during vibration, leak past the overlap, and/or wrinkle around the edge is critical. If there is poor administration in this stage, the result is a poor-quality precast component that requires capstrip. Overlap of 1″ is all that should be necessary if lacing is done correctly.

In the case of pre-made CPL tubes, dimensional stability is a serious consideration that needs to be addressed. The use of fixed diameter butt-welded tubes should not be adopted as the tube fabrication temperature versus mold installation temperature fluctuation creates thermal expansion and contraction. It is more likely to have a tube too small or large at the time of mold installation than have it fit properly. Additionally, the use of tapered dies and multiple longitudinal butt-welds in tubes constructed with a traditional 8′ wide sheet increases the likelihood of sizing problems. The use of fixed diameter butt-welded tubes creates major problems at the precaster's facility with either mold fitment or wrinkles as shown in Fig. 5.

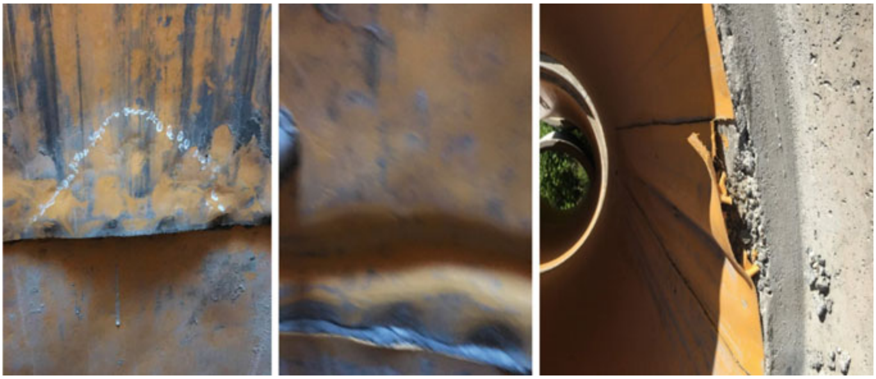

Fig. 5 Wrinkles and panel lift-off from inadequate lacing and/or panel/tube sizing

5 Cast-In-Place Formwork Design, Cladding, Gapping, and Accessory Utilization

Formwork comes in many shapes and sizes with wood as the preferred material as it is the easiest to work with. Steel formwork requires specialized fastening techniques, so the cladded CPL sheet can expand and contract. Expansion is the typical problem as this causes wrinkles that may or may not be acceptable from a structural or process flow perspective.

Aside from fastening design challenges with steel formwork, this section will focus on accessory use during the cladding process. Accessories such as tear-off and end-profiles perform multiple functions and are far superior to using tape, nails, and/or staples to hold the CPL to the formwork and keep it aligned. They also seal the CPL during the pour to minimize concrete leakage and after the pour to eliminate liquid/gas transmission. The use of accessories also minimizes field welding time and increases quality by minimizing edge wrinkling and allowing for proper gapping, so only one extrusion weld bead is needed. Failure to properly align/gap the CPL requires the use of capstrip with two weld beads and the resulting unembedded capstrip. Capstrip is either 4″ or 6″ wide and is used as a bridge across large gaps and/or misaligned sheets of CPL. See Fig. 6 for an example of wrinkling due to improper gapping which was repaired with a manufacturer's approved weld-bead filling process of each depression which was then power-planed to a smooth finish.

The ability to create a corner/bend on a sheet for smaller cast-in-place formwork is the best solution as there is still only one weld, but one that is flat versus an inferior inside/outside corner weld. The best approach to ensure welding occurs on a flat surface is with a corner accessory piece. It creates two welds, but these are superior to an inside/outside corner weld [1, 7].

Lastly, patches are necessary for tie-rod holes and should only be circular and no smaller than 6″ as an extrusion gun cannot effectively and continuously weld around a 90-degree corner on a square patch nor too small a radius.

Fig. 6 Anti-friction application that was not gapped and/or attached correctly. About $250,000 repair on right

6 In-Plant and In-Situ Extrusion Welding Quantity

As previously discussed, minimizing weld joints minimizes the opportunities for failure, but this is weighed against the quality of the welds and the need to allow for expansion and contraction, so wrinkles and large gaps requiring capstrip are avoided. Figure 7 illustrates a cast-in-place vault where capstrip was necessary on many flat wall sections where gaps were too large. It also illustrates a well-built manhole penetration for comparison.

The appropriate approach is to add quantity when there is an opportunity to replace an inside/outside corner weld with 2 flat welds. This approach does have a higher upfront cost associated as the installation of corner accessory or bent sheet adds time and materials to the project but is recovered throughout the service life of the

Fig. 7 Vault (left) with wall gaps too large so more capstrip and welding than necessary. Manhole (right) with single pass weld joints and properly shaped penetration details

system. If this approach is not applied to a project, the convergence to a 100-year design service life is reduced.

7 In-Plant and In-Situ Extrusion Welding Quality

Extrusion welding is considered the most difficult type of weld to produce properly as the rate and consistency of speed of the weld is completely determined by the welding technician. The preheat air for the substrate material and welding rod exit temperature are variable and controlled. Other factors that affect weld quality are ambient conditions such as wind speed, air temperature, and direct/indirect sunlight [8].

The first step in preparing for successful extrusion welding is to "qualify" the welder (man and machine combined). The process involves taking strips of the material and creating a mock-up of the assembly. For example, if overlap welding, as is the case with the use of capstrip, set up an overlapped material sample and staple it to a piece of wood in the vicinity of where welding will be complete to mimic the type of welding to be performed in the environment it will be performed in. The machine's temperatures are set to where the technician believes he/she will achieve a successful weld. The technician then runs a "qualification" weld, and after allowing 15–20 min for material cool-down, he/she cuts 1″ coupons with a bone cutter. These coupons are then placed in a calibrated tensiometer and tested in both shear and peel (peel only for overlap welds). If the tests meet or exceed the specification, the technician can proceed with the work until such time that the ambient or work conditions change enough to require another qualification weld.

The skill and experience of the welder is important and a key factor in ensuring a 100-year design service life. The technician must have a deep understanding of why the procedures exist. They must have experience to deal with unusual situations such as stops/starts, intersecting welds, and penetrations in the structure. It should be noted that it is preferable for the same technician who clads the formwork to be the one who welds as both skillsets are key.

Welding technician certification by the CPL manufacturers is a bare minimum requirement and insufficient when installing a system with a 100-year design service life as a person could conceivably pass all manufacturer testing without an in-person proctor and without knowing how to test their own welds on a tensiometer. The appropriate technician to utilize for CPL welding is one who is first certified by International Association of Geosynthetics Installers (IAGI), the governing body for all Certified Welding Technicians (CWTs). The CPL manufacturer's certification is then the last step as it inherently includes certification of the actual installation company who the technician works for as its procedures/policies are a key element in achieving high-quality workmanship.

Returning to the discussion about inside/outside welds being suspect, it is very difficult to qualify those welds for two reasons. The first is that a corner mock-up structure would need to be built which is not easy to do. The second is that if the

Fig. 8 Self-performed precaster in-plant welding on left and third-party in-plant welding on right. Neither piece passed QA/QC protocols

technician built a corner mock-up, he/she would not be able to properly test the sample on a tensiometer. With respect to butt joints, where one bead is being applied across two CPL panels, only a shear test would be necessary as a peel test is only necessary on overlap welds. For trunklines, an automatic welding unit is preferred for weld consistency and long-term worker safety. There is only one known automatic welder, and its design continues to be evolved with the upcoming addition of key data logging as is done with the auto-welders used for the steel pipeline industry (Figs. 8 and 9).

8 QA/QC Techniques

QA/QC techniques are an area of great interest to both owners and their engineering firms. As discussed in the section above, the quality of a job starts and ends with an abundance of accessories being applied with the CPL sheet by skilled, experienced, and certified technicians.

The QA/QC for a project starts with written/logged qualification welds at least once per day and ends with written/logged holiday/spark and/or vacuum tests. The use of proper ASTM protocols is key. Installers and general contractors have propagated the use of the concrete/rebar as the substrate conductor for spark testing welds or using low vacuum "geomembrane" pond vacuum box testing methods for vacuum testing. Neither is in line with ASTM protocols and only appropriate in a general sense and for general use for simpler installations that do not drive toward a 100-year design service life.

Fig. 9 1800 mm microtunnel with automatic welding of capstrip on right. Capstrip is unavoidable in precast pipe due to gaps too large to create a single bead

Using the conductors as per the manufacturers and ASTM recommendations allows for the voltage to be turned down significantly, so the sparks do not damage the liner material at the molecular level. Also note that too little voltage when using concrete/rebar may result in a false positive where there is not enough voltage to "jump" through a pinhole to the concrete/rebar [3]. Using a shop Vac-type vacuum box tester like those used for geomembrane ponds is inappropriate for CPL because there is not enough vacuum to suck and identify a pinhole because there is no air behind CPL but instead concrete. A pond liner has significant air behind it for a shop Vac to complete a successful test (Fig. 10).

9 On-Going Surveillance, Inspections, Maintenance, and Repairs

As with any manufactured item that carries a long-term warranty, on-going inspection is necessary with no exceptions. Complex systems such as an automobile require regular inspection to resolve small problems like oil leaks with a retorque of the oil pan or new gasket instead of waiting for a major leak and potentially damaging the engine, a very costly repair. CPL systems are no different, and a small breach or weld failure can be repaired very inexpensively versus waiting for the breach to grow larger and the leak to allow serious structural damage to the concrete.

While vessels and trunklines are difficult to access, they are still shut down for maintenance from time to time. If using the techniques as described throughout this

Fig. 10 Spark testing with multiple failures on poorly welded/repaired precast component

paper, the frequency between inspections of CPL lined systems can be as low as every two years (systems with potential for mechanical damage like ice/sand/etc.) or every five years when mechanical damage is unlikely. Inspection can be via CCTV or in-person if appropriate safety precautions can be taken. The most likely damage to watch for is mechanical damage within the invert area where objects such as pipe maintenance equipment like buggies, hoses, and/or tools can deeply scratch the liner. Chunks of ice can cause damage as can the on-going erosion from road sand and grit in combined systems. When these types of problems are identified, not only can the area be repaired, it should be reinforced with a thicker layer of material that can act as a sacrificial impingement plate/barrier.

10 Conclusion

CPL lined system has the ability to be designed to a 100-year service life as HDPE geomembrane and CPL have a 446-year half-life at 20 °C in non-UV-exposed applications [4] as well as high resistance to H2S attack (Roward 2016). Ensuring that the design intent and reality merge relies heavily on vetting every step of the process during construction and during service. No material on its own can claim to meet the service life goals of stakeholders, and it is the system outlined in this paper that will facilitate long-term infrastructure protection that lasts for generations. Selecting the correct material, ensuring that it is handled by competent and capable parties including precasters, field installers, and welders, adhering to strict QA/QC protocols, and continuing with regular inspection and maintenance are all critical in achieving this lofty goal. If these considerations are implemented, the projects of today should still be servicing our great, great, great grandchildren in the future.

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