



Article

Evaluation of Construction Methods for Ultra-High Performance Concrete Invert Linings in Corrugated Metal Pipe Culverts

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Abstract

Corrugated metal pipe (CMP) culverts are key pieces of infrastructure in drainage and waterway management, but many are reaching their end of life and require rehabilitation. While existing repair methods have a long track record of success, they can be cost prohibitive and may significantly affect the hydraulic properties of culverts. Ultra-high performance concrete is internally reinforced, stronger, and more durable than conventional concrete, offering a modern solution to culvert deterioration. The seven mockups described include trials with top-formed UHPC, thixotropic UHPC, and a UHPC shotcrete placement. Shotcrete UHPC was not found to be viable at this time due to challenges with maintaining mix consistency and adhesion to the substrate. Top forming and thixotropic UHPC were found to be the best options for building a consistent invert lining for culvert rehabilitation but posed unique challenges in design, construction, and material consistency. This paper describes the methods of construction, challenges during construction, and the results of each test. It is the author's intent to give owners a new tool for culvert rehabilitation, provide designers with each of the variables in implementation, and help contractors mitigate risks by discussing the challenges encountered for UHPC invert linings.

Keywords: UHPC; culvert; invert; rehabilitation; shotcrete; thixotropic



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1. Introduction

Culverts play a crucial role in transportation drainage infrastructure, carrying waterways beneath roads and highways. However, 45% of all culverts in the United States are currently rated in fair or poor condition [1]. This increases to 56% when focusing on corrugated metal pipe (CMP) culverts, and it reaches a concerning 69% in New England [1]. The urgency for strategic interventions and investments in culvert maintenance and rehabilitation is underscored by the American Society of Engineer's most recent report card giving a grade of C- to infrastructure in the United States [2]. One of the most prominent issues for CMP culverts is deterioration of the base or invert [3]. There is a wide range of protective systems to prevent the initiation of corrosion, including galvanization, asphalt coating, and polyethylene coating. However, rushing water and rough silt can cause severe deterioration of the invert on a culvert that is otherwise structurally sound [3]. As such, robust rehabilitation methods for a variety of site conditions must be available to restore the capacity and functionality of culverts while minimizing cost and disruption to travelers.

There are currently several rehabilitation methods available for CMP culverts. This includes concrete invert lining, shotcrete coating, and grouted slip lining [3,4]. Invert lining is focused on the rehabilitation of the base of the culvert where most deterioration

occurs. Typically, 3–6 in of reinforced concrete must be placed to restore the structural capacity of the culvert. The thickness is required to provide adequate cover for the rebar as well as to prevent future corrosion and maintain the integrity of the lining, with Ohio specifying a minimum of 3 in thickness for paved invert linings [5]. This method has its drawbacks: the thickness of the concrete can change the hydraulic properties of the culvert, which not only affects sedimentation, but also wildlife passage through the waterway [6,7]. Slip lining is another common repair method and involves inserting a smaller diameter high-density polyethylene pipe into the culvert then injecting grout into the space in between [8,9]. Typically, a low-density grout is injected, but research has been conducted on multiple types of infill [10]. The inserted pipe acts as a stay-in-place form and provides both reinforcement and corrosion resistance to the infill that acts as the main structural component. While the slip-lining method is very effective, it can significantly affect the hydraulic capacity of the culvert [11]. Research supports the idea that this can be mitigated by the smooth surface of the slip liner, permitting higher water velocity than the corrugated surface from the CMP culvert [12]. While the smooth surface allows for the same flow capacity, the higher water velocity can significantly affect the wildlife that travels through the culvert [13]. A third method of rehabilitation is shotcrete coating. Shotcrete was developed around 1910 and has been used for a wide range of applications [14], including as a protective coating for either fireproofing or corrosion resistance [15]. Shotcrete is a sprayed, low-slump concrete that retains its shape once placed, allowing it to be sprayed on vertical and overhead surfaces. The final surface is typically rough and porous, but when applied in multiple passes and troweled it can achieve a solid, smooth mass [16]. For a wet-mix shotcrete, a flowable concrete is first mixed, then poured into a pump where it is transferred to the sprayer [17]. The process of spraying typically reduces the moisture of the concrete as it exits into the air. This process helps the shotcrete stay in place on the substrate and prevents it from flowing down. This is critical for culvert lining with shotcrete to ensure a consistent layer around the perimeter is achieved [18].

One promising method of culvert repair is the use of ultra-high performance concrete (UHPC) shotcrete for culvert lining, which was first tested in France in 2017 [19]. UHPC, with its high strength and durability, holds promise for achieving thinner linings, thereby mitigating the hydraulic and ecological drawbacks of conventional methods. UHPC is a cementitious composite material characterized by its dense aggregate matrix, a water-to-cement ratio below 0.25, and the inclusion of internal fiber reinforcement [20,21]. Compared to traditional concrete, UHPC has a compressive strength exceeding 17,500 psi and a post-cracking tensile strength greater than 750 psi [22]. The post-cracking tensile strength is largely due to the integration of small-diameter steel fibers within the mix [23,24] which reduce the need for conventional rebar reinforcement. UHPC also boasts exceptional durability, as its dense microstructure and low permeability significantly enhance its resistance to environmental degradation, including freeze–thaw cycles, chemical attacks, and abrasion [25–28], and allow for thinner casts since additional cover for rebar is not required. These attributes position UHPC as an ideal material for infrastructure subjected to harsh conditions and promises an extended service life with minimal maintenance. While one large-scale pilot testing of UHPC shotcrete application has been completed in France [19], and ongoing research at Florida International University focuses on UHPC mix development for pneumatically applied UHPC for culvert strengthening [29], this approach does not have an extensive track record for use in other applications.

This research project focuses on a proof-of-concept investigation of ultra-high performance concrete (UHPC) invert linings for the repair of deteriorating CMP culverts. The project is inspired by an ellipsoid CMP culvert in Connecticut that has reached an advanced level of deterioration. Figure 1a shows a deteriorated, in-service culvert, and Figure 1b

shows a close up of deterioration and sediment built up along the waterline. Due to the centralized deterioration at only the base of the culvert, an invert lining has been proposed for rehabilitation. The Connecticut Department of Transportation (CTDOT) and project designers proposed a 2-inch thick UHPC invert lining to restore the structural capacity of the culvert and provide a long lasting, durable protective coating.



Figure 1. (a) In-service CMP culvert; (b) sediment build-up at the culvert waterline.

Bridge No. 06537, a CMP culvert in Wallingford, CT, was selected for the pilot implementation of a UHPC invert lining and was the basis of the experimental study presented in this paper. It was constructed in 1965 and lies underneath the Warton Brook connector, which connects CT Route 5 and Interstate 91, and carries an average daily traffic of 15,300 vehicles per day [30]. The culvert is an ellipsoid that is 15 feet tall, 13 feet wide (Figure 2a), and 262 feet long (Figure 2b). It is constructed from seven-gauge galvanized steel with corrugations that have a six-inch pitch and a peak-to-valley depth of two inches. The 2022 inspection report categorized this bridge as structurally deficient due to the level of deterioration present on the structure [30], with an overall structural evaluation appraisal of four. Approximately 40% of the asphaltic coating has undergone erosion along the entire length of the culvert, concentrated at the bottom of the culvert at and below the waterline. Inspection of the steel surface at the waterline reveals heavy laminar rust, measuring up to 28 inches in vertical rise from the base, accompanied by section loss along the entire length of the culvert at the waterline. Moreover, examination below the water surface reveals localized perforations in the steel near the culvert floor, ranging from 0.375-inch diameter perforations to approximately 1 inch by 4 inch perforations. Figure 2a shows the extent of the corrosion, both thinning due to laminar rust and perforations, aggregated along the length of the culvert.

During the hydrology study for Bridge No. 06537, the natural conditions that would be present if there was no existing culvert were studied as a baseline for any proposed construction. The 2000 CTDOT Drainage Manual is utilized as the governing document for water handling structures in Connecticut [31]. Bridge No. 06537 carrying the Wharton Brook is classified as an intermediate structure, meaning it provides waterway for the drainage of areas between one square mile and ten square miles. The Drainage Manual Section 9.3.5 recommends that the proposed 100-year design discharge water surface elevation (WSE) should not be more than one foot over what is achieved in the natural conditions' scenario [31]. The current deteriorated culvert did not meet this requirement

and exhibits a WSE of 6.4 feet above the natural profile in the 100-year design discharge scenario. It was thus deemed impractical to satisfy this criterion within the scope of the rehabilitation project, as this would require a full replacement of the culvert or multiple parallel conduits. However, it was preferred that the rehabilitation did not raise the 100-year design discharge WSE above the current conditions.

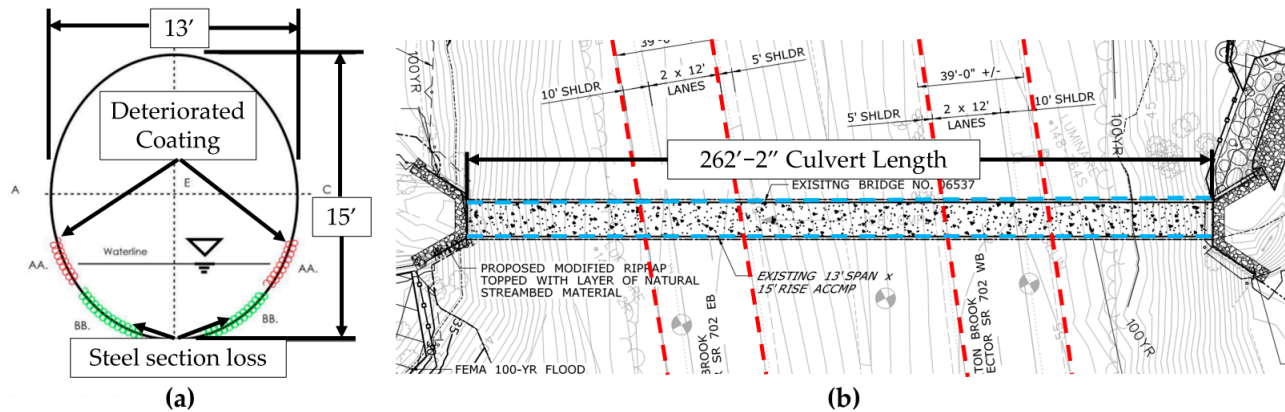


Figure 2. (a) Cross section of reference culvert; (b) plan view of reference culvert.

Two options were initially proposed for the design of the rehabilitation. The first option was a 4-inch-thick fiber reinforced concrete invert lining, with baffles included to mitigate an increase in flow velocities caused by the smoother surface and reduced diameter. The second option was a 12.5 ft diameter CMP slip lining, with a similar surface roughness as the existing culvert. Since both options would not only reduce the pipe's inside diameter but also raise the effective invert elevation, the CMP slip lining option was immediately removed from consideration as it would equate to a nearly 15 inch constriction on the culvert's flow area compared to the concrete invert lining and further affect 100- and 500-year flood discharge capacity. The second option was thoroughly investigated and showed significant promise initially.

The next main limitation was the passage of fish through the culvert. At least nine different fish species have been observed to pass through the culvert, with several using it as a migratory passage. As such, it was critical that the 2-way fish passage be maintained. This could be done by either limiting the water velocity or adding a resting area at a midpoint in the culvert. As the creation of a resting area was beyond the scope of the project, the designers focused on limiting the velocity of water through the culvert. The proposed 4-inch concrete invert lining would restrict flow and increase the velocity, decreasing the percentage of fish passing from over 87% to below 50% during the spring season. Designers countered this by proposing baffles on the top surface of the concrete invert lining. This design choice did effectively reduce the velocity of water and allow for fish migration but had the adverse effect of increasing the 100-year WSE by 0.7 ft. A final modification was proposed by adding a secondary conduit of a 60-inch reinforced concrete pipe culvert parallel to the main culvert. Unfortunately, this design choice was determined to increase the project cost approximately three times the initial budget and would not be economically feasible.

After significant discussion and investigation of alternatives, a 2-inch UHPC invert lining with no baffles was proposed. This option only slightly reduces the area of flow, with the constriction counteracted by the smooth surface of the lining to allow a very similar water output. It would reduce the 100-year WSE from the existing 6.4 feet above natural conditions to only 6.3 feet above natural conditions. While this is still above the recommended maximum elevation, it was deemed permissible within the scope of a rehabilitation project to maintain the same or better conditions than the existing structure.

Additionally, while spring season fish passage would reduce to approximately 70%, this was deemed acceptable as it was for a limited time and would allow over 95% passage during yearly average conditions. UHPC was chosen over standard concrete as it allows for much greater durability and strength even at reduced thickness. Without the need for structural rebar and corresponding clear cover, UHPC is ideal for a much thinner cast. The increased durability and water impenetrability posits UHPC as an ideal material for marine applications such as culvert linings.

Although there have been two documented attempts at culvert rehabilitation with UHPC, both lack practical depth for immediate implementation, and both focus only on spray-applied UHPC shotcrete. Huynh et al. describes the first mockup implementation in the literature and focuses on the mix properties of the UHPC, with some discussion of the need for new culvert rehabilitation methods and benefits of UHPC [19]. Afzal et al. describes a comprehensive project for developing a UHPC shotcrete, with culvert rehabilitation listed as its main use case [29]. The researchers in that study extensively developed a mix design for pneumatic spraying, as well as equipment specifically for UHPC spraying. However, its narrow focus on shotcrete UHPC and non-proprietary UHPC make it less relevant in many states that exclusively use proprietary mix designs. This limitation is due to the variability of UHPC and necessity for on-site modifications depending on temperature, placement method, and mixing equipment. These papers show a significant research gap in the practical implementation of a UHPC invert lining, as well as real-world construction challenges that can occur outside of the tightly controlled research environment. For owners and designers hoping to implement a UHPC invert lining in the field, there is a need for hands-on tests and mockups to show the practical limitations, challenges, and design constraints. Additionally, there is a lack of documented projects showing conventional UHPC with formwork being used for culvert rehabilitation and thixotropic UHPC being used outside of bridge deck overlays [32,33]. As overlays typically have a low grade requirement, the viscosity for a nearly vertical surface of an invert lining is significantly higher.

Researchers at CTDOT and the University of Connecticut have performed several mockups for the investigation of a UHPC invert lining for the rehabilitation of large CMP culverts. The first phase of the project is a proof-of-concept investigation focused on trial placements at UConn's Depot Campus, where large scale culverts were fabricated for testing. Three small-scale mock-ups were performed on 30-inch diameter culverts, and four large-scale mockups were performed on fabricated culverts of similar circumferential dimensions to the Wallingford culvert. The small-scale mockups investigated basic properties of galvanized steel culverts, including weldability to the surface, challenges with curved formwork, and casting methods. The large-scale mockups addressed constructability constraints and evaluated three different forming and casting approaches including traditional UHPC mixes with top forming and two methods that did not require top forming, a thixotropic UHPC and shotcrete UHPC. Table 1 summarizes the seven total mockups, showing the differences in size, UHPC mixture type, formwork type, bulkhead, and formwork standoffs when applicable. Five of the mockups used a standard, self-leveling UHPC with formwork to develop the curved shape and required thickness, while two used experimental UHPC consistencies for formless placement. This paper documents all the mockups conducted for this project, with lessons learned from each trial. Ultimately, this project identified two feasible placement methods for UHPC invert linings: a conventional UHPC mixture with engineered steel formwork and thixotropic UHPC with no formwork. Conventional UHPC with top forming was found to have the highest quality invert lining, with a smooth, consistent finish, at the cost of increased time and complexity for both the formwork design and fabrication. Thixotropic UHPC with no top forming also

successfully achieved 2-inch thickness with reduced fabrication time, at the cost of a less smooth and consistent finish.

Table 1. Summary of mockup implementations.

Name	Size	UHPC Mixture	Formwork	Bulkhead	Standoffs
SS1-M	Small	Conventional	MDF	MDF Laminate	Threaded Rod
SS2-P	Small	Conventional	MDF	Plywood	Threaded Rod
SS3-F	Small	Conventional	FRP	Plywood	Headed Stud
LS1-WF	Large	Conventional	Plywood	Rubber Laminate	Fiberglass Angle
LS2-SF	Large	Conventional	Steel	Rubber	Steel Angle
LS3-T	Large	Thixotropic	None	None	None
LS4-S	Large	Shotcrete	None	None	None

While the goal of this project was to support a specific implementation of culvert rehabilitation in Wallingford, CT, it is the author’s intent to provide actionable lessons and methods to designers and contractors for the implementation of UHPC invert linings. For each of the mockups, a 2-inch-thick invert lining was attempted. The mockups in this paper were designed to replicate the equipment, design, and construction methods commonly seen during real-world construction. CTDOT owners, engineers, and construction managers were regularly consulted to ensure that all activities were as realistic and feasible in field implementations. While not all the mockups were successful in developing a full invert lining, the results, methods, and lessons are included to provide a baseline for future projects attempting the same methods.

2. Methods

2.1. Small-Scale Mockup Placements

Three initial small-scale mockups were conducted to investigate the constructability of UHPC in culverts, check the viability of different materials for formwork, and test two different standoffs that would maintain a 2-inch gap between the CMP surface and the formwork. The small-scale mockups were implemented on 30-inch diameter helically corrugated CMP sections removed from service and provided by CTDOT. It is important to note that these preliminary tests were not meant to represent the closest conditions to the field trial and differed in several ways. First, the helical corrugations necessitated a different construction method for the bulkheads to prevent UHPC from leaking out the cross-sectional end of the formwork. Second, welded wire fabric was not included due to the size of the mesh and depth of corrugations making it difficult to form into the small-diameter culvert. Additionally, the dimensions of the culvert made it a confined space, which would require greater preparation for the extended welding times required to install the mesh. Third, the small-scale culverts were congruous with no bolted connections or ridges between plates that could act as a mechanical bond for the UHPC to the surface.

However, these trials allowed for much easier testing of several facets that would inform both the large mockups and the overall project. First, the viability of medium-density fiber board and fiber-reinforced polymer as top-forming materials. Second, the weldability of headed shear studs to the very thin galvanized material. Third, the use of threaded rods with nuts and washers welded to the culvert as standoffs for the formwork. Fourth, a mechanical joint between subsequent pours of UHPC. Each small-scale mockup could be prepared, poured, cured, and demolded without the use of heavy equipment and in only 1 week each. This allowed these smaller components to be tested prior to the large-scale mockups, which required heavy equipment and nearly a month of preparation for each test.

The first mockup, SS1-M, was the small-scale mockup with MDF bulkhead and featured four threaded rods, each 4 inches in length, welded onto the pipe to provide a 2-inch standoff (Figure 3a). Medium Density Fiberboard (MDF) was chosen as an alternative to plywood for the curved form material due to its flexibility and smooth surface, which facilitated easy demolding. The MDF board was affixed using washers and nuts and sealed with tape and silicone. The bulkhead was constructed from laminated MDF strips glued between each layer. Despite a smooth casting process, the MDF demonstrated significant bulging due to UHPC uplift pressure (Figure 3b).



Figure 3. (a) MDF board with standoffs and 2-inch gap; (b) completed, sealed formwork showing standoffs and bulkhead.

In the second iteration, SS2-P, was the small-scale plywood bulkhead and featured two more, for a total of six threaded rods to clamp the form and limit the bulging of the MDF. Additionally, one nut was tack-welded on each threaded rod to provide the required standoff rather than using two nuts in a locked configuration. Rubber tubing was added for the bulkhead and screwed into plywood to create a keyed interface for subsequent UHPC casts (Figure 4a). The final formed setup is shown in Figure 4b. A minor leak during casting was quickly repaired with tape, yet the MDF still bulged, proving that the setup was unsuitable as formwork material for unsupported areas. The rubber tubing interface, however, showed promise, demonstrating clear keying in the UHPC upon demolding.



Figure 4. (a) Keyed formwork with hinge in the middle; (b) completed formwork.

For the third mockup, SS3-F, the small-scale FRP-formed mockup, a fiber-reinforced polymer (FRP) form was used to overcome the bulging limitations observed with MDF. The

FRP was sourced from a 26-inch diameter, 1-inch thick form liner and cut into a half-circle to fit inside the culvert. Uplift of the form was prevented by welding threaded rods above the FRP shell. Initially, the plan was to weld headed shear studs to the interior of the culvert using a stud welding gun to provide the required standoff. However, testing revealed that the culvert was not thick enough to sustain typical stud welding and at all settings available, the welding process bored a hole completely through the culvert (Figure 5a). Consequently, the 5/8 inch by 2 inch shear studs were metal inert gas (MIG) welded to provide a consistent 2-inch standoff for the FRP shell (Figure 5b). The smooth surface of the fiberglass made formwork removal straightforward and left a smooth surface.

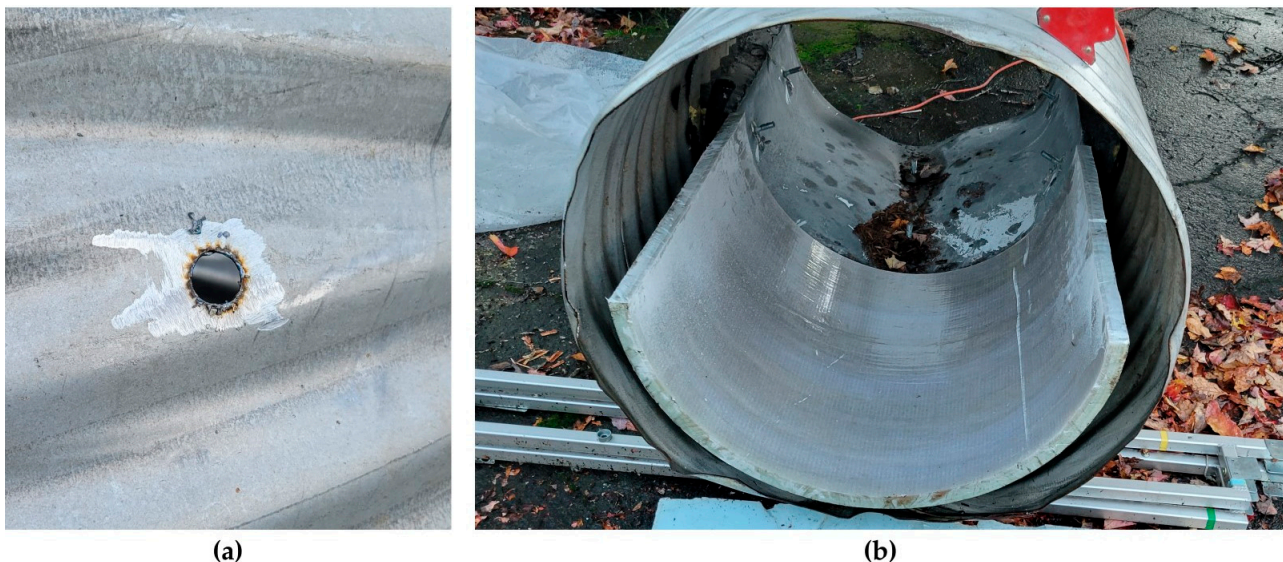


Figure 5. (a) Burned hole from stud welding attempt; (b) FRP shell installed in culvert.

2.2. Large Scale Mockup Placements

Following the completion of the small-scale placements, full-scale mockups were constructed to closely represent the dimensions of Bridge 06537 in Wallingford, CT. They were constructed using segmental galvanized steel plates with dimensions of 14.7 feet by 13.3 feet. Two 12-foot culvert sections were placed to allow for a total of four UHPC invert pours, each extending approximately six feet along the length of the culverts.

The selected site was prepared by first clearing 6 to 18 inches of topsoil to create a level grade. Next, the soil was compacted, and a layer of driveway gravel was placed, graded, and compacted to provide a stronger foundation. Finally, a groove was carved into the ground to accommodate the placement of the bottom plate, ensuring immediate stability during construction. Steel angles were attached to the exterior of the side plates, with a total of ten wood posts concreted into the ground and wedged into the angles to support the culvert. Figure 6a shows the final constructed CMP culverts. The structural design documents for Bridge 06537 in Wallingford, CT, call out welded wire mesh to be installed on the top of the culvert corrugations to provide both a stronger mechanical connection to the culvert as well as continuity between segmental UHPC pours. The design also calls for a total vertical height of 45 inches from the base of the culvert to the top of the UHPC invert. The mockup culverts were lined with 5 in by 5 in, 10-gauge (0.1 in) steel mesh along the entire length of the culvert, extended approximately 38 inches up the sides of the culvert, reduced to ensure that none of the mesh would extend past the UHPC. The mesh was directly welded to the ridges of the culverts (Figure 6b) at each point where it touched a ridge. One temperature gauge was attached to the welded wire fabric at the base of the culvert to monitor internal UHPC setting temperature, and a second was

installed approximately halfway up the side of the culvert to monitor outside ambient temperature. Due to the first two casts occurring in January and February, enclosures were built with plywood, insulated tarps, and externally powered heaters to heat the UHPC as it set, following the recommendations by the UHPC material suppliers. For these pours, an additional temperature gauge was installed inside the heated enclosure.

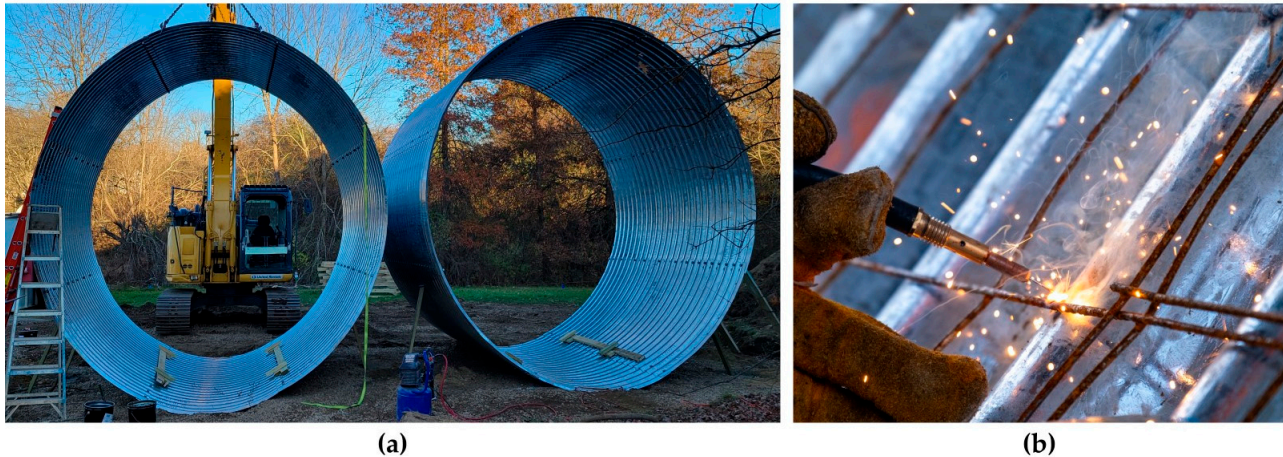


Figure 6. (a) Completed culverts before mockup casts; (b) welded wire fabric installed in the mockup culverts.

2.2.1. Wood Top-Formed Placement

The first large-scale test, LS1-WF, the large-scale wood formed mockup, employed a plywood top form supported by a wooden truss constructed from 4×4 and 2×4 dimensional lumber [34]. First, the wire mesh was installed in the base of the culvert. Next, standoffs were installed. Due to the size of the formwork, it was determined that headed shear studs and welded threaded rod would be unsuitable to support the formwork, in addition to the complications with welding on such a thin surface. Additionally, the process of aligning bolt-through standoffs and pre-drilled holes was determined to be unreliable for alignment during actual construction. Fiberglass angles were chosen as an alternative, using 3 inch by 3 inch legs, which would create a 2-inch standoff when installed with the open face downward towards the culvert (Figure 7a). Fiberglass was chosen over steel, as steel could provide a path for corrosion to return to the base of the culvert. Since the fiberglass angles could not be welded to the surface, they were notched and attached to the welded wire mesh using rebar tie wire. Next, 4×4 lumber was laid horizontally in the culvert with the ends nesting within two valleys of the corrugations (Figure 7b). Plywood sheets were laid radially in the base of the culvert with a 4×4 attached as support spine in the center and 2×4 's connecting each sheet at the seam. The 4×4 columns were then installed vertically and pressed into the 4×4 center stems. A downward force was applied to the vertical columns to bend the plywood sheets to the required curvature, and lag bolts were installed between the vertical 4×4 's and the horizontal 4×4 's once the curvature was reached. A picture showing the final formwork is shown in Figure 7c. Once all support columns were installed, a platform was built on the horizontal 4×4 's to allow counterweights to prevent uplift. Bulkheads were then built from layers of rubber landscape edging sealed with silicone, and additional wood was used externally to secure the formwork (Figure 7d). Once all formwork was completed, a bird's mouth funnel was installed in one side of the formwork for casting the UHPC into the top form.

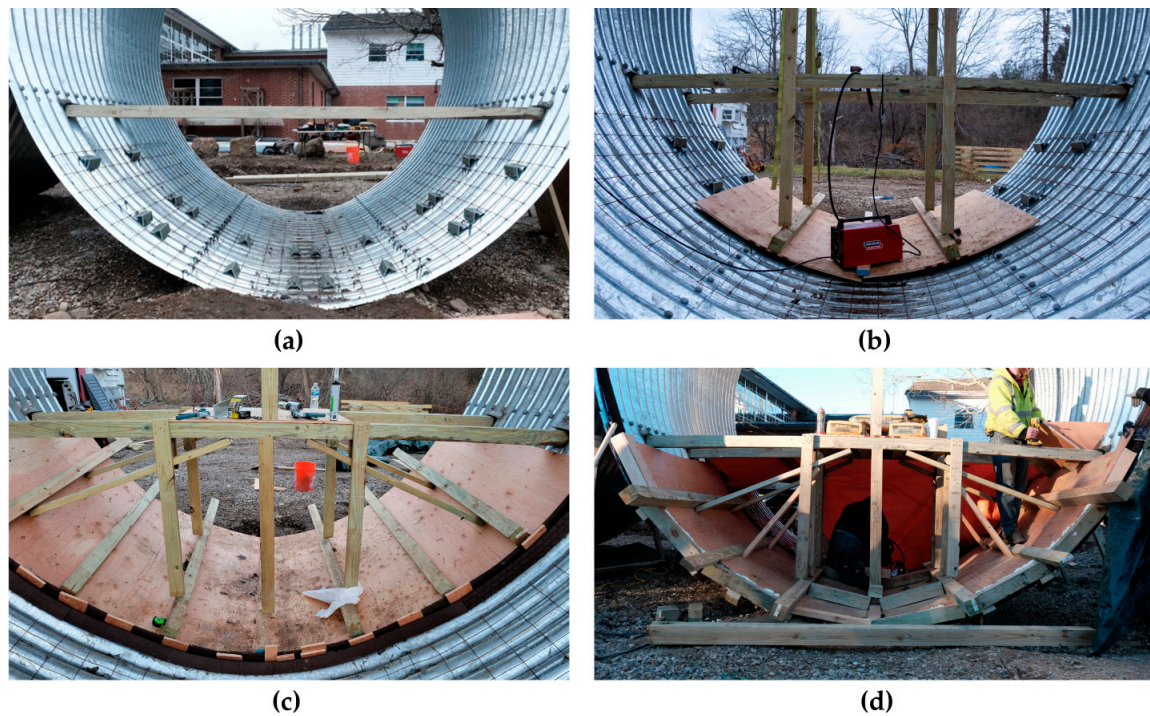


Figure 7. (a) Standoffs installed in culvert; (b) horizontal support beams connected to vertical supports; (c) completed wood formwork structure showing radial supports; (d) final formwork with counterweight on central platform.

Mixing was completed in a ready-mix truck on site and spread tests and cylinders were collected at this time in conformance to ASTM C1856 [35]. UHPC was cast directly from the ready-mix truck into the bird's mouth funnel on one side of the formwork (Figure 8a). It should be noted that UHPC can be placed from one side only as long as the other side is open to the air, due to the self-consolidating nature of UHPC. After approximately 9 cubic feet of UHPC was dispensed from the truck, cracking was heard, and the formwork began to leak at both the front and back bulkhead (Figure 8b). The casting was immediately stopped.



Figure 8. (a) UHPC cast directly from ready-mix truck into bird's mouth on one side of the formwork; (b) UHPC spilling out of the formwork through split bulkhead seal.

2.2.2. Steel Top-Formed Placement

An engineered steel formwork was also tested as a stronger alternative to wood formwork. To evaluate the performance of the steel truss formwork under UHPC uplift pressures, a numerical analysis was performed using SAP2000 [36]. The model simu-

lated the geometry, material properties, and boundary conditions of the large-scale LS2-SF mockup, which incorporated a curved steel plate supported by three vertical-chord trusses resembling a modified Warren truss [37]. The curved steel plate was idealized as a continuous compression chord connected to the truss nodes through rigid links, ensuring realistic load transfer. The truss was analyzed in an inverted configuration, such that uplift pressure from the UHPC was represented as a downward gravity load on the model.

Boundary conditions consisted of fixed supports at both ends of the tension chord and two intermediate points along its length, consistent with the mockup's physical anchorage configuration. These supports simulated the welded interface between the truss and the base frame of the formwork assembly. The uplift pressure induced by the UHPC was approximated as a uniform equivalent pressure of 4 psi, corresponding to the maximum hydrostatic pressure expected at the deepest section of the formwork (4 ft head). For the purpose of the analysis, this pressure was applied as a gravity load acting vertically downward, i.e., normal to the ground plane, rather than normal to the curved plate surface. The full 4 psi was applied uniformly over the entire surface without a reduction factor to ensure a conservative design. Figure 9 shows the full assembly in SAP2000.

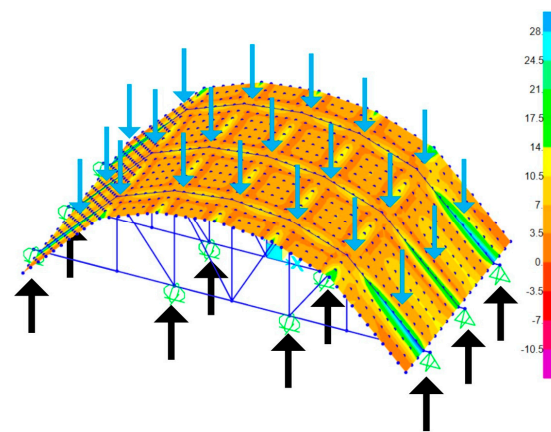


Figure 9. SAP2000 model showing gravity forces representing UHPC (blue) and supports (black).

Material properties for structural steel were defined as an elastic modulus of 29,000 ksi and a yield strength of 36 ksi, corresponding to ASTM A36 steel. The SAP2000 analysis produced nodal displacements, member forces, and stress distributions under the applied uplift load. The maximum vertical deflection occurred at the midspan of the upper chord, where the curved plate experienced the highest bending moment. Axial tension was concentrated in the lower chord, while the vertical members carried the majority of the compressive reaction from the plate. The results confirmed that the simplified truss configuration provided adequate stiffness and load distribution under design pressure, with stress remaining well below the elastic limit.

Following the initial analysis, an iterative design process was used to minimize the total number of members while maintaining structural adequacy. SAP2000 results were used to identify redundant diagonal members with negligible force contribution. Subsequent iterations showed that removing diagonals and reinforcing stress-critical joints with welded steel angles did not significantly increase maximum deflection or stress levels. The final optimized configuration, consisting primarily of vertical members with local stiffeners at the plate interface, achieved a satisfactory factor of safety and simplified fabrication.

Once the design was completed, only the vertical members of the truss remained, and additional steel angles were welded to the plate to minimize stress concentrations at the base of the truss members. Additional steel angles were added to the top of the plate where it would connect to the supports. The final prefabricated formwork is shown in Figure 10b.

Vertical columns were added at intermediate points on the top chord of the truss, aligned with the intermediate supports in the numerical model. These columns were angled to minimize deformation of the culvert once the UHPC was poured and force transferred to the columns. Finally, a bird's mouth was built for placing the UHPC. The final formwork is shown in Figure 10b.

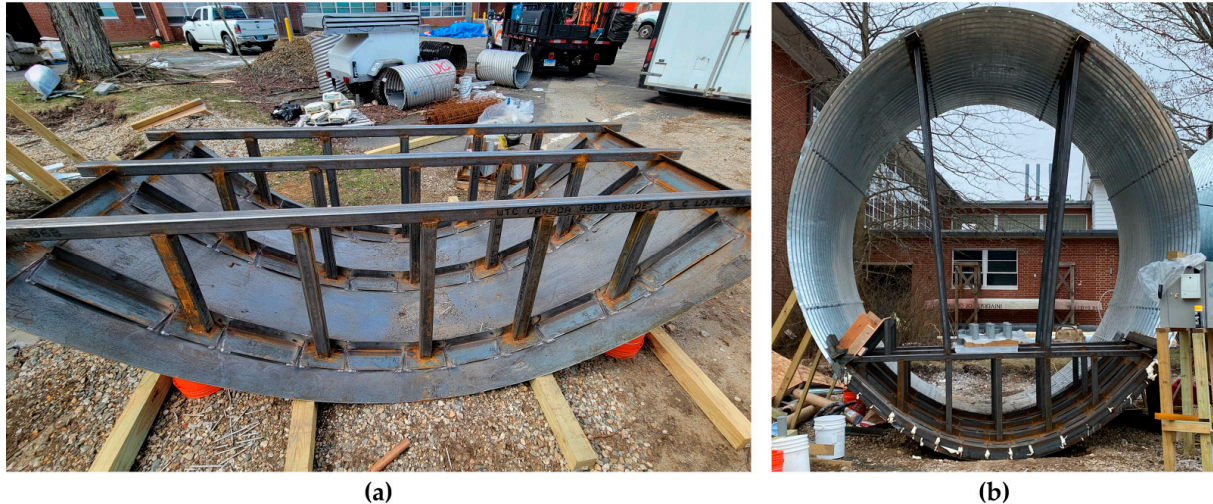


Figure 10. (a) Prefabricated steel form; (b) final view of formwork with vertical bracing.

Steel 3 in by 5 in angles were used to form the bulkheads. On the interior, the 5 in leg was welded to a crest of the culvert corrugations horizontally, with the leg pointing away from the UHPC cast and the 3 in leg extending upwards, butted against the curved steel plate. Another 3 in by 5 in angle was then placed over it, with the 5 in leg over the top of the curved steel plate and the 3 in leg welded to the base angle, forming a stepped bulkhead. The exterior bulkhead for the culvert had the 3 in leg hooked under the lip of the culvert, and the 5 in leg extending upwards, with a second angle oriented the same as for the interior (Figure 11a). These overlapping angles were supported by a backing bulkhead seal of solid rubber strips that had a cross section of 2 in by 2 in, installed with silicone caulk and construction adhesive. A ready-mix truck was again used to mix the UHPC, where it was dispensed directly into the formwork on one side (Figure 11b). Throughout the cast, minimal leakage was noticed, but it did not affect the process. No significant deformations occurred in the formwork, and the cast successfully reached the top of the formwork.



Figure 11. (a) Steel angle bulkhead showing minimal UHPC leakage; (b) ready-mix truck dispensing UHPC directly into bird's mouth funnel.

2.2.3. Thixotropic Placement

The third mockup, LS3-T, the large-scale thixotropic UHPC mockup, was able to be completed with a formless pour. The benefits of this are significantly reduced construction cost and complexity, and it can allow for seamless pours over welded wire fabric without incongruity caused by bulkheads. Thixotropic UHPC has found widespread utilization for overlays [33], as it exhibits reduced flowability but provides stability on sloping surfaces during placement [38]. However, overlays are typically limited to a grade of 2–5%, while this application required UHPC to stand up to over a 100% grade. The first step was installing the wire mesh reinforcement in the same process as the first two casts. The mesh had the additional advantage of helping to keep the UHPC in place during casting. No standoffs were necessary for this cast, but steel angle bulkheads were welded in at the front and back edge of the cast to provide a point of reference for thickness during installation and prevent leaking in case the UHPC was not thixotropic enough. Mixing began in a ready-mix truck until the UHPC mix turned over into its liquid state, then was dispensed into an Imer 360 mixer in increments of approximately three cubic feet to add an accelerator and turn the UHPC thixotropic. Exact admixtures and proportions were proprietary to the UHPC supplier and vary dependent on ambient conditions such as humidity and temperature. The UHPC was then transported and poured into the culvert with five-gallon buckets. Finally, the concrete surface was troweled to achieve a smooth finish and fill in all spaces (Figure 12a,b). This process was incredibly time-consuming and required constant troweling by three workers throughout the 1 h casting time to shape the UHPC to the required thickness and ensure it reached the desired height up the culvert. After casting, the culvert section was sealed off with a wooden frame, and a diesel heater was directed inside the enclosure to maintain a minimum temperature of 60 degrees Fahrenheit during the first 5 days of setting. The final surface was very rough and showed clear marks from the troweling. Due to the fibers and the sticky consistency of UHPC when it starts to set, it was difficult to achieve a smooth finish.



Figure 12. (a) Hand troweling thixotropic UHPC into culvert; (b) UHPC build up and surface over wire mesh.

2.2.4. Shotcrete Placement

The final mockup, LS4-S, was the large-scale shotcrete UHPC mockup. The shotcrete method involves spraying UHPC directly onto surfaces, making it particularly suitable

for complex geometries and hard-to-reach areas. Like the thixotropic mix, the shotcrete application benefits from the elimination of formwork. However, it is not widespread in application and is currently offered by only one material supplier. Special equipment is required for the pumping and spraying, which limits the rate of application. The culvert section was prepared similar to the thixotropic mix, with only steel wire mesh welded into the culvert and angles installed to prevent overspray or spilling in the case of low viscosity. This mix did not utilize a ready-mix truck but instead exclusively used an Imer 750 mixer. Following mixing, the UHPC was dispensed directly into the material supplier's custom pump trailer and sprayed into the culvert (Figure 13a). A consistent air pressure was required for the sprayer and was specified by the UHPC supplier. The mix remained wet and did not vary significantly from standard UHPC, causing most of the UHPC to flow down to the base of the culvert after being sprayed. The final thickness was approximately 0.25 inches, but due to the consistency of the UHPC, it was unable to build up the necessary two inches on the steep incline. The final product was a 3-inch thick layer at the base of the culvert, with a 1/4-inch thick layer extended nearly 4 feet above the desired top of UHPC due to overspray (Figure 13b).

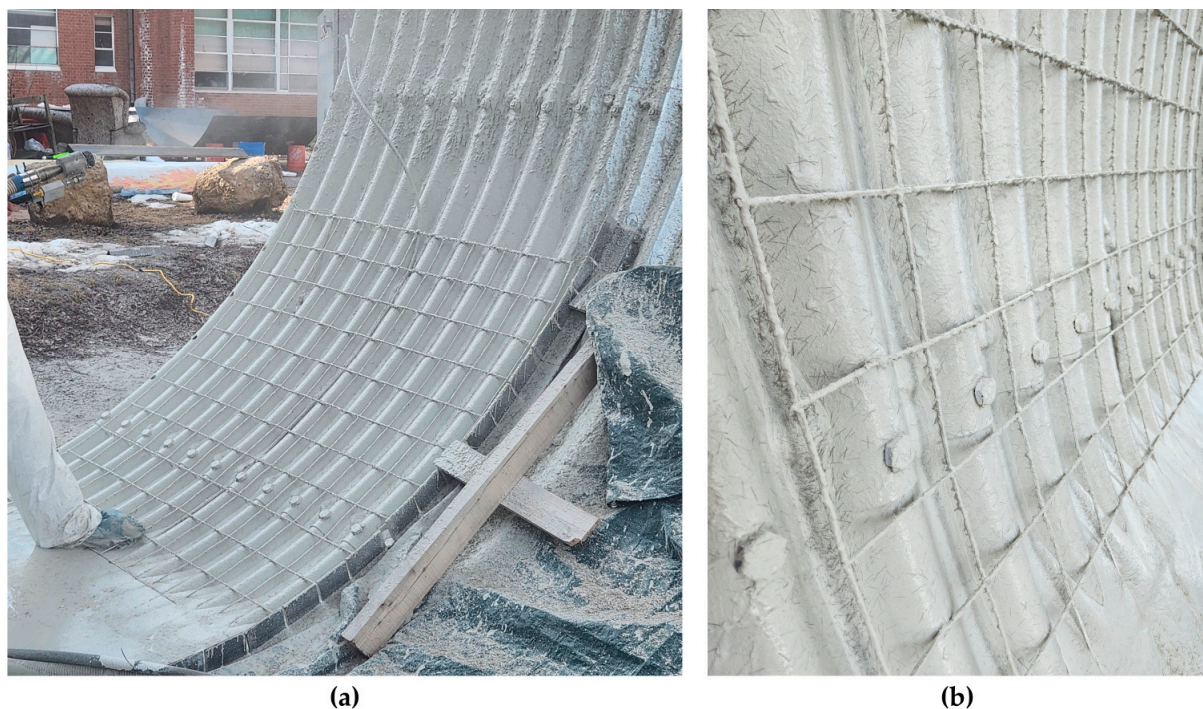


Figure 13. (a) Shotcrete UHPC being applied over wire mesh; (b) buildup and surface coating of shotcrete on culvert wall.

3. Results

3.1. Small Scale Mockup Placements

The final surfaces of each small-scale cast can be seen in Figure 14. Following the first two casts, SS1-M and SS2-P, MDF was shown to be unsuitable due to significant bulging and sticking to the surface (Figure 14a,b). Surface voids were prominent in the SS2-P cast but did not extend deep into the UHPC and may be acceptable depending on specific designs. Removal of MDF was more difficult than expected, and the smooth surface bonded to the UHPC, leaving small strips still stuck to the concrete surface after demolding. In contrast, the FRP formwork used in SS3-F demonstrated excellent performance and ease of removal (Figure 14c). After removing the threaded rods that held it down in the culvert, the FRP

detached from the UHPC without any sticking. The surface can be seen to be incredibly smooth with consistent 2 in thickness throughout.

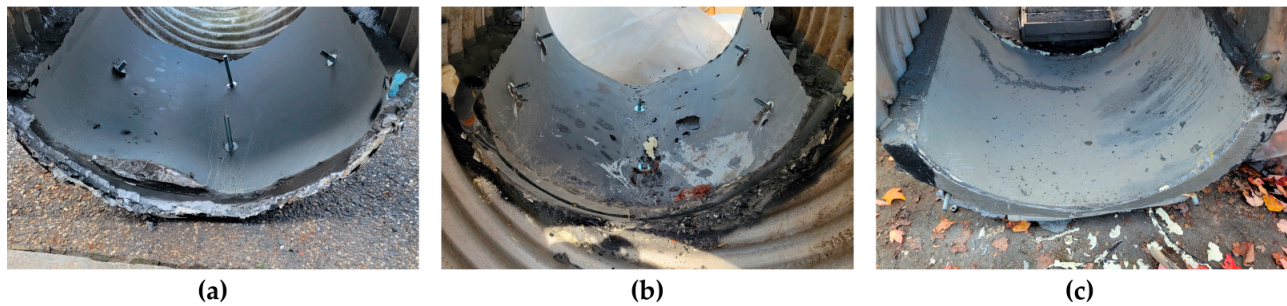


Figure 14. (a) First small-scale mockup showing bulging in UHPC surface; (b) second small-scale mockup showing bulging and voids; (c) third small-scale mockup with FRP showing smooth, consistent finish.

3.2. Large-Scale Mockup Placements

While the wood formwork used for LS1-WF was significantly easier to install and fabricate than the steel formwork, it did not maintain the required stiffness to withstand the uplift pressure from the UHPC. Initial design for the wood formwork did not consider more than a marginal uplift pressure from the UHPC and assumed that the low overall height of the formwork would not produce a significant buoyant force on the formwork. However, these assumptions did not take into consideration the flexibility of the plywood, the existing pressure on the formwork supports due to applying the curvature to the plywood, or the bond strength of the silicone at the edge of the formwork. The buoyant uplift pressure from the UHPC itself caused the wooden formwork to deform and lift off from the bulkheads at the center of the base of the formwork, breaking the silicone seal. This allowed UHPC to spill out both the front and backside of the formwork, preventing the concrete from building up the sides. Figure 15a shows the extent of the UHPC spilling out of the formwork at the base of the culvert, and Figure 15b shows the final extents of the UHPC following removal of the formwork. The remaining UHPC did exhibit a smooth finish, minimal voids, and between two to three inches of thickness throughout. However, it could not reach the design height necessary to rehabilitate an invert up to the waterline.



Figure 15. (a) UHPC spilling out of wood formwork; (b) final cast after demolding.

The steel formed UHPC in mockup LS2-SF showed the most promise as far as final product. Initially, the steel formwork was designed to be re-usable for staged casts across the length of the culvert. However, this restricted the available attachment points to the

culvert itself. The formwork was attached only at the top of the formwork, the bulkheads locking the edges down, and the vertical supports to the top of the culvert. During casting, the UHPC spilled outside the bird's mouth funnel that directed it into the formwork, and it hardened over the top edges of the formwork. Due to the high strength and ductility of UHPC, this locked the formwork into place, making removal incredibly difficult. Each of the trusses had to be individually cut out from the curved plate to allow the plate to be curved further inwards to break the bond to the underlying concrete, before being lifted out with a telehandler. The final surface was incredibly smooth and consistent, with nearly nonexistent voids and a very consistent 2-inch thickness over the entire invert. Figure 16 shows the final cast, with bulkheads still in place. It should be noted that the internal bulkheads must be removed prior to installing a second cast next to the first. Special care must be taken to ensure a structurally sound cold joint between casts.



Figure 16. Final steel formed UHPC cast showing consistent thickness and surface.

The thixotropic cast, LS3-T, also showed strong promise, as it was able to achieve a consistent thickness over the full extents of the invert. Although troweling took over an hour for a 6 ft length along the culvert, this was performed by only three workers. The welded wire mesh offered significant support preventing UHPC from sliding down the sloped sides of the culvert, and by the end of the cast, the UHPC was stiff enough to cover over the mesh without further slipping. Figure 17 shows the final surface with visible trowel marks throughout.

The shotcrete UHPC mockup, LS4-S, did not successfully build up enough to be considered a successful cast for invert repair. Figure 18 shows the final cast, with a thick pool of UHPC at the base of the culvert, and a thin coating over the rest of the surface. The process took nearly 2 h, the longest cast of any tested in this project, due to the slow rate of application. Each batch of UHPC had to be mixed and completely dispensed before another batch could begin, causing the application to pause several times during the test cast. Additionally, the steel fibers in the UHPC occasionally caused the spraying machine to clog up and stop spraying, necessitating further pauses to the casting process. These pauses did help to solidify layers of UHPC for a subsequent layer to build up easier on top, but the overall thickness did not exceed 0.25 in for any of the high-slope areas.



Figure 17. Final thixotropic UHPC cast showing consistent thickness and rough surface.



Figure 18. Final shotcrete UHPC cast showing pooling at the bottom and minimal build-up on the culvert walls.

3.3. Summary of Results

Table 2 summarizes the results of each of the mockups, using the same naming convention defined previously. The results are broken into four metrics: thickness, smoothness, effort, and cost. The thickness metric is dependent on a consistent 2-inch thickness over the entire planned surface. The smoothness metric is dependent on a consistent smooth surface with minimal voids or roughness. The level of effort is based on the amount of work and time required for design, construction, and removal of formwork. The cost is based on the relative cost estimated to design, source materials, and cast the invert. Both the effort and

cost metrics are scaled based on the culvert size, as even the greatest effort and cost for small-scale culverts were significantly lower than the lowest effort large-scale culvert.

Table 2. Summary of mockup results.

Name	Size	UHPC Mixture	Formwork Type	Correct Thickness	Smooth Surface	Level of Effort	Cost
SS1-M	Small	Conventional	MDF	No	Yes	Medium	Low
SS2-P	Small	Conventional	MDF	No	No	Low	Low
SS3-F	Small	Conventional	FRP	Yes	Yes	Low	High
LS1-WF	Large	Conventional	Plywood	No	Yes	Low	Low
LS2-SF	Large	Conventional	Steel	Yes	Yes	High	Medium
LS3-T	Large	Thixotropic	None	Yes	No	Medium	Low
LS4-S	Large	Shotcrete	None	No	No	Low	Medium

Although a full-scale cost analysis was not conducted, estimates are based on supplier discussions and scale of design. For the first two small-scale mockups, the bulging of the MDF caused a failing grade on thickness, as it was not consistent. However, the SS1-M specimen had a smoother final surface than the SS2-P specimen. It should be noted that the SS1-M specimen had the most pronounced bulging at one point, which likely allowed air to escape at one point, while the SS2-P had more even bulging both laterally and longitudinally, causing air to be trapped at midpoints and cause voids in the UHPC. While both had low cost, the lamination on the SS1-M bulkheads caused the level of effort to be greater. The SS3-F had the correct thickness, smoothness, and low effort, but an incredibly high cost due to the fabrication needs for FRP shells. This method may be feasible for culverts less than 6 feet in diameter, but based on a discussion with the FRP supplier, a single use, ellipsoid FRP shell of at 13-foot diameter would be extremely costly and unable to bend or mold to any inconsistencies on an in-service culvert's elevation.

For the large-scale mockups, only the steel formed and thixotropic mockups were considered successful, with the steel formed having both consistent thickness and surface finish, but a medium cost due to the need for professionally welded, custom curved steel formwork and an engineering design. The fabrication also caused the level of effort to increase to high, as both the fabrication and demolding took 4–5 times longer than the wood formwork, and longer than any other mockup conducted. The thixotropic UHPC had good thickness, but one of the roughest surfaces of any method conducted. However, the surface was free of significant voids and with a more experienced finishing team could achieve a better surface. The cost was low, as it required no preparation and only consulting services from the material supplier. Its level of effort was medium only due to the requirement for constant smoothing from a finishing team of several people, while all the other methods only required casting directly from a truck or a single operator spraying UHPC. The wood formed cast had a smooth surface, but only where it was able to build up. The failure of the formwork caused this mockup to fail the thickness metric. However, the ease of construction and low cost of formwork materials permitted a low score in both. Engineering services may be recommended if wood is used in the future, which may increase the cost. Finally, the shotcrete UHPC failed both thickness and smoothness metrics, being unable to build up to any appreciable thickness and leaving a rough, fibrous finish. It was low effort, as only one person was needed for spraying, but the cost is increased as it requires significant effort from the material supplier. UHPC shotcrete is offered by very few suppliers in the United States, making it much less competitive and cost effective to implement on the large scale.

4. Discussion

Each of the small- and large-scale placements provided insight into important factors for the implementation. The small-scale placements provided initial insight into the use of shear studs for thin-walled culvert sections and complications with building up the bulkheads at the ends of formwork. The first main consideration when designing a UHPC invert lining is whether to use a formed or formless cast. For formed casts, engineers must carefully consider the strength, flexibility, and reusability of formwork, in addition to the bulkheads and standoffs to achieve consistent thickness. For formless casts, engineers must carefully test the consistency of the mix and the speed of application to ensure it can be completed with reasonable effort and to desired surface condition.

Formed casts may be the most logical method to attempt when a high-quality finish is desired. While preparation, design, and fabrication require significantly more effort, an engineered steel form can be designed to mitigate the risk of bad finish or inconsistent UHPC mixes. Typical UHPC is self-consolidating and highly flowable and must be modified heavily for thixotropic or shotcrete applications, which introduces variability between material suppliers and even individual batches. It is much more sensitive to temperature and vibration and requires contractors to be more experienced with the material before working with it hands-on. Designed for quick demolding and movement, steel formwork can be viable. It is critical to plan for any deviations in the culvert shape due to long term deflections, however, as many in-service culverts can deviate by several inches in elevation and local radius over their length. CMP culverts are particularly sensitive to soil shifting below, above, and to the sides that may cause areas to bend within their structural tolerance. This poses a challenge to prefabricated formwork as it must be able to adapt to these variations and still provide a consistent concrete thickness.

Details such as bulkheads, cold joints, and standoffs are also important to consider when designing formwork for UHPC invert lining. Due to the curvature of the culvert section, the bulkhead must be flexible, durable, and easy to insert. The MDF strips were both flexible and durable, but very time consuming to place, especially in a helically corrugated culvert, seen in the small-scale tests (Figure 19a), as opposed to a circumferential corrugations seen in the large tests. The second small test, with a plywood bulkhead and attached rubber tube, exhibited a very clean keyway for subsequent UHPC pours to flow into (Figure 19b). Ultimately, the rubber strips in the large-scale steel formed placement were ideal and did not break even after stripping the formwork and may be the most feasible for large scale implementation. The only drawback was a lack of intrusion into the UHPC that could form a mechanical joint.

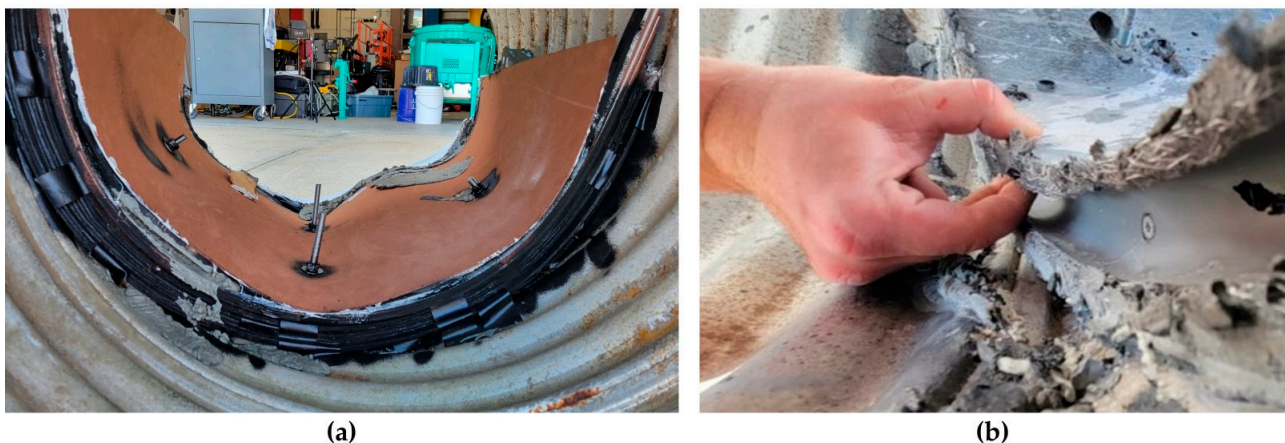


Figure 19. (a) Laminated MDF bulkhead on first small-scale mockup; (b) keyed rubber bulkhead on second small-scale mockup.

Formwork standoffs are another challenge that must be considered when designing a formed UHPC invert lining. Headed shear studs were very promising as they could act as both a formwork standoff and mechanical attachment for the UHPC, but due to the thickness of the culvert plate, it would be very difficult to utilize a standard stud welding gun due to the mechanized process involved in stud welding [39,40]. Additionally, the best practice for welding to galvanized steel recommends first surface grinding all zinc material off, which would further reduce the thickness. Although the tops of the studs were visible through the UHPC, raising concerns about potential corrosion paths, mitigative measures such as coating the studs or using stainless steel studs may be considered for future implementations. Threaded rods with nuts and washers can be considered a viable stand-off and hold-down method for wooden formwork, but may be less reliable for any other material, as they would require very exact placement to correctly pass through the formwork and be bolted in place. Fiberglass angles were successful in the large-scale wooden formwork and can be considered a long-term solution for a durable, high-strength standoff. In this project, the fiberglass angles were attached only to the welded wire mesh through twisted rebar ties, making them a non-structural component that could only act as a standoff. Alternative attachment methods, such as a 2" × 2" angle bolted directly to the culvert wall, may be able to act as structural attachments as well, but designers should carefully consider all options.

Formless casts for UHPC invert linings have the potential to greatly simplify the design and overhead of a culvert rehabilitation project. However, they are much more sensitive to the rheology of the UHPC, which in turn is sensitive to temperature, vibration, chemistry, and working time. Thixotropic UHPC was a promising solution to the task, and the researchers were successfully able to cast an invert lining over the test area. Preparation of the culvert was minimal, requiring only the welded wire mesh that was installed in each of the other tests. Mixing and moving the UHPC was a critical step that required the constant attention of the material supplier to ensure consistency and make on-site adjustments to the mix. The final step of mixing was completed in small batches, individually adjusted with admixtures to make it thixotropic. While this allowed the material supplier complete control and the ability to adjust the admixtures based on communication with the finishing crew, it is critical that this step be performed by personnel with significant experience. The fast-setting nature of UHPC, accelerated by the admixtures to reduce flowability, makes full experimental testing of each small batch difficult. The material supplier representative conducted empirical tests during mixing by picking up a handful of UHPC to feel its consistency and visually check how its rate of flow. This method requires significant knowledge and experience with the material, along with regular feedback from the finishing team to quickly make any adjustments. The thixotropic UHPC must be flowable enough to be discharged from the mixer but stiff enough to remain in place once cast. Upon recommendation from the material supplier, touchups and movement of the material once in place must be minimized, as an energy input increases and extends the flowability of the mixture [41,42]. However, due to the surface requirements of a culvert, the UHPC must be as smooth as possible to minimize the restrictions on water velocity. Any other smoothing or leveling techniques such as vibration may worsen the stiffness of the material. Overall, thixotropic UHPC is feasible as an invert and should be considered by designers, but with the caveat that the final surface may not be as smooth as top forming and must have an engineer with significant experience in mix design and placement.

One of the final lessons from the placements was that UHPC shotcrete requires further development or mockup installation prior to field application. The consistency of UHPC is vital in the repair process. UHPC shotcrete needs a combination of high flowability through the pump and blower system and high stiffness upon contact with the culvert

wall substrate. Two main issues were encountered in this project: the slow discharge of the UHPC and the flowability upon contact with the substrate. Due to the high concentration of fibers in UHPC compared to other shotcrete mixtures, the volume of UHPC that can be sprayed over a unit time is much lower than conventional shotcrete, greatly slowing down the process. The flowability of the mixture aids in the spraying process but causes the UHPC to flow down the sides of the culvert once placed and be unable to build up the required thickness. During testing, the UHPC was only able to build up a single layer of approximately 0.25 inches on the culvert wall. This was largely aided by the fibers providing some structure to the UHPC once they hit the wall of the culvert. There was no noticeable difference in UHPC build-up in places where the culvert steel was roughened with an angle grinder as recommended by the material supplier. Ultimately, only a quarter of the planned volume of UHPC was sprayed as it flowed down to the very base of the culvert and had extended to nearly three inches with no noticeable improvement on the wall layers.

The findings from this study highlight several important future research needs to advance the application of UHPC invert linings in culvert rehabilitation. Further investigation is required to quantify the structural performance of the rehabilitated systems under service and extreme loading conditions, including both experimental load testing and advanced numerical simulations. Additional studies should also examine long-term durability, bond behavior, and interface performance between UHPC and existing substrates to ensure reliable field implementation. Finally, there is a need to evaluate construction methods and quality control procedures across a wider range of geometries, materials, and environmental conditions to support the eventual development of standardized design practices for UHPC rehabilitation systems.

5. Conclusions

The rehabilitation of CMP culverts is essential for maintaining the integrity and functionality of transportation drainage infrastructure, particularly given the widespread deterioration of these systems. Through a series of small- and large-scale mockups, the research identified critical parameters for successful UHPC application, including the use of shear studs, flexible and durable formwork, and the need for engineered formwork to withstand uplift pressures. The findings underscore the importance of consistency in UHPC mixtures and the complexities involved in developing methods that balance flowability with stability upon placement. The staged placement approach emerged as a promising technique, allowing for manageable construction cycles and immediate quality assessment of individual sections. Further research is required prior to the recommendation of a cold joint between subsequent UHPC casts. Overall, this research contributes valuable insights into the practicalities of UHPC application for culvert rehabilitation. The outcomes of this study lay the groundwork for future advancements, ensuring the continued safety and efficiency of the nation's transportation infrastructure. The following bullets summarize the key findings of this study:

- UHPC promises a stronger, thinner, more durable material for invert linings, minimizing the effect of an invert lining on waterway hydraulics and providing a longer lasting rehabilitation solution.
- Top forming with engineered formwork provides the lowest risk and cleanest finish but suffers from design and fabrication overhead. It is critical to design for uplift pressure on the seam of the bulkhead as well as on the formwork itself.
- Thixotropic UHPC does not require heavy equipment beyond a mixer and offers a straightforward, easy method of placement. However, it falls short by having a rough finish and requires significant labor to shape into a smooth finish.

- Shotcrete is not recommended due to challenges in achieving uniform thickness and the complexity of the required equipment, although future technological advancements might improve its feasibility.
- Owners must balance cost, time, and experience when considering a UHPC invert lining. While a conventional steel top form provides the highest quality and lowest risk, heavy equipment and more intensive design may make it less desirable than thixotropic UHPC. Thixotropic UHPC, while fast and easy, requires more contractor experience and may result in a lower quality finish.
- Designers should carefully test standoffs, formwork, and bulkheads to ensure they can withstand the structural and environmental hurdles in a constantly wet, underground environment.
- Contractors must determine the most appropriate construction method, clearance for equipment, and experience of laborers when choosing a construction method. It is recommended that a mockup be constructed to ensure comfortability with UHPC.

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Abbreviations

The following abbreviations are used in this manuscript:

ASTM	American Society of Testing Materials
CMP	Corrugated Metal Pipe (Culvert)
CTDOT	Connecticut Department of Transportation
FRP	Fiber Reinforced Polymer
MDF	Medium Density Fiberboard
MIG	Metal Inert Gas (Welding)
UConn	University of Connecticut
UHPC	Ultra-High Performance Concrete
WSE	Water Surface Elevation

References

1. FHWA. *LTBP InfoBridge-Data*; US Department of Transportation, Federal Highway Administration: Washington, DC, USA, 2024.
2. ASCE. 2021 Report Card for America's Infrastructure. 2021. Available online: www.infrastructurereportcard.org (accessed on 1 August 2024).

3. Meegoda, J.N.; Juliano, T.M. *Corrugated Steel Culvert Pipe Deterioration*; National Center for Transportation and Industrial Productivity: Newark, NJ, USA, 2009.
4. Jin, H. Decision-Making Guidance for Selecting Culvert Renewal Techniques. Ph.D. Dissertation, Clemson University, Clemson, SC, USA, 2016.
5. ODOT. 611.11 Field Paving of New or Existing Conduit. In *Construction & Material Specifications*; Ohio Department of Transportation: Columbus, OH, USA, 2023; p. 473.
6. Votapka, F.E. Considerations for Fish Passage Through Culverts. *Transp. Res. Rec.* **1991**, *31*, 347–353.
7. Makrakis, S.; Castro-Santos, T.; Makrakis, M.C.; Wagner, R.L.; Adames, M.S. Culverts in paved roads as suitable passages for Neotropical fish species. *Neotrop. Ichthyol.* **2012**, *10*, 763–770. [\[CrossRef\]](#)
8. Chennareddy, R. Retrofit of Corroded Metal Culverts Using GFRP Slip-Liner. Ph.D. Dissertation, University of New Mexico, Albuquerque, NM, USA, 2019.
9. Thomas, R. *Culvert-Slip-Liner Repair Method*; Purdue Road School: West Lafayette, IN, USA, 2000.
10. Tetreault, J.; Moore, I.D.; Eng, P.; Asce, M.; Hoult, N.A. Laboratory Study on Effect of Grout Choice on Culvert Rehabilitation Using Sliplining. *J. Pipeline Syst. Eng. Pract.* **2019**, *11*, 04019044. [\[CrossRef\]](#)
11. Olsen, A.H.; Tullis, B.P. Laboratory Study of Fish Passage and Discharge Capacity in Slip-Lined, Baffled Culverts. *J. Hydraul. Eng.* **2013**, *139*, 424–432. [\[CrossRef\]](#)
12. Duguay, J.; Lacey, R.W.J. Effect of Fish Baffles on the Hydraulic Roughness of Slip-Lined Culverts. *J. Hydraul. Eng.* **2015**, *141*, 04014065. [\[CrossRef\]](#)
13. Webb, J.R. Slip Lined Culvert Retrofit and Fish Passage. Master's Thesis, Brigham Young University, Provo, UT, USA, 2009. Available online: <https://scholarsarchive.byu.edu/etd> (accessed on 23 July 2024).
14. Yoggy, G.D. The History of Shotcrete. *Shotcrete. Am. Shotcrete Assoc.* **2005**, *2*, 26–32.
15. Pye, J.H. Shotcrete. In *Significance of Tests and Properties of Concrete and Concrete-Making Materials*; ASTM International: West Conshohocken, PA, USA, 2006; pp. 616–624.
16. Basnet, C.B.; Panthi, K.K. Roughness evaluation in shotcrete-lined water tunnels with invert concrete based on cases from Nepal. *J. Rock Mech. Geotech. Eng.* **2018**, *10*, 42–59. [\[CrossRef\]](#)
17. Bernardo, G.; Guida, A.; Mecca, I. Advancements in shotcrete technology. In *Structural Studies, Repairs and Maintenance of Heritage Architecture XIV*; WIT Press: Billerica, MA, USA, 2015; pp. 591–602.
18. Dave, R. Full Scale Testing of Corrugated Metal Culvert Pipe Rehabilitated with Shotcrete Liner. Master's Thesis, University of Manitoba, Winnipeg, MB, Canada, 2019.
19. Huynh, A.; Petit, B.; Teply, F.; Larive, C. Innovative Rehabilitation Technology for Corrugated Metal Pipe Culverts Using Wet-Mix Sprayed UHPFRC. In *International Symposium on Ultra-High Performance Fibre-Reinforced Concrete*; Toutlemonde, F., Resplendino, J., Eds.; RILEM Publications SARL: Montpellier, France, 2017; pp. 717–724.
20. Graybeal, B.A.; De La Varga, I.; Duque, L.F.M. Fiber Reinforcement Influence on the Tensile Response of UHPFRC. In *First International Interactive Symposium on UHPC*; Iowa State University Digital Press: Ames, IA, USA, 2016; Available online: <https://www.iastatedigitalpress.com/uhpc/article/id/9584/> (accessed on 12 July 2023).
21. Graybeal, B.A.; De La Varga, I.; Yuan, J.; Haber, Z. Material Property Evaluation of Different Commercially-Available UHPC-Class Materials. In *First International Interactive Symposium on UHPC*; Iowa State University Digital Press: Ames, IA, USA, 2016; Available online: <https://www.iastatedigitalpress.com/uhpc/article/id/9606/> (accessed on 18 May 2023).
22. FHWA. *Structural Design with Ultra-High Performance Concrete*; FHWA-HRT-23-077 United States; Federal Highway Administration: Washington, DC, USA, 2023. Available online: https://rosap.ntl.bts.gov/view/dot/72525/dot_72525_DS1.pdf (accessed on 27 March 2024).
23. Kusumawardaningsih, Y.; Fehling, E.; Ismail, M.; Aboubakr, A.A.M. Tensile strength behavior of UHPC and UHPFRC. In *Procedia Engineering*; Elsevier Ltd.: Amsterdam, The Netherlands, 2015; pp. 1081–1086.
24. Graybeal, B.A. Tensile mechanical response of ultra-high-performance concrete. *Adv. Civ. Eng. Mater.* **2015**, *4*, 62–74. [\[CrossRef\]](#)
25. Spragg, R.P. *Electrical Resistivity Testing to Rapidly Assess the Durability of UHPC-Class Materials*; Federal Highway Administration: McLean, VA, USA, 2022. Available online: <https://highways.dot.gov/research> (accessed on 23 May 2024).
26. Graybeal, B.A.; Hartmann, J.L. Strength and Durability of Ultra-High Performance Concrete. In *Concrete Bridge Conference*; ResearchGate: Berlin, Germany, 2003.
27. Li, J.; Wu, Z.; Shi, C.; Yuan, Q.; Zhang, Z. Durability of ultra-high performance concrete—A review. In *Construction and Building Materials*; Elsevier Ltd.: Amsterdam, The Netherlands, 2020; Volume 255.
28. Graybeal, B.; Tanesi, J. Durability of an Ultrahigh-Performance Concrete. *J. Mater. Civ. Eng.* **2007**, *19*, 848–854. Available online: <https://ascelibrary.org/doi/10.1061/%28ASCE%290899-1561%282007%2919%3A10%28848%29> (accessed on 18 May 2023). [\[CrossRef\]](#)
29. Afzal, M.F.U.D.; Aziznamini, A. *Use of UHPC in Conjunction with Pneumatic Spray Application and Robotics for Repair and Strengthening of Culverts—Phase I*; Florida International University: Miami, FL, USA, 2023.

30. Plate, C. *Routine Inspection of Bridge No. 06537*; McLaren Engineering Group: Greenwich CT, USA, 2022.
31. CTDOT. *2000 Drainage Manual*; Connecticut Department of Transportation: Newington, Australia, 2019.
32. Haber, Z.B.; Munoz, J.F.; Graybeal, B.A. Field Testing of an Ultra-High Performance Concrete Overlay. 2017. Available online: <https://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/17096/index.cfm> (accessed on 18 May 2023).
33. Du, J.; Guo, P.; Liu, Z.; Meng, W. Highly thixotropic ultra-high-performance concrete (UHPC) as an overlay. *Constr. Build. Mater.* **2023**, *366*, 130130. [[CrossRef](#)]
34. Curtis, O.J. Nominal Versus Actual: A History of the 2 x 4. *Harv. Des. Mag.* **2018**, *45*, 40–41.
35. C1856/C1856M; ASTM. Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete. ASTM International: West Conshohocken, PA, USA, 2017. Available online: www.astm.org (accessed on 25 May 2023).
36. SAP2000, Structural Analysis and Design; Computers and Structures, Inc.: Walnut Creek, CA, USA, 2022. Available online: <https://www.csiamerica.com/products/sap2000> (accessed on 20 November 2025).
37. Griggs, F., Jr. The Warren Truss. *Struct. Mag.* **2015**, 44–48. Available online: <https://www.structuremag.org/article/the-warren-truss> (accessed on 29 July 2024).
38. Jiao, D.; De Schryver, R.; Shi, C.; De Schutter, G. Thixotropic structural build-up of cement-based materials: A state-of-the-art review. *Cem. Concr. Compos.* **2021**, *122*, 104152. [[CrossRef](#)]
39. Chambers, H.A. Principles and Practices of Stud Welding. *PCI J.* **2001**, *46*, 46–58. [[CrossRef](#)]
40. Nishikawa, W. The principle and application field of stud welding. *Weld. Int.* **2003**, *17*, 699–705. Available online: <http://www.tandfonline.com/doi/abs/10.1533/wint.2003.3170> (accessed on 24 May 2023). [[CrossRef](#)]
41. Shaughnessy, R., III; Clark, P.E. The Rheological Behavior of Fresh Cement Pastes. *Cem. Concr. Res.* **1988**, *18*, 327–341. [[CrossRef](#)]
42. Assaad, J.; Khayat, K.; Mesbah, H. Assessment of Thixotropy of Flowable and Self-Consolidating Concrete. *ACI Mater. J.* **2003**, *100*, 99–107. [[CrossRef](#)] [[PubMed](#)]

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