Self-Bearing Shotcrete in Lieu of Self-Consolidating Concrete for Tunnel Rehabilitation

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ABSTRACT: Pennsylvania Department of Transportation's almost 100 year old Liberty Tunnels underwent significant rehabilitation measures, including the replacement of aging ventilation arch walls. The arch walls act as tunnel shaped jet structures for fresh air supply. The original design foresaw the use of self-consolidating concrete and formwork for the replacement. The authors developed an alternative concept and subsequent design for a shotcrete arch wall solution in lieu of the self-consolidating concrete foreseen by the contract design. The alternate shotcrete concept provided the contractor with a schedule and cost saving solution under the given tight, two week long, construction window allowed during a complete shutdown of the tunnel.

PROJECT OVERVIEW

The alignment of the Liberty Tunnels crosses Mount Washington in Pittsburgh, Pennsylvania. The twin tunnels provide a direct route from the South Hills suburbs to Pittsburgh and ease the commute from and to downtown Pittsburgh. The Liberty Tunnels are horseshoe shaped tubes. Each tube serves one direction and has an overall length of 1,795 m (5,888 ft).

The tunnels were opened to traffic in January 1924 and have gone through a series of upgrades and repairs during their service life. Originally the tunnels had no ventilation system, because the expected traffic volume through the tunnels was very limited. However, this was subject to change already shortly after the tunnels were opened to traffic and the traffic flow exceeded the predicted numbers. Only limited numbers of vehicles were permitted through the tunnels to keep the exhaust gases below dangerous levels. In 1928, the tunnels were upgraded and a ventilation system was designed to accommodate the increasing traffic flow. Two vertical vent shafts were constructed to draw exhaust from the midpoint of each tunnel and force a supply of fresh air into the tunnel through the so-called "arch walls." An arch wall is an arch structure, which is offset from the structural lining of the tunnel to provide for air-channels. The ventilation arch wall section acts like macroscopic air nozzle; fresh air is supplied from the ventilation shaft and pushed along the vent supply area on either side of the arch wall. At the end of the nozzle the arch walls are open, allowing the fresh air to enter into the tunnel, away from the exhaust point (see Figure 1, 2, 5, and 10).

Swank Construction Company (Swank) was awarded the Liberty Tunnels Rehabilitation project by the Pennsylvania Department of Transportation (PennDOT) in May 2013. The project included amongst other scope, the demolition and renewal of the ventilation arch walls inside the tunnels, close to the ventilation shaft. The subject section is located between STA 13+029 and STA 13+110 in the inbound tunnel and between STA 12+991 and STA 12+910 in the outbound tunnel. Each arch wall section is 24.7 m (81 ft) long. The existing ventilation arch wall has an intrados radius of 4.05 m (13 ft, 3¼ in.) and spans the entire arch with an opening angle of 180 degrees. In addition, two vertical walls divide the void space for the air supply along the left and right side of the arch wall (see Figure 3).

Structurally, the arch wall section can be divided into three sections from left to right in Figures 1 and 2: (1) merging area from the shaft, (2) full-arch area, where the arch wall is closed at the bottom, and (3) suspended arch area, where the arch wall is open at the bottom to provide an outlet for the fresh air (see also Figure 10). This paper focuses on the full-arch area (center) and does not address the merging area from the shaft (left) or the suspended arch area (right).

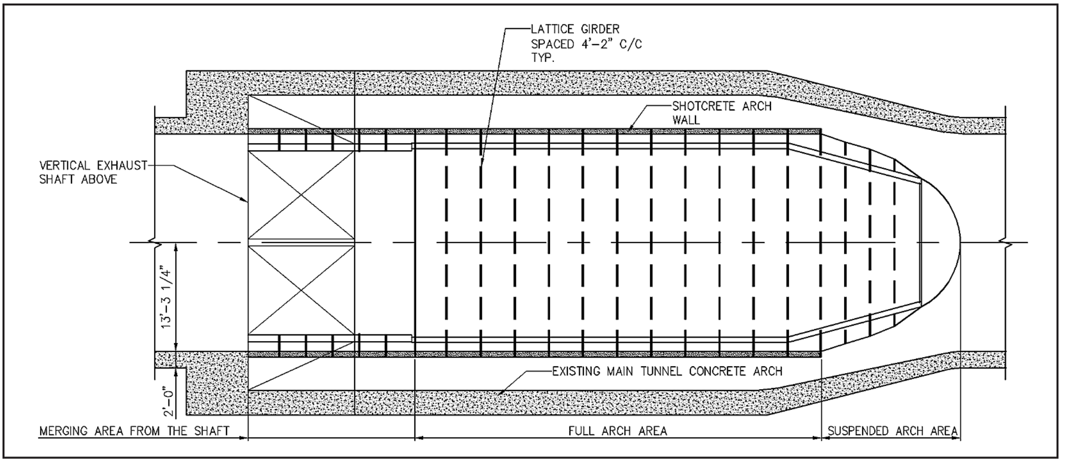

Figure 1. tunnel ventilation arch wall section plan view

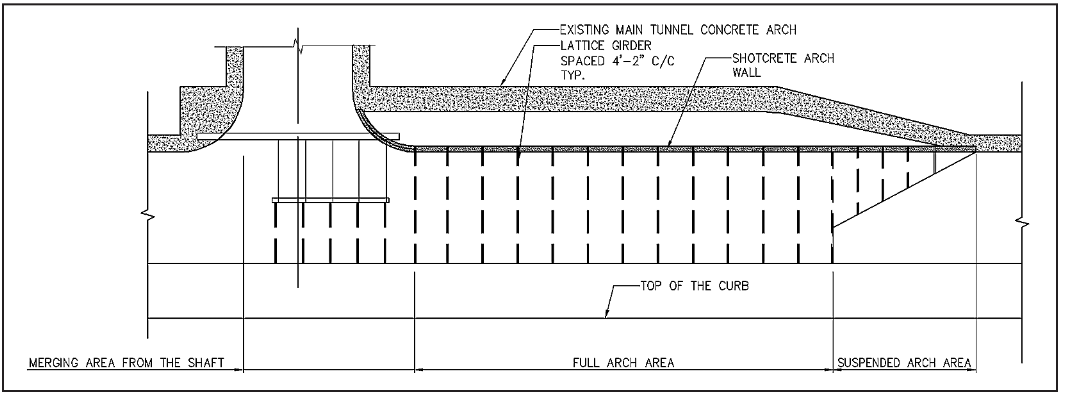

Figure 2. Tunnel ventilation arch wall section—longitudinal section

The original arch wall used u-shaped steel profiles as structural members, which were tied with radial hangers to the structural tunnel arch above. The fresh air travelled through the void space along the left and the right side wall. The center part was not utilized for ventilation. Vertical walls separated the center part from the sidewall areas, as shown in Figure 3.

All steel members, including the radial hangers (Figure 3), were later embedded in concrete to provide protection against corrosion as shown in the photograph in Figure 4.

The original rehabilitation design proposed the same structural approach with u-shaped beams and hangers embedded in reinforced, self-consolidating concrete.

Gall Zeidler Consultants (GZ), in cooperation with Swank Construction and Coastal Gunite, provided an alternate design and construction concept for the Liberty Tunnels Rehabilitation project. The proposed alternate concept used a self-bearing shotcrete arch wall, which allowed avoiding the utilization of the radial hangers as well as the cast-in-place, self-consolidating concrete.

REHABILITATION DESIGN

Original Design

The original design proposed demolishing and renewing the existing ventilation arch walls, following the original design approach with u-shaped steel beam and radial hangers embedded in concrete (Figure 3 and 4). The concrete arch was supposed to be reinforced with welded wire fabric. During the arch wall demolition it was intended to utilize the existing steel framing hangers, which are in good condition and replace hangers, which are deteriorated. A curved steel formwork, forming both sides of the free-standing arch wall was supposed to be used to form the cast-in-place arch. In addition, the

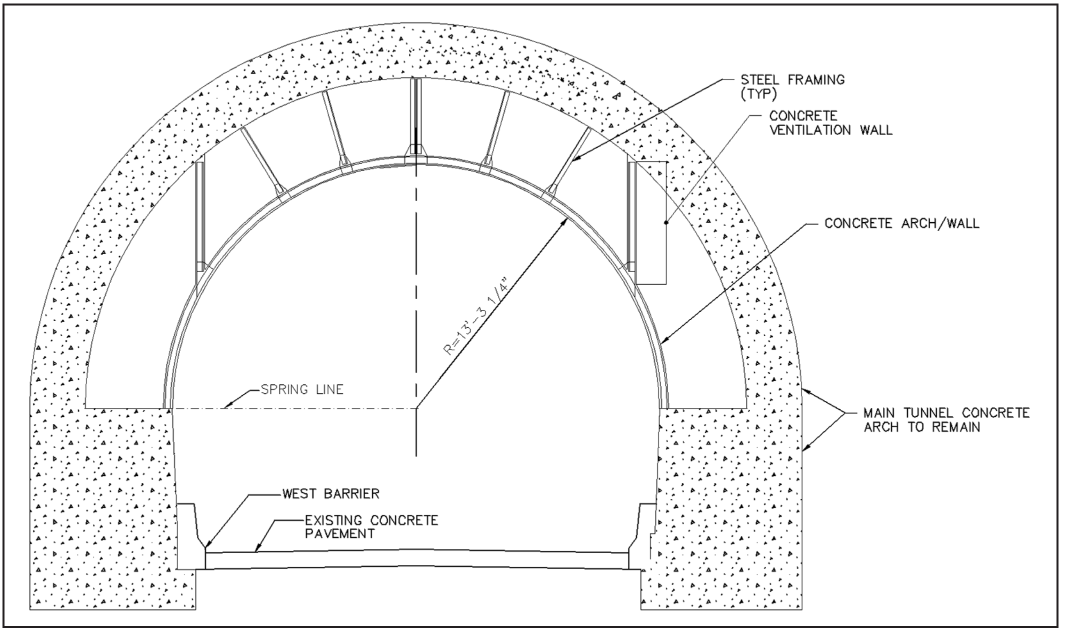

Figure 3. Existing tunnel ventilation arch wall section—cross section

Figure 4. Embedded hangers in existing void space between main tunnel and ventilation arch wall

two vertical walls and concrete embedment of the hangers on top of the arch were to be formed and poured as well. To account for the relatively thin, reinforced walls, limited accessibility and tight schedule during the given shutdown period the use of self-consolidating concrete was foreseen.

Self-consolidating concrete is a high-performance concrete that can flow easily into tight and constricted spaces without segregating and without requiring vibration. This was required due to the very limited accessibility. However, fresh self-consolidating concrete exerts high hydrostatic stresses, which have to be born by the formwork, and has a risk to rupture the formwork and create concrete blowouts. Therefore ordinary formwork could not be used for the envisioned application and required stronger formwork either made of steel or very strong timber formwork. The formwork also had to be embedded with studs and anchors of sufficient strength to prevent concrete blowouts or lifting from hydraulic

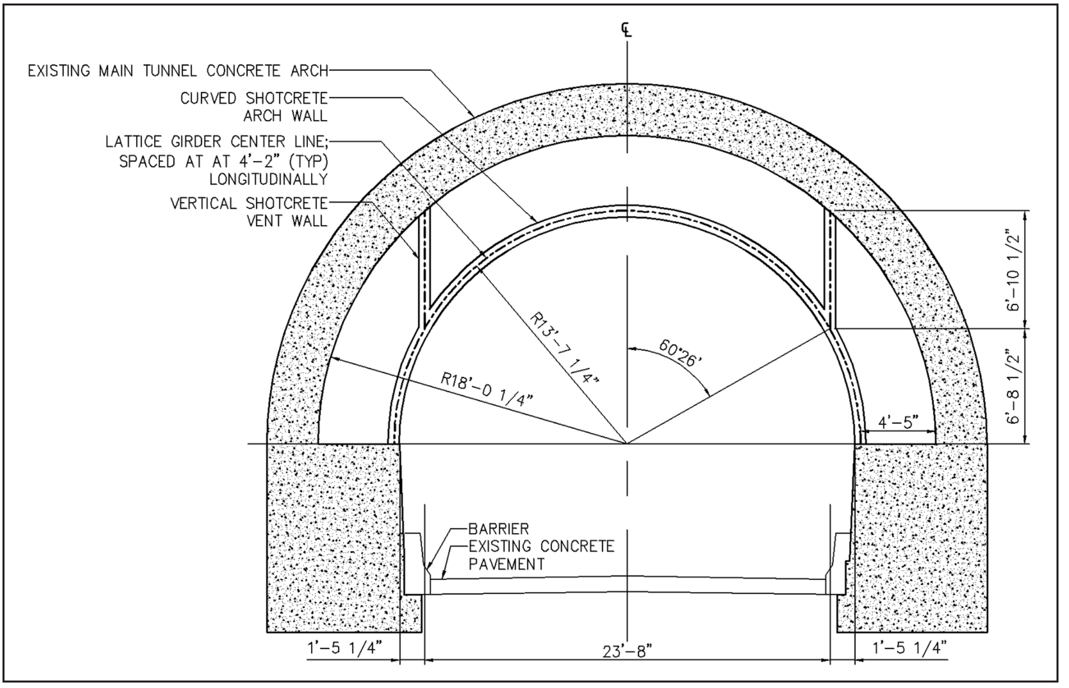

Figure 5. Alternative design self-bearing shotcrete arch section

stresses especially at the lower part of the formwork. Such custom-made formwork incurs high costs, especially due to its very limited reuse at the given application. In addition, the schedule impact by the risk of blowouts or deformation of the formwork was considered very high by the Contractor, because the limited shutdown period of the tunnel left no time for on site adjustments.

Another uncertainty was posed by the reuse of the existing hangers, which were embedded in concrete. To evaluate a potential reusability of the hangers the existing arch wall had to be demolished first, while the shutdown period had already started. The number of deteriorated hangers or hangers, which were damaged during the demolishing, was therefore unknown at the start of construction. Further, sorting out the hangers and replacing the deteriorated ones was considered a time consuming activity in itself. The hangers also posed an additional hindrance during formwork installation.

Alternative Design

To reduce the schedule risk and provide cost savings an alternative design was developed in order to simplify the construction process. The alternative design focused on two critical aspects of the original design (1) the use of self-consolidating, cast-in-place concrete and (2) the structural utilization of hangers.

The cast-in-place concrete was avoided by the introduction of shotcrete, while the structural system was changed into a self-bearing arch, avoiding hangers as structural members. The latter allowed the complete removal of all hangers during the demolishing process, independently from their condition, without the need of replacement.

The alternative design utilized self-bearing shotcrete arch for the ventilation arch wall. The self-bearing shotcrete arch concept is often used to extend the underground section of a mined tunnel into the open portal area by providing a free-standing arch or so-called shotcrete canopy. Recent examples for the utilization of shotcrete canopies can be found at the Weehawken Tunnel, New Jersey and Devil's Slide Tunnel, California. Similarly, FHWA Technical Manual for Design and Construction of Road Tunnels (FHWA, 2009) also describes shotcrete canopy use and construction techniques.

Shotcrete canopies utilize the same materials as typically used for tunnel shotcrete linings for ground support. These materials are shotcrete, lattice girders, and reinforcement. While the initial lining during tunnel excavation and support is applied against the ground, an artificial surface on the backside has to be provided for a free-standing arch to allow for the built-up of the shotcrete lining. In case of the Liberty Tunnel relatively lightweight plywood was used, which could be easily removed at completion.

Alternatively expanded metal sheets may be used at the backside.

The cross section in Figure 5 provides a typical situation for the self-bearing shotcrete arch of the alternative design. It has to be noted that the two vertical walls shown in Figure 5 do not have any structural function and are for ventilation purposes, only. Structurally the arch wall supports itself as a free-standing, self-bearing arch, loaded by the weight of the two vertical overlying walls. Additional hangers such as in the original design are not necessary for the structural system.

The arch walls and the vertical walls have embedded lattice girders at a typical spacing of 1.27 m (4 ft 2 in.) center to center. The lattice girders were bolted on the abutment and anchored with undercut anchors at the tunnel main arch to provide stability during construction. The lattice girders were structurally not utilized in the design, despite the fact they provide additional reinforcement. The primary purpose of the lattice girders was the provision of a geometrical template for the sprayed shotcrete and temporary support for the reinforcement and shotcrete during the construction process. Structurally the arch was designed with a wall thickness of 6 inches. However, to account for construction and wall thickness tolerances in the design the weight of the wall was assumed for a wall thickness of 8 inches.

Linear elastic beam models were used to calculate structural forces acting on the ventilation arch walls. All ground and external loads are born by the main tunnel arch and do not affect the inner, self-bearing arch. The design loads considered self-weight of the structure, loads from overlying vertical walls, and earthquake load and air pressure of 2.39 kPa (50 psf) radially to the walls. The design resulted in minimum reinforcement in the arches as required per ACI 318 (ACI, 2005). The arches were reinforced with two layers of welded wire fabric, W9×W9 at 6 inch center to center spacing in both directions. The minimum reinforcement was important for the durability of the arch including controlling cracking from shrinkage and temperature changes. Following PennDOT's requirements all reinforcement as well as the lattice girders were galvanized.

CONSTRUCTION SEQUENCE

Due to the two layers of reinforcement as well as the vertical walls on top of the arch walls, the design directed a mandatory construction sequence, which had to be followed by the Contractor during construction. The construction sequence is described below and shown in Figure 6.

The construction started with demolition of the existing ventilation arch wall (Step 1). In the second step, lattice girders were installed along the arch periphery as well as for the two vertical wall sections. The lattice girders were secured with undercut anchors at the top and dowels at the bottom of the arch of the main tunnel lining. The lattice girders were comprised of a three-piece arch plus one piece each for each vertical ventilation wall on either side. The lattice girder pieces were connected with bolts using butt plates welded at the end of each lattice girder section. In Step 3 a light plywood formwork was setup along with first layer of welded wire fabric at the extrados side of the lattice girder. To ensure sufficient concrete cover, spacers were used between the reinforcement and the plywood. In this step it is important to highlight that the center part of the arch had to be left open to provide access for the construction of the vertical walls. In Step 4 shotcrete was applied at the rounded as well at the vertical wall sections—excluding the center part. Only the vertical wall sections were completed to full thickness and with both layers of reinforcement, while the intrados layer of reinforcement at the arch wall sidewall was left out for later completion. During Step 5, the center arch section was closed by installation of the plywood and reinforcement at the extrados side of the arch. In the last step the center arch section was sprayed up to the intrados layer of reinforcement, followed by the installation of the intrados layer of reinforcement along the entire arch and completion of the shotcrete arch wall to full thickness, including a trowel finish. In a final step the plywood at the backside was removed, completing the arch wall construction.

EXPERIENCE AND CHALLENGES DURING CONSTRUCTION

As mentioned before, the Liberty Tunnels are a primary commuting route to and from downtown Pittsburgh. Due to their importance the allowable shutdown period was very limited and demanded a very tight and compact construction schedule. In an early planning stage the ventilation arch walls were identified as a potential high impact risk for the schedule and were the controlling operation during the closure period for different rehabilitation measures in the tunnel.

The construction was split into two phases, phase 1 for the southbound tunnel and phase 2 for the northbound tunnel. As part of the bid documents PennDOT set forth 18 day closures per phase to run consecutively between the 4th of July and Labor Day. Failure to meet the 18-day closure would result in a penalty of $ 40,000 per day. During the planning phase it was apparent that meeting the 18-day restriction with the original design would be extremely challenging and alternatives were investigated. During development stages of the alternative design it was determined the arch walls could be completed in 16 days. This led to a schedule change that

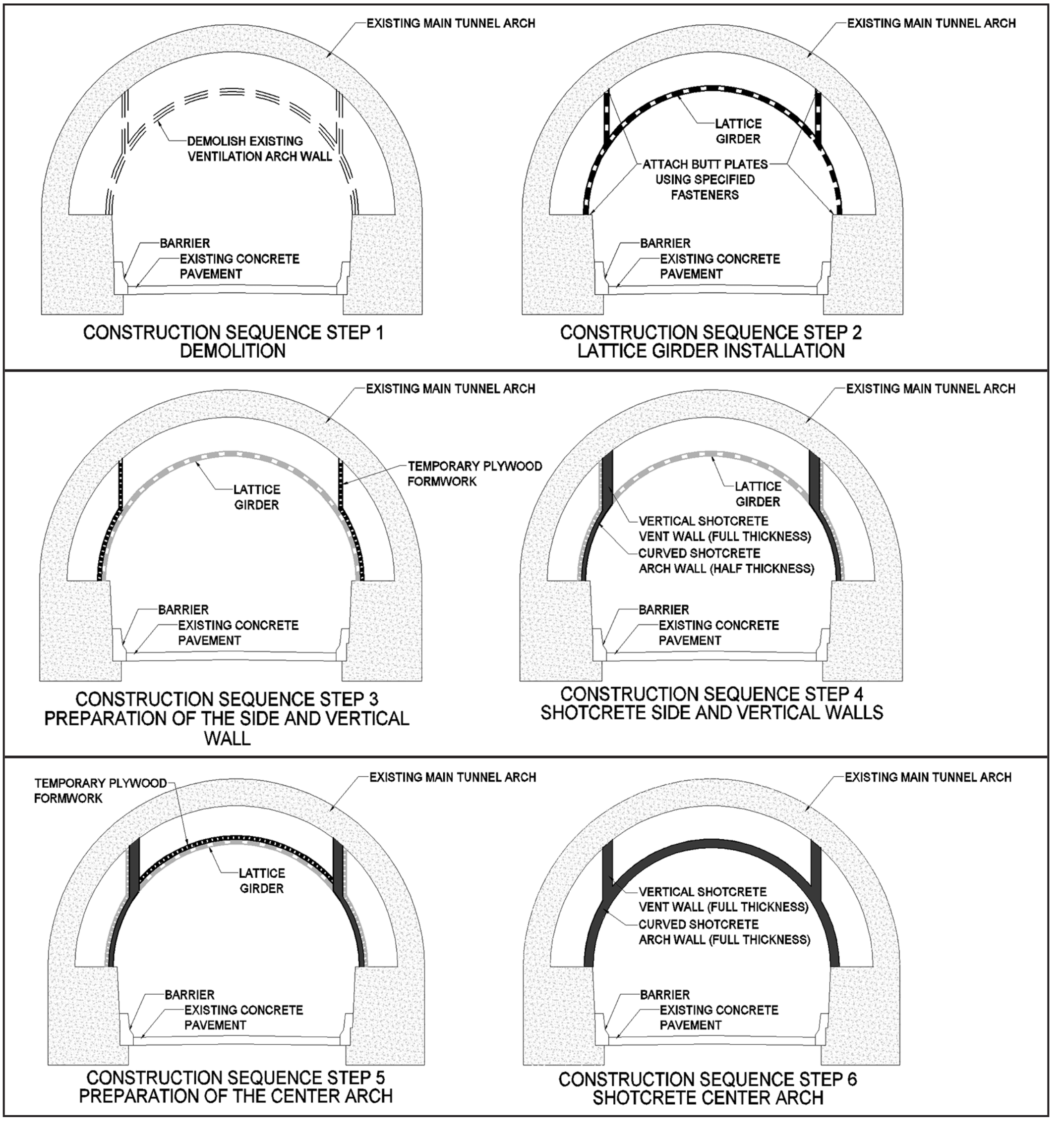

Figure 6. Typical construction sequence

reduced the allowable closure periods to be reduced to 16 day per phase in exchange for 2 weekend closures prior to each long-term closure. The two weekend closures were used on areas not associated with the ventilation arch walls. This allowed Swank to complete other activities prior to the scheduled long-term closure, which internally freed up resources and allowed to focus on the ventilation arch walls during the long-term closures.

Already one hour after the start of the closure the demolition of the existing arch walls began followed by the installation of the new shotcrete arch walls, following the construction sequence as described above. In the southbound tunnel (Phase 1) the work was completed with the second layer of shotcrete just hours before the opening of the tunnel for traffic. The delays were caused by logistical problems and a delayed delivery of lattice girders and undercut anchors. However, the phase 2 construction (northbound) was completed in around 14 days and much quicker than the southbound and 2 days under the maximum allowable 16 days, due higher efficiency in the sites' logistic and lessons learned as well as learning curve effects from the previous phase.

Figure 7. Construction sequence Step 3—Lattice girder and extrados reinforcement sidewall sections

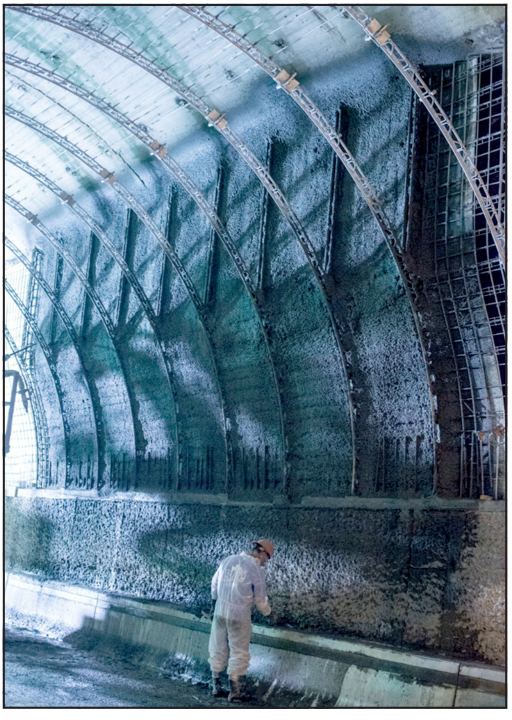

Figure 8. Construction sequence Step 4—Curved and vertical sidewall sections are shotcreted

Crew assembly and size varied for each operation of the construction. Swank's portion of the installation was mainly demolition and installation of lattice girders, rebar and forming. In total, approximately 20 to 25 men per 12 hour shift worked on Swank's crew during the construction of the arch. Coastal Gunite was responsible for the installation of shotcrete and worked with a crew of 9 to 12 people per 12 hour shift.

Figure 7 depicts construction sequence Step 3. The lattice girders of the arch walls as well as the vertical walls sections have been erected. The extrados layer of reinforcement as well as plywood in the back has been installed. The center arch section is open to allow shotcreting of the vertical walls. In the back the suspended section of the arch wall, acting as a ventilation nozzle, which was not discussed in detail in this paper, can be seen.

Figure 8 shows the situation during construction sequence Step 4. The curved and vertical sidewall sections are already partially shotcreted. During this step the vertical sidewall sections will be completed with both layers of reinforcement and shotcreted to full thickness.

Figure 9 shows the construction sequence at Step 5. As soon as the vertical wall sections are completed, access through the center arch section is no longer needed. In this step the plywood and reinforcement in the center arch section can be installed and shotcreted. After this step the intrados level of reinforcement, covered by the final layer of trowel-finished shotctete can be installed.

Figure 10 shows the arch wall section after its rehabilitation, looking into the air nozzle opening. The smooth trowel-finish of the shotcrete makes it difficult to recognize that shotcrete in lieu of cast-in-place concrete was used.

The design specified stringent experience requirements for the shotcrete applicator to ensure the required high quality. Swank decided therefore

Figure 9. Construction sequence Step 5—preparation of center arch section

Figure 10. Finished rehabilitation

to subcontract the shotcrete work to the shotcrete specialists Coastal Gunite. The shotcrete was placed using an Allentown (Putzmeister) Elite 40 Shotcrete Pump. The concrete material was brought into the tunnel dry in bulk sacks and mixed inside a ready mix truck in order to both use the material specified and have enough available to place it in sufficient quantity given the tight construction schedule. The material itself included poly-fibers and a corrosion inhibitor. Excluding the finish coat, the shotcrete process involved the addition of a liquid accelerator at the shotcrete nozzle to reach the specified set times and meet the early strength requirements per design.

The Contractor was able to demonstrate proficiency encapsulating the lattice girders and both layers of mesh simultaneously by alternating the location of shotcrete and mesh installation. This approach allowed the project to move forward more quickly when needed. Overall the shotcrete was placed in three lifts per wall. The first layer of shotcrete was placed encapsulating the first layer of mesh and left enough of the lattice girder exposed such that the second layer could be installed. The second placement encapsulated all of the steel and was left rough so that a monolithic finish coat could be applied last as to be more appealing aesthetically.

The final layer was finished with a broom and was sprayed with a curing compound to attain proper cure and avoid surface cracking.

CONCLUSION

For the Liberty Tunnel Rehabilitation project time was of the essence due to a short and limited closure of the tunnel. The alternative design of self-bearing shotcrete ventilation arch wall provided the contractor greater flexibility and reduced construction risk during the ventilation arch wall installation. The alternative design cut down the time required for the installation of an otherwise heavy formwork, which would have been required by the self-consolidating concrete. Further it was not required to retain the existing hangers supporting the ventilation arch walls since the shotcrete arch wall was self-supported.

The rehabilitation work conducted in the Liberty Tunnel showed a unique collaborative effort between the designer and contractors, which allowed the work to be completed on schedule, below the original cost, and with much less construction risk for the contractor as well as the owner.

The presented approach of the self-bearing shotcrete arch is a showcase for similar rehabilitation and repair works of aging tunnels, which have to be rehabilitated with a high quality under a limited time frame for tunnel closures and within the given budget.

REFERENCES

American Concrete Institute (ACI)—Building Code Requirements for Structural Concrete, 2005 (ACI 318-05).

Federal Highway Administration (FHWA) 2009. "Technical Manual for Design and Construction of Road Tunnels—Civil Element," FHWA-NHI-09-010, Washington DC.