2014 Honorable Mention

Liberty Tunnel Arch Restoration with a Shotcrete Alternative

By Axel G. Nitschke and John Becker

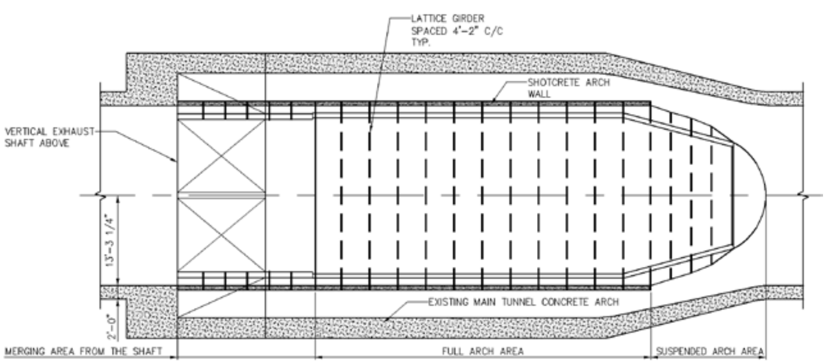

Fig. 1: Tunnel ventilation arch wall section plan view

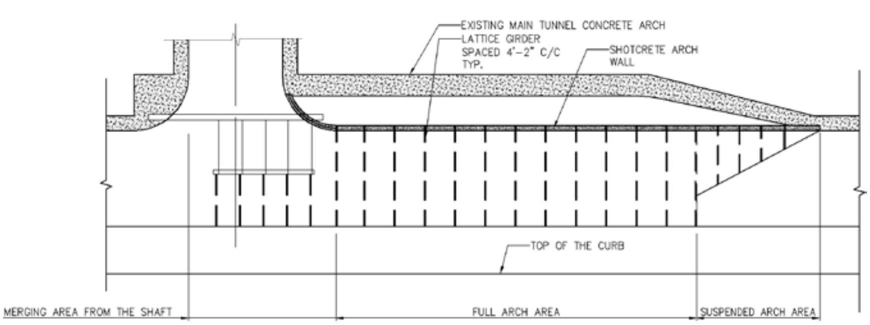

Fig. 2: Tunnel ventilation arch wall section—longitudinal section

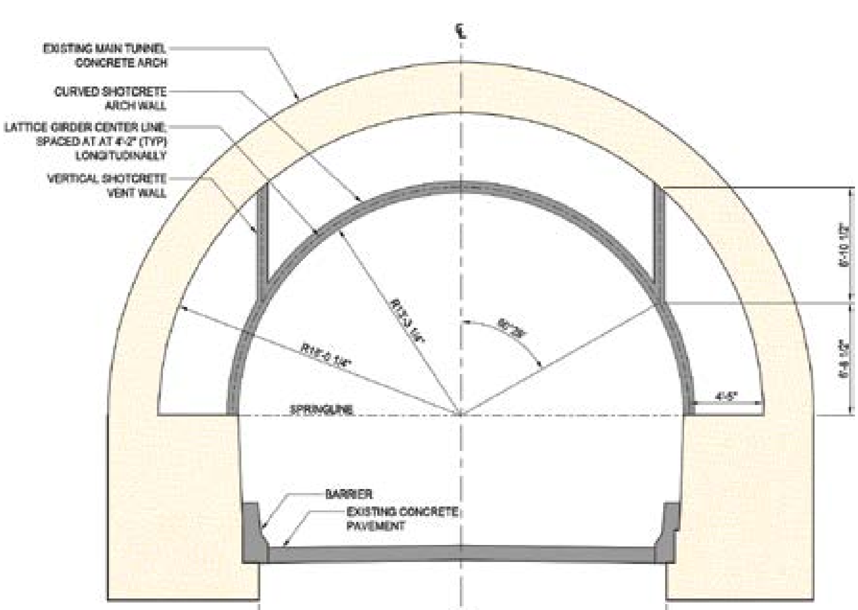

Fig. 3: Alternative design self-bearing shotcrete arch section

The Liberty Tunnel provides a direct commuting route from the South Hills suburbs to downtown Pittsburgh, PA. The Liberty Tunnel is a horseshoe-shaped tunnel consisting of two northbound and southbound tubes and has an overall length of 5888 ft (1795 m). The tunnel consists of two vertical vent shafts 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 a 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. The arch walls are open at the end of the nozzle, which allows the fresh air to enter into the tunnel away from the exhaust point (Fig. 1 through 4).

Swank Construction Company was awarded the Liberty Tunnels rehabilitation project by the Pennsylvania Department of Transportation (PennDOT) in May 2013. The project included, among other scopes, the demolition and renewal of the ventilation arch walls inside the tunnels, close to the ventilation shaft. 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.

Structurally, the arch wall section can be divided into three sections from left to right in Fig. 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 Fig. 4). This article focuses on the full-arch area (center) and does not address the merging area from the shaft (left) or the suspended arch area (right).

Arch Restoration

Original Design

The original arch wall used U-shaped steel profiles as structural members, which were tied with radial hangers to the structural tunnel arch above. Vertical walls separated the center part from the sidewall areas, as shown in Fig. 5. The original rehabilitation design proposed demolishing and renewing the existing ventilation arch walls, following the original design with U-shaped steel beams and radial hangers embedded in the concrete (refer to Fig. 5 and 6). The concrete arch was supposed to be reinforced with welded wire reinforcement. During the arch wall demolition, it was intended to use the existing steel framing hangers that were in good condition and replace the deteriorated ones. 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, two vertical walls and concrete embedment of the hangers on top of the arch were to be formed and placed.

Self-consolidating concrete (SCC) is a high-performance concrete that can flow easily into tight and constricted spaces without segregating and without requiring vibration. However, fresh SCC exerts high hydrostatic stress, which has to be borne entirely by the formwork until the concrete develops strength. This creates the risk of rupturing the formwork and concrete blowouts. Therefore, specialized formwork consisting of steel or very strong timber formwork embedded with studs and anchors of sufficient strength is required to prevent concrete blowouts or lifting of the form from hydraulic stresses. 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 or rework.

Reusability of the existing hangers embedded in the concrete also posed an uncertainty because its usability could only be determined after the demolition of the existing arch wall. The number of deteriorated hangers or hangers which were damaged during the demolition 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

As an alternative design, the use of cast-in-place concrete was replaced by sprayed shotcrete and the structural system was modified into a self-bearing arch. The self-bearing arch allowed the complete removal of all hangers during the demolishing process.

The self-bearing shotcrete arch concept is often used to extend the underground section of a mined

Fig. 4: Finished rehabilitation

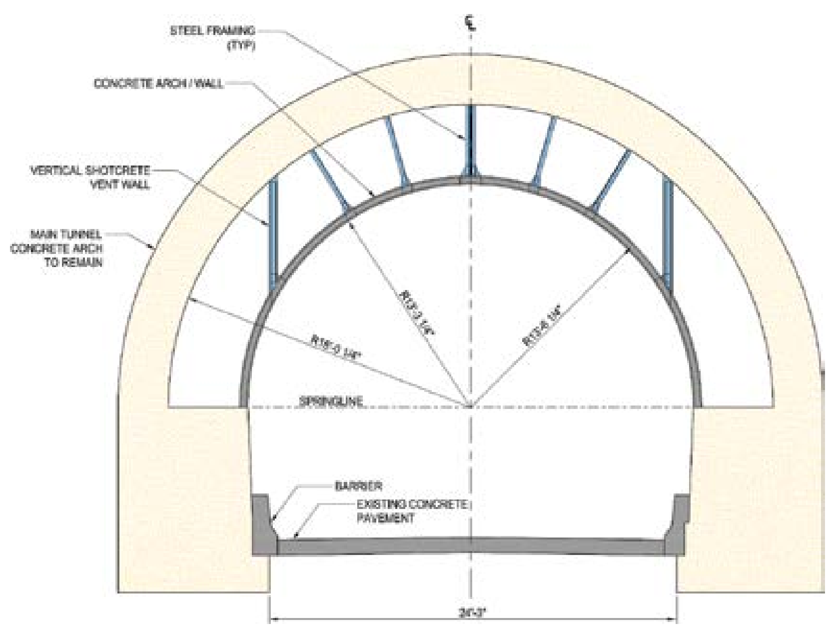

Fig. 5: Existing tunnel ventilation arch wall section—cross section

Fig. 6: Embedded hangers in existing void space between main tunnel and ventilation arch wall

tunnel into the open portal area by providing a free-standing arch often termed as shotcrete canopy. Recent examples for the use of shotcrete canopies can be found at the Weehawken Tunnel in New Jersey and Devil's Slide Tunnel in California. 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 buildup of the shotcrete lining.

The cross section in Fig. 3 illustrates a typical configuration of a self-bearing shotcrete arch. Structurally, the arch wall is 6 in. (152 mm) thick and supports itself as a free-standing, self-bearing arch, loaded by the weight of the two vertical overlying walls. These vertical walls do not have any structural function and are for ventilation purposes only. The arch walls and the vertical walls have embedded lattice girders at a typical spacing of 4 ft-2 in. (1.27 m) center-to-center. The arches were reinforced with two layers of welded wire reinforcement, W9 x W9 at 6 in. (152 mm) center-to-center spacing in both directions, as a minimum reinforcement to control cracking from shrinkage and temperature changes.

Construction Sequence

The schematic of the construction sequence is illustrated in Fig. 7 and detailed in the following steps (see Fig. 4 and 7 through 10):

Step 1: The construction started with demolition of the existing ventilation arch wall.

Step 2: In the second step, lattice girders were installed along the arch periphery and along 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

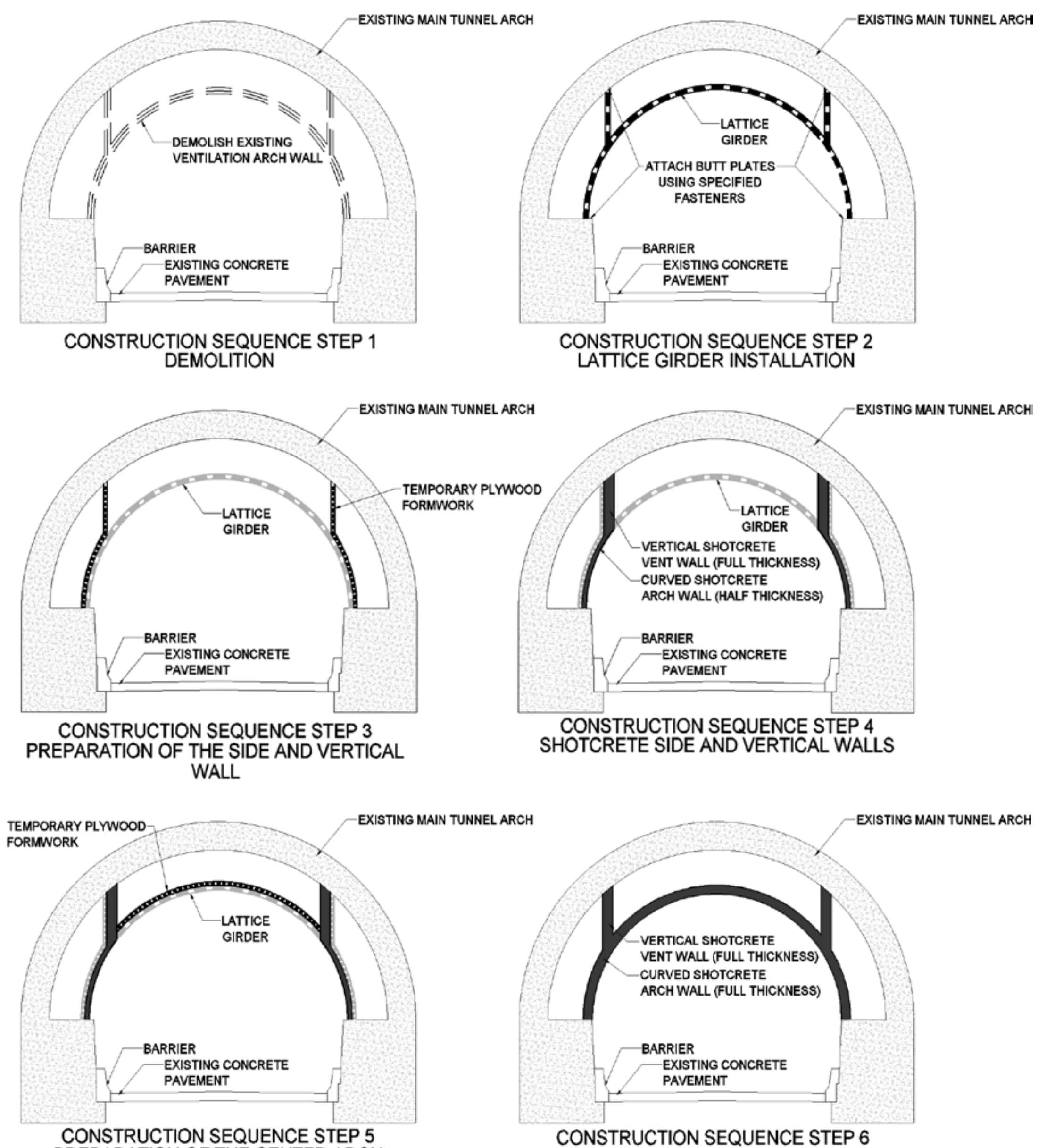

Fig. 7: Typical construction sequence

Fig. 8 (left and above): Construction sequence Step 3—lattice girder and extrados reinforcement sidewall sections

three-piece arch plus one piece each for each vertical ventilation wall on either side.

Step 3: A light plywood formwork was set up along with first layer of welded wire reinforcement at the extrados (exterior curve of the arch) side of the lattice girder. The center part of the arch was left open to provide access for the construction of the vertical walls. Figure 8 illustrates the erected lattice girders of the arch walls and vertical wall sections. 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.

Step 4: Shotcrete was applied at the rounded and 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. As observed in Fig. 9, the

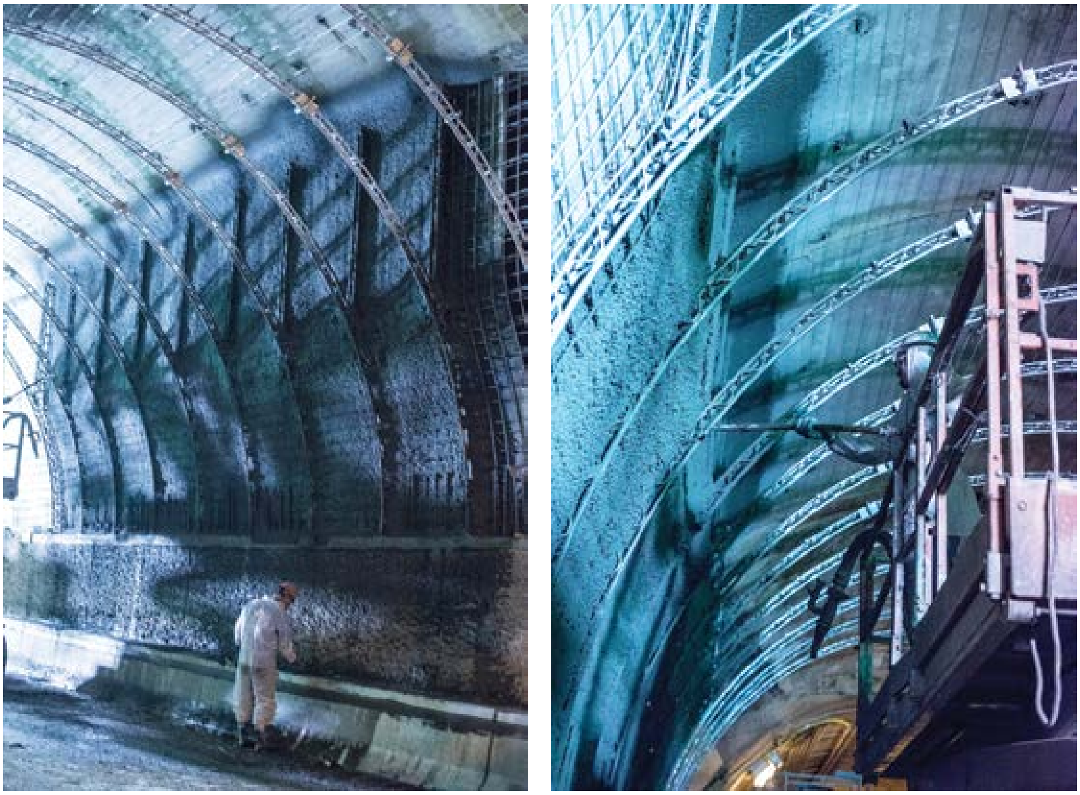

Fig. 9: Construction sequence Step 4—curved and vertical sidewall sections are shotcreted

Fig. 10: Construction sequence Step 5—preparation of center arch section

curved and vertical sidewall sections have been partially shotcreted.

Step 5: The center arch section was closed by installation of the plywood and reinforcement at the extrados side of the arch. As soon as the vertical wall sections were completed, the plywood and reinforcement in the center arch section could be installed and shotcreted, which is illustrated in Fig. 10. After this step, the intrados (interior curve of the arch) level of reinforcement covered by the final layer of trowel-finished shotcrete can be installed.

Step 6: 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. Finally, at the end, the plywood at the backside was removed, completing the arch wall construction. Figure 4 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.

Construction Challenges

The shutdown period for tunnel closure was very limited and demanded a very tight and compact construction schedule. 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. 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 shotcrete design, it was determined the arch walls could be completed in 16 days.

The demolition of the existing arch walls started immediately after tunnel closure, followed by the installation of new shotcrete arch walls. The southbound tunnel (Phase 1) was completed just hours before the opening of the tunnel for traffic. However, the northbound tunnel (Phase 2) was completed in about 14 days; 2 days under the maximum allowed 16 days.

The design specified stringent experience requirements for the shotcrete applicator to ensure the required high quality. Coastal Gunite was the subcontracted shotcrete specialist contractor and worked with a crew of nine to 12 people per 12-hour shift. The concrete material was hauled in dry bulk sacks and mixed on site inside a concrete truck inside the tunnel, which ensured sufficient quantities available in place given the tight construction schedule. The concrete mixture included polyfibers and a corrosion inhibitor. Excluding the finish coat, the wet-mix shotcrete used a liquid accelerator, injected at the shotcrete nozzle, to reach the specified set times and meet the early strength requirements required by the design. 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 to provide aesthetic appeal. The final layer was finished with a broom and was sprayed with a curing compound to attain proper cure and avoid surface cracking.

Conclusions

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 the self-bearing shotcrete ventilation arch wall provided the contractor greater flexibility and reduced construction risk during the ventilation arch wall installation.

The simplicity in the design and the easy and quick installation of the shotcrete arch wall system allowed the project to be completed on time and within budget. The tunnel was even completed 2 days earlier than the proposed schedule and on budget with 18% cost savings to the owner. Such design has showcased the effective and fast use of shotcrete as means for rehabilitation and repair works in existing tunnels that only allow limited time for tunnel closures.

Honorable Mention

Project Name
Liberty Tunnel Arch Restoration

Project Location
Pittsburgh, PA

Shotcrete Contractor
Coastal Gunite Construction Company*

General Contractor
Swank Construction Company, LLC

Architect/Engineer
Gall Zeidler Consultants

Project Consultant/Inspection
Hill International Inc.

Material Supplier/Manufacturer
The QUIKRETE Companies*

Project Owner
Pennsylvania Department of Transportation

*Corporate Member of the American Shotcrete Association

References

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ACI Committee 318, 2005, "Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary," American Concrete Institute, Farmington Hills, MI, 430 pp.

***Axel G. Nitschke** received his MSc and PhD in civil engineering in 1993 and 1998, respectively, from Ruhr University Bochum, Bochum, Germany, and is a licensed professional engineer in Virginia and California. He has gained more than 20 years of in-depth, on-the-job experience in all aspects of underground construction, geotechnical engineering, and mining. He has worked on the engineering and construction of a large number of tunnel projects in Europe, the United States, Canada, and Colombia. He is well-experienced in all ground conditions, ranging from soft ground to hard rock, and the associated implications for design and construction methods. Nitschke has held key positions such as Senior NATM Engineer, Contract/Claims Manager, Risk Manager, Design Manager, and Project Manager.*

***John Becker** is an ACI Certified Nozzleman who, for the last 5 years, has worked in many capacities—most recently as Project Manager—for Coastal Gunite Construction Company, based in Cambridge, MD. In addition to the Fort McHenry Tunnel, he has been involved with many shotcrete projects large and small, including the $15 million Bonner Bridge Rehabilitation Project in Nags Head, NC, and the $5 million Old Mill Creek Sewer Rehabilitation Project in St. Louis, MO.*