Shotcrete as Final Liner — Design Considerations

By Andy Thompson

Summary

The use of shotcrete placement (often called sprayed concrete) for the final permanent structural lining of underground structures and facilities continues to increase around the world. Where non-uniform shapes are required, shotcreting provides great flexibility, eliminating the need for complex and time-consuming formwork installation. This can improve the logistics and reduce the cost of the final lining work. As a placement method for concrete, there are certain elements of the design process where shotcreting can be beneficial.

Initial Considerations

Some key factors in determining whether and how shotcrete may be used for the installation of the permanent lining are the governing codes and standards where the work is being undertaken. There may be restrictions on where such methods can be used or local design codes and standards that have a direct impact on the design, quality control, and other factors that need to be considered by both the designer (when preparing the project drawings and specifications) and the contractor (when developing their placement plans). For this article, the author has primarily drawn on U.S. practice for examples of design impacts.

Shotcrete Linings

Where shotcrete is used for the permanent lining, it is also commonly used for the initial or primary ground support that is installed immediately after the excavation of the ground. Depending on the ground conditions, the shotcreted concrete may form part of a support system comprising rock bolts/dowels, lattice girders, etc., and welded wire mesh or steel fibers may be used to enhance the tensile capacity of the concrete and ensure ductile behavior. The thickness of the concrete to be shotcrete-applied will depend on the span to be supported, the specific ground conditions, and the use of other support elements. Typically, the initial lining is designed to resist external forces due to short-term ground loads as well as the effects of other transient loads such as compensation grouting and any surcharge loads applied at the surface level during construction works. It may also be designed to resist a certain percentage of the long-term ground loading, while hydrostatic loading from groundwater is more typically designed to be carried by the permanent lining.

This initial lining will usually be installed in layers to achieve the required thickness and — depending on whether steel fibers are used and the type of waterproofing system to be installed between the primary lining and the permanent lining — may require that a plain unreinforced layer of concrete be shotcreted to provide a suitable substrate for the waterproofing system. One critical item that requires specification in any use of shotcrete placement for primary lining is a "smoothness" criterion, to be achieved prior to the installation of a sheet membrane system to reduce the potential for pillowing and potential damage to the sheet waterproofing membrane during installation of the permanent lining. This is relevant both in the use of shotcrete or form-and-pour concrete as the placement method for the permanent concrete lining. Typically, the membrane manufacturer will provide details of what the membrane can tolerate as part of the membrane material data sheets. These should be reflected in the project contract documents along with a clear process that outlines who is responsible for determining whether these tolerances have been met prior to permitting membrane installation to proceed. Similarly, if spray-applied membranes are being used, the surface preparation and sign-off needs to be established and reflected in the project specifications and drawings based on the manufacturer's requirements.

Routinely, the initial lining design uses two-dimensional (2D) and three-dimensional (3D) numerical modeling techniques utilizing software packages such as Fast Lagrangian Analysis of Continua (FLAC), which can represent the non-linear behavior of the ground and provide a reliable representation of the ground-structure interaction. 2D numerical models of selected critical sections, highest cover, lowest cover, etc. are used to confirm the stability of the excavation and to determine the tunnel lining internal forces both in the long term and the intermediate construction stages. 3D analyses may be needed in more complex excavations, such as junctions or caverns, where the presence of a headwall has an influence on the final output of the internal lining forces. These models will include the effects of all the adjoining structures — including the appropriate surcharge loading — and make allowances for tolerances at each construction stage. The time-dependent development of shotcreted concrete strength and stiffness can also be included in these models using the strength gain curves. If there is historical data from previously excavated tunnels in the same ground, the lining design models can be calibrated against any historical data.

The permanent lining design must consider the following:

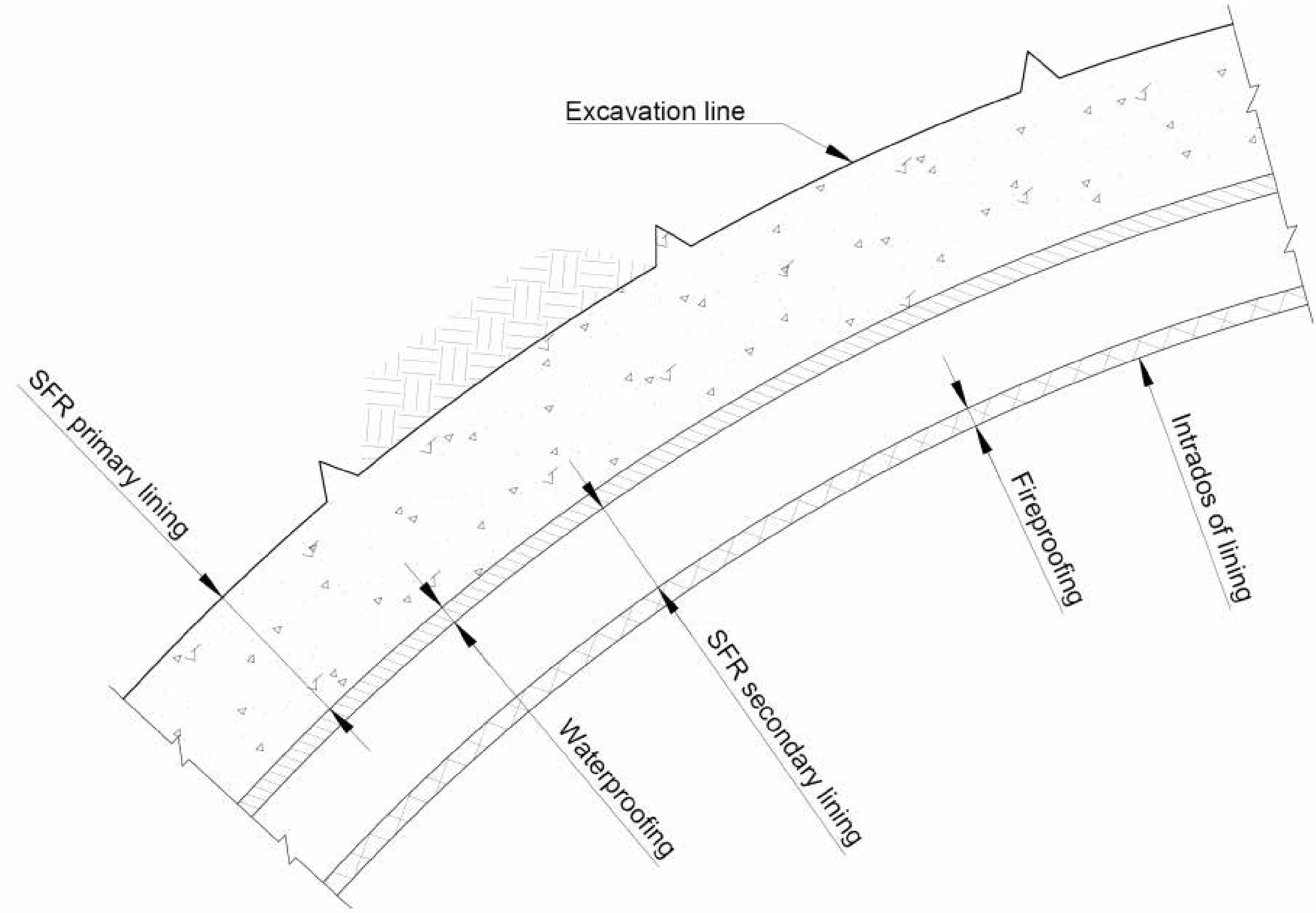

Fig. 1: Example of a shotcreted lining used on Crossrail, UK, using steel fibers

- The internal forces generated by its self weight
- Long-term ground loadings
- Hydrostatic loading
- Temperature
- Concrete shrinkage effects

Depending on the use of the tunnel, there may also be a need to consider fixing loads for the support of tunnel systems, like jet fans, as well as the effects of a fire on the lining. For fire resistance, it may be necessary to provide a final layer of shotcreted concrete containing polypropylene fibers as a 'sacrificial' layer to protect the remainder of the permanent lining. For example, on the Crossrail Project in London, the shotcreted linings were designed to provide sufficient residual capacity to resist ground and hydrostatic loads after a tunnel fire, as represented by the RABT-ZTV (Eureka) (EC 1196, 2008) time-temperature fire curve. Fire testing of shotcreted panels was undertaken with various combinations of lining layers to demonstrate the lining's ability to resist the RABT-ZTV fire curve. The end use of the underground facility is a major factor in determining whether such requirements and testing need to be accommodated in the project drawings and specifications. It is incumbent upon the designer to identify these and design for them.

When a waterproofing membrane is required for the long-term durability of the linings or to ensure a dry facility, the choice of membrane type will affect how the shotcrete is placed and the lining's long-term performance. Although some composite action between the initial support and the permanent lining can be considered, there are some limitations that need to be recognized based on the performance of spray-applied membranes. Where sheet membrane is used, a fully composite action cannot be assumed, and local codes should be consulted to determine how much capacity of the initial lining can be considered in the long-term performance of the lining. For spray-applied membrane, the material needs to be tested to determine its bond strength with the concrete and whether it can be relied upon in the long term to allow full composite action to be assumed in the design.

Final Lining Variations

As noted previously, shotcrete (or sprayed concrete) is a method of concrete placement; in and of itself, the final lining structural design is not dependent on the placement method. However, if a decision is made to utilize shotcrete placement, there are elements of the design that should be considered to allow for the use of this method that meets the performance requirements.

In determining the detail of the permanent lining, the codes, standards, and local practices also need to be considered. For example, in the U.S., hand-sprayed shotcreting is used alongside remotely manipulated nozzling (robotic) applications, whereas in many locations, shotcrete applications are almost entirely remotely manipulated. This will, to some extent, dictate the designs that can be constructed using shotcrete as a placement method. To further illustrate this, some examples will be presented to show how these factors can influence the design.

Shotcrete final lining designs typically use lattice girders to support the lightweight steel reinforcement and assist in controlling the profile/geometry of the tunnel cross-section. Concrete is shotcreted in layers to build up the thickness of the final lining. Reinforcement in such applications is typically small-diameter, well-spaced bars, as recommended by ACI 506, to minimize the potential for shadowing that may create voids in concrete around the lattice girders and reinforcing bars. An increasingly common alternative is the use of steel fiber-reinforced (SFR) concrete, which removes the need for the lattice girders and steel wire or bar reinforcement. In both cases, high levels of application skill and workmanship, as well as rigorous quality control processes, are needed to ensure the concrete is correctly placed and that the required profile is being met. Depth control and profile bars are routinely used to provide a visual guide for the shotcreter. Depending on the finish required and the final use of the underground space, a smoothing layer may need to be placed over the final lining to provide the necessary finish.

For example, a generic sequence for the shotcreted final lining (SFL) may include:

1. Installation of lattice girders at 5 ft (1.5 m) centers with a steel reinforcing bar mat placed against the waterproofing membrane at the extrados side of the girders, and partial encasement of the lattice girders;
2. Shotcreting of an infill first layer between the lattice girders;
3. Shotcreting of a second layer;
4. Installation of reinforcing bars on the intrados side of the lining; and
5. Installing a final shotcreted layer to provide minimum cover over the reinforcement.

The number of shotcreted layer installations would depend on the total design thickness of the final lining. The designer should prepare the design drawings and specifications to provide this level of detail and any quality control requirements.

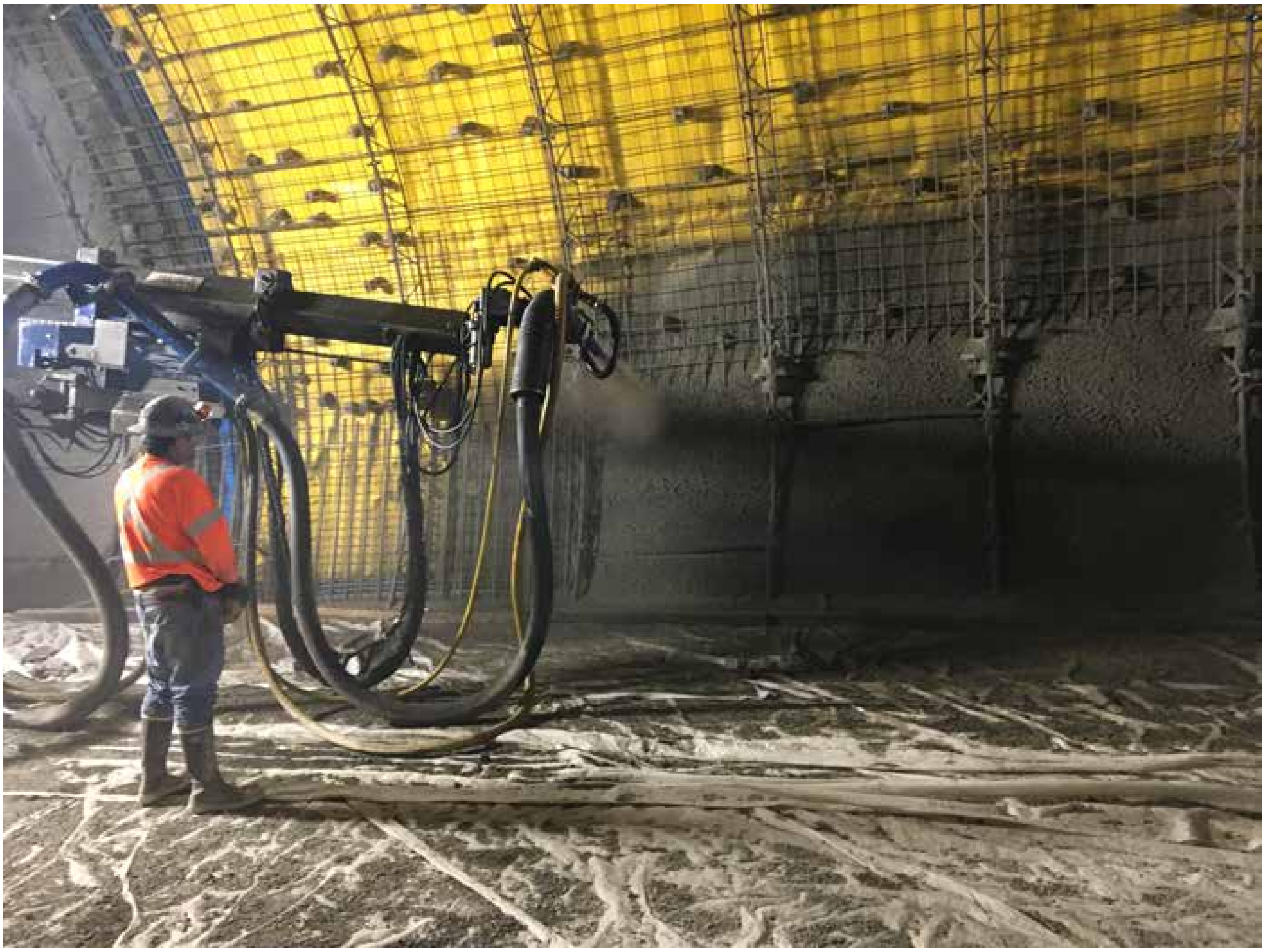

Fig. 2: Installation of SFL

Fig. 3: Preconstruction mockup panel

Fig. 4: Production Spraying

SHOTCRETE LINING ALTERNATIVES

On the East Side Access project in New York, an alternative shotcrete lining was used extensively to replace the use of form-and-pour concrete, as well as in some cases, the previously designed SFL . In this application, concrete was shotcreted around the reinforcement using hand-spraying methods and the final lining was designed with no consideration for the method of placement. As expected, this presented significant challenges and required a very different approach to the testing and approval of shotcreters as well as the quality control processes that needed to be followed. What did not change was the structural design, which performed in the same way as if these linings were to be placed by form-and-pour methods. However, when shotcrete was specified, accommodations in the reinforcement design could have optimized this approach — by considering shotcrete's proclivity towards layered placement and potentially adjusting the reinforcing layout.

Given that this was a commuter railroad project, the underground structures were considered to be occupied structures, and as such, the New York State Building Code (NYSBC) applied to the designs. NYSBC Section 1914 contains specific requirements for the use and testing of shotcrete. The steps taken to allow shotcrete to be used in this particular application provide a good example of how local codes and standards can influence the design and specifications.

Section 1914.4 of the NYSBC states: "The maximum size of reinforcement shall be No. 5 bars unless it is demonstrated by preconstruction tests that adequate encasement of larger bars will be achieved," and that "When No. 5 or smaller bars are used, there shall be a minimum clearance between parallel reinforcement bars of [2.5 in.]. When bars larger than No. 5 are permitted, there shall be a minimum clearance between parallel bars equal to six diameters of the bars used. When two curtains of steel are provided, the curtain nearer the nozzle shall have a minimum spacing equal to 12 bar diameters and the remaining curtain shall have a minimum spacing of six bar diameters." This is similar to the requirements of ACI 506, and on the face of it, rules out the use of shotcreting in applications where the structural reinforcement needed is heavier than this. But, the NYSBC also provides an exception: "Subject to the approval of the code enforcement official, required clearances shall be reduced where it is demonstrated by preconstruction tests that adequate encasement of the bars used in the design will be achieved."

NYSBC also restricts the use of lap splices. "Lap splices of reinforcing bars shall utilize the noncontact lap splice method with a minimum clearance of [2 in.] between bars. The use of contact lap splices necessary for support of the reinforcing is permitted when approved by the code enforcement official, based on satisfactory preconstruction tests that show that adequate encasement of the bars will be achieved, and provided that the splice is oriented so that a plane through the center of the spliced bars is perpendicular to the surface of the shotcreted concrete."

Regarding testing, the NYSBC states the following: "When required by the code enforcement official, a test panel shall be shot, cured, cored or sawn, examined, and tested prior to commencement of the project. The sample panel shall be representative of the project and simulate job conditions as closely as possible. The panel thickness and reinforcing shall reproduce the thickest and most congested area specified in the structural design. It shall be shot at the same angle, using the same [shotcreter] and with the same concrete mix design that will be used on the project. The equipment used in preconstruction testing shall be the same equipment used in the work requiring such testing, unless substitute equipment is approved by the code enforcement official."

To advance the use of shotcrete placement for the permanent linings that had been designed with the use of form-and-pour concrete placement, the project team — including the NYSBC Code Enforcement official — developed the following strategy, which was reflected in the specifications and required no changes to the design drawings.

1. Requiring a full-scale mockup for each separate contract
2. The mockup to represent the most congested rebar layouts horizontally and vertically
3. Demonstration by *each* shotcreter that encapsulation of rebar was satisfactory to the engineer-of-record

Shotcreters qualified through these measures would be allowed to place shotcrete in the same reinforcement designs previously intended for form-and-pour placement.

OTHER DESIGN CONSIDERATIONS

Where shotcrete placement is to be used, the entity responsible for producing the project specifications — be it the designer or owner — needs to address issues such as:

- Applicability of local codes and standards (as discussed above)
- Quality control (QC) for both pre-construction and production testing, which includes:
  - Concrete mixture design testing and approvals
  - Shotcreter project qualification and ACI certification
  - Placement quality through the use of mockups and destructive testing
  - Production QC for thickness, shape, concrete quality, proper placement, surface finish, etc.
- Need for detailed Construction Work Plans from the contractor that include realistic quality control processes, especially where hand spraying is to be performed
- Readiness reviews before production operations start, to ensure that all necessary preparation work has been performed and everyone involved understands the process as well as the safety and quality considerations required
- Surface preparation
- Layering control and bond strength
- Exclusion zones for entry after overhead placement
- Early strength testing
- Interaction with waterproofing supplier and installer and the approvals process to create hold points that demonstrate compliance with the project requirements before work is covered up
- Construction tolerances
- Surface finish, including acoustic considerations as well as operation and maintenance issues for the finished facility
- Ventilation, lighting, and working at heights during concreting operations

WORKING UNDER NEW PLACEMENT

In underground overhead shotcrete applications, gravity has a constant impact on shotcrete placement. According to the project records for the Crossrail project in the UK, the majority of shotcrete fallouts occurred within 15 minutes of overhead shotcrete placement. Following a fatality on that project from falling shotcreted concrete, the project introduced a rigorous exclusion zone approach. A similar approach was developed on the East Side Access Project in New York, also after a fatality. In both cases, the approach was to eliminate the need for workers to work under freshly shotcreted concrete and restrict access to these areas after placement was completed. As a result of these actions, no further serious injuries occurred. The use of such exclusion zones, as well as the concept of painting yourself out of the room, is one that should be considered for implementation on any underground project where overhead shotcrete placement is being used, but especially where the permanent lining is being placed by this method. Such a process should be written into the project specifications if appropriate.

The use of early age strength testing may also be appropriate to permit work to resume once the shotcreted concrete has reached a certain strength. That strength requirement is dependent on what the concrete is required to do. For example, in a Sequential Excavated Tunnel the initial lining will be required to resist the relaxation of the ground. As such, the designer should determine what the strength requirement is and the time in which the strength needs to be achieved to ensure that the lined excavation is safe to enter. This requirement may be different in a rock tunnel, a rehab project, or in a mining environment. There are a variety of different methods to determine the early strength gain — including the beam test, needle guns, etc. — and the designer needs to specify an appropriate method for the specific application. The ASA Underground Committee has written an article concerning the use of these different methods (**shotcrete.org/wp-content/uploads/2024/12/SCM4Q2024_Early-Age-Strength-Testing.pdf**).

Conclusion

Shotcreting for permanent final lining applications is a well-established placement method. When specifying shotcrete as a placement method, the project designer must consider a significant number of factors to ensure the required quality of the product can be delivered safely. The method of shotcrete placement — whether remotely manipulated or hand sprayed — together with the local codes must be taken into account in developing the design. Still, the final product is ultimately a reinforced concrete lining that has been placed using shotcrete rather than the form-and-pour method. As such, the structural design is not impacted by the selected method.

References

1. EC (European Community) (1996) Council Directive 96/48/EC of 23 July 1996 on the interoperability of the trans-European high-speed rail system. *Official Journal of the European Union* **L235:** 6–24.
2. EC (2008) Directive 2001/16/EC of the European Parliament and of the Council of 19 March 2001 on the interoperability of the trans-European conventional rail system. *Official Journal of the European Union* **L110:** 1–27
3. ACI PRC 506-22 Shotcrete Guide, American Concrete Institute (2022)

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