FIBER REINFORCED SHOTCRETE FOR TUNNEL LININGS

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Abstract

The use of shotcrete for ground support is well established since several decades. However, the development of high quality shotcrete, in particular wet-mix application methods allowed the application of shotcrete in complex underground schemes under difficult ground conditions. The request for fast acting ground support as well as for durable sprayed concrete for permanent support initiated the development of excavation sequences and spraying techniques as well as mix designs that allowed the addition of steel and synthetic fiber reinforced shotcrete to achieve a uniform, high quality product. Today, fibers are added to shotcrete in a wide range of applications. The paper will outline various applications where fiber reinforced shotcrete is being used in recent projects and design criteria applied at these jobs.

Keywords: Shotcrete, Ground Support, Tunnel Lining, Tunnel Design, Fiber Reinforced Shotcrete, Structural Calculations

1 Fiber reinforced shotcrete in Tunnel Design

Since many years steel fibre reinforced concrete/shotcrete has been used in tunnelling applications. However due to lack of design codes and due to high cost of steel fibres (compared to conventional bar reinforcement) in central Europe most tunnels are still built using conventional bar reinforcement.

The main advantages of fibre reinforced concrete/shotcrete in tunnelling over bar reinforcement can be summarised as follows:

- No steel fixing required, therefore safer working conditions during excavation
- Higher quality can be achieved with steel fibres in shotcrete applications, because there is no risk of voids due to bad encapsulation of reinforcement bars
- The concrete is reinforced throughout its entire thickness and in all directions. Multiaxial loads can be transferred and the risk of spalling is reduced.

However the downside of fibre concrete is the much lower tensile strength, the softening behaviour in post peak and the not standardized design procedures. For a typical fibre dosage in shotcrete applications of 40 kg/m^3 (around 0.5 Vol%) the tensile strength of steel fibre reinforced shotcrete is the same as of plain shotcrete. Higher dosages than 40kg/m^3 may cause application-problems (workability, mixing, dosing, application). For low fibre content (< 2 Vol%), the behaviour is softening. For large fibre contents (> 2 Vol%), the strength can be greater than the strength of the cementituous matrix. This is because of the hardening behaviour, connected with a multicracking phenomenon.

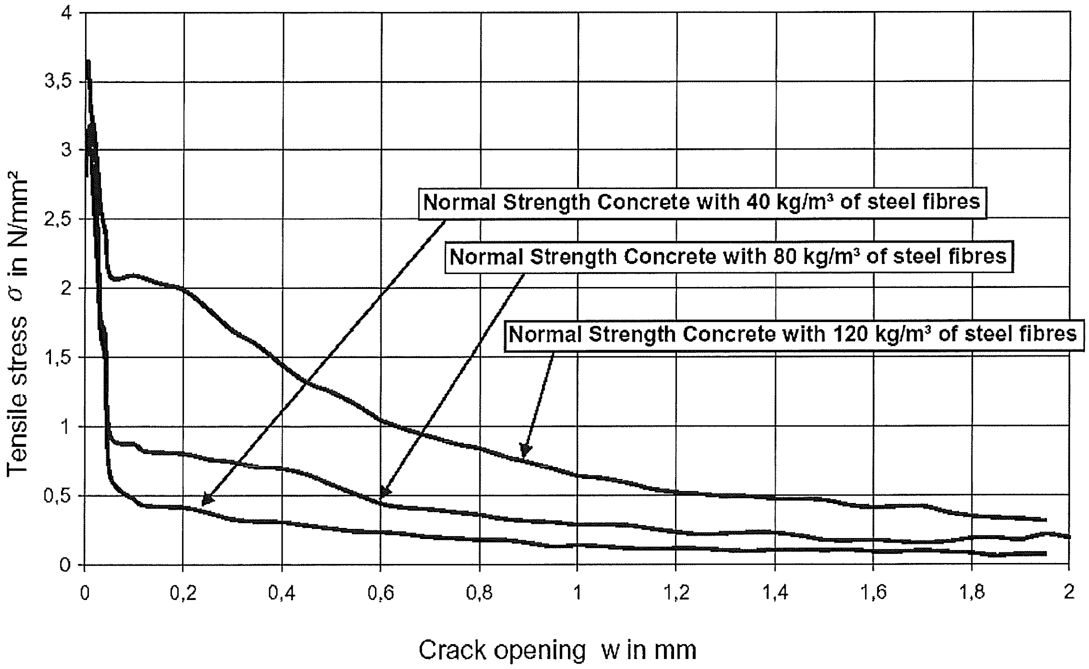

Figure 1: Post crack behaviour of steel fibre reinforced concrete for different fibre dosages[6]

The main benefit coming from the steel fibres is the improved post crack behaviour, which essentially is an increased ductility of the concrete. This property allows for elastoplastic modelling of the sprayed concrete lining by assuming linear elasticity in compression and elastoplastic behaviour in tension as shown in Figure 2 for uniaxial conditions:

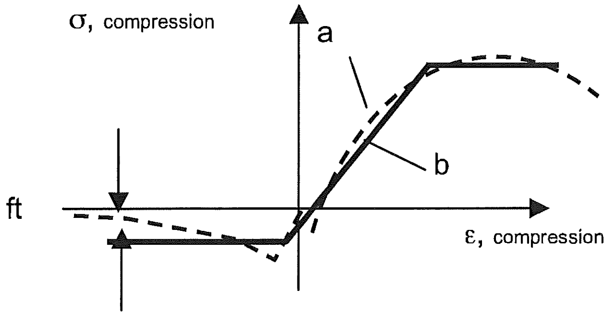

Figure 2: Representation of the characteristic stress-strain relation (a) and its simplification (b)

Although steel fibre reinforced concrete shows significant strain softening in the post peak domain (see Figure 1), for the purpose of stress analysis, it is considered sufficiently accurate and safe to neglect softening post peak behaviour. When running a tunnel lining analysis with a stress strain relation as sketched in Figure 2 smaller bending moments and moderately increased axial forces compared to a purely linear elastic stress strain law can be achieved. Therefore the requirement for high tensile capacity of the lining is mitigated. This is true however only where ground conditions prevail, which allow for load distribution.

There exist different approaches on how the capacity of steel fibre concrete (shotcrete) section can be calculated. The design procedure used for the shotcrete design of the three projects presented in this paper is based on the Austrian Guideline [12]. There, the ultimate limit state is defined by means of strain state. The ultimate strain in compression is □ $_{cu}$= 0.35% and the ultimate strain of fibre concrete in tension is □ $_{ftu}$= 1%

Concrete in compression is considered in the same way as in standard reinforced concrete design. In Figure 3, f_{cd} denotes the design compressive strength. The design tensile strength f_{fdu} is evaluated from flexural test results with third point loading. Although f_{fdu} is used as a strength value its actual value rather reflects the toughness of the material. This becomes more evident when following the procedure outlined in the guideline [12]. There the area under the load deflection curve is computed within a predefined deflection interval and from this value the equivalent flexural strength and then the direct tensile strength f_{fdu} is evaluated.

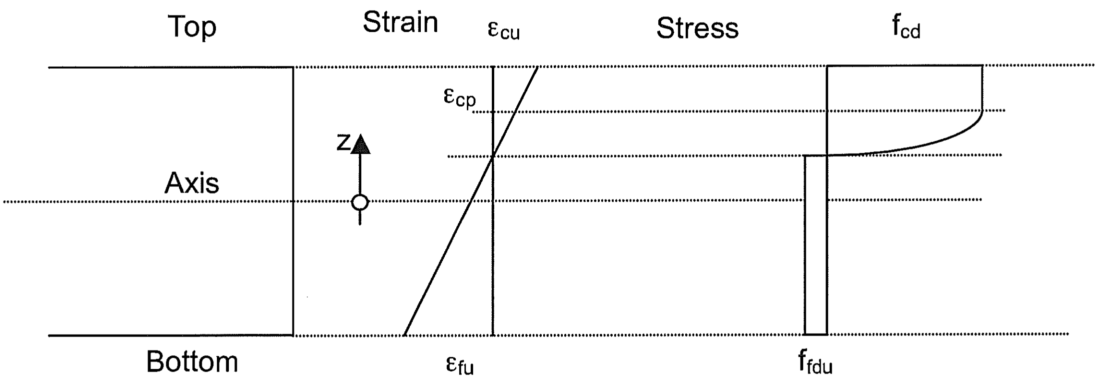

Figure 3: Strain and Stress diagram

In summary the section capacity steel fibre shotcrete lining in most cases cannot compete with the section capacity of bar reinforced shotcrete. However there are some characteristics of steel fibre reinforced shotcrete that are attractive in particular for tunneling applications. Tunnel linings are subject mainly to axial forces. The greater flexibility of the steel fibre reinforced shotcrete lining compared to a bar reinforced lining may help in reducing bending moments. Tunneling analysis is a ground-structure-interaction problem, where the relative stiffness of ground and support govern the bending moment of the lining. Therefore a reduced stiffness of the lining most likely will deliver a smaller bending moment. When assessing the lining forces and bending moments it is recommended to model the nonlinear stiffness of the lining in order to achieve reduced, but more realistic bending moments. Therefore when modeling nonlinear stiffness high capacity in bending often is not required for demonstrating adequateness of the design.

2 Massachusetts Bay Transit Authority, Russia Wharf Segment, Boston, USA

Tunnel construction for the Massachusetts Bay Transit Authority's new South Piers Transitway in Boston beneath two buildings at Russia Wharf complex called for particular tunneling methods and means of building underpinning. The tunneling was carried out using sequential excavation and shotcrete support methods in soft ground, commonly referred to as the New Austrian Tunnelling Method (NATM) or SEM/SCL. The buildings, which are founded on timber piles, remained in service during the construction period. Thus, all underpinning systems have been designed to enable tunneling within permissible foundation deformations.

The Contractors' JV Modern Continental and Beton und Monierbau Innsbruck, Austria carried out the tunnel construction following a design by Frederick R. Harris, Inc as general designer with the Dr. G. Sauer Corporation and Mueser Rutledge Consulting Engineers as specialty designers.

The tunnel structure traverses the Russia Wharf complex entering at the west corner (Congress Street/Atlantic Avenue intersection) and passes easterly toward Fort Point Channel. The Russia Wharf complex consists of three buildings, the Russia, Graphic Arts and Tufts building, of which the first two were affected by the tunnel construction. The buildings are founded on wooden piles that have been driven into the ground. Granite blocks that sit directly on the pile groups and carry the building columns build up the pile caps.

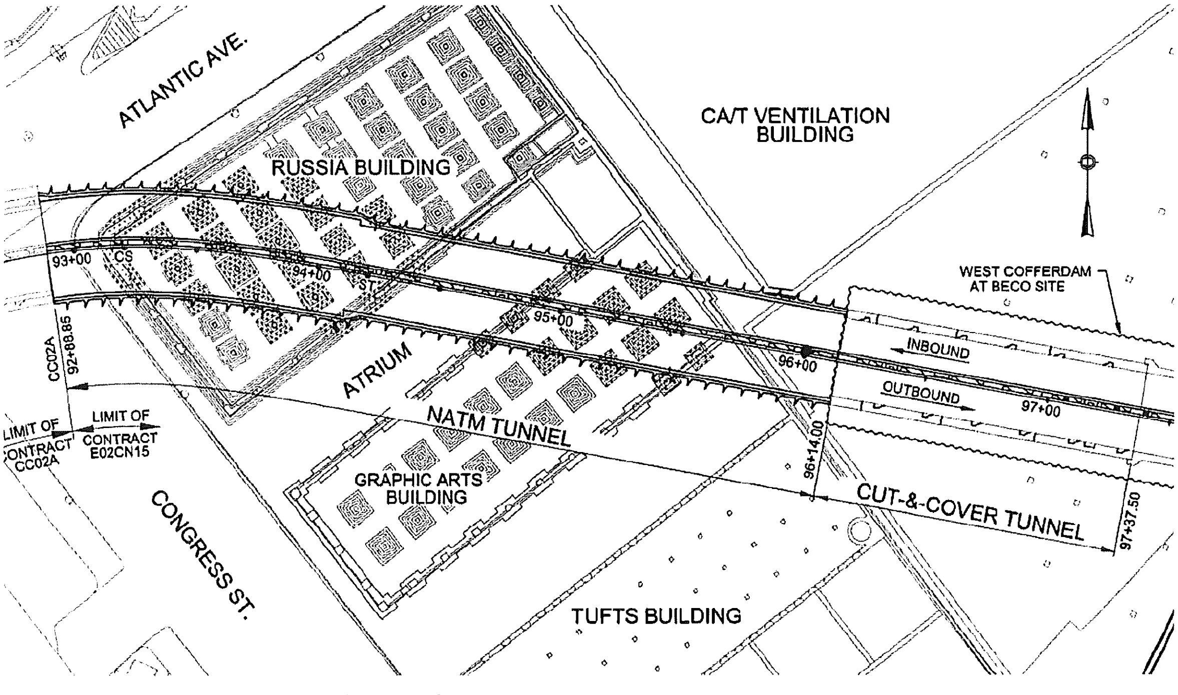

Figure 4: Plan view of NATM-Tunnel

2.1 Ground Conditions

The tunnels are located in recent organic deposits and fill deposits that are composed of organic very soft silt, sand and clay with minimal stand-up time. Below the organic deposits, soft to stiff clay ('Boston Blue Clay') is located. On top of the clay, a desiccation layer ('hard pan') of clay is located that forms a competent foundation layer for traditional pile foundations in the Boston area. Tunnel construction in such materials requires systematic ground improvement to enable a safe excavation and support installation. However, the presence of the historical buildings above the tunnels and the wooden pile foundations within the tunnel excavation cross section posed further challenges on the design. The clearance between the tunnel roof and the base of the buildings was approximately 0.5 to 3 m.

2.2 Design

During the design iterations a series of alternative construction methods such as cut&cover, groundwater draw down etc. have been considered, but a mined NATM tunnel in combination with ground freezing and permanent underpinning was selected to limit the impact on the buildings as well as the environment. The underpinning of the façade of the Russia Building was accomplished by a permanent underpinning system using mini piles. Underneath the Graphic Arts building and parts of the Russia Wharf Building, ground freezing was used as the sole means of temporary building support as the tunnel excavation cut through the existing timber pile supports. Ground freezing was limited to the organic sediments, tying in with the top of the clay. The frozen soil encapsulated the timber piles, formed a foundation for the pile caps and, hence, acted as a supporting structure for the building loads above the tunnel alignment until the trimmed piles were integrated into the tunnel lining.

The trimmed piles were supported by pile shoes, which, in turn, were fully integrated in the initial tunnel shotcrete lining. Thus, the tunnel structure forms a permanent underpinning scheme for the historical buildings after thawing.

Due to headroom limitations, a tunnel cross section had to be developed that allowed the forming of a roof arch while maintaining a minimum clearance from the building foundations and that provides space for two bus lanes. A cross section with two partially overlapping tunnels ("binocular tunnel") was developed. The first tunnel was excavated and fully supported before the second tunnel was commenced. The excavation and support installation followed a top heading, bench and invert sequence. After completion of excavation and initial support of the first tunnel, the waterproofing system (full round waterproofing) was installed and the permanent lining shell as well the common separation wall was installed. The second tunnel used the common middle wall to support the tunnel arch on one side while the extreme side was supported in the traditional NATM manner. After completion of the excavation and the installation of the initial shotcrete lining, the waterproofing and the shotcrete secondary lining was installed.

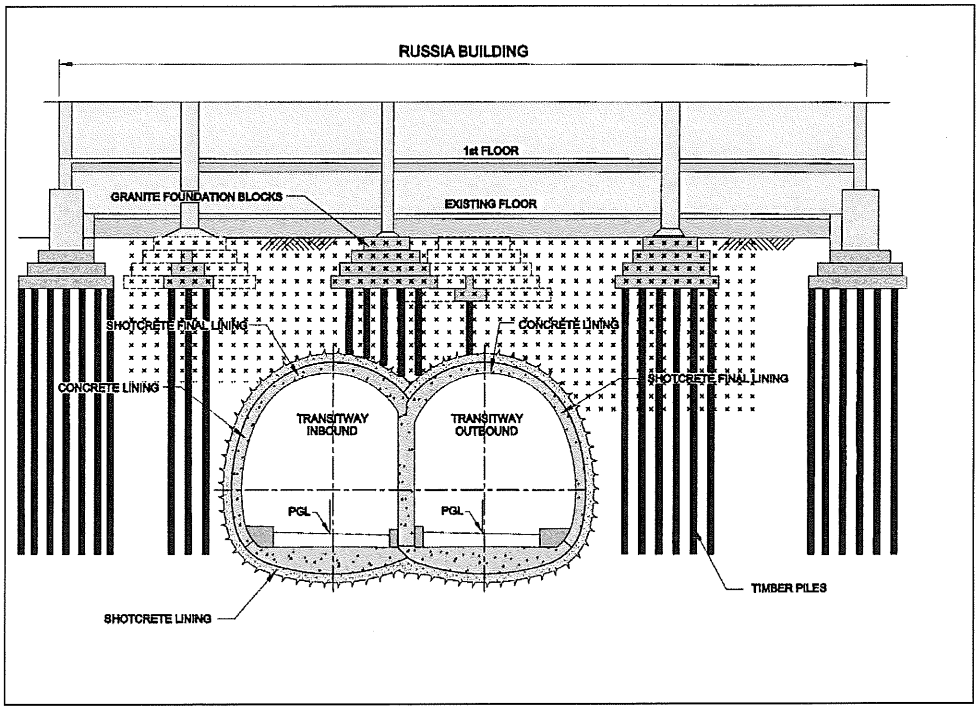

Figure 5: Typical cross section

Due to the complex geometry of the tunnel cross section a conventional cast-in-place reinforced concrete secondary lining would have caused significant effort and delays for steel fixing and adaption of formwork. Since the contractor produced already high quality shotcrete for the initial lining with a computerized batching plant he made a Value Engineering Proposal (VECP) to replace the cast-in-place concrete with steel fibre reinforced shotcrete. Finally the owner and the designer accepted this.

Center wall and invert were built using conventional bar reinforced cast-in-place concrete. The 350 mm thick SFRS lining was covered with a 50 mm unreinforced shotcrete layer with 6mm long Polypropylene fibers for fire protection.

For SFRS lining the following properties have been specified:

Compressive strength at 28 days	38 MPa
Flexural strength at First crack after 7 days	3.4 MPa
Average for first crack strength after 28 days	4.2 MPa
Residual Strength factor $R_{30/10}$ after 28 days	70
Toughness Indices after 28 days	$I_{10} > 8$; $I_{30} > 22$

During testing it became evident, that toughness indices and residual strength factors may be misleading in quantifying actual toughness of the material, especially when using high quality shotcrete. As for reasons discussed in [7] and from experience on this job site it is recommended to specify rather by toughness performance levels rather than by residual strength factors.

More detailed information on numerical modeling and construction can be found in [3], [4], [5].

3 London Heathrow International Airport, Terminal 5

London Heathrow is the world's busiest airport and the new terminal building will increase its passenger handling capacity by 50%. The T5 project consists of a terminal building, two satellites, aircraft stands, car parks, and road and underground rail infrastructure. Approximately 14 km of tunnels provide the terminal with road and underground rail links. The running tunnels were built using TBM with precast segmental lining (some of them steel fibre reinforced). All the connecting structures, such as head shunts, shafts, emergency exits, ventilation openings, cross passages etc. have been constructed using single pass, steel fibre reinforced shoctcrete (SFRS) lining. In total more than 40 SFRS structures with an overall length of more than 1100 m have been built. The tunneling work has been completed successfully in 2006 and T5 is about to open in 2008. Morgan Vinci, the specially-formed joint-venture for T5 was responsible for the construction of the new tunnel network. Mott MacDonald was appointed by BAA as the principal design engineer of all the underground tunnels and structures. Beton- und Monierbau designed all works involving sprayed-concrete linings and provided on site specialist support [11].

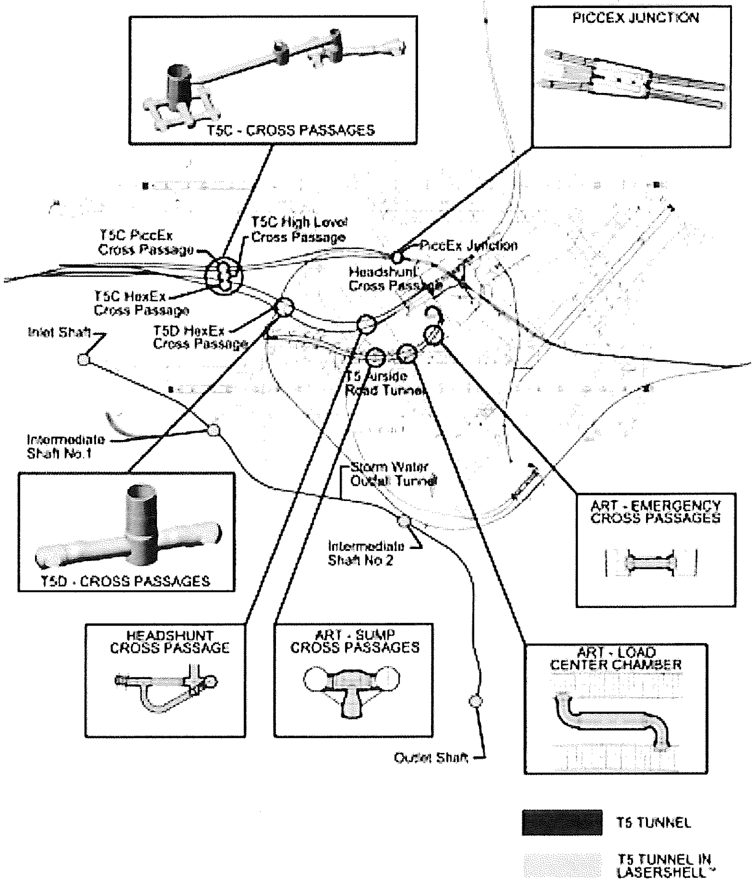

Figure 6: Shotcrete structures built for Terminal 5 [10]

3.1 Ground Conditions

Ground conditions at Heathrow are typical for the London area. A several meter thick layer of superficial deposits and gravel overly an approximately 50 m thick layer of London Clay. Below the London Clay there is a 20 m thick layer of “Lambeth Group”. The depth of the tunnels has been chosen so that there is a clay cover of one diameter at least, far enough away from water-bearing gravel on the surface and from the variable, sandy clay of the Lambeth group.
The London Clay is a stiff, highly over-consolidated clay. In the upper 3-5 m the horizontal in-situ stress may be 2.5 times as high as the in-situ vertical stress. With increasing depth the ratio between horizontal and vertical stress decreases continually and approaches a value of 1 at a depth of about 30 m.

Loads in London clay are time-dependent. Without considering specific boundary conditions (overburden, drainages states, construction sequence) the loads are generally considered to approach about 50% of full overburden load after ring closure and about 80% of full overburden in the long term.

A permeability coefficient of 10^{-10} m/s , the high, undrained shear strength and the homogeneity of London Clay allow for tunnel construction without additional pre-support measures.

3.2 Single Pass Tunnel Lining LaserShell™

Traditionally in soft ground tunneling the shotcrete lining includes lattice girder and welded wire fabric. Girders provide immediate support, assist in profile control and are required to fix the first layer of mesh. Mesh and girders can only be installed manually. This requires workers to enter the unsupported heading.
Thus, a tunneling method called LaserShell™ has been developed by Beton-und Monierbau and Morgan=Est which satisfies the British health and safety requirements. There is no need for girders and steel mesh, and it is applicable in London Clay [8],[9]. An inclined face ensures that no tunnel operatives are exposed to unsupported ground in the roof at any time and enhances face stability compared to a vertical face.

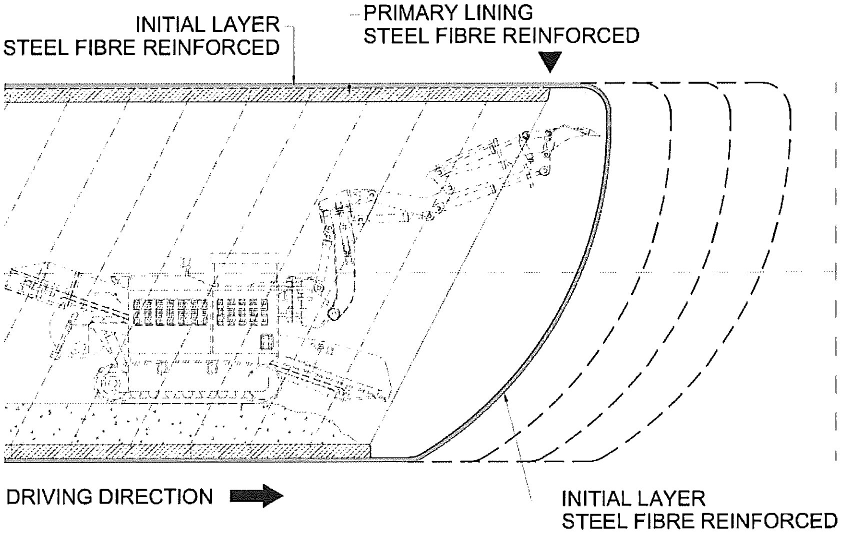

Figure 7: LaserShell™, inclined face [8].

The first layer of steel fibre reinforced shotcrete that is placed immediately after excavation is called the initial layer. The purpose of this layer is twofold. First it should provide some initial stabilization of ground to provide a relatively safe working environment for the miners working close to the excavation face. Second, in the long term, it is supposed to protect the structural lining which is the main supporting structure, from being attacked by chemicals over the years. The initial layer is considered to be a sacrificial layer.

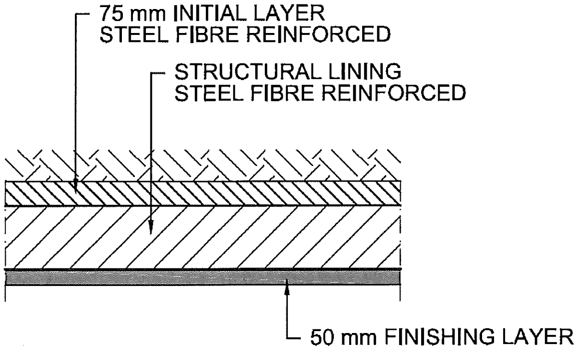

Figure 8: Shotcrete layers of single pass LaserShell^{TM}

The thicknesses of the steel fibre reinforced structural lining have been computed considering loads developing at intermediate construction stages and for long-term conditions. At intermediate construction stages, the tensile capacity of steel fibre reinforced shotcrete has been taken into account. For permanent works design however, sprayed concrete linings have been assumed to have zero tensile strength and have generally been designed as unreinforced structures. This approach was driven by the assumption that steel fibers may corrode during the design life of 120 years.

Where reinforcement was required to resist induced tensile stresses (portals, shat openings etc.) traditional bar reinforcement has been provided, which has been sprayed in with plain shotcrete.

A 50 mm finishing layer has been applied to provide a smooth surface covering all fibers. No steel fibers but polypropylene fibre have been added to the finishing layer to provide some fire protection.

Excessive pre-commencement development trials for a high quality, Morgan Est Tunneling Division has carried out permanent sprayed concrete mix in co-operation with Beton-und Monierbau and Prof. W. Kusterle. The purpose of the trial was to prove structural integrity from application up to 120 years, while providing a mix with sufficient workability [8].

The finally selected shotcrete mix provided a characteristic compressive strength varying between 0.5 MPa after 1 hour and 40 MPa after 90 days. The characteristic tensile strength evaluated from beam bending tests varies between 0.75 MPa after 1 day and 1.5 MPa after 90 days. The same mix was used for the project presented in the following section.

4 Kings Cross Station Redevelopment, Phase 2, London, UK

The Kings Station Redevelopment, Phase 2 includes the construction of a series of new passenger tunnels to improve the station's capacity and safety features. Based on a design by Arup, Ltd the Contractors JV Morgan Est – Beton und Monierbau produced the design of the temporary works and are currently constructing the tunnels. Gall Zeidler Consultants, LLC are SCL (NATM) consultants for Metronet and ABBA the construction managers.

The new tunnels will provide passengers with improved facilities to connect between the existing Victoria (VLA), Piccadilly (PLA) and Northern (NLA) underground lines as well as the railway terminals of the new Channel Tunnel Rail Link (St. Pancras) and Kings Cross Station. The new PLA comprises a high level passageway tunnel, upper concourse tunnel, an inclined escalator tunnel to the existing Piccadilly Line platform tunnels, a lower concourse tunnel, new cross passages and a temporary passageway tunnel and a MIP lift shaft. The new NLA comprises two inclined escalator tunnels, a passageway tunnel and a MIP lift shaft. The new VLA includes staircase and access tunnels and a shaft that houses a MIP lift and parts of the staircase.

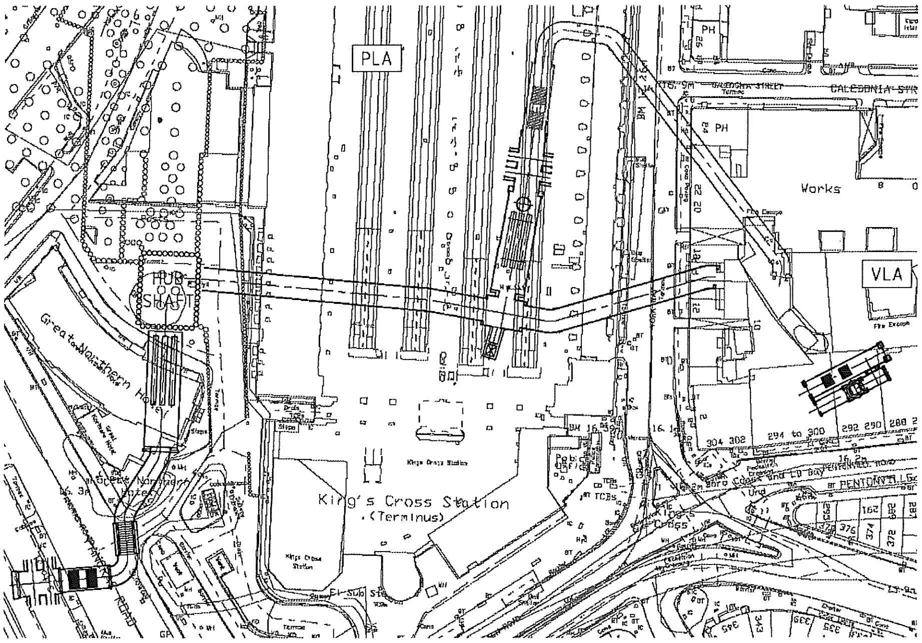

Figure 9: Plan view of the project

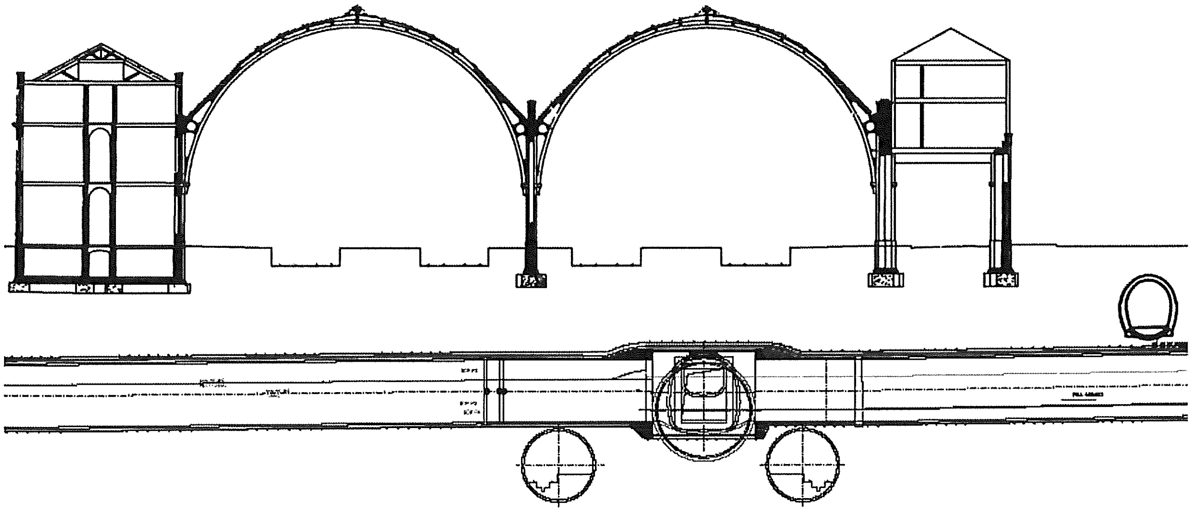

Figure 10: Long section underneath the Kings Cross train shed

After many years of design development and safety considerations, it was decided by the client to construct the tunnels using SCL for the initial tunnel support and segmental cast iron (SGI) rings for the secondary tunnel lining.

The majority of the new tunnels for the Piccadilly Access are located below the train shed of the Kings Cross Train Station under a ground cover of approx.12 to 20 m. The Northern Line Access tunnels lead under an existing hotel complex (The Great Northern) with a min. vertical clearance between the foundations and tunnel crown of 2 m. Ground cover increases to max. 20 m. The Victoria Line Access tunnels are at approximately similar depths as the Piccadilly Line Access tunnels.

4.1 Ground Conditions

All tunneling takes place in London Clay. Made Ground is located above the London Clay. In the deeper sections, the sediments of the Lambeth Beds (over-consolidated clays with the potential for the presence of water bearing send lenses) will be intersected.

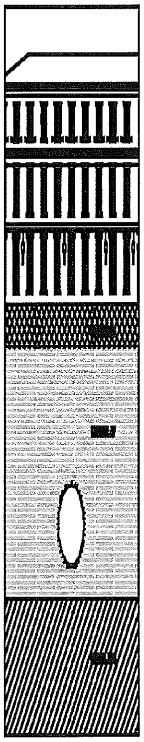

Figure 11: Ground conditions

4.2 Design

The Contractor opted for using the LaserShell^{TM} Method to construct the tunnels using NATM for the initial support. The Laser controlled excavation and shotcrete application provides high accuracy for shape and shotcrete thickness control.

All tunnels are excavated and supported in a sequential construction approach. For tunnels larger than 5m in diameter, a pilot tunnel is constructed from which the enlargement to the full section size progresses. The pilot tunnels are constructed in the roof area of the future tunnel such that they slightly reach beyond the future tunnel roof. This additional headroom is used to install a reinforced, sprayed concrete roof beam that provides head protection during the enlargement operation. During the subsequent step, the pilot tunnel is enlarged to top heading size of the full tunnel profile. For tunnels larger than 6m DIA, a temporary invert is installed after the enlargement to top heading size ("Cod's Mouth"). Subsequently, the bench and invert of the final tunnel cross section is excavated and supported. A short ring closure is an integral part of the design, whether the temporary top heading invert or a short distance between the top heading enlargement and the final invert provides it. Steel fiber reinforced shotcrete is used for the initial support lining.

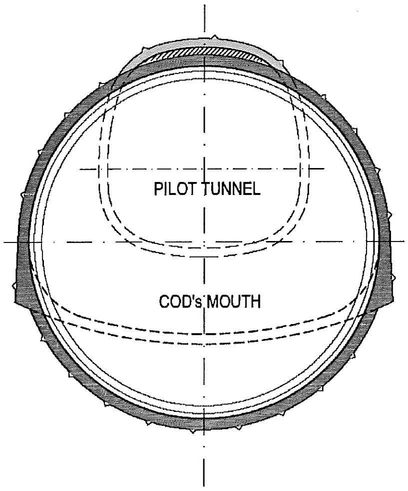

Figure 12: tunnel cross section with Pilot Tunnel and Cod's mouth profile

The SGI is installed inside the completed shotcrete tunnel following in a practical distance from the construction face. The annular gap between the SCL and SGI rings is grouted.

In order to protect the railway station and hotel structure above the various tunnels for the new Piccadilly Line Access, a compensation grouting system was installed that allows the neutralization of undue ground settlements caused by tunneling. Three rows of heavy gage steel pipes were installed in the area of compensation grouting. The upper and lower rows are passive rows providing stiffening of the ground and additional means for ground conditioning.

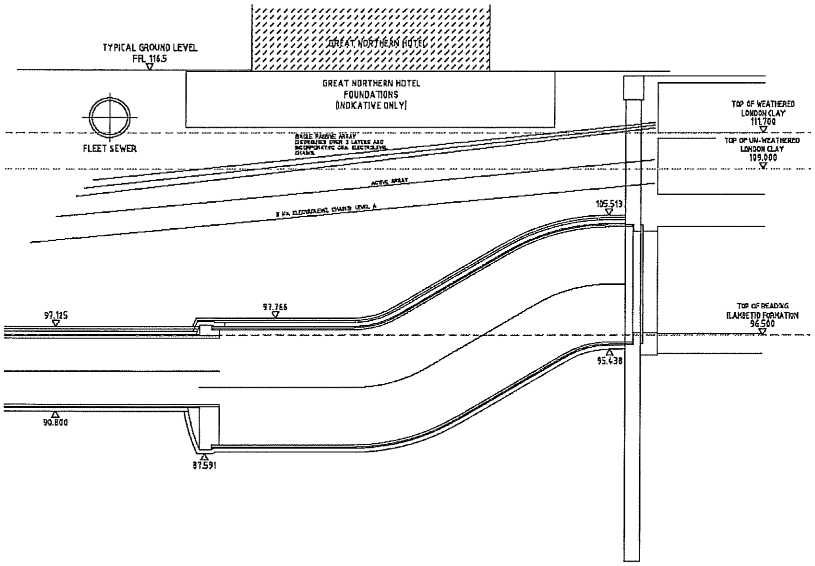

Figure 13: Long section with compensation grouting pipes

As part of the access tunnel works for the Northern Line construction of a 9m DIA escalator shaft beneath the existing historic Great Northern Hotel is required with minimum clearance between the building foundations and the tunnel roof. In order to protect the hotel structure from undue settlements a compensation grouting array was installed between the tunnel roof and the building foundation.

All tunnel linings have to be designed to withstand overburden loads as well as additional loads generated by buildings, traffic and, where relevant, compensation grouting above the tunnels.

For crossing underneath an existing, abandoned brick railway tunnel with small clearance, a grouted steel pipe arch will be installed.

An extensive instrumentation and reading scheme is installed to automatically monitor the behavior of the buildings in the vicinity of the new works and to provide real time data for compensation grouting and other protective measures. The new and existing tunnels are observed by a dense system of movement monitoring points that are read with surveying instruments.

Different to shotcrete linings at Terminal 5 the shotcrete lining at Kings Cross was for temporary support only. However all shotcrete linings have been designed for long term conditions as well. A similar approach like in T5 has been chosen for the design of the steel fibre reinforced shotcrete linings, where the tensile capacity of the steel fibers has been considered in the short term only. In the long term loading conditions no action of steel fibers has been taken into account.

5 Conclusion

The introduction on steel fibre reinforced concrete indicates the advantages and disadvantages of this in relation to traditionally reinforced concrete, as it is seen today. The successful use of steel fibre reinforced shotcrete for tunnel support, however, can be demonstrated with numerous case histories, three of which have been selected for this paper.

Though designed and constructed under dissimilar design and construction criteria, steel fibre reinforced shotcrete proved its practicality, versatility and applicability in all of the before mentioned projects and lead to high quality tunnel structures.

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