Simulating composite behaviour in SCL tunnels with sprayed waterproofing membrane interface: a state-of-the-art review

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Abstract

Introduction of sprayed waterproofing has led to innovation of composite sprayed concrete lined (SCL) tunnels, where placing the waterproofing between primary and secondary layers gives potential for composite structural action, by transmission of tension, compression and shear stresses across the interface. Numerical analysis is required to design such structures taking into account soil-structure interaction and staged construction, but there is currently very limited guidance on how to conduct such analyses.

This paper reviews use of numerical analysis to simulate composite SCL tunnels, focussing on soft ground tunnelling. It introduces types of sprayed membrane, their benefits in design and current industry practice for simulating the sprayed membrane interface. Numerical strategies for simulating composite action and their verification against laboratory test data are then described. Recommendations are made of design principles to optimise design of SCL tunnels with spray-applied waterproofing. Further opportunities for research on this topic are discussed.

Keywords: Sprayed concrete lining, sprayed waterproofing membrane, composite action, soft ground tunnelling

1. Introduction

The introduction in recent years of sprayed waterproofing has led to the innovation of composite sprayed concrete lined (SCL) tunnels, comprising of a permanent sprayed primary lining, a double-bonded (i.e. with assumed bond to both primary and secondary layers) spray-applied waterproofing membrane, and a sprayed or cast in situ concrete secondary lining. This configuration is gaining popularity and has been selected and constructed for some major metro projects in soft ground in London [1-5]. The main rationale behind this new configuration is that the industry claims the double-bonded spray-applied membrane will enable composite structural action (i.e. the ability to transmit shear) to be considered at the membrane interface between the permanent primary and secondary linings, improving the structural efficiency and leading to reduction in overall lining thickness [6]. Assumed stresses at the sprayed membrane interface sandwiched in the sprayed primary and secondary linings are shown in Figure 1.

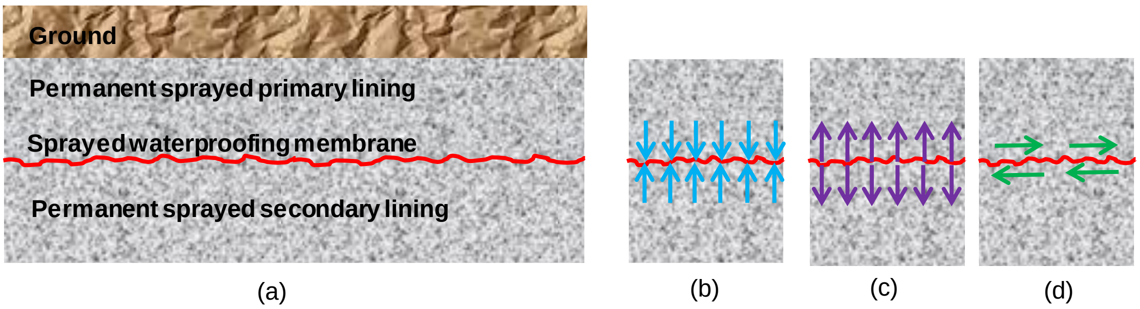

Figure 1. (a) Sprayed membrane interface and potential stresses: (b) compression, (c) tension and (d) shear

Although several tunnels with this composite configuration have been successfully constructed, composite structural action has so far not been considered in the design, even though it is widely thought to be beneficial to the lining behaviour. With the aim of achieving a consistent approach to the design and construction of composite SCL, the ITATech Lining and Waterproofing Activity Group published its Design Guidance for Spray Applied Waterproofing Membranes in April 2013 [7]. This gives details on construction of spray-applied waterproofing membranes but provides little information to aid designers on the structural behaviour of, design principles and numerical modelling methods for composite SCL tunnels [8]. Since about 2013, there has been a flurry of research on this topic with many articles published, greatly improving understanding of this topic.

By means of a critical review of the current industry practice and academic research, this paper aims to address the aforementioned missing aspects in ITA [7]. The main aims are to: (1) Describe numerical modelling methodologies available for simulating composite structural behaviour of a sprayed waterproofing membrane interface in SCL tunnels, (2) show how to predict performance of composite SCL tunnels for a range of membrane interface stiffnesses, and (3) present a set of design principles for composite SCL tunnels, derived from numerical analysis. Although these strategies are applicable to any soft ground situation, it is incumbent on the analyst to select an appropriate soil model for their situation to work alongside them. It should also be noted the main focus of this paper is on the modelling of spray-applied membrane interface and its impact on the tunnel linings. Detailed discussion on general modelling techniques and design considerations for sprayed concrete tunnel linings, such as shrinkage and creep, is out of the scope of this paper.

2. Technical background

2.1 Sprayed waterproofing membrane

There are three main categories of sprayed waterproofing membrane materials:

(1) Ethylene vinyl acetate (EVA) water-based

(2) Methacrylate reactive resin-based

(3) Styrene-butadiene rubber (SBR) polymer-based

The types of membrane and commercial products currently available on the market are listed in alphabetical order in Table 1. Detailed information on material properties, including durability and performance under ageing and chemical attack, is available in manufacturers' datasheets [9-13]. The design life of an SCL tunnel is usually at least 100 years; this criterion also applying to any sprayed waterproofing membrane used. ITA [7] in its example specification sets out a variety of standard tests for durability and infers that if good performance is shown in those tests, the membrane can be assumed chemically stable in the long term. The membrane is not exposed to ultraviolet light or high temperature, which are the most damaging environmental conditions for polymeric materials. ITA [7] sets out further functional requirements for bond strength (minimum 0.5MPa), watertightness (zero water penetration) and flammability. Information on performance with respect to these and other requirements for the membrane such as substrate preparation, thickness of application, curing conditions and time and resistance to impact are also given in manufacturers' datasheets.

Table 1 Spray-applied waterproofing membranes used in tunnels

Product Name	Type of Membrane	Supplier	Links to further information
Integritank HF	Resin	Stirling Lloyd	Stirling Lloyd [9]
Mapelastic TU System	SBR	Maple	MAPEI [10]
MasterSeal 345	EVA	BASF	BASF [11]
TamSeal 800	EVA	Normet	Normet [12]
Tekflex DS-W	EVA	Minova	Minova [13]

Sprayed waterproofing membranes are able to bridge cracks that may occur in the primary lining and continue to perform to prevent water ingress. ITA [7] specifies that the membrane should bridge a crack up to 2.5mm, and according to manufacturers they are typically able to remain effective when spanning a crack of width equal to the thickness of the membrane [10-13]. Current SCL tunnel design usually follows membrane manufacturer's recommended minimum thickness of 3mm, which thus can bridge a crack of 3mm width, well above the Eurocode 2 allowable crack width of 0.3mm [14].

For composite lining, the sandwich sprayed membrane and the primary and secondary linings may fail in any of the failure modes listed below or a combination of them:

(1) Tensile failure due to adhesion break between concrete and membrane

(2) Tensile failure due to cohesion break within the membrane

(3) Shear failure due to adhesion break between concrete and membrane

(4) Shear failure due to cohesion break within the membrane

These failure modes were reported in Su and Bloodworth [15] and Lee et al. [16]. It was also reported that tensile and shear failures in the concrete itself do not generally occur, mostly due to higher tensile and shear strength of the concrete than the interface and the membrane.

Sprayed waterproofing membrane has two main advantages over conventional polyvinyl chloride (PVC) sheet waterproofing membranes: (1) It avoids the health and safety risk of working at height to fix the sheet membrane at the tunnel crown, and (2) it is a convenient way of ensuring watertightness at geometrically difficult locations, such as tunnel junctions. There is however a limitation that it is not possible to apply the sprayed membrane effectively where there is active water ingress through the substrate [17]. Quite low rates of seepage can cause water pressure to develop behind the membrane, causing the concrete/membrane interface to fail before the membrane has cured sufficiently to achieve adequate adhesion. One of the key properties of the membrane is that the secondary lining, whether sprayed or cast, should be able to adhere to the membrane after the membrane is cured.

2.2 Consideration for sprayed concrete primary lining thickness

The main purpose of adopting a composite lining configuration and using sprayed waterproofing membrane is to achieve improved lining thickness efficiency (i.e. reduced overall lining thickness). There are three possible options of achieving this objective: (1) reduce the primary lining thickness only; (2) reduce the secondary lining thickness only, and (3) reduce both lining thicknesses simultaneously. Option (3) in theory is the most efficient solution as the ratio of composite action is the greatest if the membrane can be maintained at approximately half-depth of the overall lining [18]. However, there is limitation on further reduction of the primary lining thickness from the current typical value, and the lining thickness reduction is only possible from the secondary lining.

For urban soft ground SCL tunnels, not only is the primary lining required to exhibit structural integrity (i.e. to satisfy the Ultimate Limit State (ULS) and Serviceability Limit State (SLS) requirements), but also minimise short-term volume loss. This is defined as the volume loss measured immediately after completion of the respective tunnel construction that results in potential damage to buildings above. Long-term settlement is perceived as not as critical as short-term, because it is a gradual consolidation process [19].

For urban tunnels, clients usually request maximum short-term volume loss to be limited to 1.50%, to prevent excessive damage to existing buildings, based on past experience [20-21]. Volume loss associated with SCL tunnel construction can be perceived as two phases [22]: (1) Deformation of ground ahead to the tunnel face and (2) deflection and convergence of the lining during and after its construction.

The former is mostly dependent on the excavation option (e.g. pilot tunnel/enlargement or top heading/bench/invert) and the time elapsed before ring closure. An example of the latter is an investigation by Karakuş and Fowell [23] on the impact of SCL tunnel lining thickness on volume loss using Heathrow Express Trial Tunnel Type 2 tunnel data. A 150mm thick lining was sufficient for structural integrity for a tunnel with 60m^2 excavation area (8.6m equivalent diameter), leading to a maximum short-term surface settlement of 32mm. The analysis also predicted 27mm maximum settlement for a 250mm thick lining, which agreed with the measured field maximum settlement and the actual lining thickness in the project. It should be noted that Karakus and Fowell's analyses did not take into account the impact of construction of adjacent platform and concourse tunnels, nor compensation grouting, which may require a thicker lining for structural integrity purposes.

Table 2 lists dimensions, lining thicknesses and short-term volume loss information for SCL tunnels constructed in soft ground, mostly within London Clay with a few touching Lambeth cohesive or granular materials at the tunnel invert. Water tables usually exist 3-5m below ground surface, below which water pressure was assumed to increase linearly sub-hydrostatically for the short-term scenario and hydrostatically in the long term.

Utilisation of compressive strength in the SCL primary lining was assessed for Crossrail Whitechapel Station platform tunnels [24-25]. The utilisation factor was shown to be mostly below 20%, with maximum around 25%. Design of the primary lining following Eurocode 2 [14] requires checks at both ULS and SLS. For the ULS check, lining thickness is usually selected so that the design compression load effect is about 50% of the maximum compressive capacity on the thrust-bending interaction diagram [26], with the aims: (1) To most efficiently utilise the bending moment capacity, and (2) to avoid potential brittle failure due to overloading in compression. With a Eurocode partial material factor of 1.5 and partial load factor of 1.35, this explains why the resulting utilisation is around 24% (providing ground conditions are not far from the estimated parameters used in the numerical analysis). It was found that with such a "conservative" ULS design for the SCL primary lining, short-term volume loss for Whitechapel Station platform tunnel was from 1.22-1.29%, close to the maximum limit of 1.50%. This illustrates again that the governing factor for SCL tunnel primary lining thickness may be limiting the volume loss, rather than its own structural integrity. Therefore, the primary lining thickness needs to be between 250-400mm for a typical large diameter SCL tunnel in soft ground, as shown in **Table 2**.

Table 2 Dimensions, primary lining thickness and short-term volume loss data for SCL tunnels

Project	Tunnel diameter (m)	Primary lining thickness (mm)	Thickness / diameter ratio (mm/m)	Short-term volume loss (%)	Reference(s)
Heathrow Express trial tunnel	8.66 (equivalent dia.)	250	28.8	1.05-1.26	Bowers et al. [29]
Heathrow Express T4 Station platform tunnel	9.2 x 8.3	300-350	34.2-40 (based on average diameter of 8.75m)	0.50-0.60 0.60-1.20*	Van Der Berg et al. [30] Powell et al. [31]
Heathrow T5 front-shunt tunnel launch chamber	5.0	275	55.0	0.97-1.10	Jones et al. [32]
King's Cross Station Redevelopment Phase II	7.0	225	32.1	0.65-1.25	Mair [21] Gall and Zeidler [33]
Jubilee Line Extension – Waterloo Station	8.0 (platform) 11.5 (concourse)	300 (platform) 400 (Concourse)	37.5 (platform) 34.8 (concourse)	1.0-1.50	Bonapace [34] Mair [21]
Jubilee Line Extension – London Bridge Station	8.8 (platform) 11.8 (concourse)	300 (platform) 400 (concourse)	34.1 (platform) 33.9 (concourse)	1.50	Grove and Morgan [35] Zeidler et al. [36]
Crossrail Liverpool Street Station platform tunnel	10.5	400 (including 75 initial layer)	38.1	0.92-1.41	Stärk et al. [25] Mair [21]
Crossrail Whitechapel Station platform tunnel	10.5	400 (including 75 initial layer)	38.1	1.22-1.29	Stärk et al. [25] Mair [21]
Crossrail Stepney Green caverns	16.5 x 13.4	500 (including 75 initial layer)	33.4 (based on average diameter of 14.95m)	1.25	Uhrin et al. [37] Mair [21]

In the SLS check, crack width is usually not a major concern for the primary lining as the relatively large axial compressive force and relatively small magnitude of bending moment will result in the cross-section of the majority of the primary lining either in full compression or with minor cracking that does not exceed the required 0.3mm criterion. Deflection of the primary lining is also normally well within the 1% limit on ovalisation set out in the BTS Specification for Tunnelling [27].

Guidance on the material performance of sprayed concrete, e.g. early-age stiffness and strength, durability, permeability, creep, ductility and fire behavior may be found in Thomas [28].

2.3 Design Considerations

When sprayed waterproofing membrane is used in SCL tunnels, the main question to the industry is how it functions structurally between the two layers of tunnel linings. There are three design options.

The first, and arguably most conservative, is to assume the sprayed membrane can transfer only compressive stress but not tensile and shear stresses across the interface, known as “unbonded double shell“. The sprayed membrane functions the same as a sheet membrane from the design perspective. Even if the primary lining is of good quality and designed as a permanent structure, it is still usually assumed that groundwater will permeate the primary lining in the long term, and hence all the long-term water pressure and a proportion of the ground load will be carried by the secondary lining, resulting in relatively thick secondary lining. The shear stresses transfer in a unbonded double shell system using sheet membrane is not reliable. This is due to the existence of water pressure on the back of sheet membrane that will introduce a gap between the sheet membrane and SCL primary lining.

The second option is to assume the sprayed membrane can transfer both compressive and tensile stresses but not shear stresses across the interface, known as “bonded double shell”. The primary lining resists the short-term loading, and once the secondary lining is in place, the long-term consolidation load (i.e. the difference in ground loading applied to the tunnel lining between the short and long terms) is shared between primary and secondary linings. Tensile bond between the spray-applied membrane and the primary is assumed to be adequate to resist the groundwater pressure, so that tensile debonding does not occur and the
long-term water pressure can be assumed to apply to the extrados of the primary lining and be shared between primary and secondary. This is expected to lead to a reduction in overall lining thickness, i.e.

give a lining thickness efficiency, compared to “unbonded double shell” [5]. However, although the primary lining (resisting the majority of the total long-term ground loading) is well prestressed in compression and able to resist large bending moments, the secondary by contrast is under much smaller compression and will have a correspondingly lower moment capacity than the primary [38]. This may cause difficulty for the secondary in resisting its share of water pressure, particularly if the lining cross-section shape is significantly non-circular, because this leads to inherently greater lining moments.

The third design option is to assume the membrane can transfer compressive, tensile and shear stresses across the interface, i.e. as a structurally composite interface, known as “composite shell“. The load sharing between the primary and secondary linings is in principle assumed to be as for a bonded double shell, but the composite action is expected to give more efficient structural behaviour under the action of the long-term consolidation load and long-term water pressure.

To design a composite shell lining, the sprayed or cast in situ concrete secondary lining is required to be able to bond to the cured sprayed membrane and the mechanical properties of the sprayed membrane interface need to be understood.

There is concern when reactive resin-based membranes are used as to whether a sprayed secondary lining has the ability to bond effectively to them, which potentially preclude the use of such membranes if composite action was desired in a fully sprayed lining.

Properties of EVA and SBR membranes are heavily influenced by their moisture content. It is found that a ‘wet’ EVA or SBR membrane, i.e. one partially or fully saturated due to water coming through cracks in the primary lining, has considerably lower compressive, tensile and shear stiffness and strength than a ‘dry’ membrane, i.e. one exposed only to the ambient atmospheric environment without direct contact with water [39]. This will theoretically cause a waterproofing membrane interface that was originally bonded to degrade to unbonded, resulting in significant change in load sharing between the primary and secondary linings. The mechanical behaviour induced by this change will be discussed in more detail later. The saturation process has been discussed in detail in Holter [39] and Holter and Geving [40].

Due to lack of confidence in the membrane interface properties and the membrane's ability to transmit the required shear, particularly when "wet", the composite shell option has not yet been assumed in design [3, 5, 41]. One of the main aims of this paper is to provide guidance on analysis and on the effect of variation in membrane mechanical properties due to for example creep and water saturation, to address this lack of confidence in design.

2.4 Current Industry Practice

Several tunnel projects have recently been constructed in the UK with the composite lining configuration. Although progress has been made in the design concept such that the primary lining has been designed as a permanent structure rather than temporary, none were designed to act compositely structurally. Six are reported here, listed in **Table 3**. For all projects, the design assumption made concerning groundwater loading was its application to the extrados of the membrane and resistance by the secondary lining only.

Table 3 Key design assumptions for selected SCL projects in the UK

Project	Primary lining design assumption	Waterproofing membrane	Membrane interface design assumption	Secondary lining construction*
A3 Hindhead	Permanent	Spray-applied	Unbonded	Sprayed in the crown, cast side walls and invert
Tottenham Court Road Station Upgrade	Temporary	Spray-applied	Unbonded	Cast in situ
Bond Street Station Upgrade	Temporary	Spray-applied	Unbonded	Sprayed
Crossrail C410	Permanent	Spray-applied	Unbonded	Sprayed
Crossrail C510	Permanent	Spray-applied above knee, sheet below	Unbonded	Sprayed in crown, cast at invert
Bank Station Upgrade	Permanent	Spray-applied	Unbonded	Cast in straight section and sprayed in curved section

2.4.1 A3 Hindhead

A3 Hindhead was the first UK project to use a spray-applied membrane as the main waterproofing system. The membrane was sprayed over the entire whole crown and finished at the bottom of the side walls. No waterproofing membrane but groundwater drainage is installed at the invert [42]. Due to lack of testing data, the design specified a tensile bond strength (0.5MPa) between the membrane and the concrete substrate only in the short term. In the long term, neither tensile nor shear bond was considered (i.e. “unbonded double shell”).

2.4.2 Tottenham Court Road Station Upgrade

This was the first UK metro project to use spray-applied membrane as the main waterproofing measure. However, due to concern with regard to long-term durability of the sprayed concrete, the primary lining was treated as temporary and the configuration not designed any differently from a traditional SCL tunnel with sheet waterproofing membrane, with neither tension nor shear considered at the interface [1].

2.4.3 Bond Street Station Upgrade

In this project, in addition to use of spray-applied waterproofing, a further step forward was made by replacing the traditional bar-reinforced cast in situ secondary lining with a steel fibre-reinforced sprayed secondary [2, 43-44]. However, as the sprayed primary lining was still considered temporary, the lining configuration was essentially still designed as a traditional SCL tunnel, again with neither tension nor shear transfer considered at the interface.

2.4.4 Crossrail C410 - Bond Street and Tottenham Court Road stations

In this project, the step forward was to regard the steel fibre-reinforced primary lining as part of the permanent structure rather than temporary [3-4]. Although a great advance in SCL tunnel design, lack of knowledge on composite structural action meant that Crossrail in their engineering standard [45] specified no tension and full slip in shear should be assumed at the membrane interface in numerical modelling. This was based on the limited knowledge by that time, namely that interface tension and shear (if they exist) are both be beneficial to the tunnel and ignoring them generate a conservative design [41]. Therefore, the composite SCL tunnel was essentially designed as an unbonded double shell.

2.4.5 Crossrail C510 – Liverpool Street and Whitechapel stations

As these two stations are further east and at greater depth than the two in Crossrail C410, it was expected to encounter Lambeth Group cohesionless layers and hence groundwater ingress at the tunnel invert. Therefore, a sheet membrane was installed at this location, with spray-applied membrane above [46]. From the logistical perspective, sheet membrane is easier to be installed at the invert and facilitates the construction of steel bar reinforced cast invert. From a designer's point of view, this did not affect the original design because neither tension nor shear were assumed at the membrane interface.

2.4.6 Bank Station Upgrade

By the time of this project, research had given understanding that the sprayed membrane interface is expected to exhibit bond and shear strength under "dry" conditions [15], but that there is the possibility of reduced strength under "wet" conditions [39-40], leading to debonding in service. Therefore, a lower bound assumption for the membrane capability (intuitively thought to be conservative) was made, neglecting both tension and shear at the interface, so the system became "unbonded double shell", similar to Crossrail. The possibility of inducing cracking in the secondary lining if bond actually existed in the interface [38], was not regarded as problematic, because interior architectural panels will be installed, so such cracks will not be visible [5].

The next section considers how designers may simulate the composite action of a sprayed membrane interface.

3. Modelling considerations

Commercially available finite element or finite difference software have been successfully used in the last few years for simulating composite action in a sprayed membrane interface. Closed-form analytical solutions are rarely used, due to the complexity of SCL design, the construction sequence and non-circular tunnel profiles. "Beam and Spring" models are used for simulating the secondary lining behaviour but not for the primary lining because they cannot realistically model the stage construction of the primary lining and complex soil-structure interaction. 3D models may be used in geometrically complicated situations, such as junctions and caverns with multiple side galleries [37, 47-48]. However, for routine design of SCL tunnels, 2D plane strain modelling is most common, and is used with stress relief factors obtained from experience of conducting detailed 3D modelling [3]. A list of key considerations for simulating composite SCL tunnels is listed in Table 4. A good number of these, particularly in the areas of modelling procedure, modelling of the sprayed concrete and the ground as materials (including sprayed concrete creep [26, 49] and the soil small strain behaviour [32, 50-52] respectively) and modelling of staged construction [26, 53] will be recognised by experienced SCL designers and this paper does not attempt to change these established practices but focusses on the additional modelling requirements relating to the membrane interface in composite SCL.

Traditionally, beam elements are used for representation of primary and secondary linings in 2D plane strain analysis of an SCL tunnel. Whilst providing some convenience in building the construction sequence of the linings and extracting lining forces, this approach cannot simulate composite action between the two lining layers, mainly because beam elements do not have physical thickness and hence cannot simulate the stress distribution correctly through their depth. In order to model composite action, 2D zones or elements should be used for the primary and secondary linings, and interface elements for the sprayed concrete-sprayed membrane interface. The explicit thickness property of the zones or elements allows composite action to be simulated. A sufficient number of elements needs to be present through the thickness of the linings to model the flexural behaviour, perhaps including cracking, to adequate precision.

One drawback of this approach is that outputs from 2D zones or elements are stresses rather than internal stress resultants (axial force, bending moment) that provide direct input to thrust-moment capacity curves for design verification. An efficient method to obtain the stress resultants in 2D models is to attach beam elements with negligible stiffness (of the order of 1/1000 of either primary or secondary linings) to the centroidal axis of each lining layer, so that they follow their deformation.

Table 4 Key considerations for simulating composite SCL tunnels

Modelling Strategy	Modelling procedure	Mesh refinement Boundary conditions Lining capacity evaluation - stresses or axial force/bending moment stress resultants Crack width criteria Use of plastic hinge(s) to allow redistribution of bending moment Membrane interface capacity evaluation
	Membrane/membrane interface simulation	Option 1: Model concrete-membrane interface using interface elements Option 2: Use explicit zones for the membrane, tied to the linings and with equivalent concrete-membrane interface properties assigned to membrane zones Option 3: Use explicit zones for membrane (assigned with membrane material properties) and two series of interface elements representing interfaces with primary and secondary linings (each assigned with respective properties).
Material properties	Sprayed concrete	Mechanical characteristics: compressive and tensile strength, Young's modulus, Poisson's ratio, creep and shrinkage. Linear or non-linear behaviour Discrete or smeared crack model Time-dependent behaviour: early-age stiffness and strength
	Reinforcing steel / fibres	Perfect/strain hardening/strain softening plastic behaviour
	Sprayed membrane interface	Surface preparation to primary lining, or presence of regulating layer Membrane thickness Membrane moisture content Parameters for concrete-membrane interface elements (including membrane material behaviour) for Option 1 Parameters for zones representing concrete-membrane interface (including membrane material behaviour) for Option 2 Membrane mechanical characteristics: compressive and tensile strength, Young's modulus, Poisson's ratio, creep and shrinkage, etc. for Option 3 Parameters for concrete-membrane interface elements (excluding membrane material behaviour) for Option 3
	Ground	Linear/nonlinear elastic behaviour Small-strain stiffness Perfect plasticity/kinematic hardening Permeability/consolidation Short-term negative pore water pressure Long-term groundwater pressure
Construction Sequence	Staged construction of primary lining	Pilot tunnel / gallery Top heading, bench and invert Initial sealing layer Regulating layer Ground relaxation
	Secondary lining	Existence of prestress in the primary lining when secondary lining is installed Soil-structure-membrane interaction in the long term Fireproofing layer

Output of axial force and bending moment from the beam elements is then scaled appropriately during the post-processing stage.

The key feature for simulating composite action is representation of the sprayed membrane interface, which needs to be able to transfer compressive, tensile and shear stresses between the two layers of zones or elements. Option 1 in Table 4, using interface elements, is usually suitable for simulating a membrane interface for a whole composite SCL tunnel, as the membrane thickness is relatively small compared to the lining thickness. Interface elements for Option 1 may be realised by means of in-plane and perpendicular springs with strength cut-offs; a schematic example is shown in **Figure 2**. Option 1 is able to simulate both adhesion and cohesion failure modes.

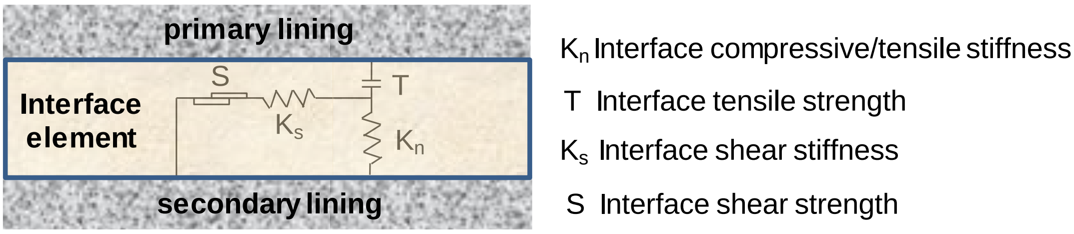

Figure 2**. Membrane interface simulated using interface element (Option 1)**

On the other hand, when carrying out numerical calibration against composite beam tests, neither adhesion nor cohesion failure is usually a concern. Instead, the membrane thickness is significant compared with the total lining thickness (e.g. >5% of total thickness) and if ignored, predicted results will differ significantly from laboratory test results. In this case, Option 2 should be adopted with the sprayed membrane simulated with 2D zones or elements, as shown in **Figure 3**. Input parameters for the membrane are not the fundamental material parameters, but equivalent interface parameters, which are calculated by the following equations:

$E_{equ} = K_n \times t$ (1)

$G_{equ} = K_s \times t$ (2)

$\nu_{equ} = E_{equ}/ 2G_{equ} - 1$ (3)

Where

E_{equ} : Equivalent Young's modulus derived from laboratory test obtained K_n

G_{equ} : Equivalent shear modulus derived from laboratory test obtained K_s

ν_{equ} : Equivalent Poisson's ratio derived from E_{equ} and G_{equ}

t: membrane thickness

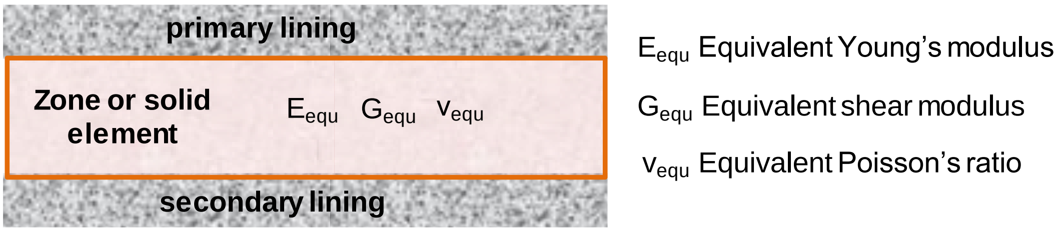

Figure 3. **Membrane interface simulated using zone or solid element (Option 2)**

Option 3 should be used if both the membrane thickness effect and both adhesion and cohesion failure mechanisms are to be included in the model. This is especially important when the tensile and shear stiffnesses and strengths differ significantly between the membrane interfaces with the primary and secondary linings. In this case, actual membrane material parameters should be assigned to the 2D zone or elements representing the membrane and the appropriate interface parameters assigned to each interface elements. A schematic example is shown in **Figure 4.**

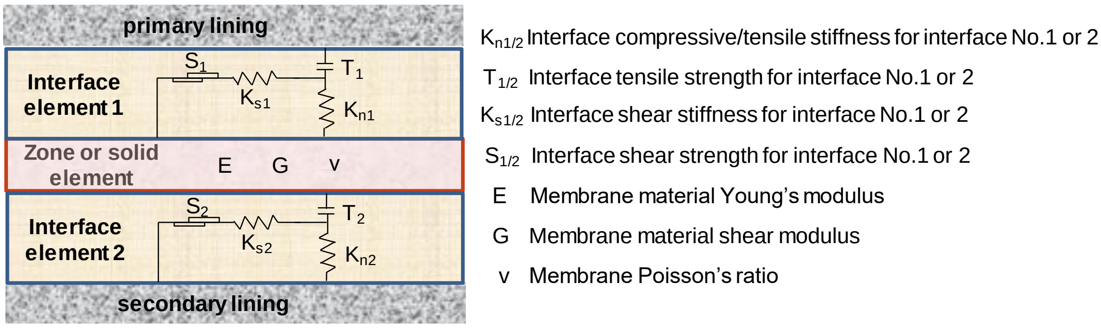

Figure 4. **Membrane interface simulated using both zone or solid elements and interface elements (Option 3)**

The authors have undertaken numerical analysis for the full composite SCL tunnel using Option 1 [26] and numerical calibration of composite beams using Option 2 [18]. Option 3 has not so far been used, due to lack of testing data on the mechanical properties of each individual interface.

In order to obtain input parameters for the waterproofing membrane interface and validate the aforementioned numerical simulation approaches, laboratory tests may be carried out on elemental and beam samples, followed by calibration of the model against laboratory beam test results. Example of this process are reported in the next sections. The parameters derived can be used in Options 1 and 2.

It should be noted that because the creep of the membrane is much faster than the long-term ground consolidation loading rate it experiences, and is also much faster than the creep of the concretes, the creep of the membrane can be handled acceptably in a pseudo-static analysis in which a long-term stiffness for the membrane is applied, appropriate to the environmental conditions it experiences (e.g. wet, dry, partially saturated).

It should also be noted that environmentally induced changes in membrane interface properties (e.g. water saturation or drying) can all be treated as variation of mechanical membrane or membrane interface properties (e.g. variation in stiffness and strength). The extreme interface properties are usually to be considered in the design as the “worst case scenarios”.

3.1 Interface parameters derived from elemental tests

Su and Bloodworth [15] carried out a comprehensive laboratory testing programme on element specimens cut from composite SCL panels (with sandwiched EVA-based sprayed membrane) with different primary lining substrate surface preparations and membrane thicknesses, loaded in compression, tension and shear under ambient laboratory climate conditions (e.g. 15-20°C temperature and 40-60% relative humidity) under immediate short-term loading and for a longer period up to two weeks. It was found that membrane thickness and interface roughness have significant impact on compressive stiffness and strength, with impact to a lesser extent on tensile and shear stiffness and strength. A thicker membrane will generally lead to lower interface shear stiffness. Ranges of recommended interface parameter short- and long-term (after creep) values are suggested in the paper. The long-term values are approximately 50% of the short-term ones, which is consistent with the conclusion drawn by Johnson et al. [54] for a different membrane type.

Johnson et al. [54] conducted laboratory tests on resin-based waterproofing membrane samples, with the membrane sandwiched between steel plates rather than sprayed concrete. These tests gave an indication of the tensile and shear stiffnesses in the short term and in the long term taking account of the effect of creep (but not alteration of membrane properties due to moisture uptake, as the tests were carried out under 'dry' conditions). However, because the membrane tests were carried out between steel plates and not sprayed concrete, it was not proven whether sprayed concrete can adhere to a cured resin-based membrane and if so, what bond strength can be achieved in tension and shear.

Pillai et al. [55] conducted a series of compression tests under ambient laboratory climate conditions on cylindrical cores with EVA based waterproofing membrane orientated at various angles to understand shear failure behaviour (in combination with normal stress). Different combination of sprayed and cast in situ concrete were used for primary and secondary linings to understand the impact of lining installation methods. Mohr-Coulomb parameters for the interface shear failure criteria and interface shear stiffness (mistakenly stated as shear modulus in the paper) were proposed. Values of interface compression and tension stiffness and strength were not proposed.

3.2 Observations from beam tests

Verani and Aldrian [56] reported three-point bending tests on pure sprayed concrete beams and composite beams with EVA-based sprayed membrane sandwiched at half-depth under ambient laboratory conditions. They found the composite beam had 50% of the peak flexural strength of the pure sprayed concrete beam, but greater residual flexural strength. No information is given on membrane thickness and interface roughness of the test specimens.

Nakashima et al. [57] presented flexural tests on two composite SCL beams (with sandwiched EVA based sprayed membrane) with and without axial force under ambient laboratory conditions. No information is given on mechanical properties of the membrane interface. For the beam tested without axial force, although the longitudinal strains and midspan deflections did not match theoretical values derived for a fully-composite beam, the authors nevertheless concluded that the beams were indeed fully composite and that instead there was a problem with the strain measurement. In fact, composite SCL beams are only partially composite structurally [18, 58] and are expected to exhibit larger deflections under the same loading and a different distribution of strain in the cross-section [18] compared to pure sprayed concrete or 'fully composite' beams.

3.3 Calibration of numerical simulation approaches

Su and Bloodworth [18] carried out a programme of laboratory tests on beam samples cut from the same batch of composite shell test panels described in Su and Bloodworth [15] and subjected to four-point bending under immediate short-term loading. Partial composite structural action was proved, a range of membrane thicknesses and substrate roughness were compared, and composite action quantification methods developed. The behaviour of composite beams was understood, and in particular the longitudinal strain distribution in the cross-section was identified. Su and Bloodworth [18] also quantified the degree of composite action [59] for beams in the pre- and post-peak moment stages and concluded it was very similar in those two stages. No sudden loss of composite action occurs after the formation of cracks.

A numerical model by the finite difference method was then set up for the beams and verified against the pre-peak test data. With interface stiffnesses inputted as obtained from the associated element tests [15], the model proved capable of predicting the observed strains and deflections to within an acceptable level of accuracy, taking into account variations arising from workmanship (such as membrane interface position when the lining layers were not of equal thickness). Sensitivity studies were performed to understand the impact of interface properties and membrane interface position on the degree of composite action.

Vogel et al. [58] reported calibration of a numerical analysis for composite SCL beams. Using interface parameter values presented by Su and Bloodworth [15], a good match was achieved between beam deflections from the analysis model and those observed in four-point bending laboratory tests prior to and post-peak.

Pillai et al. [55] also reported calibration of a numerical analysis for composite SCL beams, using interface parameters derived from their own tests. The numerical model simulated both pre- and post-crack behaviour of composite beams and a good match was achieved between the beam deflection from the analysis model and those observed in three-point notched bending laboratory tests.

3.4 Impact of membrane moisture content

All the aforementioned laboratory investigations, with the exception of Johnson et al. [54], were carried out on samples with EVA- based membrane that were essentially ‘dry’, i.e. under ambient laboratory conditions, without the samples in contact with or immersed in water such as - the case if a crack in a primary lining in water-bearing ground led to water contacting the extrados of the membrane.

Negro et al. [60] reported laboratory test results on ‘dry’ and ‘wet’ SBR type of sprayed membrane. Although the tensile strengths of the membrane itself under ‘dry’ condition for 7 days and under a combined 14 days (‘dry’ for 7 days and ‘wet’ for 7 days) are very close, between 0.7-0.8MPa, the elongation has been increased from 340% under ‘dry’ condition to between 400-430% under combined condition, which implies a softer membrane with lower compressive, tensile and shear stiffness. The interface properties were not reported.

Field measurements by Holter and Geving [40] on a rock SCL tunnel with sprayed waterproofing found the moisture content of the membrane to vary between 30% and 40%, governed by the moisture properties of the concrete and sprayed membrane and the interface between them. Further research by Holter [39] suggested that high moisture content in an EVA-based membrane may affect its mechanical properties. Ranges of key mechanical interface parameters observed for EVA-based membranes in “dry” and “wet” conditions are listed in **Table 5.**

Table 5: Comparison of “dry” and “wet” membrane interface properties

Membrane condition	Shear strength (MPa)	Shear Stiffness (GPa/m)	Tensile Strength (MPa)	Tensile Stiffness (GPa/m)
Dry membrane[1]	1.94-3.41	0.48-1.05	0.75-1.13	3.4-59.3
Wet membrane[2]	0.55-0.85	0.30-0.35	0.35-1.00	Not reported

1. Data from Su and Bloodworth [15]
2. Data from Holter [39]

King [61] presented a series of laboratory tests on elements cut from composite SCL panels, comparing three different membrane products, two of which were EVA water-based and one reactive resin-based. Both short- and long-term interface strength and stiffness under “dry” and “wet” conditions were tested but only interface tensile strength (from pull-off tests) was reported, as shown in Table 6. The results show a 38% reduction in tensile strength from “dry” to “wet” conditions, a 35% reduction from short to long term under “dry” conditions and an overall 63% reduction from short-term “dry” to long-term “wet” conditions. Average and minimum long-term “pull off” tensile strengths under “wet” conditions were around 0.34MPa and 0.24MPa respectively, close to values reported by Holter [39]. It is also observed the failure mechanism for EVA based membrane interface has changed from dominantly failure of adhesion between the membrane and either the primary or secondary lining when membrane is dry [15] to membrane cohesive failure when membrane is fully saturated [61]. In contrast, the failure mechanism for resin based membrane interface does not change and the debonding is still occurring at the interface with either the primary or secondary lining, mostly because the properties of resin based membrane is not significantly affected by the water saturation condition. It should be noted, although complex moisture transport mechanism and chemical changes may occur when membrane is changed from “dry” to “wet” conditions, from a designer’s perspective the only important input to the numerical analyses is the reduced interface mechanical properties (i.e. compression/tension/shear stiffness and strength).

With the understanding of interface mechanical properties for both “dry” and “wet” membrane described in this section and summarised in the data in Tables 5 and 6, it becomes possible to undertake parametric studies using the numerical analysis methods described earlier, to understand the influence of variation of interface mechanical properties on the global structural behaviour of composite SCL beams or complete linings. This will be discussed further in the next section.

Table 6: Comparison of "dry" and "wet" membrane interface tensile pull-off stresses from King (2015)

	Upper bound pull-off stress (MPa)		Lower bound pull-off stress (MPa)		Average value (MPa)	
	Test value	Normalised	Test value	Normalised	Test value	Normalised
Short-term "dry" condition	1.40	100%	0.60	100%	0.91	100%
Short-term "wet" condition	1.08	77%	0.22	37%	0.57	62%
Long-term "dry" condition	1.50	107%	0.50	83%	0.59	65%
Long-term "wet" condition	0.82	58%	0.24	40%	0.34	37%

Note: Average values quoted directly from King [61]. Upper and lower bound values estimated from data presented in King [61].

4. Analysis of structural behaviour

To capture the structural behaviour of composite SCL tunnels properly, analysis and design should consider the following key aspects, as mentioned in Table 4.

(1) Staged construction of the primary lining (e.g. top heading, bench and invert) with representation of age-dependent SCL stiffness and strength
(2) Groundwater pressure
(3) Existence of prestress in the primary lining when secondary lining is installed
(4) Soil-structure interaction in both short and long terms (e.g. undrained and drained behaviour of the ground)
(5) Variation in membrane interface stiffness as a function of membrane thickness, membrane saturation, substrate roughness and other lining workmanship effects
(6) Lining capacity evaluation under action of combined thrust and bending moment

These key aspects apply whether the lining is single shell or comprises primary and secondary layers. Introduction of a sandwiched spray-applied waterproofing membrane and simulation of a composite lining system is a further complication. No benefit to the design from composite structural action can be deduced unless the performance of the composite lining is correctly evaluated, by means of an analysis of the requisite capability.

Attempts have been made to predict the behaviour of composite SCL tunnels using either analytical solutions or numerical modelling [6, 55, 62-64] but none of these have considered all the key factors as listed above, as shown in **Table 7**. A complete numerical modelling of composite SCL tunnels, which captures all these effects, needs to be undertaken.

Table 7: Key aspects considered in the analyses from different researchers

Reference	(1)	(2)	(3)	(4)	(5)	(6)
Marcher et al. [62]				√		
Thomas and Pickett [6]					√	
Sun et al. [63]			√	√	√	
Jager [64]		√	√		√	√
Pillai et al. [55]		√	√	√	√	
Bloodworth and Su [18]	√	√	√	√	√	√

Bloodworth and Su [26] present a programme of numerical modelling on a composite SCL tunnel that considers all the factors listed in the above table, from which an understanding of the general behaviour of composite SCL tunnels can be obtained.

4.1 Structural action in a composite lining

A composite shell lining experiences combined global actions of bending moment M_{global} and axial force N_{global} (

Figure 5). Increments in M_{global} and N_{global} at a particular construction stage will be shared between the primary and secondary lining layers, depending on their relative stiffness and the tunnel deformation shape, which is defined as “load sharing” (the load sharing ratio is affected significantly by the sprayed membrane interface properties). Evaluation of the performance of the CSL tunnel as a whole requires capacity evaluation of each individual component lining layer (primary or secondary) under the action of the load effects induced in it by the global actions. **Figure 6** shows stress distributions expected due to M_{global} in fully-composite, non-composite and intermediate composite linings, assuming Euler bending and linear elastic behaviour (appropriate to the pre-cracked state). The key point is that with composite structural action, M_{global} induces a combination of local bending moment M and local axial force N in each layer, as illustrated in **Figure 7** for the 'High' composite case. Furthermore, N_{global} will divide between the components in proportion to their relative axial stiffness, producing in each layer a local N additional to that induced by M_{global}. This is shown in **Figure 8**, where the ratio of $N_{primary}$: $N_{secondary}$ will equal that of $t_{primary}$: $t_{secondary}$, assuming that the Young's moduli of the layers are the same in the long term once the concrete is fully cured. Hence, the design N and M in each component lining layer depend on both M_{global} and N_{global}.

Once the design values of local M and N in each layer are obtained, at each key design stage during the construction sequence, the adequacy of the individual layer can be checked at the Ultimate Limit State (ULS) and Serviceability Limit State (SLS) as for a single shell or double shell SCL tunnels.

As the degree of composite action increases, a greater proportion of M_{global} is resisted by the couple of the pair of local forces N, and a smaller proportion of M_{global} is reacted by the local M's. Bloodworth and Su [26] indicate that this can happen with increasing interface shear stiffness Ks. This explains why Pillai et al. [55] observed reduced bending moment in each component beam for a composite lining compared to a non-composite lining. Reduction of bending moment in a component beam is beneficial. However, the tensile local N in a component beam due to bending may exceed the compression force from the share of global axial force N_{global}, causing direct tension. This is more likely in a component for which the share of N_{global} is small compression, typically the secondary lining. Even

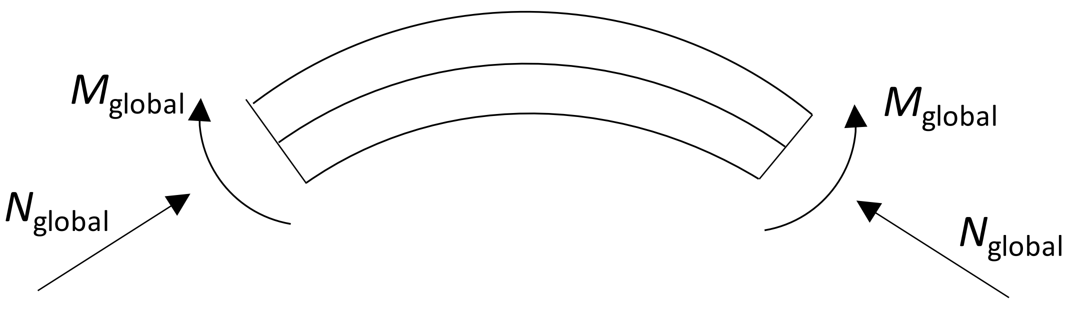

Figure 5 Global load effects on composite lining

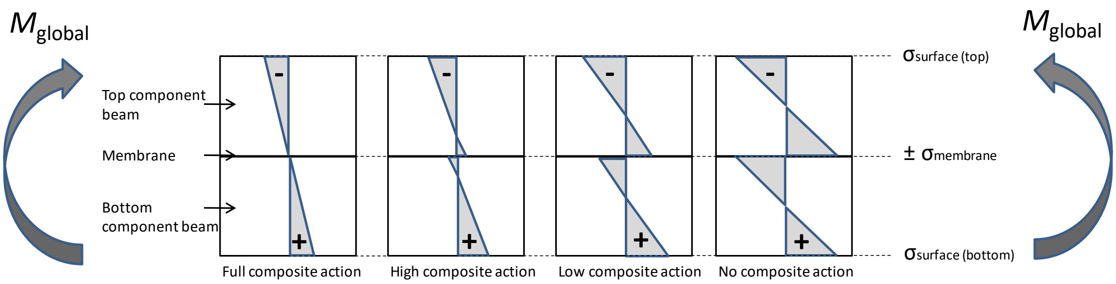

Figure 6 Composite lining stresses due to global bending

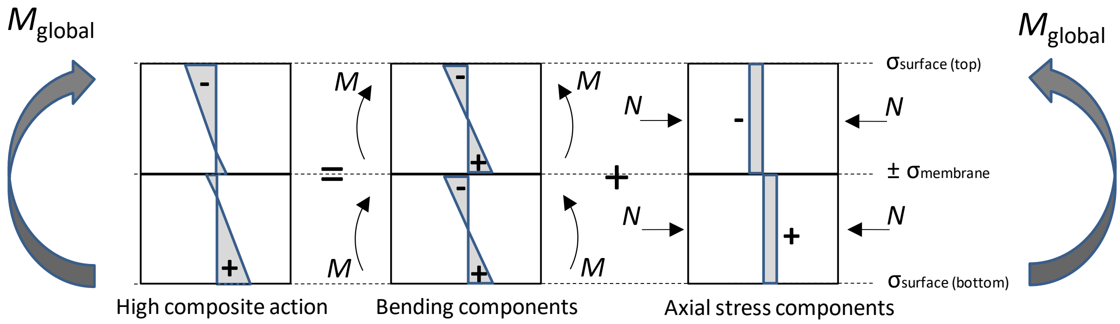

Figure 7 Breakdown of composite lining stresses due to global bending into bending and axial stress components

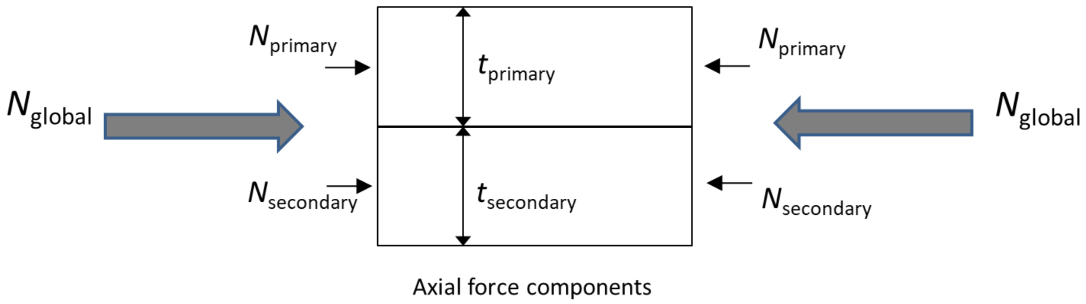

Figure 8 Sharing of applied global axial force between primary and secondary lining layers

if N does not cause net tension in the secondary lining, its effect in reducing the net compression will be to increase the M/N ratio, making the secondary lining more likely to fail under conditions of relatively high bending moment. Providing the primary lining is thick enough that a compressive N in combination with its share of N_{global} does not lead to compressive failure in the ULS check, cracking of the secondary lining at SLS is the failure mode that usually occurs first – and is made more likely by a tensile N in the secondary as a result of composite action. For this reason, composite action is not necessarily beneficial to the lining, at least not everywhere – it can reduce the safety of the secondary lining under combined bending and axial force.

A guaranteed advantage of a composite SCL structure arises from the tensile bond between the primary and the membrane, which results in the long-term groundwater pressure effectively being applied at the extrados of the primary and resisted mostly by the primary lining. The secondary lining carries only a small proportion of the ground and groundwater loads which allows for a significant reduction in its thickness, provided that the local M and N in the secondary are obtained by a rational analysis method (as described above) and the structural adequacy of the secondary lining checked at both limit states.

4.2 Impact of “wet” membrane on composite structure utilisation

Section 3.4 described how research has indicated that the mechanical properties of the membrane under “dry” and “wet” conditions are different – the latter results in lower tensile and shear stiffness and strength. This lower tensile strength may in theory lead to debonding of the membrane from the primary lining. Bloodworth and Su [26] carried out numerical parametric studies on the impact of varying interface parameters as low as 1% of the short-term tested stiffness on the behaviour of membrane interface. The purpose of the parametric study is to investigate the impact of “wet” membrane on the performance of the composite SCL tunnel. This will also help to understand weather the “dry” or “wet” membrane conditions will propose the worst scenarios for the primary and secondary linings, which will be the cases to be considered in the design. The analyses show that reduced interface stiffness (caused, for example, by “wet” membrane conditions) will cause a proportionally greater reduction in interface stress, and therefore a “safer” membrane interface, providing the interface strength remains greater than the interface stress and the membrane deformation is within its limit.

5. Principles for design

5.1 Inherent shortcoming in composite linings

Comparing with composite construction typically used in building structures, where structural steel elements are used compositely with concrete to achieve improved structural efficiency compared to considering the elements separately, the pursuit of composite action in SCL tunnels faces two inherent shortcomings:

(1) Steel-concrete composite structures use shear studs to achieve essentially full composite action. In comparison, the SCL sprayed membrane is a relatively soft material, only able to transfer a certain magnitude of shear force for a given deformation, leading to partial composite action.

(2) The sprayed concrete secondary lining is not capable of resisting large tension without the addition of steel bar reinforcement.

To overcome the shortcoming (1), the sprayed membrane interface should be as stiff a material as possible, able to transfer a large magnitude of shear force and give full composite action. However, full composite action means more tension will be generated at the secondary lining (typically at the crown), which leads to shortcoming (2) that can only be resolved either by (1) addition of steel bar reinforcement, (2) relaxing the crack width criterion in projects where the crack width does not adversely affect the tunnel functions and with the agreement of the client [5], or (3) increasing the secondary lining thickness. Installing bar reinforcement in the secondary lining and especially at crown is not a preferred option because it was required neither for the traditional “sacrificial primary lining” nor the more recent “unbonded double shell” SCL [3]. If secondary lining thickness needs to be increased to resist tension, there will be wasted material in it around most of the tunnel profile, because most load has been resisted by the primary lining already. In addition, increasing the secondary lining thickness contradicts the original purpose of using composite SCL – reducing overall lining thickness. Relaxing crack width criterion may not be possible for every project. One of the possible solutions is to increase the membrane thickness in order to reduce its shear stiffness and hence reduce or even eliminate the tension in the secondary lining crown [26].

5.2 Proposed design principles

Based on all the findings discussed above, a set of design principles for composite SCL tunnels is proposed:

(1) Limit the application of composite lining SCL tunnel depth below ground, in order to limit the water pressure acting on the extrados of the membrane that may pull the membrane from the primary lining. The lowest interface tensile strength noted for “wet” composite lining SCL element samples is around 240kPa [61]. Hence, to give an adequate margin of safety, the tunnel invert should be limited to no more than 20 – 25m below the water table. This will eliminate the risk of tensile interface adhesion and membrane cohesion failures.

(2) Design the primary lining (either including or excluding the 75mm thick initial sealing layer) to take the short-term ground load and water pressure regarded as appropriate during the construction period until the installation of the secondary lining. The analysis to achieve this may assume the concrete elastic (which is valid up to first cracking of the primary lining) or elastic-plastic allowing for the formation of one or more hinges before collapse, in which case crack widths may be the determining factor, particularly if steel fibre reinforced concrete is used for the primary. Standards may allow for a reduced partial factor on loading at ULS for the primary in this temporary situation during construction [5]. At ULS, it is recommended to keep the combined load effects in the lower half of the capacity curve, in order to minimise any risk of brittle compressive failure. At SLS, crack widths will in general be checked, along with ground settlements.

(3) Analyse the composite SCL structure (according to the methods described in this paper) under long-term consolidation load so as to achieve a safe design for the secondary lining, by assuming upper estimates of interface stiffness in tension and shear (either “dry” values or upper bound short-term “wet” values) but low tensile and shear strengths (“wet” values). The goal is to achieve a minimum secondary lining thickness within these constraints, because this will achieve minimum overall lining thickness, reduce the shear stress at the interface and lead to a safer secondary lining. It is not necessarily conservative to add further unnecessary thickness to the secondary. Consideration may be given to specifying a thicker membrane to reduce the interface shear stiffness, which reduces the interface shear stress, as mentioned in Bloodworth and Su [26].

(4) With the secondary lining thickness having been set according to (3), re-analyse the composite SCL structure under long-term consolidation load with assumptions for the interface properties that are complementary to those in (3), i.e. lower bound estimates of interface shear stiffness. This will cause less load sharing into the secondary lining than the result from (3), which will be conservative for the primary lining. The adequacy of the primary lining can then be checked at ULS and SLS under the action of the sum of the short-term load effects from (2) and these conservative consolidation effects, with partial load factors applied that are appropriate to the limit state under consideration,

In addition to all above design principles, it is fundamental to check if the membrane at specified minimum thickness has the ability to bridge the maximum allowable crack width in the design.

6. Future works

The most immediate need is for more laboratory testing data on the behaviour of sprayed concrete-membrane interfaces under various ambient conditions and different levels of water saturation, which will improve the calibration of numerical models and eventually lead to a standard set of agreed parameters for the membrane strength and stiffness to be used by designers. It is vitally important to understand that the composite SCL tunnel is a statically indeterminate structure and that creep of the membrane will result in reduced shear force transfer in the membrane and redistribution of loading. Long-term shear tests should be performed on statically indeterminate composite structures if they are to be representative of the true boundary conditions and loading.

The design principles presented in this paper have been developed from research and experience of composite SCL tunnels typically of nearly circular shapes in over-consolidated cohesive ground conditions, such as London Clay. Experience gained in the future on the performance and lining efficiency achieved in composite SCL tunnels of significantly different shapes in other type of soils will potentially lead to adjustment to these design principles.

In addition, numerical modelling using more advanced constitutive models for the sprayed concrete that model crack widths and crack distributions will allow better understanding of the performance of composite SCL linings at the serviceability limit state. Such models will benefit from being backed by further tests focussing on the post-yield cracking behaviour of composite SCL.

7. Conclusions

General conclusions can be made on the behaviour and optimisation of the design of composite SCL tunnels from numerical analysis:

(1) Composite action (i.e. interface shear) is beneficial to the primary lining but not to the secondary lining. This is contrary to the prevailing perception that composite action is beneficial to both lining layers, which comes from observation purely from the lining deformation perspective, without consideration of the force induced in the lining.

(2) A guaranteed benefit of the composite SCL configuration arises from the tensile bond strength of the interface, provided that the sprayed membrane is capable of mobilising such tension. This tensile strength means that long-term water pressure is resisted by both primary and secondary layers sharing the load, rather than just the secondary. Long-term consolidation ground loading is also shared. This enables secondary lining thickness reduction.

(3) There is incomplete data in the literature to be able to give firm guidance on the membrane interface properties under “wet” conditions, of which the tensile strength is key for resisting the water pressure as described in (2). Nevertheless, from the data that is available and the numerical parametric studies that have been carried out utilising it, it is evident that composite SCL tunnel is an attractive design option for shallow SCL tunnels in soft ground.

(4) If more experimental data on the properties of the membrane when partially or fully saturated, and field data on the actual saturation conditions of the membrane in tunnels (particularly in soft ground), is obtained, this should provide confidence to increase the assumed interface tensile strength, enabling composite SCL structures to be used at greater water heads than proposed in this paper.

COI Statements

Compliance with Ethical Standards: The corresponding author can confirm that the work described has not been published before; it is not under consideration for publication anywhere else; and publication has been approved by all co-authors and the responsible authorities at the institutes where the work has been carried out.

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