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Determination of Load-Sharing Effects in Sprayed Concrete Tunnel Linings

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ABSTRACT: In many cases, the primary sprayed concrete lining (SCL) has sufficient load-bearing capacity after the deformations have ceased to be capable of guaranteeing full functional efficiency of the structure. Therefore, the necessity of a secondary lining, i.e. a final lining, is frequently questioned. In this context, it has to be kept in mind that long-term durability and water-tightness are functional requirements which together with sufficient load-bearing capacity shall ensure that the lining remains serviceable throughout its design life. The new sprayed concrete technology has lead to the use of single shell and double shell linings in various compositions. The design and construction of a composite lining consisting of a dual or multiple layer system is challenging. The feasibility and durability of the permanent sprayed concrete depends on the geological and hydrological conditions, environmental influences and the structural requirements for lining reinforcement. In addition to the concrete quality, reinforcement type and effective long-term ground loads, the decisive factors for the durability of the sprayed concrete are hygric, thermal and chemical influences. The load-sharing effect, i.e. the interaction between the individual sprayed concrete layers including various options for waterproofing and secondary lining are presented in the paper.

1 INTRODUCTION

Over the past 20 years, advances in installation and material technologies including reliability of early-age strength of sprayed concrete in combination with fibre reinforcement and mechanization of the spraying process and consequent quality control mechanisms including highly sophisticated surveying technologies have significantly improved the sprayed concrete lining method. This still evolving technology is applied in various compositions to projects worldwide. Especially in London underground, SCL tunnelling will be applied in large-scale project developments, such as Crossrail or the Victoria and Tottenham Court Road station upgrade.

The developments in waterproofing systems and the application of fibre-reinforced sprayed concrete have lead to the use of single shell and double shell linings in various compositions.

In principle, distinction shall be made between waterproofing system against water pressure and against seepage water. For seepage water a waterproofing sheet membrane with an appropriate drainage layer is used in conjunction with drainage pipe at the invert (‘drained system’). A waterproofing system against water pressure is often referred to as a ‘fully tanked system’ where the groundwater meets a waterproofing membrane but the design does not include a managed drainage system. The paper is mainly focusing on ‘fully tanked systems’.

Besides the well-established method of waterproofing using sheet membranes, sprayed membranes have recently become available on the market. However, these two types differ completely with respect to how water pressure will be counteracted as well as with regard to their structural behaviour.

2 LINING CONFIGURATIONS

Three SCL configurations exist: single, double and composite shell linings (see Fig. 1 for a section of the different systems).

- Single Shell Linings (SSL) by definition do not employ an internal waterproofing system and may consist of a single layer or several layers of sprayed concrete placed at different times. This approach can be applied in certain ground conditions such as dry rock or low-permeability ground. (see example in Fig. 2).
- Composite Shell Linings (CSL) consist of a sprayed waterproof layer applied directly to the primary sprayed concrete layer in

order to allow a secondary sprayed concrete lining to be applied on top. Depending on the method of sprayed waterproofing, the lining either acts as a composite shell or shows a reduced shear interaction when loaded.

- Double Shell Linings (DSL) incorporate the use of a waterproofing membrane between the primary and secondary lining. It is assumed that the membrane effectively decouples the primary and secondary lining and thus no shear transfer occurs across this interface. The secondary lining can be either cast-in-place (CIP) or sprayed concrete (see Fig. 2).

The DSL with CIP secondary lining used to be the standard method. Initial support to the rock is provided by a rather thin sprayed concrete layer designed for short-term loads which reduces the ground pressure caused by movements. It is only after the ground deformations have subsided that the secondary lining will be installed. This makes the lining subject to less stresses (long-term loads only) and enables the installation of a significantly less thick lining.

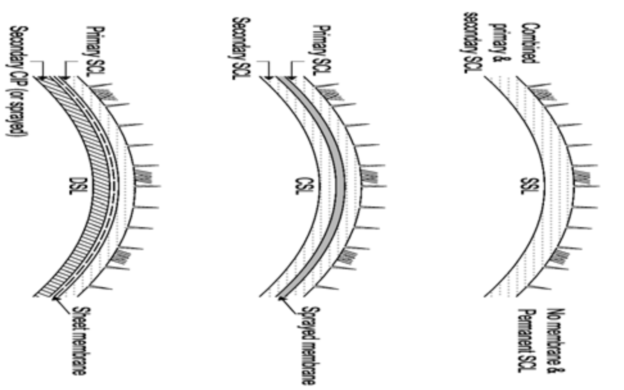
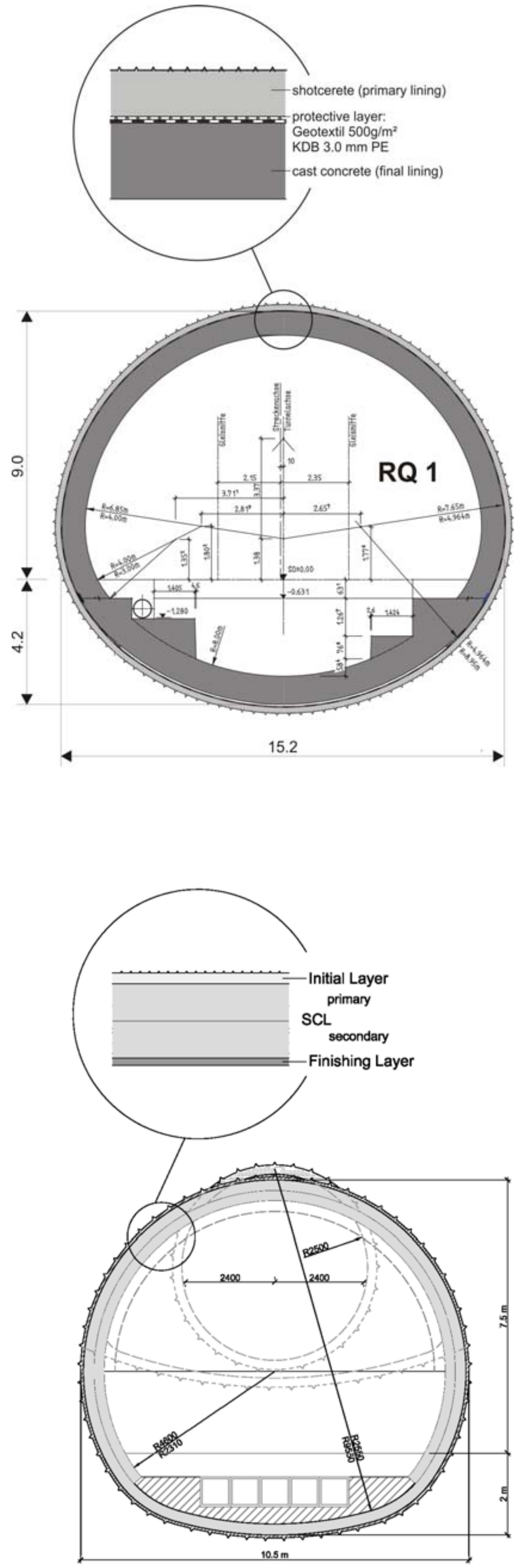


Fig. 1:Principle lining configurations: SSL, CSL, DSL

The finishing layer of a sprayed secondary lining may be applied after completion of construction of all structures. In the first instance, this sprayed concrete layer shall provide sufficient protection to the structural sprayed concrete in case of fire and can be used as a part of architectural finishing.

The paper at hand discusses the load-sharing effects, i.e. the interaction between the primary and secondary linings depending on the waterproofing used.



(a)

(b)

Fig. 2: Examples of standard tunnel cross-sections:
(a) DSL-CIP with a waterproof membrane
(b) SSL with sprayed concrete

3 DESIGN REQUIREMENTS

3.1 Project Requirements

In general, tunnel linings have to be designed to withstand all foreseeable loads (the load-bearing capacity must be ensured) and environmental influences. The linings have to be robust in order to last over the defined design life of the structure without repair guaranteeing the functional efficiency and serviceability of the structure. Hence, long-term durability of the permanent support is essential.

3.2 Structural Requirements

Primary Lining

The primary lining shall be designed to provide support to the excavated ground and enable the safe excavation of the full tunnel size by a sequence of subdivisions. The primary lining mostly contains an initial (sealing) layer to stabilise the exposed excavated surfaces and for safety of the miners. The thickness of the initial layer ranges from 50 – 100 mm.

Specifications often allow the incorporation of primary lining into the permanent structure. To which extent the primary lining can be attributed to be permanent depends on as far it is affected by detoriation.

Secondary Lining

The secondary lining has to resist all loads resulting from any detoriation of the primary lining, long term effects of the ground, i.e. consolidation, and water pressure in case of an undrained tunnel (i.e. fully tanked system) using a waterproof membrane.

In case of sprayed waterproof layer water pressure behind that layer may develop only locally, while full water pressure may act behind the primary lining as a result of detoriation of the initial sprayed concrete.

The secondary lining type such as sprayed concrete or cast-in-place has to be selected considering the constructability, the time frame and the required quality of the finishing. Sprayed concrete as a secondary lining is feasible in case of using sprayed waterproof layers. The use in case of sheet waterproof membranes is rather an exceptional case as it requires special care and control of quality.

Single Shell Lining

In low permeability grounds (such as London Clay), a single SCL can be proposed without a waterproofing membrane. So far, in the London underground system such approaches are limited to so-called "non-public" areas. This approach requires the primary lining concrete to be watertight so that it can accommodate the long-term water pressure. This can be achieved e.g. by using modern mix design (producing sprayed concrete with a permeability of $\leq 10^{-12}$ m/s) and advanced spraying technologies at areas where rather moderate deformation of the ground are expected.

Double Shell Lining

At high permeable ground sprayed waterproof layers cannot be applied successfully so far, therefor waterproofing membranes are to be used which are based on geotextile sheets for protection. The waterproofing membrane carries the full water pressure (see Fig. 3).

The waterproofing system consisting of a sheet membrane shall prevent leakage of groundwater into the tunnel and protect the secondary lining against deleterious chemical influence. Due the rigidity of sheet membrane and an unevenness of the primary sprayed concrete surface the waterproofing sheet membrane will not fully be in contact to the primary sprayed concrete. This leads to voids between sheet membrane and primary sprayed concrete, which in addition can create insufficient bedding of the secondary lining and undue stresses with potential cracking. To counteract the risk of voids a post lining grouting shall be carried out.

Composite Shell Lining

The sprayed waterproofing must bond with the primary lining and with the secondary sprayed concrete lining to allow adequate shear capacity in a composite structure.

4 DURABILITY OF SPRAYED CONCRETE LININGS

The durability of both unreinforced and reinforced sprayed concrete not only depends on the chosen concrete and steel quality (in case any mesh or steel fibre reinforcement exists). Hygric, thermal and chemical influences are decisive. A realistic delineation is achieved by making a multi-phase analysis, i.e. examining all involved components such as the mass matrix and the different fluid phases in the pore spaces. Physically-motivated numerical models to reproduce the complex interaction between induced load and hygric/thermal/chemical damages are being developed as a result of the progress made in the field of damage mechanics, inter alia de Borst et al. (2001)

and Bangert et al. (2003). The use of these models in engineering practice is very complex (Grasberger et al., 2003), but they enable numerous conclusions using a simplified approach.

In case of groundwater or surface water ingress, which damages concrete, the load-bearing capacity of the thin sprayed concrete lining will gradually deteriorate. The cemented granular skeleton gradually disintegrates, and the released forces are distributed to the supporting ground ring, to the remaining granular skeleton and to the secondary lining.

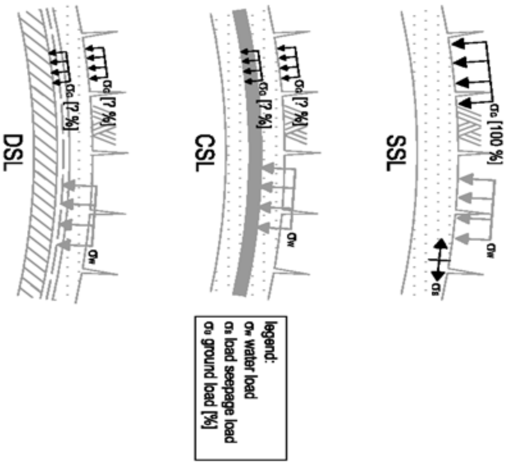


Fig. 3: Structural models for various lining configurations for tanked tunnels

The assumption regarding the long-term degradation of the primary lining is based on the fact that the structural steel elements (rock bolts, wire mesh, ribs, spiles, etc.) used in the sprayed concrete are not sufficiently protected against corrosion. A concrete cover for the wire mesh and the steel ribs would be feasible in principle, but subsequent ground deformations of the primary lining could cause cracks in the lining. Boreholes for radial rock dowles cause water ingress, because complete sealing by cement grouting cannot be guaranteed.

5 DERIVATION OF THE LOADS ACTING ON THE LINING

5.1 General

For the design and dimensioning of the secondary lining the ground load and load cases such as dead weight, water pressure, loads resulting from the operation of the tunnel, shrinkage and creep, pressure and suction load have to be considered (see various secondary lining guidelines, e.g. Ril 853). While most of the above mentioned load cases have been clearly defined in the literature, this is not the case for the ground load. Ground pressure on the lining generally only builds up over time and depends on the interaction between linings, durability of support measures and longterm effects.

The secondary lining shall be designed bearing in mind the time-dependent changes of the ground properties as well as the degradation of the support measures of the lining.

5.2 Ground Load

Key geotechnical issues which have an impact on the initial ground load include the soil-structure interaction, depth-varying parameters (both ground properties and loads), in-situ stress conditions, non-linear stress-strain behaviour and plasticity.

In many structural analyses, the entire loads acting on the primary lining are applied to the secondary lining which is a conservative simplification.

Attention has to be paid to the possible changes of the ground properties over time when designing the secondary lining. In case of solid rock, water ingress may lead to a deterioration of the strength properties (see e.g. 'variable hard rock' according to DIN EN ISO 14688-2 and Ril 853) thus causing additional loads to act on the secondary lining.

Water ingress in combination with varying stresses lead to time-dependent swelling pressures when swelling clay minerals with impaired deformation are present, or to swelling heave in case of stress release. The swelling potential and its influence on the design of the secondary lining has to be assessed for each specific case.

Viscoplastic material properties, which can be found in rocks such as phyllite or slate/schist, in combination with a high overburden lead to creep deformations which put an additional load on the secondary lining in the long-term.

Depending on the geological conditions, impacts resulting from mass movements and tectonics are also to be taken into account.

If highly cohesive soils are encountered effects of consolidation have to be taken into consideration, e.g. due to the stress release in the area of the tunnel during the excavation, negative pore water pressures may initially build up in the soil and at first cause only small loads on the lining. However, when the negative pore water pressure (i.e. suction) is released over time, the secondary lining is subject to additional loads.

In the case of clay soils (e.g. London Clay) there will be a gradual increase in ground loads on the tunnel lining as pore pressures change to a long-term equilibrium condition. The time taken for this increase of the ground load will depend on groundwater conditions and on ground properties (i.e. soil permeability and stiffness of ground) as well as on the construction sequences.

5.3 Ground Load Distribution

The definition of a load distribution which corresponds to the ground load is necessary, among other things, when using elastically bedded beam elements as the method of calculation for the secondary (inner) lining.

Typical distributions which have been used frequently for dimensioning DSLsecondary linings are depicted in Fig. 4. Distribution 1 results from the consideration that the axial force in the primary lining stresses the secondary lining more evenly after the degradation of the primary lining. Distribution 2 assumes that, based on loosening of ground, the top heading only is loaded. Load distributions 3 to 6 represent combinations of the above mentioned load distributions.

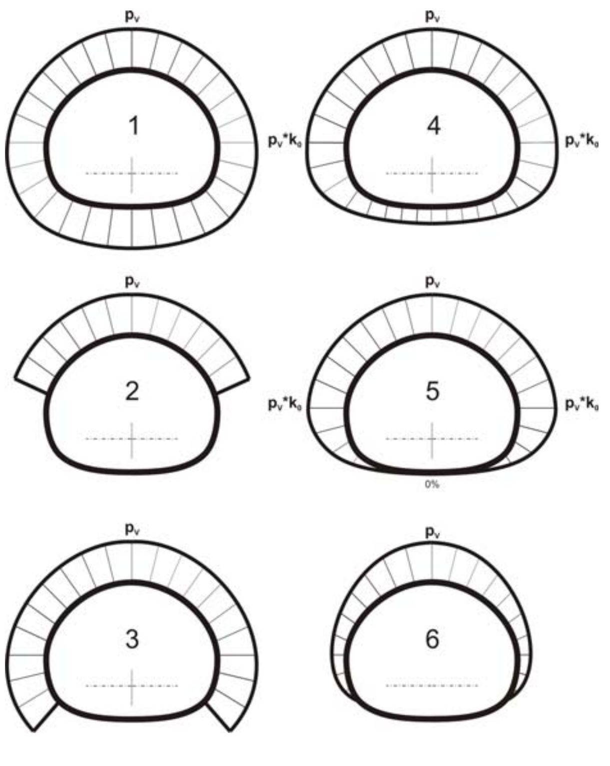


Fig. 4: Examples of distribution of ground loads acting on the secondary lining

The waterproofing system applied has a significant influence on the transfer of the shear force between primary and secondary linings and thus considerably determine the distribution of the ground load. In the case of ‘umbrella sealing’ the invert arch is in full contact with the surrounding ground whereby tangential forces can be transferred, and thus a load distribution as shown in 3 or 6 in Fig. 4 is applicable. In contrast, in case of a all around waterproof membrane (i.e. ‘fully tanked system’) shear forces between the linings are eliminated and the ground load is distributed over the entire cross-section in analogous to sketches 1 or 4 in Fig. 4.

The stresses which are released on account of the degradation of the primary lining become redistributed depending on the ratio of the stiffnesses (comparing the elasticity modulus) of the lining and the ground (for calculation examples refer to John et al., 2004 and Marcher et al., 2004). In case of a very stiff ground or rock, where the rock medium is much stiffer than the lining, the rock will attract the main portion of the forces. In this case, the numerically deduced ground loads primarily result from the ratio of rock stiffness and lining stiffness (comparing the elasticity modulus).

In addition, the geometry of the tunnel cross-section plays a significant role since a greater curvature of the structural line attracts stresses.

In general, the normal forces around the circumference of the tunnel, which is rather erratic in the primary lining (i.e. unevenly distributed), become more evenly distributed because of the degradation of the primary lining. The ground load on the secondary lining has a more constant effect the more the tunnel cross section approximates a circle and the more the stress state approximates an isotropic state (for calculation examples refer to Marcher et al., 2004).

6 MODELLING

6.1 Numerical Simulation Using a Degraded Primary Lining

The primary lining may be subject to changes of stresses and strains during its life time regarding ground load, water load, chemical/physical impact of aggressive water, swelling phenomena of the surrounding rock, swelling and shrinking processes in the concrete, etc. The changes in stiffness and in strength distribution determine the load-bearing behaviour of this highly hyperstatic (statically indeterminate) system. For this highly redundant structural member the stresses will be continuously distributed within the shell. In plastic limit analyses of lining elements subject to bending, it is assumed that a transition from elastic to ideally plastic behaviour occurs. The plastic zone allows rotations to occur at a constant plastic bending moment and stress redistribution takes place in transition zones where spreading of plasticity along plastic hinge lengths takes place.

A full contribution to load bearing of the primary lining during the whole life time may generally be ruled out due to the above mentioned impacts and combinations of effects.

It is general practice to regard the sprayed concrete initial (sealing) as 'sacrificial'; for modelling purposes, strength properties of gravel are used instead. When spiles are used the part of primary lining perforated shall be considered to detoriate. In addition lattice girders to support spiles and wire mesh may be included in the primary lining which is prone to corrosion. In case deformation beyond the elastic limits occur cracks in the sprayed concrete cannot be avoided. This will result in degradation of the whole primary lining in long-term.

The above mentioned degradation of the primary lining is simulated by modelling a transition from a purely elastic to an elasto-plastic material behaviour. Taking into account the stiffness and strength behaviour of the primary lining an approach similar to the *Gray Rock Philosophy* (Hurt, 2002) is taken for modelling. In this article, it is recommended to model the primary lining elasto-plastically as part of the rock with low strength parameters. Any reinforcement in the primary lining should not contribute to the load bearing in the long-term (i.e. there is a tension cut-off in the long-term case). This type of modelling eliminates tensile stresses in the primary lining, and reduces compressive stresses as well as the modulus of elasticity. Thus, it is possible to analyse the reduced load-bearing capacity which is a consequence of the time-dependent degradation of the material properties and the ensuing stresses in the secondary lining.

The degradation of temporary rock dowels is taken into account by simulating the failure of these dowels which leads to an increase of the ground load on the secondary lining, especially in squeezing rock conditions.

Calculation models shall be developed depending on the type of lining shell (see Fig. 5). Two-dimensional beam-spring models are generally used for the secondary lining. Either linear-elastic or non-linear beam elements can be used. When using linear-elastic beam elements, appropriate reductions in element stiffness are needed to account for the concrete cracking.

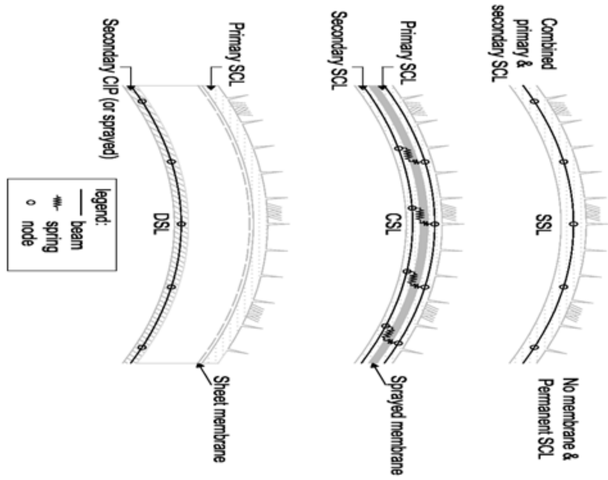


Fig. 5: Model assumptions for different lining configurations

In beam-spring models, the ground is represented by radial and tangential springs. The beam elements are elastically embedded in the surrounding ground to simulate the interaction between ground and support.

6.2 Secondary Lining in DSL Configuration

Due to the waterproofing system, tangential springs have to be ignored in the model, i.e. full slip shall be simulated. In order to prevent a tangential stress transfer, contact elements are placed between the two modelled linings (primary and secondary), which ensure that only radial stresses act on the secondary lining.

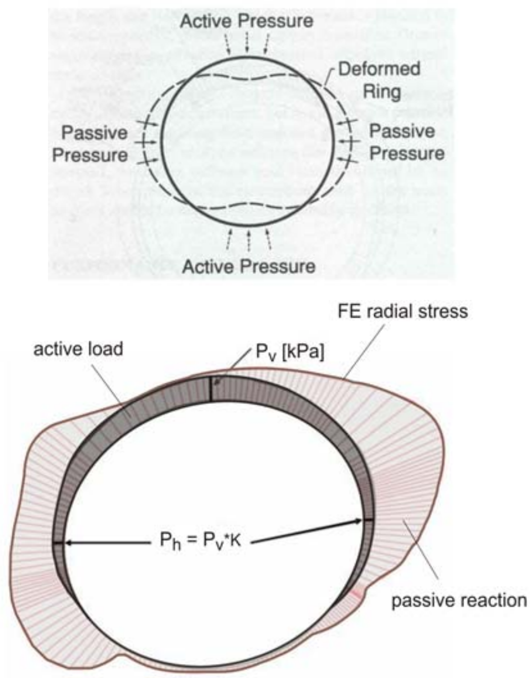


Fig. 6: Example of active / passive loads on lining system

The ground loads will be calculated in advance and applied to the beam directly. In Double Shell Lining configurations, the K0-value (horizontal stress ratio of the in-situ ground stress conditions) is not applicable. In accordance with the ICE guide (1996), the horizontal pressure remaining in the ground after completing the SCL construction of the tunnel is usually significantly less than the original at-rest pressure K0. The K-value for the beam-spring model should be chosen so that the combined active and passive load on the lining is in line with the output from the FE/FD model – see Fig. 6.

The non-linear behaviour of a reinforced concrete secondary lining can be calculated in accordance with rules and regulations given in Eurocode 2 (e.g. taking into account a reduced stiffness due to the effects of cracks and reinforcement using a so-called M-N-k diagram).

The behaviour of an unreinforced or fibre-reinforced CIP lining can be calculated taking into account the reduced stiffness due to the effects of cracks. An example of stress redistribution in the 'crack area' of the lining is shown in Fig 7.

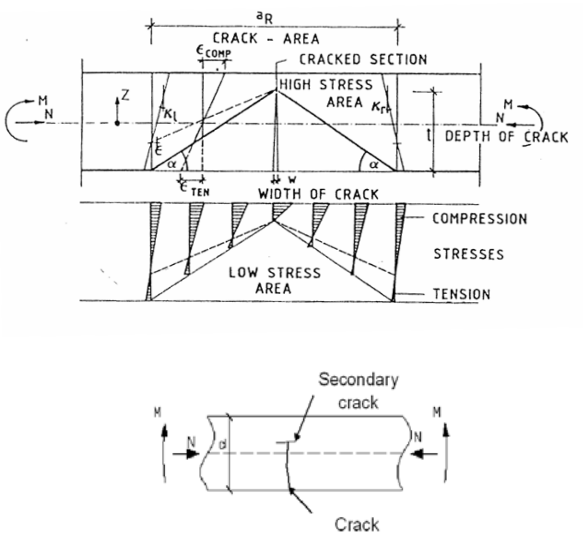


Fig. 7: Behaviour of Unreinforced Concrete (Pöttler, 1993)

A procedure for designing unreinforced or fibre-reinforced concrete linings is given e.g. in Saurer et al. (2011).

6.3 Load Assumptions for CIP Concrete Models

Ground pressure acting on the secondary lining has to be deduced from the FE/FD-models taking the result of load sharing into account. The radial contact pressure on the interface between primary and secondary lining, as represented in the numerical model (FE/FD), consists of both an "active" pressure (load) and a "passive" pressure (bedding reaction from deformation of tunnel lining) – see Fig. 6. Only active pressures are to be applied as a load to the secondary lining when using bedded beam-spring models. An example of these active pressures is shown as black line in Fig. 6.

6.4 Model Assumptions for Sprayed Concrete Secondary Linings

SCL in DSL Configuration

Due to the waterproofing system, tangential springs have to be ignored, i.e. full slip has to be simulated. The sprayed concrete stress-strain behaviour has to be taken into account including the age and loading conditions.

SCL in CSL Configuration

The boundary conditions of the calculation model (e.g. beam-spring model) for the SCL lining system depend on the specific behaviour of the sprayed membrane layer (or layers) sandwiched between the two SCL layers. The compression and tension behaviour as well as the shear and normal characteristics of this membrane have to be analysed in order to be able to establish relevant spring and beam stress-strain relationships. It is difficult to derive specific parameters for such models. It would be necessary to determine the stress-strain behaviour in tests (e.g. shear box test), but such tests are not established yet. Hence, the maximum and minimum values of shear-stiffness for spray-on membranes have to be applied to the calculation model, i.e. 'full-slip' and 'no-slip' conditions shall be considered (see also Thomas, 2010).

7 CONCLUSIONS

This paper discusses the load-sharing effects on the secondary lining after the loss of load-bearing capacity of the degraded primary lining. In summary, the following findings can be listed:

- Design loads do have to take into account the loads, deformations and stresses already developed in the primary lining prior to the application of the secondary lining. The amount of permanent ground load to be applied to the secondary lining has to be determined based on a detailed analysis considering the consolidation effects and degradation as described above.
- The initial (sealing) layer of sprayed concrete, which is in direct contact with the ground, may be subject to aggressive attack from

groundwater; its contribution to the bearing capacity of the tunnel lining shall be neglected. A full contribution of the primary lining to load bearing throughout the design life of the tunnel lining shall be ruled out. The reduced load-bearing capacity of the primary layer of sprayed concrete has to be analysed as a consequence of time-dependent degradation of the material properties.

- Some papers propagate a predefined ratio of load sharing (e.g. for tunnelling in London Clay by Dimmock, 2011). However, there is no constant ratio for load sharing between primary and secondary lining as no two tunnel projects have the same long-term conditions.
- In low permeability grounds (such as London Clay), a single SCL without a waterproofing membrane seems to be feasible in 'non-public' areas. The water load on the Single Shell Lining shall be applied on the inner face of the initial (non-cohesive) layer.
- Composite Shell Linings with a sprayed waterproofing layer are still difficult to establish due to few project references existing so far. The transfer of shear is permitted and this must be modelled with an elastoplastic spring stiffness both in the radial and tangential direction at the interface between the primary and secondary lining. The properties at the interface depend on the type of the proposed sprayed membrane.

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