Multi layered shotcrete design for tunnel construction

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Shotcrete for Underground Support XIII

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The ILF Group
General Presentation

**ILF at a Glance**

Established in 1967
Leading engineering, consulting and project management firm
Completely independent - fully privately owned

> 2,000 employees  > 40 offices  > 6,000 projects  > 100 countries  > 220 million € revenue

Each ILF firm is a separate legal entity and has no liability for another such entity’s acts or omissions.
The ILF Group
General Presentation

- **Offices and Projects**

  - Over **6,000** international projects successfully completed

  **Europe**
  - Innsbruck
  - Graz
  - Salzburg
  - Vienna
  - Linz
  - Dornbirn
  - Munich
  - Stuttgart
  - Leipzig
  - Zurich
  - Prague
  - Milan
  - Genoa
  - Warsaw
  - Katowice
  - Bratislava
  - Stathelle
  - Tirana

  **Americas**
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  - Kelowna, BC
  - Toronto, ON
  - Traverse City, MI
  - Seattle, WA
  - Fairfax, VA
  - Atlanta, GA
  - Mexico City
  - Bogota
  - Santiago de Chile

  **Middle East**
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  - Amman
  - Doha
  - Erbil
  - Riyadh

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  - Addis Ababa
  - Lagos

  **Asia-Pacific**
  - Ashgabat
  - Lahore
  - Bangkok
  - Beijing
  - Laos

  **Europe**
  - Ankara
  - Baku
  - Ploiesti
  - Moscow
  - Tbilisi
  - Almaty

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Structural Design of Shotcrete Lining

- up to the 1970’s design was based mainly on experience gathered throughout the construction and some simplified analyses

Today:

- Accurate estimation of deformations and stress state in the shotcrete lining
- Consideration of time and construction sequence
- Applying simplified time dependent material laws for shotcrete

⇒⇒⇒ Eurocode 2 (EC 2) for ultimate limit state (ULS) and serviceability limit state (SLS)
Structural Design of the Shotcrete Lining

Challenge: optimize the lining thickness by utilizing the load bearing capacity of the surrounding ground

- Limitation of deformation and plastification to an acceptable amount
- The stiffer the lining is designed the more loads it will attract
Convergence Confinement Diagram

- Ground Reaction Curve
- Radius of Plasticication

Ground Stress/Support Pressure MPa

Displacement m

Radius of Plasticication m

lining with high stiffness
lining with low stiffness
Convergence Confinement Diagram

Ground Reaction Curve

Indicates radial displacements of the tunnel lining, which are depending on the support pressure.

Ground Reaction Curve

Ground Stress/Support Pressure MPa

Displacement [m]

blue line shows a lining with low stiffness (thin lining)

- high deformations but less load on the lining
red line shows a lining with high stiffness (thick lining)

▶ lower deformations resulting in higher load on the lining!!
Conclusion:

It makes sense to apply shotcrete in various layers following individual construction stages rather than applying the whole shotcrete thickness at once!
Convergence Confinement Diagram

- **Ground Reaction Curve**
- **Radius of Plastification**

- **Radius of plastification**

- Ground Stress/Support Pressure MPa vs. Displacement [m]

- Lining with high stiffness
- Lining with low stiffness

- Page 10
Convergence Confinement Diagram

Radius of plastification for **lining with low stiffness**
For the stiff lining the radius of plastification is less than for the lining with low stiffness!!
Reinforcement of existing shotcrete lining

Typical applications for a **second shotcrete** lining:

- **Additional loads** resulting from unexpected ground conditions (additional surface loads, load redistributions etc.)
- A **second, parallel tunnel** is driven while the first tunnel is already in place
- **Cross sections** between two main tunnels need to be installed
Reinforcement of existing tunnel lining

Strengthening of the shotcrete lining through a second layer, which is added subsequently
Interaction of two shotcrete layers

For structural reasons it is obviously advantageous that both layers act together as one homogeneous cross section (full bond).

- bending stiffness is much higher (no slip between layers)

Indented construction joint – EC 2

construction joint e.g. by a high-pressure water jet
Construction phases and implementation of shear dowels

- It is assumed that a full bond between the shotcrete layers is reached.
Design and positioning of shear dowels
ULS (Ultimate Limit State) Design for bending with axial force - general assumptions

The assumptions for the design are:

- plane sections remain plane
- the strain in bonded reinforcement, whether in tension or in compression, is the same as that in the surrounding concrete
- the tensile strength of the concrete is ignored
- the stresses in the concrete in compression and in the reinforcing steel are derived from the design stress/strain relationship
**Strain/Stress State** for design of (Single) Concrete Cross Section

Possible **strain distributions** in the **ultimate limit state** (according to EC 2)

▶ For the **design process** the **strain distribution is varied** (under the boundary conditions as shown) until a **balance between calculated actions and the inner forces** derived from the strain state is reached.

\[ \Sigma H = 0 \]
\[ \Sigma M = 0 \]

**Strain and stress state** for design of single concrete cross section
Bending moment – axial force interaction diagram
(M-N interaction diagram – single layer concrete cross section)

M-N combinations for allowable and unallowable (limit strain exceeded) strain states
Two layer shotcrete design

Challenge:

A part of the cross section, the **first shotcrete layer**, is already **loaded** while the newly applied shotcrete, the **second layer**, is **stress free** !!
Two layer shotcrete design

Procedure to determine the **additional capacity** of the whole cross section:

1. apply **additional strain** (Δε) to the **whole cross section** (consisting of 2 layers)
   - Additional strain (Δε) is added to existing strain (ε₀)
   - assumption: plane sections remain plane

2. **strain distribution is varied** until the **limit strains** according to EC 2 are reached in
   - **top** fibre
   - **bottom** fibre
   - **Interface** fibre (between first and second layer)
Two layer shotcrete design

Strain and stress state for design of composite concrete cross section

\[ \Sigma H = 0 \]
\[ \Sigma M = 0 \]
Bending moment – axial force interaction diagram (M-N interaction diagram)

▶ **Additional capacity** of the composite concrete cross section is **no more symmetric** !!
Bending moment – axial force interaction diagram (M-N interaction diagram)

**Additional capacity** of the composite concrete cross section is **no more symmetric**!!
Discussion of specific results – base case

Base case of composite cross section and definition of positive sectional forces

<table>
<thead>
<tr>
<th>Shotcrete layer</th>
<th>Concrete strength</th>
<th>Reinforcement strength</th>
<th>Reinforcement area</th>
</tr>
</thead>
<tbody>
<tr>
<td>First shotcrete layer</td>
<td>C25/30</td>
<td>B550</td>
<td>$A_{S1} = 2.57 \text{ cm}^2/\text{m}$</td>
</tr>
<tr>
<td></td>
<td>$f_{ck} = 25 \text{ MPa}$</td>
<td>$f_{yk} = 550 \text{ MPa}$</td>
<td>$A_{S2} = 2.57 \text{ cm}^2/\text{m}$</td>
</tr>
<tr>
<td>Second shotcrete layer</td>
<td>$\alpha_{cc} = 1.0$</td>
<td>$\gamma_s = 1.15$</td>
<td>$A_{S3} = 2.57 \text{ cm}^2/\text{m}$</td>
</tr>
<tr>
<td></td>
<td>$\gamma_c = 1.5$</td>
<td></td>
<td>$A_{S4} = 2.57 \text{ cm}^2/\text{m}$</td>
</tr>
</tbody>
</table>

Input data for base case
Discussion of specific results – base case

Three pre-strain states of the first shotcrete layer are investigated:

Case 1: low utilization of the initial cross section

Case 2: moderate utilization of the initial cross section

Case 3: maximum utilization of the initial cross section
Discussion of specific results – base case

<table>
<thead>
<tr>
<th>Case</th>
<th>1a</th>
<th>2a</th>
<th>3a</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{top}}$ [‰]</td>
<td>-0,1</td>
<td>-0,8</td>
<td>-3,5</td>
</tr>
<tr>
<td>$\varepsilon_{\text{bottom}}$ [‰]</td>
<td>1,0</td>
<td>12,5</td>
<td>25</td>
</tr>
</tbody>
</table>

pre-strain distribution

<table>
<thead>
<tr>
<th>Case</th>
<th>1b</th>
<th>2b</th>
<th>3b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{top}}$ [‰]</td>
<td>1,0</td>
<td>12,5</td>
<td>25</td>
</tr>
<tr>
<td>$\varepsilon_{\text{bottom}}$ [‰]</td>
<td>-0,1</td>
<td>-0,8</td>
<td>-3,5</td>
</tr>
</tbody>
</table>

pre-strain distribution

Cases of **pre-strain conditions** of **first** shotcrete layer
Discussion of specific results – base case

For low utilization, the interaction diagram is very similar to the base case without any pre strain.

In case of maximum utilization only very specific M-N combinations (within the blue area) can be applied ⇔ design approach with very high utilization of the first shotcrete layer is not recommended!

Moderate utilization:
Higher additional capacity for cases with negative bending moment for the combined cross section.

The higher the utilization of the first shotcrete layer, the lower the additional load bearing capacity of the combined cross section!!

General case – M-N interaction diagrams
Discussion of specific results – influence of concrete strength

M-N interaction diagrams – influence of the concrete strength
Discussion of specific results – influence of **concrete strength**

**Low utilization initial cross section**

M-N interaction diagrams – influence of the concrete strength
Discussion of specific results – influence of **concrete strength**

**Medium utilization initial cross sec.**

**M-N interaction diagrams – influence of the concrete strength**
Discussion of specific results – influence of concrete strength

M-N interaction diagrams – influence of the concrete strength
Discussion of specific results – influence of reinforcement amount

M-N interaction diagrams – influence of reinforcement amount
Discussion of specific results – influence of reinforcement amount

M-N interaction diagrams – influence of reinforcement amount
Discussion of specific results – influence of reinforcement amount

M-N interaction diagrams – influence of reinforcement amount
Discussion of specific results – influence of reinforcement amount

M-N interaction diagrams – influence of reinforcement amount
Discussion of specific results – influence of thickness of the second shotcrete layer

M-N interaction diagrams – influence of the thickness of the second shotcrete layer
Discussion of specific results – influence of **thickness** of the second shotcrete layer

M-N interaction diagrams – influence of the thickness of the second shotcrete layer
Discussion of specific results – influence of thickness of the second shotcrete layer

M-N interaction diagrams – influence of the thickness of the second shotcrete layer
Discussion of specific results – influence of thickness of the second shotcrete layer

M-N interaction diagrams – influence of the thickness of the second shotcrete layer
Conclusion

• Pre-strain is to be considered

• No fibre shall exceed limit strain as per EC2

• First shotcrete layer shall not be at limit state of strain

• General Interaction diagrams can NOT be provided due to unlimited number of pre-strain combinations

• Design only possible by applying specific software
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General Presentation

Service Portfolio

Decision Gates

Project Life Cycle

Appraise
Select
Define
Execute
Operate
Close

Business Identification
Project Framing
Project Definition
Project Realisation
Business Control
Business Closure

ILF Services

Pre-/Feasibility Studies
Due Diligence
Conceptual Design
Permit Application Design
Supply Chain Management
Operations Audit
Due Diligence

Environmental & Social Impact Assessment
Environmental & Social Impact Assessment

Basic Design, FEED, Tender Design
Detailed Design
Design Review

Execution Strategies
Project Management
Project Management
Modification Planning

Due Diligence
Decommissioning Planning

Optimisation Studies
Rehabilitation Planning

Construction Supervision
Commissioning & Trial Operation
Maintenance Support

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Trend of project costs

- **Trend of costs throughout the project life cycle (cumulative)**
- **Degree of controllability of costs (construction costs and operating costs)**

### Timeline:
- **Concept**
- **Preliminary design**
- **Permit application design**
- **Tender design**
- **Construction design**
- **Construction phase**
- **Operational phase**
- **Rehabilitation**
- **Start-up = handover**

### Degree of controllability:
- Concept: 100%
- Preliminary design: 65%
- Permit application design: 40%
- Tender design: 0%
- Construction design: 22%
- Construction phase: 12%
- Operational phase: 12%
- Rehabilitation: 12%

### Timeline:
- Service life
- Duration of project
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Thank you for your attention!