Considerations of new approaches for TBM tunnel design

Considérations sur de nouvelles approches du projet de tunnels réalisés par tunneliers

Peter -M. Mayer, Ana Libreros, Christoph Niklasch
Ed. Zueblin AG, Technical Head Office, Department of Tunnel Design

Claudia Klotz
former employer Ed. Zueblin AG, Technical Head Office, Department of Tunnel Design

ABSTRACT

Advances in the design and reliability of tunnel boring machines have led to a significant increase in their utilization in recent decades. One consequence has been the increased demand for mechanisation and automation of the entire tunnelling process. It was observed in many tunnel projects that cracking (damage) of the rings has direct influence of the bearing capacity of the concrete lining and represents an important factor for the major loss of lining quality with a detrimental influence on the long-term behavior of segments. A large part of the damage to segments occurs during the construction process, when the TBM occasionally produces large forces and deformations that will lead to failure of the segments due to cracking or compressive failure. This paper presents important aspects of the research that Ed. Zueblin AG performed for the integrated project, Technology Innovation in Underground Construction (TUNCONSTRUCT). New design approaches for TBM tunnels and three-dimensional finite element analyses of a TBM tunnel are shown in this paper. Examples of look-up tables as presented in this paper provide information for the pre-design of segmental linings including a preliminary risk evaluation.

RÉSUMÉ

Les progrès dans la conception et la fiabilité des tunneliers (TBM) ont mené à une augmentation significative de leur utilisation dans les niéres décennies. La demande accrue de la mécanisation et de l'automatisation des travaux de perçage d'un tunnel en est une conséquence. On l'a observé dans beaucoup de projets de tunnels que la fissuration (dommages) des anneaux a une influence directe sur la portance du revêtement de béton et qu'elle représente un facteur important de la perte principale de qualité du revêtement, avec une influence nuisible sur le comportement à long terme des segments. Une grande partie des dommages aux segments se produit pendant les travaux, quand le tunnelier produit de temps en temps des forces importantes et les déformations qui mèneront à la rupture des segments en raison de la fissuration ou la rupture par compression.

Ce document présente des aspects importants de la recherche qui Ed. Zueblin AG a effectuée pour le projet intégré, Technology Innovation in Underground Construction (TUNCONSTRUCT). De nouvelles approches pour les tunnels réalisés par tunneliers et des analyses tridimensionnelles en éléments finis d'un tunnel réalisé par tunnelier sont également montrées. Les exemples des tableaux de consultation présentés dans ce document fournissent des informations pour l'avant-projet des revêtements de secteurs annulaires, comprenant une évaluation préliminaire des risques.

Keywords : numerical modeling, qualitative risk evaluation, look-up tables

1 INTRODUCTION

In order to meet the societie's demands for increased transport capacities in urban congested environment, new design solutions for tunnels are required. Conventional engineering models and codes for lining design are often based on simplification such as neglecting longitudinal joints the interaction between rings through lateral joints. However, these days, in mechanized tunneling we have to deal with a segmented lining system in contrast to a continuous tube (conventional design approach) that provide no information regarding lateral coupling and the longitudinal joints of the segmented lining system. In order to design any tunnel lining it is important to know and understand the functional requirements. These can widely vary, as they are influenced by many factors. A durable lining performs satisfactorily in its working environment throughout its designated service life.

Design of joints should provide for fast and durable connections with sufficient strength to meet erection sequences, support requirements and to maintain the compression of the sealing gaskets. Particular attention must be paid to the design of the longitudinal joints. High Performance Concrete (HPC) (made of steel fibres), as new material for tunnel lining was analysed during research carried out by Ed. Zueblin for TUNCONSTRUCT. This presentation focuses on two aspects:

a) optimization of numerical models to simulate failure mechanisms of tunnel lining made of high performance concrete that considered the influence of connections between the lining segments and

b) consideration of damage of the tunnel lining during construction processes with a qualitative evaluation of the possible risks using proposed look-up tables.

2 NUMERICAL MODELLING

2.1 *Segmental tunnel lining*

The simulation of the longitudinal and circumferential joints assumes a non-linear behaviour of the joint material (Blom 2002). In order to describe the non-linear contact behaviour, numerical and laboratory tests were conducted, the results of which were used for model adjustment. The longitudinal joint is

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-2524

acting as a concrete hinge when adjoining segments are rotating relatively to each other.

These concrete hinges resist the rotation and causes moments (Janßen 1983). The parameters which characterize the longitudinal joint behaviour are the plastic moment and the rotational stiffness. The rotational stiffness is constant as long as the longitudinal joints are closed and decreased when the longitudinal joints are opening.

The relation moment-rotation was empirically established from laboratory tests performed by Leonhardt (Leonhardt 1965). Figure 1 shows a realistic model of the tunnel lining ring, where longitudinal and lateral joints are not neglected. Coupled rings consider the ring-joint interaction and can be imple-mented into the model in two ways: using discrete coupling elements representing the "cam and pocket" or using special continuum elements that describe the friction force that is activated within the hardboard placed between two adjacent segments.The tunnel lining is modeled with quadratic shape functions elements (27 nodes). These higher-order elements allow for more accurate calculations than the linear elements regarding momentum, normal and shear forces.

Figure 1: Realistic simulation of tunnel lining

2.2 *Material model*

An elasto-plastic three-dimensional concrete material model based on the work of B. Thomée (Thomée 2005) is used for the description of the High Performance Concrete material properties. The failure surface can be expressed with primary stresses and describes the different multi-axial stress states for which material failure occurs. Two failure surfaces are combined (Feenstra 1993) in the implemented concrete material model. The compressive region is described by a generalised Drucker-Prager failure criterion. The Drucker-Prager failure criterion is hyperbolically rounded and continuously differentiable to improve the numerical stability. In the tensile region a rounded and continuously differentiable Rankine criterion is used. The influence of the isotropic material hardening and softening onto the failure surfaces for tensile and compressive regions can be seen in Figure 2 (Thomèe 2005). After exceeding the maximum tensile strength (A) the yield surface is contracted in both directions. Under compressive loads the yield surface is expanded up to the failure surface (B). After exceeding the maximum compressive strength (B) softening leads to a contraction of the yield surface (C) tension-softening due to fracture localization. The parameters necessary for the evaluation of cracking of the high performance concrete are: initial mean uniaxial tension strength f_{ctm} , post fracture tension strength f_{ctm1}, tension fracture energy of concrete G_{f1} and tension fracture energy of steel fibres G_{f2}.

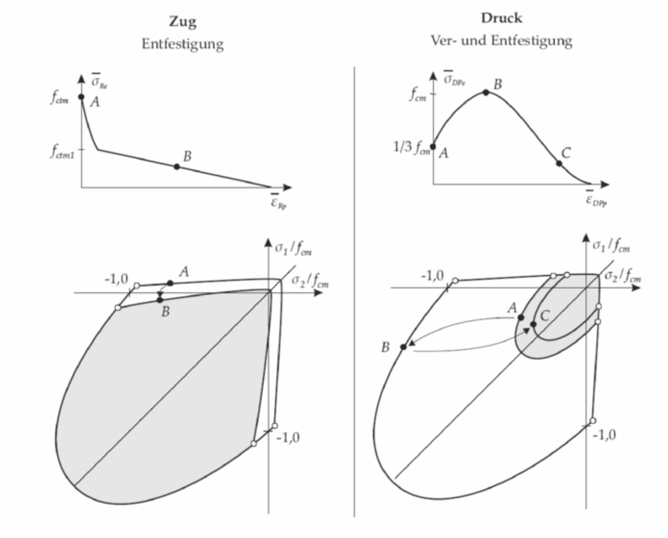

Figure 2: Principle of influence of hardening and softening onto failure surfaces for a two-dimensional principle stress state

2.3 *Verification example: L-shaped panel*

The implementation and mesh size dependency of the concrete material model has been tested with the calculation of a L-shaped panel. Experimental results are based on the work of Winkler (Winkler 2001). The geometry of the specimen and the material parameters are shown in Figure 3.

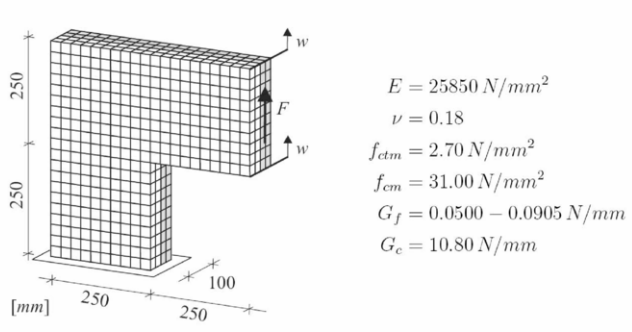

Figure 3: L-shaped concrete panel

Three different meshes with different mesh sizes have been calculated. In Figure 4 a comparison between the numerical results and the upper and lower experimental boundary is shown. In general a good agreement between experiment and calculation can be seen. The influence of the different mesh sizes is low due to the fracture mechanic approach in the description of the uniaxial stress-strain curves.

3 MANAGING RISKS

3.1 *Introduction*

The first procedure for risk evaluations is to model the tunnel lining realistically. A failure analysis software for segmental lining was developed during the research performed by Ed.

Zueblin for TUNCONSTRUCT. This product represents a collection of software tools and input files of FE models that allow to the tunnel designer to create so called look-up tables which assess possible risk of "his" design. Based on the chosen parameters, calculations for various models (material, geometry) and various boundary conditions are made to determine internal forces, stresses and deformations.

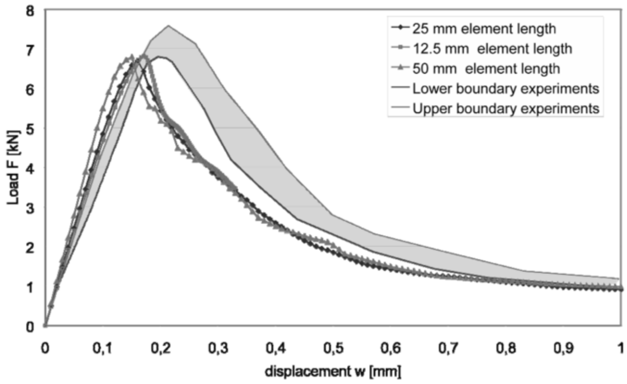

Figure 4: Comparison of numerical and experimental results

3.2 *Damage mechanism due to misalignment between shield jack and lining*

A large part of the damage to segments occurs during the construction process, when the TBM temporarily can produce large forces and deformations that will lead to failure of the segments due to cracking or compressive failure. A large distance between the center of thrust of the hydraulic jack and the center of segment surface provides a large bending moment along the longitudinal direction of the tunnel that cause an increase of internal forces that involve cracking of the lining see Figure 5.

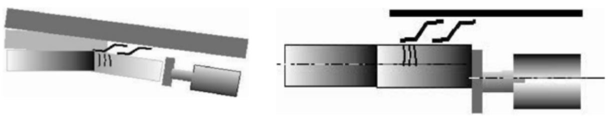

Figure 5: Damage mechanism due to misalignment between shield jack and lining segment

3.3 *Risk levels and criteria used for assessing possible risk*

Three risk levels are defined for the look-up tables. Each level contains sets of normalized paramter. Two threshold values are given for each criterion. The threshold values are based on specifications of EC2 (Eurocode 2, part 1, 1992) . The calculated/predicted values are normalized by the lower threshold value:

- Low risk, if the predicted value is less than the lower value or the normalized predicted value is less than 1.0.
- Intermediate risk, if the predicted value is between the lower and higher threshold values or the normalized predicted value is equal or greater then 1.0 and less than 1.3.
- High risk, if the predicted value is less than the lower value or the normalized predicted value is greater than 1.3. In Table 1 the proposed criteria and corresponding threshold values are presented.

Table 1: Summary of criteria and corresponding threshold values.

criterion	**description**	**threshold values**
C1	compressive strength of segments	0.45 f_{cm}
C2	tensile strength of segments	0.75 f_{ctm}
C3	cracking	0.30 [mm]
C4	compressive strength of long. joints	1.00 f_{cm}
C5	rotation of long. joint	1.50 [%]
C6	relative displacements in circ. joints	4.00 mm

4 EXAMPLE OF LOOK-UP TABLES

Look-up tables are delivered using the results of numerical calculations. This process involve variation of options for different aspects of tunnel design as the applied loads on the tunnel (e.g. hydraulic jack pressure) and type of lining. Two different scenarios are considered to study the influence of the hydraulic jacks forces on the possible failure of the lining: a) eccentric value and b) 50 % increased value. Figure 6 shows graphically the possible failure of the segmental tunnel lining for case b). For the longitudinal joints the cam-pocket coupling system is considered.

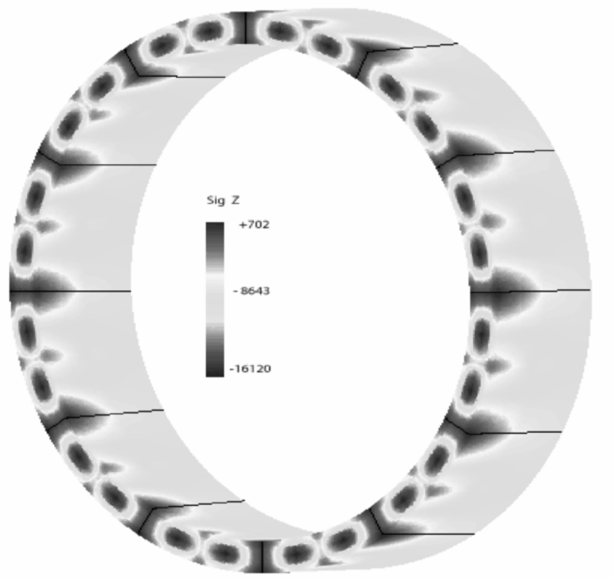

Figure 6: Comparison of numerical and experimental results

Table 2: Look-up tables that consider the influence of hydraulic jacks on the tunnel lining design

Phase I					
ength of contact		25			
		6 Segments		**7 Segments**	
load case		**ecc.P**	**inc.P**	**ecc.P**	**inc.P**
	σ_{cs1}	0.36	0.64	0.45	0.81
compressive	σ_{cs2}	0.36	0.64	0.45	0.81
stress	σ_{cs3}	0.36	0.64	0.45	0.81
C1:	σ_{cs4}	0.36	0.64	0.45	0.81
$\frac{\sigma_{c_s}}{0.45 f_{cm}}$	σ_{cs5}	0.36	0.64	0.45	0.81
	σ_{cs6}	0.36	0.64	0.45	0.81
	σ_{cs7}			0.45	0.81
	rick	low	low	low	low
	σ_{ts1}	0.96	1.20	0.86	1.17
tensile	σ_{ts2}	0.96	1.20	0.86	1.17
stress	σ_{ts3}	0.96	1.20	0.86	1.17
C2:	σ_{ts4}	0.96	1.20	0.86	1.17
$\frac{\sigma_{ts}}{0.75 f_{ctm}}$	σ_{ts5}	0.96	1.20	0.86	1.17
	σ_{ts6}	0.96	1.20	0.86	1.17
	σ_{ts7}			0.86	1.17
	rick	low	**inter-mediate**	low	**inter-mediate**
crack	W_{s1}	0.00	0.08	0.00	0.04
width	W_{s2}	0.00	0.08	0.00	0.04
C3:	W_{s3}	0.00	0.08	0.00	0.04
	W_{s4}	0.00	0.08	0.00	0.04
$\frac{\sigma_{ts}}{0.75 f_{ctm}}$	W_{s5}	0.00	0.08	0.00	0.04
	W_{s6}	0.00	0.08	0.00	0.04
	W_{s7}	0.00	0.08	0.00	0.04
	rick	low	low	low	low

Table 2 presents look-up tables that was obtained from FE non-linear calculations that considered the tunnel lining made of HPC with six or seven segments and length of the contact area in the longitudinal joint equal to 25 cm. For each segment of the tunnel lining the maximum values of compressive strength, tensile strength and crack width were normalized by lower threshold value (see paragraph 3.3.) For the increased value of the hydraulic jacks' forces, the normalized tensile strength is higher than the values based on the specifications of EC2 (Criterion C2), which implies that damage of the material exist (intermediate risk) and failure is qualitative predicted.

5 CONCLUSIONS

Through the consideration of one of the main factor of risk during construction processes it was shown that the tunnel designersare required to undertake risk analyses of different design alternatives in order to predict possible failure of the lining. Look-up tables presented in this paper and risk levels enable the designer to consider possible matters of safety that include risks at one glance.

REFERENCES

Blom, C. (2002). Design Philosophy of concrete linings for tunnels in soft soils. University of Delft. Eurocode 2, Teil 1. 1992. Planung von Stahlbeton- und Spannbeton

Feenstra, P.H. (1993). Computational aspects of biaxial stress in plane and reinforced concrete. Delft University of Technology, The Netherlands

Janßen, P., (1983). Tragverhalten von Tunnelausbauten mit Gelenktübbings. Bericht Nr. 83-41 aus dem Institut für Statik der Technischen Universität Braunschweig, Braunschweig

Leonhardt, F. und Horst, F.R. (1965). Vorschläge zur Bemessung und konstruktiven Ausbildun., Versuchsbericht, Verlag Ernst and Sohn, Berlin., Heft 175 Betongelenke

Thomée, B. (2005). Physikalisch nichtlineare Berechnung von Stahlfaserbeton-Konstruktionen. Dissertation, TU München.

Winkler, B. (2001). Traglastuntersuchungen von bewehrten und unbewehrten Betonstrukturen. Universitat Innsbruck.