

## Summary

### Aim

This thesis aims at the investigation of Tunnel linings in the serviceability (SLS) and ultimate limit state (ULS) with different reinforcements (concrete with reinforcing steel, with steel fibres and a combination of both). In addition to the optimization of reinforcement the tunnel lining has to be designed as thin as possible in order to reduce its bending resistance. The stiffness relation between soil and lining influences the bending moments of the lining. Therefore a reduced bending resistance of the lining leads to diminished bending moments and a growing membrane effect. This is advantageous, as a membrane effect results in a better utilization of the material concrete. The increased deformations of the lining induce a greater support reaction of the soil, that is the more thin the lining, the more less is its subjection to bending. The investigations refer to inner linings built of cast in-situ concrete and prefabricated segments, so-called tubbings. The tunnel has to be watertight. Physically nonlinear methods for the determination of the inner moments and forces taking cracking into account should be used to make use of reserves of the system and to obtain a realistic stiffness of the lining.

### Proceeding

The tunnel lining is subjected to various loadings during the way from casting to the final state. In order to investigate the decisive states, a comprehensive experimental programme was carried out. The tests were focussed on the behaviour of specimen, similar to a part of the tunnel lining under the circumstances of the SLS and ULS with respect to the prevailing action of bending moments  $M$  and compressive forces  $N$ . To control the specimen serving as a substitute for a part of the tunnel and a tubing a special test stand was developed to examine tubbings under the same circumstances. Based on the test results the existing rules for design (SLS and ULS) were examined with regard to suitability for the peculiar conditions of tunnelling (especially  $M + N$ ). After having developed design rules for the different reinforcements finite element analysis (FEA) on the system "tunnel-soil" was used to make investigations dealing with the essential parameters that are responsible for the limit state of watertightness (SLS).

### Results

It was found out that the existing standards for calculating the crack width of structural members consisting of unreinforced, conventionally reinforced, steel fibre reinforced and a mix of reinforced concrete and steel fibres do not fit for structural members subjected to bending moments and compressive forces. The additional compressive force leads to a reduction of crack widths and spacings. It was found out, that because of the great concrete cover the crack controlling influence does not reach up to the edge. Existing design rules were modified and new models were proposed. Existing laws for the calculation of the bearing capacity (ULS) were examined especially with respect to the bearing part of the steel fibres. Concerning the rotation capacity it was found out that the design rules for building construction cannot be transferred to tunnelling conditions and must be modified.

As the FEA of the tests with the developed material strengths and laws showed satisfying results, a comprehensive FE model existing of the lining and a simplified model for the soil was developed and used for reliability studies. After having derived on a probabilistic way the partial safety factors for soil and tunnel lining material in case of physically nonlinear methods of determining the internal moments and forces further parameter studies based on the FEA were done to find out the differences between the reinforcements. The reliability study shows that only the lateral pressure of the soil plays an important role in the SLS. Furthermore it is shown that the SLS and not the ULS is responsible for the design of the tunnel lining. With respect to an optimized lining a combination of reinforcing steel and steel fibres combined with a reduction of thickness of the lining come out from the tests and FEA to be the best choice in most cases. Diagrams for quick and easy design of tunnel linings with regard to SLS and ULS are placed at the users' disposal.

### Conclusion

The thesis provides the user with rules for an improved, technically as economically, design of tunnel linings. Steel fibre concrete leads to reduced cracks compared to conventionally reinforced linings. It is recommended to reduce the thickness of the lining as much as possible and to use a combination of reinforcing steel and steel fibres. The usage of nonlinear methods leads to a more realistic and economical design of tunnel linings.