Highly Deformable Shotcrete Lining – Design and Experience

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Abstract

Shotcrete has proved to be the most appropriate lining material for many applications when tunnelling through different types of rock mass. Under "squeezing ground" conditions the magnitude of deformation often far exceeds the deformability of the shotcrete lining. In order to provide more ductility and avoid damage to the support, one solution, first introduced in 1970, was the division of the shotcrete lining into circumferential "segments", leaving gaps between these "segmental arches". This approach in combination with a dense rock bolt pattern was successfully used on many alpine tunnels, on tunnel projects in foreign countries and in mines. The shortcoming of this support system is the missing thrust transmission between the lining "segments", resulting in a rather low radial support pressure.

Recently in Austria low-cost, yielding-steel-elements called LSC ("Lining Stress Controller") have been introduced. These consist of multiple steel pipes in a concentric assembly which are installed between the shotrcete "segments". This system proved to be very efficient in terms of reducing displacements and controlling stresses in the shotcrete support, hence avoiding failures of the lining, increasing support resistance and safety. Other objectives of such devices are lightness, ease of construction and a high potential of energy absorption with a constant average collapse load at failure. The capacity of the energy absorbing elements can be custom-tailored to individual requirements depending on the geological and stress conditions on site by using different combinations of steel pipe dimensions. Numerical simulation is used for the design of elements. The support system can be used with any type of lining e.g. concrete, steel, segmental, shotcrete etc.

Introduction

Large deformations -- "squeezing conditions" -- are observed frequently, when tunnelling through fault zones under high overburden. Problems in tunnelling with large displacements have been appreciated for decades and various techniques have been developed to cope with the difficulties.

A number of alpine tunnels [1,2,3] have been successfully constructed by using an approach, which was first introduced by Rabcewicz [4] at the Austrian "Tauerntunnel" (Figure 1).

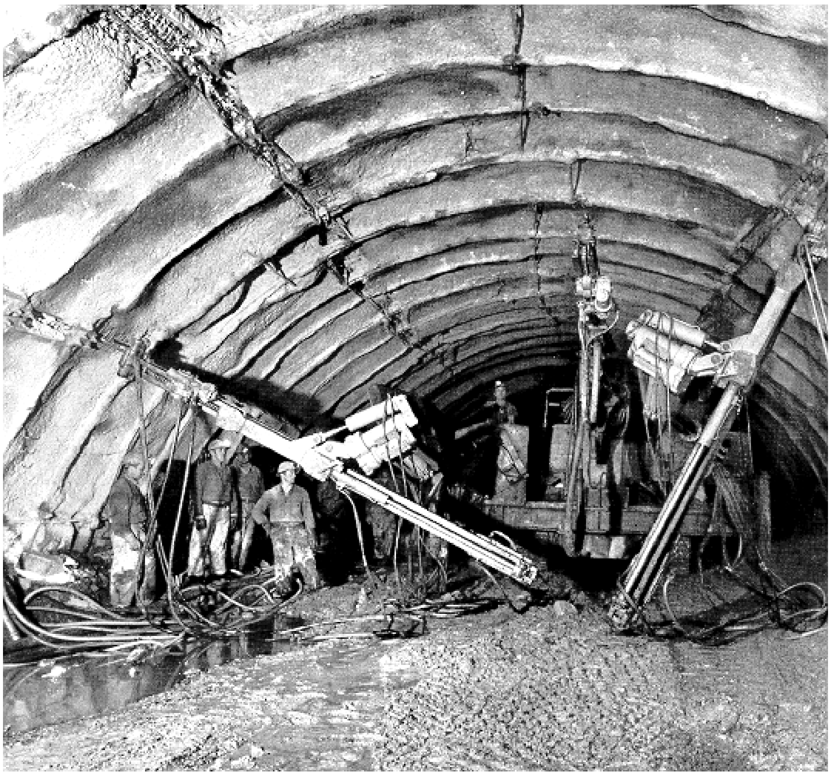

Figure 1: "Tauerntunnel" / Austria; Shotcrete lining with deformation gaps [4]

Longitudinal gaps were left in the lining to allow displacements without damage to the shotcrete. Additionally yielding steel arch couplings were used in the deformation gaps. A dense rock bolt pattern was utilised to increase the shear strength of the rock mass and to reduce asymmetrical deformation of the tunnel. This approach has also been successfully used on tunnel projects in foreign countries [5] and in mines [6].

The obvious shortcoming of this system is the low degree of utilisation of the lining capacity due to the missing thrust transmission between the lining "segments". This results in a rather low radial support resistance.

In recent years several attempts have been made to develop elements which allow a controllable deformation for integration in tunnel linings. However, no system for site application proved to be feasible.

Initial Application of a New Support System

For the very heterogeneous “Haberl Fault” at the “Galgenbergtunnel” in Austria low-cost, yielding elements consisting of groups of steel pipes were developed [7]. Such yielding-steel-tubes are a suitable energy absorbing device. The elements were installed in the longitudinal deformation gaps in a circumferential direction (Figure 2).

This system in combination with regroutable rockbolts led to a considerable reduction of displacements when compared to those which occurred by using a conventional support system in similar fault zones. Furthermore, an increase in safety was achieved.

Figure 2: “Haberl Fault”-“Galgenbergtunnel” / Austria; Yielding-steel-elements integrated in deformation gaps of the shotcrete lining [7]

For the application on site the steel pipes were assembled in groups and connected to base- and top plates. Final adjustment of the system to the shearing capacity of the shotcrete lining was performed on site by varying numbers and dimensions of yielding-steel-elements.

Laboratory Tests with the Prototype

Prior to the first application, laboratory tests were conducted with prototype cylinders having a height of H=400 mm, a diameter D=88.9 mm and a wall thickness of t= 2.9 mm (Figure 3). The steel pipe was perforated at the bottom by drilling a number of holes. This modification localised the onset of buckling at these perforations. It also reduced the peak load, to be always less than the low strength of the young shotcrete, in this way avoiding failures in the lining.

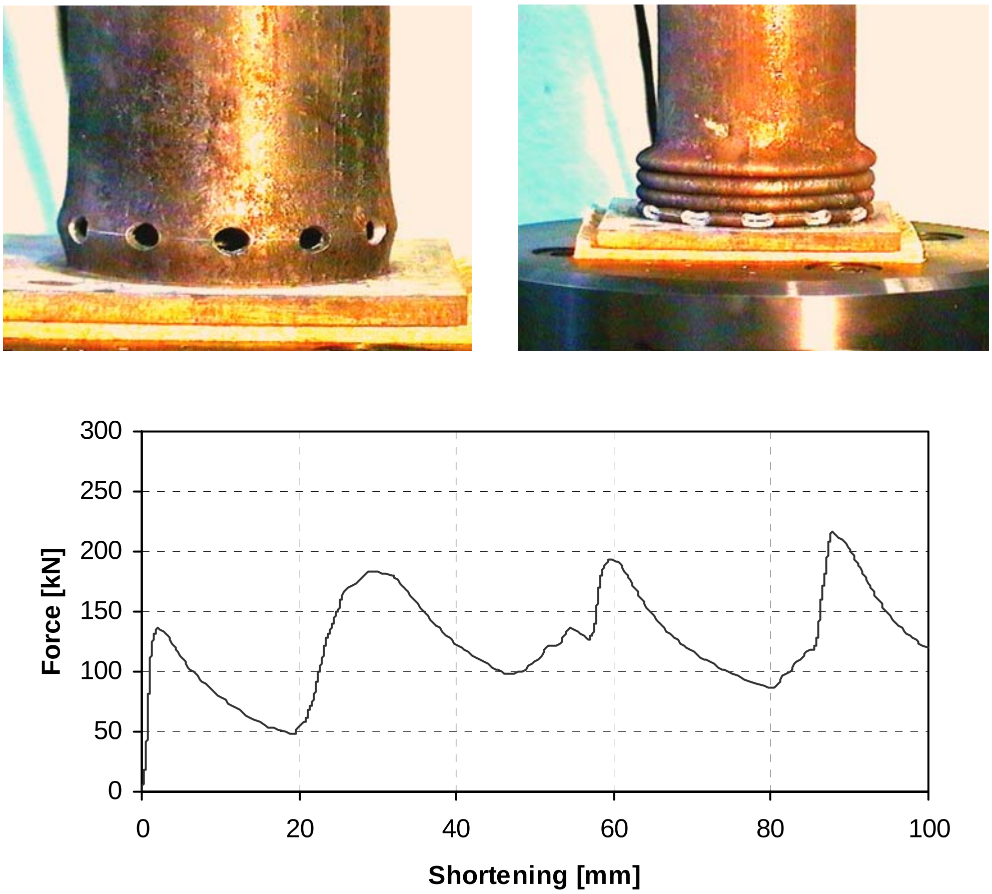

Figure 3: Yielding-steel-element with perforations; buckling modes (above) and corresponding load-displacement curve (bottom) in a laboratory test

One of the disadvantages of this type of yielding-steel-pipe is the extreme oscillation of the load-displacement curve (Figure 3). This effect is caused by a strong drop in load-bearing-capacity after initiation of buckling (in this case from a peak of 140 kN to a post-buckling load of 50 kN after a shortening of approximately 20 mm).

Another problem is the possibility of asymmetric buckling and non symmetric folding behaviour of the single tubes as observed on site, resulting in rhombic folds or buckling with webs. In this case the drop in load-bearing-capacity is even stronger. Figure 4 shows a group of yielding-steel-elements, which had been installed in a section of the “Haberl Fault”.

Figure 4: Asymmetrical buckling behaviour of yielding-steel-elements during a shortening of approximately 120 mm

Numerical Simulation of the Prototype

It showed that an optimisation of the system with laboratory tests alone is time consuming and costly. Consequently a finite element program [8] was used and the results verified by comparison with the laboratory tests.

First an attempt was made to simulate the deformation process of the prototype used at the Austrian “Galgenbergtunnel”. The test was performed on a tube with mild steel, with a height of H=400 mm, a diameter of D=88.9 mm and a wall thickness of t=2.9 mm. The tube lacked any imperfections. Figure 5 compares the results obtained from a laboratory test and its numerical simulation.

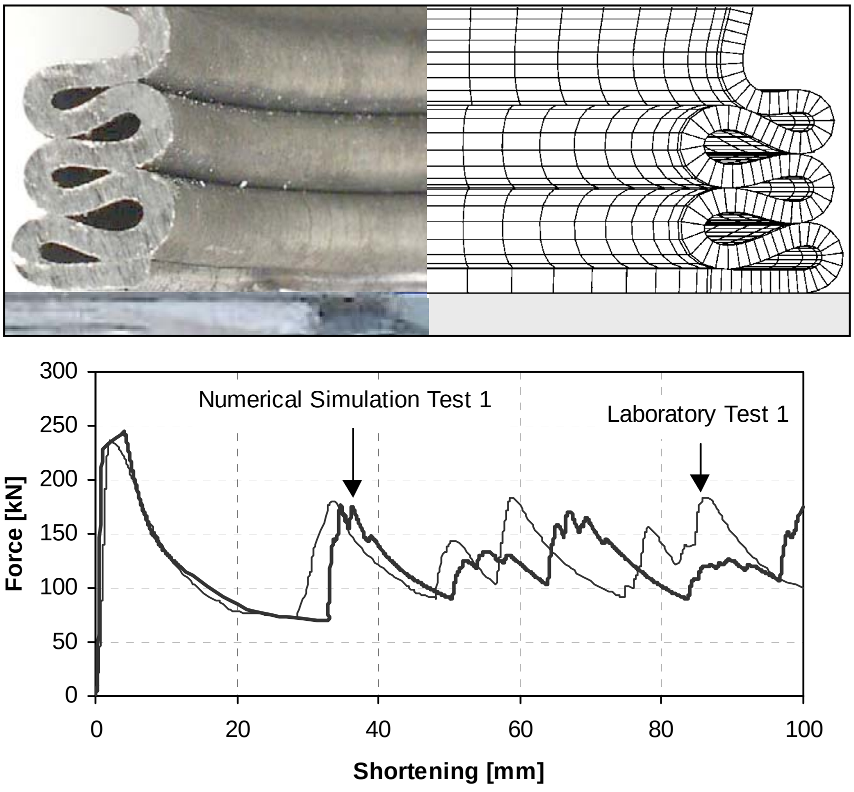

Figure 5: Comparison between laboratory test and numerical simulation; deformed yielding element after a shortening of 100 mm cut open across a diameter (above) and load-displacement curve (bottom)

It is evident from Figure 5 that the development of axisymmetric buckles with symmetric ring folds during shortening is practically identical in both laboratory test and numerical simulation.

In this case the load-bearing-capacity drops from a peak of approximately 245 kN monotonically to a post-buckling load of 80 kN. This means a strong decrease in load-bearing capacity. Due to self-contact of the inner surface, the load-bearing-capacity increases again until the next bulge occurs and the process continues.

An excellent agreement between laboratory test and simulation is evident from the correspondence between the peaks and troughs of the load-displacement curves.

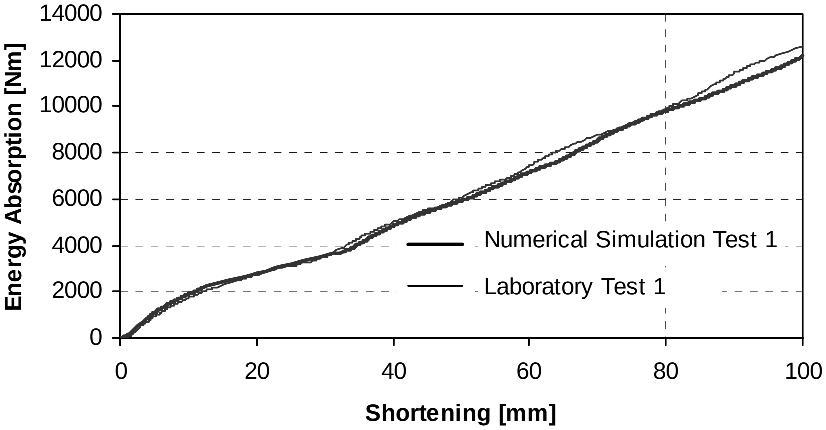

Figure 6: Comparison of energy absorption capacity during a shortening up to 100 mm

Figure 6 shows the rates of energy absorption up to a shortening of 100 mm and a total energy absorption of approximately 12.500 Nm. One can see that the development of energy absorption during shortening hardly differs between the numerical simulation and laboratory test.

Optimisation and Improvement of the Protoype

The optimisation process for improving the characteristic of the load-displacement curve and therefore increasing energy absorption of the system passed through several test phases with numerical simulations. A great number of calculations were carried out. The result of computer-aided optimisation of the system, verified by a laboratory test, is shown in Figure 7.

The investigation resulted in an arrangement of multiple concentric steel pipes termed “Lining Stress Controller” (LSC) [9,10]. One tube is compressed between an inner and outer steel pipe which restrain the folding. To restrain buckles developing at the top of the yielding element inner and outer tubes were added to the top plate as well.

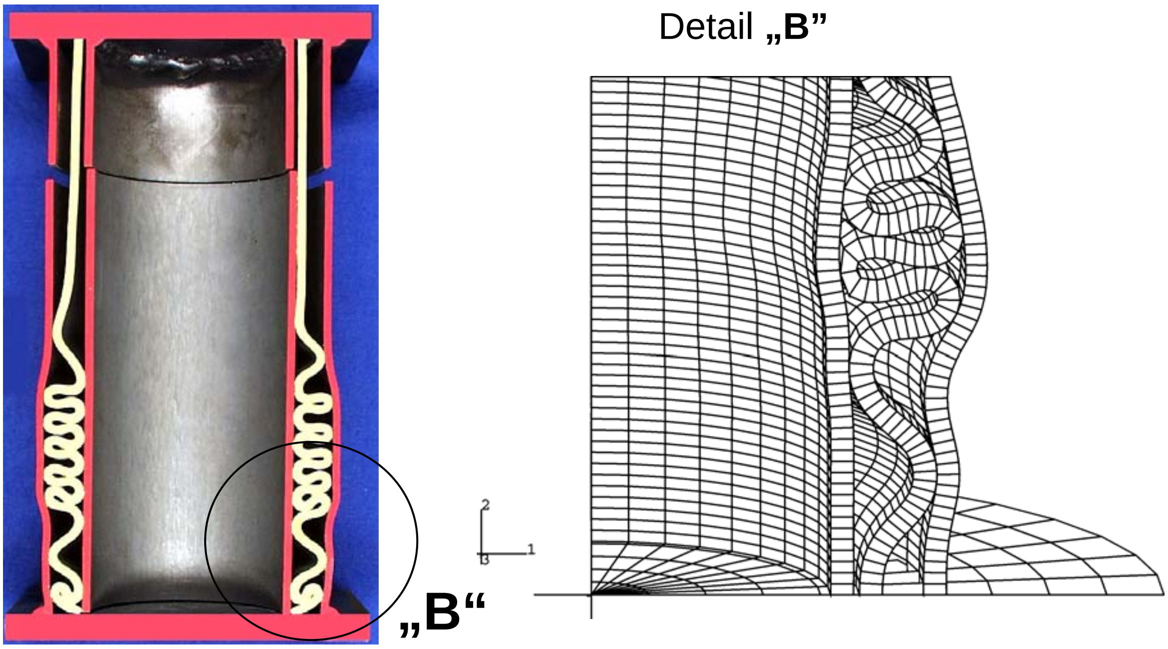

Figure 7: Deformation pattern of the improved yielding element (cut open across a diameter) after laboratory testing (left) and a detail of the numerical calculation result (right)

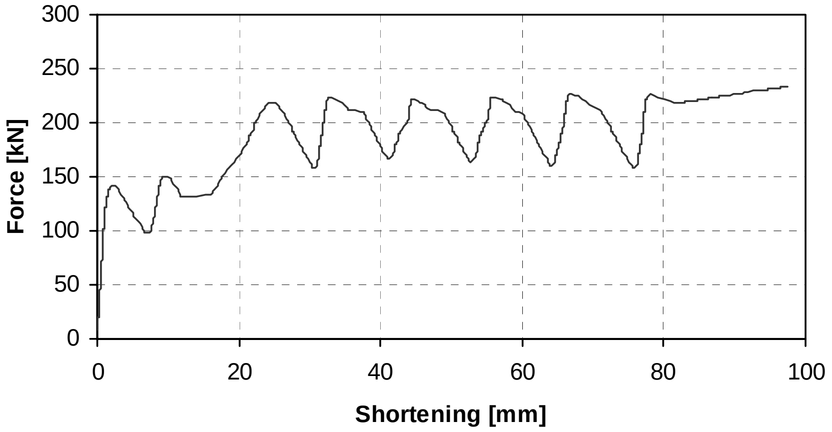

Figure 8: Load-displacement curve of the improved yielding element (laboratory test)

As can be seen from Figure 7 axisymmetric buckling conditions during the deformation process are ensured.

The improved system shows much less variation of loads (Figure 8). Compared to the load-displacement curve of the prototype the maximum load is at nearly 230 kN and the minimum at approximately 160 kN. The energy absorption capacity increases about 40% to 50% with the tested shortening of 100 mm.

Different LSC Types

Three LSC types for shotcrete application have been developed. The LSC type shown in Figure 7 has the designation A/I. The axisymmetric buckling modes and the corresponding load-displacement curve with a shortening of 100 mm of the LSC A/III type is shown in Figure 9. The yielding element was simulated with a height of H=400 mm, a diameter of D=139.7 mm and a wall thickness of t=6.3 mm. The load-displacement curve with peaks at approximately 850 kN and lows at 610 kN, shows again a nearly bi-linear characteristic.

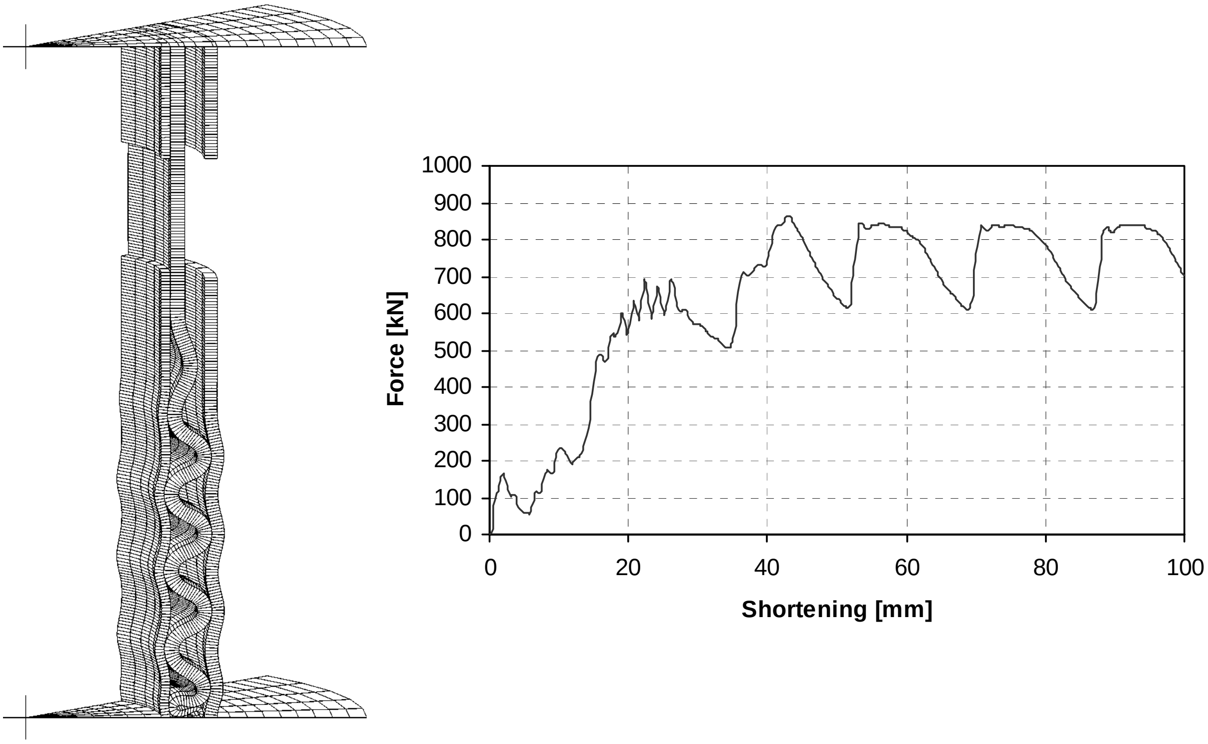

Figure 9: Numerical simulation result of the LSC A/III type; deformation pattern (left) and load-displacement curve (right)

Tuning of the LSC to the Bearing Capacity of the Shotcrete Lining

In the first field of Figure 10 a typical displacement history diagram of a cross section of a tunnel [2] is shown. In the vertical axis also the percentage of strain related to the excavation radius is entered.

In the second field the idealised load-displacement curve of two “Lining Stress Controllers” A/II type with a load-bearing capacity of 1.50 MN per unit length is displayed. To simplify the description the oscillating behaviour in this case is not shown.

The fourth field displays the time-dependent development of shotcrete strength obtained from the Austrian guideline for shotcrete [11].

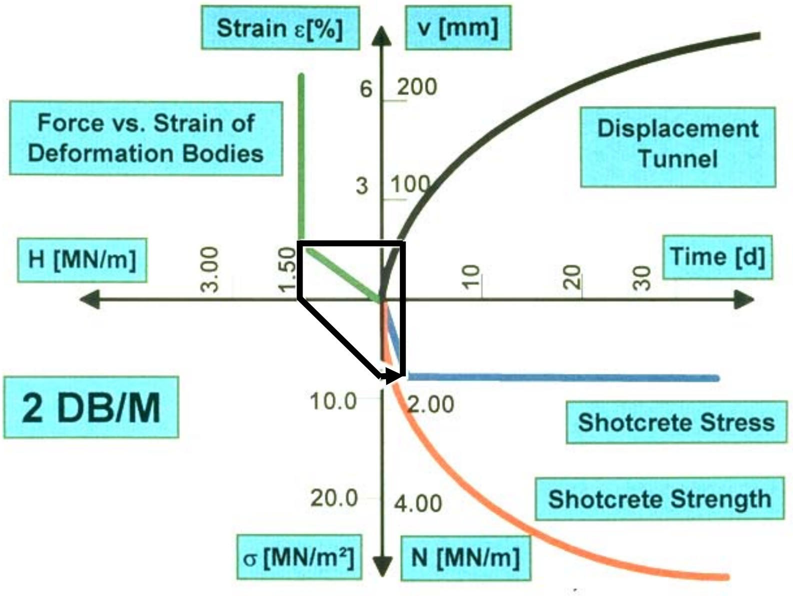

Figure 10: Correlation between load-displacement curve of “Lining Stress Controllers” with two elements per unit length, time-dependent deformation of the tunnel and time-dependent increase in shotcrete strength [12]

With the time-dependent deformation of the tunnel and the load-displacement curve of the two LSC’s, the corresponding stress and normal force can be calculated. The case is shown for a 20 cm thick shotcrete lining. It can be seen that the stress and normal force in the lining are well below the time-dependent development of the shotcrete strength.

Figure 11 shows the same example with six LSC’s per unit length. Here the stress and normal force which would be introduced by the yielding elements are considerably higher than the time-dependent development of shotcrete strength. In this case the lining may fail.

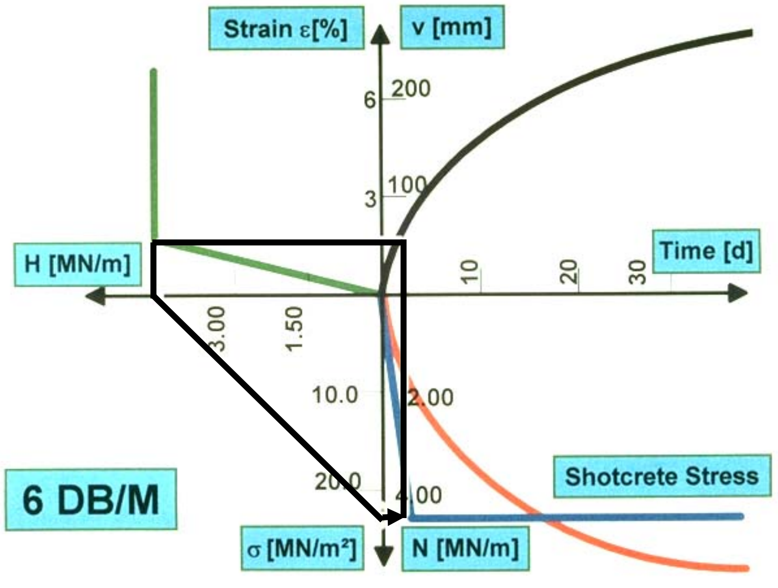

Figure 11: Correlation between load-displacement curve of “Lining Stress Controllers” with six elements per unit length, time-dependent deformation of the tunnel and time-dependent increase in shotcrete strength

Currently some work is being done to modify and improve this kind of nomogram.

Effect of the Yielding Support System

To verify the efficiency of the new support element LSC, numerical simulations with the two dimensional finite difference code UDEC [13] were carried out. Back analyses of a cross section of the "Hinterberg Fault Zone" at the Austrian "Galgenbergtunnel" were performed, where open deformation gaps had been used. In a second step the same section was computed with yielding-steel-elements integrated in the deformation gaps, but otherwise unchanged support.

The rock mass in this cross section consisted of mainly sheared greenschist, platy greenschist, an intercalated fault gouge, and sheared graphitic phyllite.

Figure 12 shows the monitored displacement vectors at the section under consideration. The maximum displacements were in the range of 600 mm.

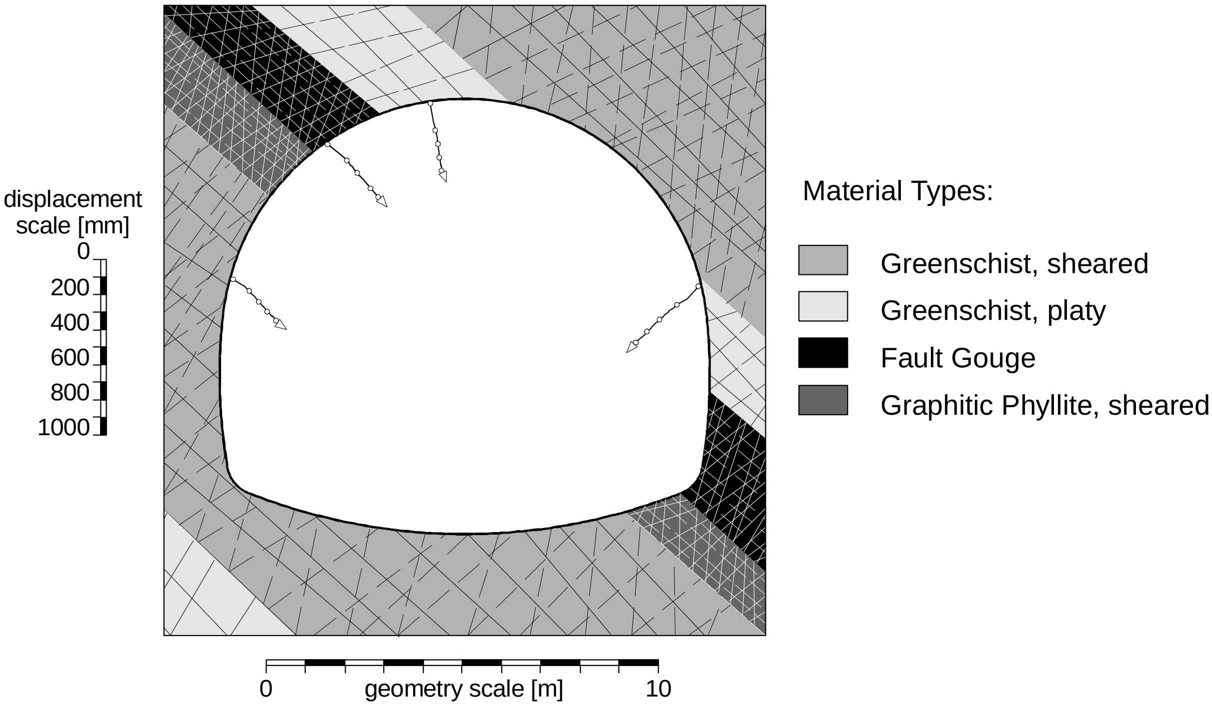

Figure 12: "Galgenbergtunnel" / "Hinterberg Fault Zone"; Monitored cross section at chainage 1194.0, displacement vector orientations, and magnitude of displacements

By using the support as installed on site, the computation showed heavy asymmetrical deformations of the tunnel (Figure 13). Considerable floor heaving and large deformations of the rock bolts. This was all observed during construction. The displacement vector orientations and amount of displacements especially at the left crown with approximately 500 mm compared well to the measurements on site (Figure 12).

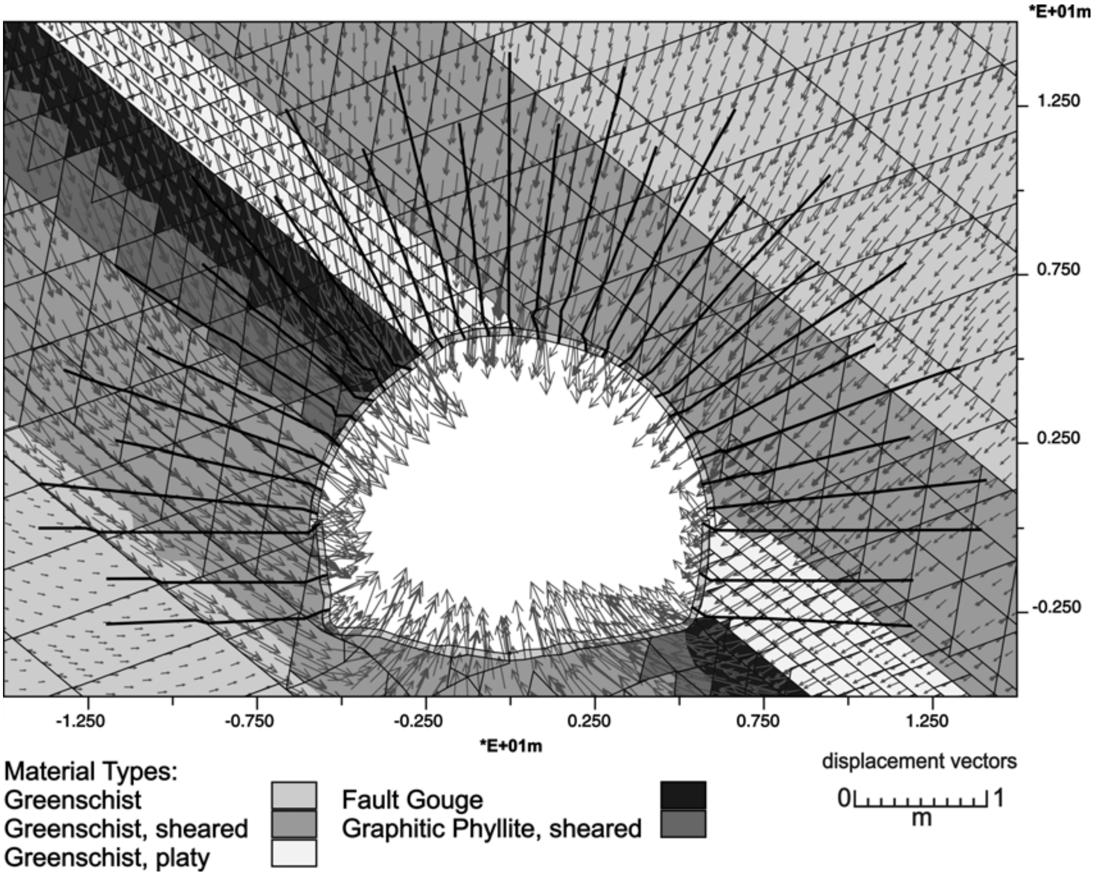

Figure 13: "Galgenbergtunnel" / "Hinterberg" Fault Zone"; Back analysis of a cross section at chainage 1190.3, Shotcrete lining with deformation gaps, displacement vector orientations, and magnitude of displacements

The numerical simulation with yielding-steel-elements installed in the gaps showed a reduction of displacements by more than 50% (Figure 14) compared to the support system with open longitudinal gaps. The yielding supporting elements lead to a better utilisation of the shotcrete lining, thus increasing the support resistance. The stresses in the lining are well below its capacity and failures of the lining were avoided. Favourable side effects are reduced shear displacements, a better stress distribution in the rock mass and, accordingly, reduction in the rock bolt loads.

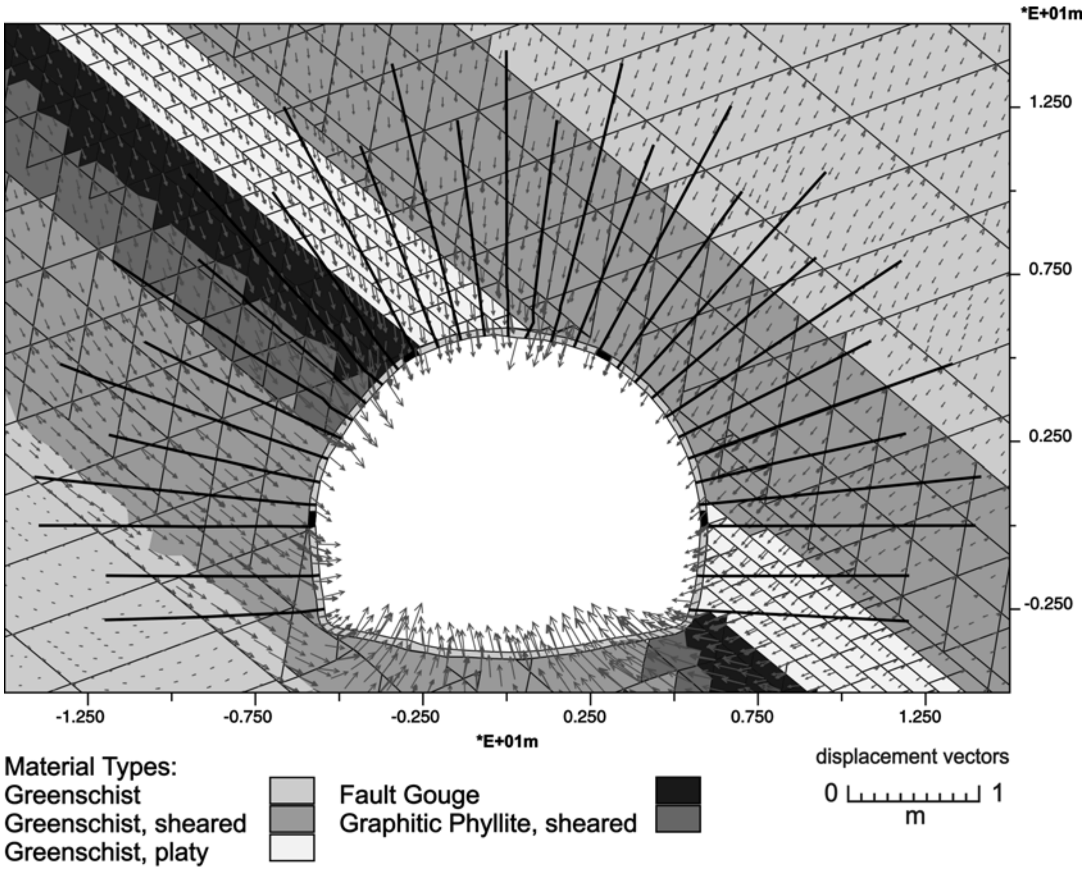

Figure 14: Analysis of the same section with yielding-steel-elements integrated in the deformation gaps, displacement vector orientations, and magnitude of displacements

Experience with the Improved Support System

The improved support system with the LSC A/I type was successfully used at the Austrian “Semmering” road tunnel S6 for the first time in September 1998 and at the “Semmering” railway tunnel in February 1999.

To show the effectiveness and advantages of the ductile support system in comparison with a conventional support in practice, a 100 m long profile enlargement in squeezing ground at the Austrian “Semmering” railway tunnel was excavated.

The first fifty metres have been constructed using a shotcrete-rock bolt-steel arch support. The diameter of the tunnel is 12 m and the shotcrete lining is 20 cm thick. The magnitude of the measured displacements ranged between 200 and 250 mm. In this case the deformability of the shotcrete lining was far exceeded.

Figure 15 shows two photographs of the heavily damaged shotcrete lining in this fifty metres section. A considerable amount of repair work was required.

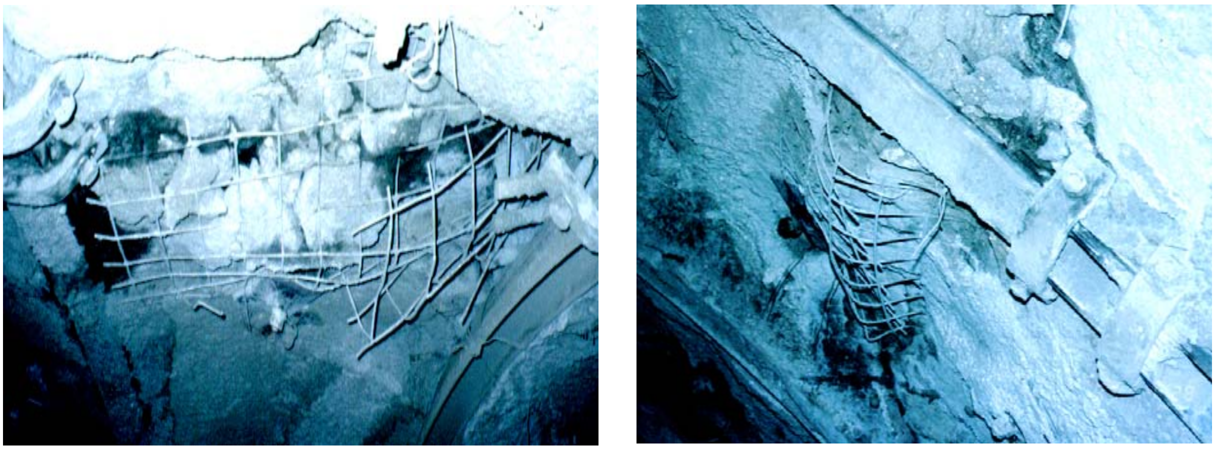

Figure 15: “Semmering” railway tunnel / Austria; two photographs of the profile enlargement constructed with a conventional shotcrete-rock bolt-steel arch support showing the damaged lining

The next fifty metres have been constructed with the new support elements but otherwise unchanged support. The shotcrete lining in the heading has been divided into four segments. “Lining Stress Controllers” A/I type units with a height of 350 mm were installed on the left and right sidewalls and in the crown between the “segmental arches”.

Figure 16 shows the ductile support system on the left side of the heading after approximately 150 mm of shortening of the LSC`s and after the deformation process. Due to the control of stresses and deformations in the support no failures and no damage occurred in the lining.

Figure 16: “Semmering” railway tunnel / Austria; improved support system with 150 mm deformed “Lining Stress Controllers” between the lining “segments”

Figure 17 shows a detail of the LSC A/I type unit, integrated between the lining “segments”, before and after the deformation process. To prevent shearing of the shotcrete close to the yielding elements, special care has to be taken to install the elements properly. A perfect alignment with the shotcrete lining should be achieved. In addition some shear reinforcement close to the LSC’s should be installed.

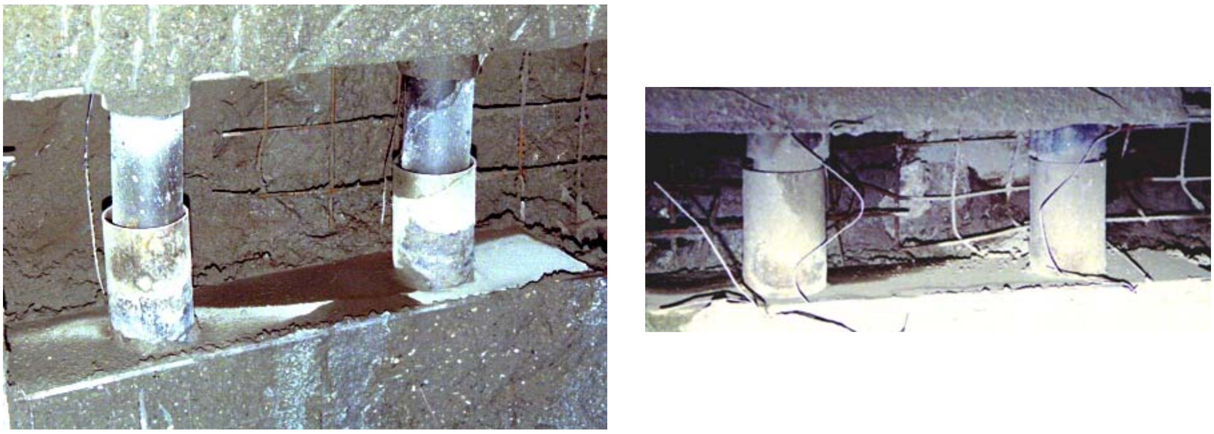

Figure 17: LSC A/I type unit installed in deformation gaps before (left) and after (right) deformation

Conclusion

A new tunnel support element was developed *
that:

- controls stresses in the lining
- avoids failures of the lining
- is tuneable to rock mass behaviour and to a selected support system by computer-aided optimisation
- optimises the utilisation of bearing capacity of the lining resulting in an increase in radial support resistance
- reduces displacements
- shows symmetrical buckling modes
- increases safety for the tunnelling crew
- is economical because inexpensive
- reduces the demand for repair and reshaping

The application of the yielding-steel-elements is not limited to rock-bolt shotcrete support, although for the time being the NATM is most commonly used for tunnels in squeezing rock. The LSC can also be used for steel supports as yielding couplings between the single arch sections. The application with segmental linings seems to be feasible as well, helping to extend the application of TBMs also to squeezing ground in future.

* A patent application is pending [14,15]

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