Segmental Lining

Investigations for a Convergence Compatible Lining System

Under »squeezing« conditions, a tunnel lining must have a certain structural capacity but also should allow a controlled development of deformations. The idea to use precast segments with external ribs was already presented. Laboratory tests showed the expected and intended characteristic of an initial stiff phase when the ribs get in touch with the rock, followed by a rather ductile deformation phase and a final stiff reaction again when the segments are fully in contact with the rock mass.

Squeezing is defined as long lasting large deformations, occurring as a result of tunnel excavation [1]. This means that a combination of failure due to overstressing, big deformations and rock mass disintegration occurs around the tunnel.

Using shielded TBM and segmental lining, the excavation system together with the lining must be able to cope with those phenomena as well in terms of high load bearing capacity as in terms of deformation compatibility.

For the lining system this means that the following must be considered in particular:

- Proper lining capacity higher than the TBM-shield capacity,
- Controlled development of the radial deformations behind the shield,
- Closed system to prevent rock mass losses,
- Simple working principle without decision requirements,
- Full compatibility with all types of lining under consideration on the whole project.

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In order to cope with these requirements a number of ideas already have been investigated [2] focusing on:

- A circumferential deformability of the lining,
- A deformable backfilling material in the annular gap between lining and rock mass, and
- A radial deformability of the system.

The last idea already was published as the »CO-CO« – convergence compatible lining system [2]. This system is a modular segmental lining system working with ribbed precast segments. The special idea is that the ribs are located at the extrados of the segments and support the rock mass initially while they allow a controlled radial deformation into the fields between the ribs and thereby allow the convergence development related (*figure 1*). It is interesting to note, that *Rabcewicz* already in 1944 proposed a similar system for conventional excavations [3].

At the intrados the segments are showing a plain face which is identical to all common segments and which allows water transfer at low roughness or the application of a sealing membrane or an inner lining without restrictions. A further feature of that system is its compatibility with other segments, with a heavy or slim full section for instance.

Within the first publication of the »CO-CO« segmental lining system a research programme has been proposed which now has been carried out. The lining investigations were based on the basic idea of the »CO-

CO-CO System composed of »ribbed« segments

Figure 1. *CO-CO System composed of »ribbed« segments [2].*

CO« system of ribbed segments [2] and the targets were:

- Verify or optimize the geometrical shape of the segments and the ribs,
- Obtain the load deformation behaviour of the system,
- Test the segment material technology,
- Test different reinforcement concepts, and
- Test the suitability for industrial production.

Ribbed segment design

As already outlined above, a lining system in squeezing conditions must offer both, a certain load bearing capacity together with a certain ability to allow controlled radial deformations. Due to experience and due to project studies, a common lining load bearing capacity of about 1 to 2 MPa combined with a radial deformation allowance of about 35 to 45 cm is covering a wide and common range in Alpine TBM tunnelling.

As already lined out in [2] the convergences to be considered available in TBM tunnelling can be added as follows:

- Shield range + overcutting + annular gap: from the gauge cutters towards the external segment (ribs) diameter ≈ 15 cm radially,
- Ribs: ≈ 10 to 15 cm,
- Preconvergence: ≈ 1/3 of total convergence ≈ 10 to 15 cm radially,
- In total: ≈ 35 to 45 cm allowance of radial deformations.

The ribs are located at the extrados of the segments forming »supporting-rings« and »expanding-fields« in between (see *figure 1*).

Lining system

The requirements for ribbed segments are (*figure 2*):

- Possibility to combine ribbed segments with other segments,
- Smooth and plain inner surface,
- Installation with standard equipment,
- Simple and high performance serial production.

Physical model tests

The target of the physical model tests was to determine the load deformation behaviour of the ribbed segments in squeezed rock. In a first step the »squeezed rock« had to be defined for the tests. This was based on the experience with the »squeezing« phenomenon at TBM excavations. As it could be seen in numerous cases, under squeezing conditions the rock mass is already disintegrating in front of the face and around the cutter head. When the disintegrated rock mass is passing

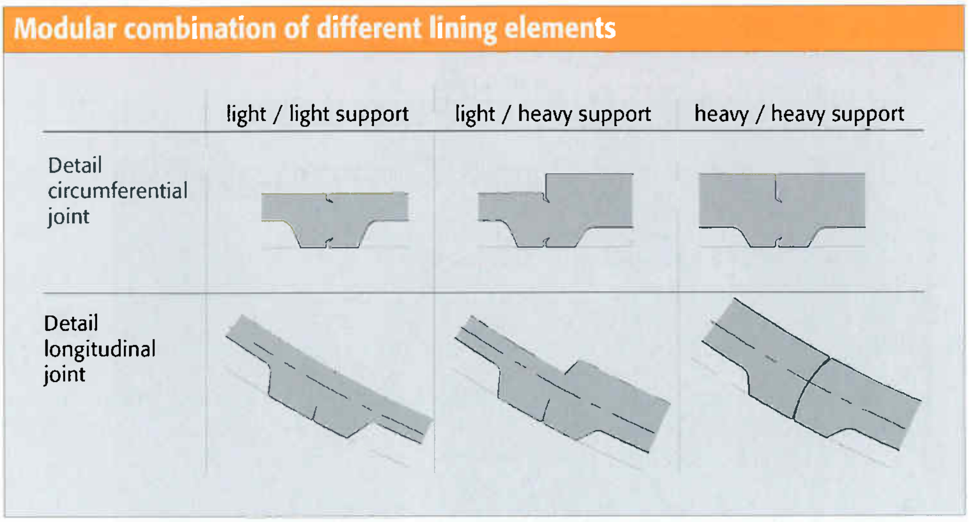

Figure 2. *Modular combination of different lining elements [2].*

UCS of the »artificial rock«

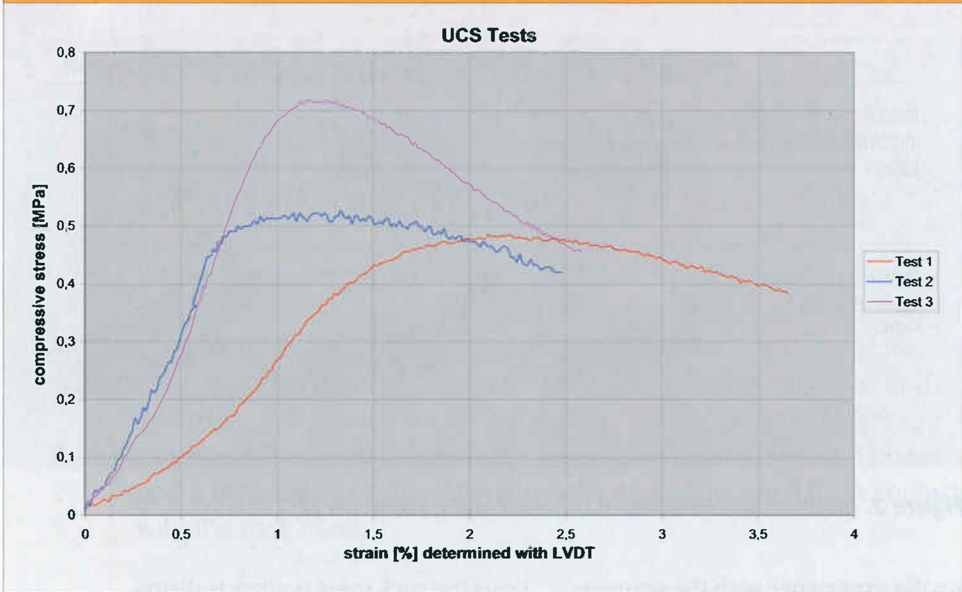

Figure 3. *UCS of the »artificial rock« for the physical model tests with 0.48, 0.52 and 0.72 MPa.*

Test arrangement

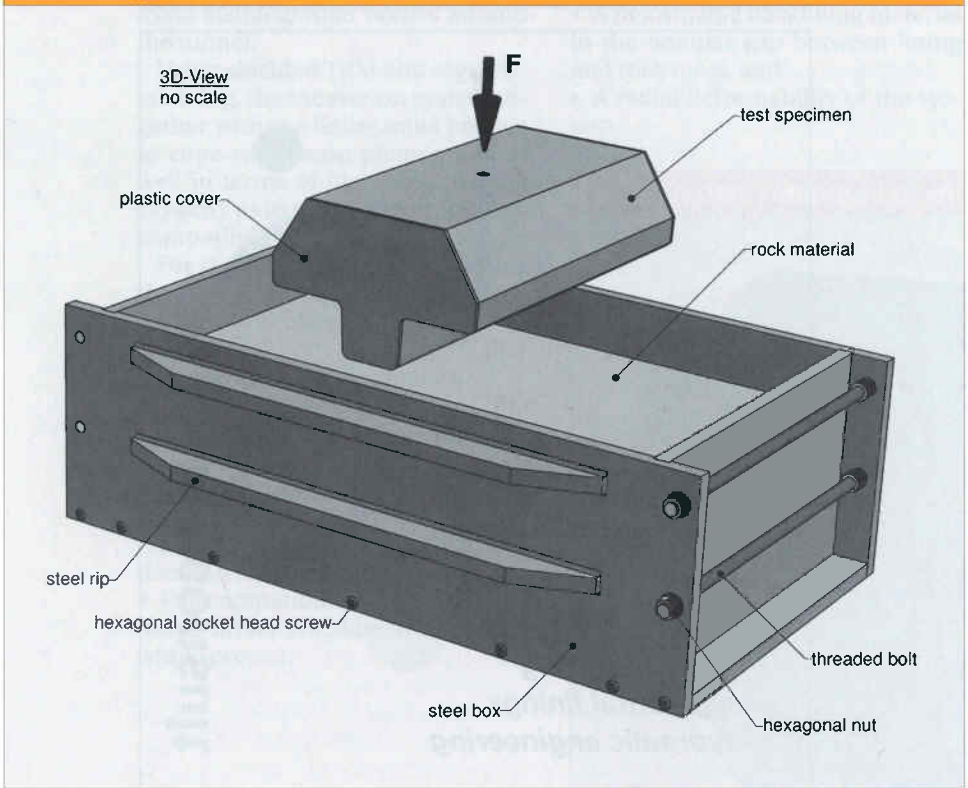

Figure 4. *Test arrangement consisting of a segment rib and »squeezed rock«.*

the shield section it is physically »re-compacted« by the resistance of the shield. This pressure in practice is limited by the shield capacity which commonly is within the range of 0.5 to 1 MPa. The »re-compacted« rock mass now is passing from the tail of the shield to the segmental lined section where it is disintegrating or deforming again towards the annular gap and is »re-compacted« a second time when it gets in contact with the lining.

In case of the ribbed segments a first support on the squeezed rock should be provided by the ribs in the initial phase behind the shield and disintegration or deformation should be allowed in-between them afterwards. The strength of the »re-compacted« rock mass behind the shield is rather low and was estimated between 0 (self disintegrating) to ≈1 MPa (well compacted).

For the physical model tests the »squeezed rock« was modelled as a weak concrete with weak aggregates (schist) slightly bound with cement to gain a UCS around 0.5 MPa (*figure 3*).

The test setup included a steel box formwork for the »squeezed rock« (*l*, *w*, *h*: 800, 480, 200 mm) and 480 mm long »testing ribs« with a rib width of 80 mm and a rib height of 70 mm (*figures 4* and *5*).

A number of test series was carried out with different artificial rock mixtures to obtain the load deformation behaviour (*figure 6*). In the first phase, when the ribs get in contact with the rock, load increases rather quickly. In a second phase, when the ribs penetrate the rock mass, the reaction is quasi ductile, with a more or less constant load until the rock mass gets in contact with the segment itself. In the last phase, the load again is increasing rapidly with further displacement.

Figures 7 and *8* are showing how the ribs have penetrated the artificial rock and *figure 9* is showing the related load deformation behaviour. For the interpretation of the test results it must be considered, that the test box had a limited length (800 mm) which obviously somehow did affect the failure and in practice the ultimate stress of the first failure must be estimated somewhat lower. In addition it must be considered that the height of the test ribs was 70 mm thereby marking the point of the increased gradient of the load deformation curve after the ribs have penetrated the »squeezed rock«.

Industrial investigation programme

During the industrial investigation programme the following topics have been investigated:

- Formwork,
- Concrete recipes,

Test ribs geometry

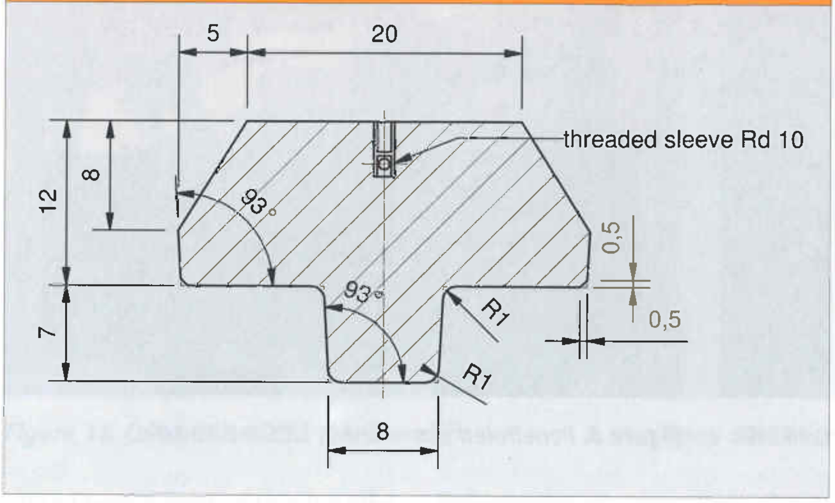

Figure 5. *Test ribs geometry.*

Test arrangement

Figure 6. *Test arrangement (compression frame) at rock mechanical laboratory of the Graz University of Technology.*

- Reinforcement,
- Production.

The target of the »formwork investigations« (*figure 10*) was to gain slim ribs at the end of the formwork with a high quality (*figure 11*). The »concrete recipe« had to be optimized in order to achieve a concrete

Figure 7. *Penetrated ribs – test 1: UCS = 0.48 MPa.*

Figure 8. *Penetrated ribs – test 2: UCS = 0.52 MPa.*

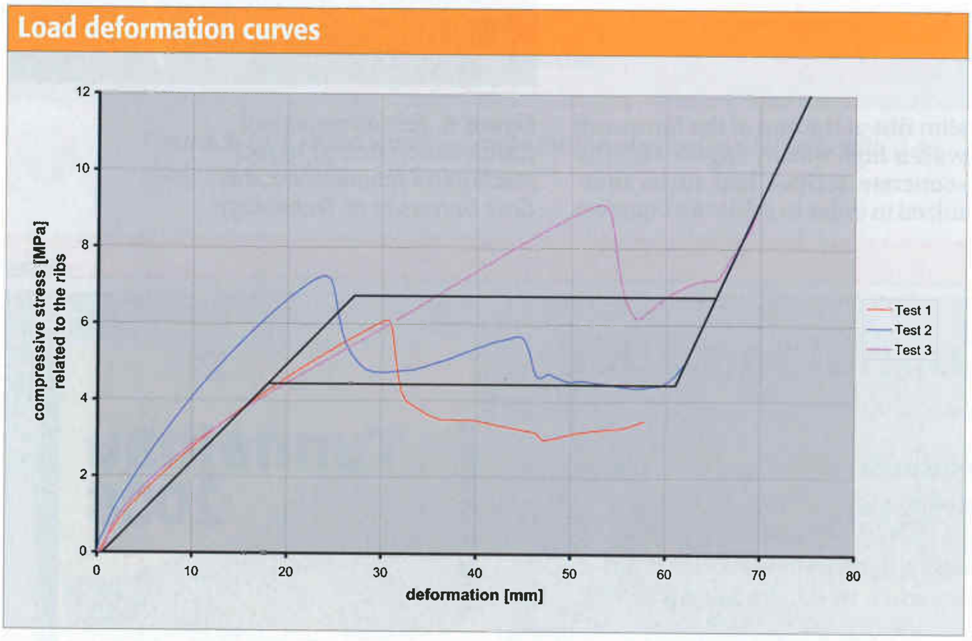

Figure 9. *Load deformation curves.*

Figure 10. *Special moulds for ribbed segments.*

with a liquid consistence and a stable behaviour at the beginning to allow a good filling of the ribs and to avoid any aggregate separation and to gain a early high strength for short demoulding cycles. The target of the reinforcement tests was to find an economical design for a conventional reinforcement and to compare a conventional reinforcement with steel fibre reinforcement. During the »production tests« the industrial production was optimized in fabrication as well as in handling and storage (*figure 12*).

Results of investigations

The test results and the load deformation curves gained during the physical model tests are well confirming such behaviour. The design of the ribs width is used to control the penetration force while the ribs height allows controlling the limit of the »yielding« deformation phase.

The ribbed segments can be produced efficiently with common concrete and conventional reinforcements or with steel fibres. The material technologies to be applied are not limited to the ones which have been investigated during the research programme.

Due to the feature, that the ribbed segments have the ribs on their extrados but are identical to common segments on their intrados, they can be combined with common segments in a modular way without restrictions. And if no squeezing appears, the ribbed segments are commonly backfilled with standard backfill material.

So the results of the research programme can be summarized as follows:

Conventional ribs reinforcement

Figure 11. *Conventional ribs reinforcement.*

Serial production of ribbed segments

Figure 12. *Serial production of ribbed segments.*

- Confirmation of the need for ribbed segments,
- Suitability of the gained load deformation behaviour,
- Confirmation of the geometrical shape of the ribs,
- Suitability of common material properties,
- Suitability of industrial production,
- Suitability to be applied within a modular lining system.

References

[1] ISRM: Definition of the ISRM Commission on Squeezing Rocks in Tunnels. Italian Geotechnical Journal, 34, No 1.

[2] *Vigl, A.*: TBM Support in Squeezing Rock – a Convergence Compatible Segmental Lining System. Felsbau 21 (2003) No. 6.

[3] *Rabcewicz, L.v.*: Gebirgsdruck und Tunnelbau. Vienna: Springer, 1944.

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