Recommendations for the design, production and installation of segmental rings

Deutscher Ausschuss für unterirdisches Bauen e. V.
German Tunnelling Committee (ITA-AITES)

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Abstract

The recommendations give an overview of the state of the art for the design, the production and the assembly of the tunnel lining made of precast segmental rings. They were executed by the working group “Segmental Ring Design” of DAUB (German Tunnelling Committee). The recommendations give a résumé of the construction fundamentals and the necessary calculations and verifications for the dimensioning of the precast segments according to the actual standards. Moreover they give references for the design of transverse constructions to cross passages and portal buildings. Also treated are the dimensioning for fire loads and the use of steel fibres.

1 General

1.1 Purpose of the recommendations

The recommendations for the design, production and installation of segmental rings were prepared by the German Tunnelling Committee (DAUB) working group „Lining Segment Design“. They are intended to reflect the state of the art in the field of tunnel linings using precast concrete components and comprise a basis for the design and calculation of the segment rings with regard to serviceability properties, construction and quality assurance.

The findings and experience from design practice already available and regulations already published, such as Guideline 853 of the DB AG [1], the ZTV-ING Part 5, Section 3 [3] and the corresponding Austrian guideline [48], Concrete Lining Segment Systems, are summarized below and presented in relation to one another. Recommendations are thus provided for the production of qualitatively high grade tunnel linings to ensure their usability over a service life of about 100 years with low maintenance costs.

1.2 Scope of application

The recommendations can be applied for the manufacture of linings made of precast reinforced concrete or steel fiber reinforced concrete parts (reinforced concrete or steel fiber reinforced concrete segments) in traffic tunnelling, for water tunnels (headrace tunnels for hydroelectric power stations, drinking water tunnels, waste water tunnels) as well as in infrastructure tunnelling. They deal mainly with one-pass segmental lining, where particularly high demands are placed on the individual segment and on the ring system. They can, however, also be applied mutatis mutandis for lining segment systems without sealing and two-pass lining as well as for shaft construction with segmental lining.

1.3 Definitions

To prevent conceptual (mis)interpretations, the key technical terms used are summarized and explained below.

Sealing system Sealing system consisting of sealing strips (sealing frames) that enclose each individual segment and in the interaction of all the segments as a shell ensure permanent sealing of the tunnel tube against groundwater.

One-pass lining All static and structural requirements of the tunnel lining are handled by the segmental ring. No further internal concrete shell is installed that contributes to load bearing or sealing. The annular gap grouting mortar and any fire protection linings on the inner side of the lining segment, if they have no static or sealing function, do not count as an additional shell.

Tapering („conicity“) of the segmental ring Difference between the maximum and minimum ring width (dimension of the ring in the longitudinal direction of the tunnel).

Longitudinal joint Periphery and contact area between the lining segments within a ring. The longitudinal joints run approximately parallel to the tunnel axis.

Mechanized tunnelling Tunnelling using a tunnel boring machine (TBM), where the individual operations of loosening, loading and installing support are carried out mechanically in a fixed working cycle.

Ovalization Deformation of an initially circular segmental ring e. g. to a vertical or horizontal oval shape.

Crosscut (cross passage, connecting tunnel) Connecting structure between two tunnel tubes or between a tunnel tube and the ground surface or a shaft, with special transition structures in the service area (usually connection in the side wall area) of the main tube. The cross-sectional design is dependent on the intended purpose.

Ring joint Joint practically perpendicular to the tunnel axis between two adjacent segment rings (also called circumferential joints).

Ring coupling Statically effective connection between two adjacent segmental rings, for example, by means of connecting elements across the ring joint such as dowels, tongue and groove or cam and pocket designs, or by the friction in the ring joints (friction coupling), which is generally activated by residual longitudinal forces from the drive of the TBM.

Ring width (lining segment width) Dimension of the segment ring in its center axis in the longitudinal direction of the tunnel (mean ring width).

Annular gap Space between the excavation cross-section in the ground or rock and the outer surface of the segment ring.

Annular gap filling, annular gap grouting, annular gap blowing Process of filling or grouting the annular gap with mortar or blowing pea gravel into the annular gap to produce a frictional connection between the subsoil and the segmental tube.

Shield driving Tunnelling with a TBM with a front steel jacket in which the excavating and driving equipment are housed (cutting edge and center shield), and a rear steel jacket in the protection of which the segmental ring is installed (tailskin).

Segment Curved prefabricated element made of concrete (reinforced concrete/steel fiber reinforced concrete), steel, cast steel or cast iron for lining rock cavities of tunnels, galleries and shafts.

Segment thickness Distance between the inner and outer sides of the lining segment.

Universal ring Tapered segmental ring, where the ring can be installed in any possible position of the key segment (i.e. also with key segment positions in the invert).

Connections Connecting elements subjectable to tensile stress and shearing for temporary or permanent fixed connecting of two segments or segmental rings in the longitudinal and ring joints (e. g. bolts, dowels).

Two-pass lining Tunnel lining consisting of two shells with different structural and constructional requirements which are produced in independent operations and with different construction methods (e. g. outer shell segment lining, inner shell in situ concrete).

1.4 Abbreviations

CEN	Comitée Européen de Normalisation (European Standards Committee)
DIN	Deutsche Industrie Norm (German Industrial Standard)
EPDM	Ethylene propylene diene monomer
GW	Groundwater
ISO	International Standardization Organization
QM:	Quality management
QSS	Quality assurance system
SM	Shield tunnel boring machine
TBM	Tunnel boring machine
TBM-DS	Double Shield TBM
TVM	Tunnel boring machine
SLS	Serviceabilty limit state
UPL	Limit state with a loss of equilibrium of the structure or of the ground as a result of floating by water pressure or other vertical actions (uplift)
STR	Limit state of failure or very large deformations of the structure or its parts (structural)
GEO-2	Limit states of the ground where verification method 2 is applied
GEO-3	Limit states of the ground where verification method 3 is applied
BS-P	Permanent design situation
BS-T	Temporary design situation
DSV	Jet grouting method

2 Overview of typical lining segment systems

The typical concrete segment rings can be divided into various systems (Figure 1).

Fundamentally a difference can be made between rings with flat ring end faces (ring joints) and rings with offset ring joints (hexagonal or honeycomb segment rings).

With the rings with flat ring joints, a difference is made between tapered and parallel rings.

Notes on the ring types:

a) Rings with flat ring joints
With this, by far the most frequently used type of ring; usually 6 to 9 individual segments are assembled to form a complete ring.

b) Tapered ("conical") segment rings
In order to allow installation of the segments horizontally and vertically without secondary bending even with curve drives, the ring geometry must be executed accordingly: on the outside of the curve the ring width in the longitudinal direction of the tunnel must be made somewhat greater, on the inside of the curve somewhat smaller. The simplest implementation is with tapered segment rings which can be twisted against each other as desired when installed (universal ring). The greatest ring width can be at any point of the circumference. Rings tapered on one side and on both sides are possible. One-sided tapered rings, with the *sloping side at the back in the driving direction*, are more suitable for immediate corrections when installing in the tailskin.

If the key segment is to be installed above the side wall if possible, in the top area of the ring, two separate rings must be used ("left and right ring").

c) Expanding segment rings
Expanding segment rings are mostly used in two-pass lining as simple rock stabilization. The segment ring is preassembled in the greatly simplified tailskin (without tailskin sealing) with a laterally tapered key segment shorter in width. After the TBM has moved forward, and the ring has left the tailskin, the key segment is pushed further into the ring and thus the entire ring is expanded so far apart that the segment ring abuts the rock. Filling the annular gap can thus be dispensed with. Expanding segment rings can only be used on their own in at least temporarily stable, non-water-bearing subsoil. For a watertight tunnel, groundwater drainage during construction and an inner shell for the final state are imperative.

d) Economical segment ring with reduced requirements
The economical segment can be used as a simplified ring where the main loading will only occur after installa-

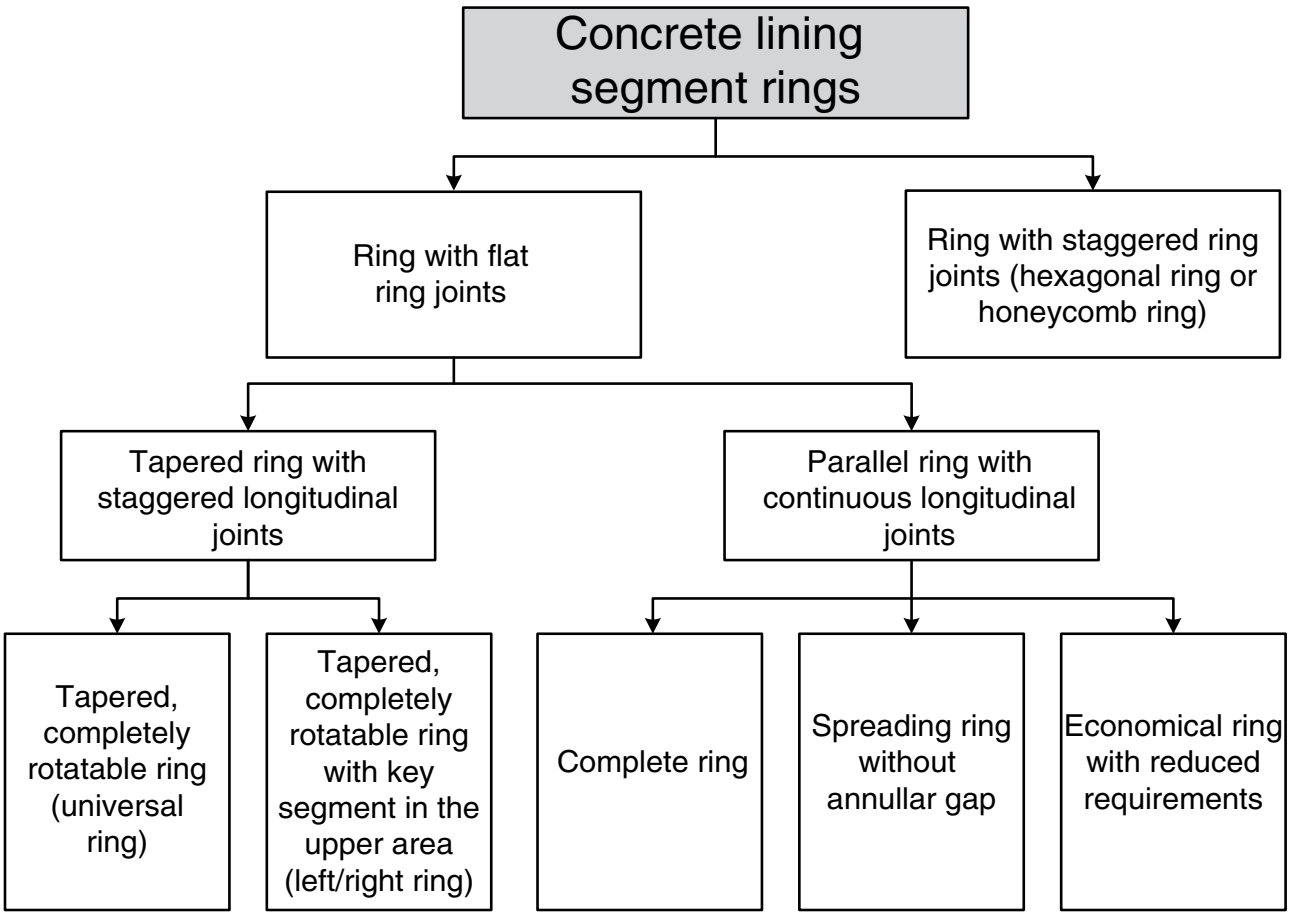

Figure 1: Classification of concrete lining segment rings in ring types

tion of the inner shell, for example when tunnelling with groundwater lowering or in swelling rock. Damage to the segment ring can be tolerated as long as there is stability.

This type of ring can also be used as a variant for situations in which the segmental ring is removed after a temporary function, for example to pass through non-dug pits for shaft or station constructions.

e) Rings with offset ring joints (hexagonal or honeycomb segmental rings)
This type of ring is very easy and quick to install and is therefore used in particular in the construction of water tunnels in hard rock with low groundwater ingress. The concrete segments all have a hexagonal shape and are not bolted together. After tunnelling half a segment length, half of the segments of a complete ring are installed.

With this ring type, a watertight lining is not readily possible. For curve drives the resulting gap in the ring joints must be compensated by installing intermediate layers of varying thicknesses.

The tunnel can be pretensioned by deep rock injections; the installation of an inner shell is also possible.

f) Other ring types
In hard rock in particular, other ring types are also used:

- Rings with special invert segments
- One-pass parallel ring system in head-race construction
- Two-pass ring system with umbrella sealing
- One-pass lining in the invert and two-pass lining in the crown

With all rings one can differentiate between one-pass and two-pass lining. In Germany one-pass lining is usual. In Austria and Switzerland, many large-diameter tunnels, especially in hard rock, are constructed with two-pass lining (outer shell: segment, inner shell: reinforced and plain in situ concrete). With the two-pass ring a parallel ring is usually used.

With one-pass lining the relationships regarding load transfer are clearly identifiable as the segment ring must handle all external and internal influences. With two-pass lining the load handling by the two shells depends on various factors. Usually it is assumed that the segment ring as the outer shell without sealing handles all external influences (except water pressure) and the in situ concrete inner shell deals with the internal loads and, in the case of water pressure-retaining sealing, has to handle the water pressure.

3 Segment design

3.1 Description of the one-pass precast segmental ring

3.1.1 General aspects of tunnel lining

The lining of tunnels built by underground construction must fulfill several requirements both during construction as well as in the final structure:

- Securing the rock to prevent rock falls
- Handling the effects of dead weight, loading, rock and groundwater
- Sealing the tunnel against groundwater
- Mounting system for equipment components (for example catenary, lighting, fans)
- Absorbing the tunnelling and steering forces of the tunnel boring machine

In lining with one-pass reinforced concrete segments the segmental ring must handle all of the above-mentioned tasks.

When the segmental ring leaves the TBM, it can absorb loads immediately. After annular gap grouting or backfilling it has largely reached its ultimate load bearing capacity. Because reinforced concrete segments are manufactured in a precast plant with extensive quality control capabilities, the quality is usually high and consistent. By means of compression sealing frames the tunnel is immediately sealed against the prevailing groundwater pressure.

Annular gap grouting, best done through the tailskin, is performed continuously with the advance. It results in an equalization of the actions on the segmental ring and ensures immediate bedding.

The segmental ring forms a hinged ring which receives its stability mainly through the bedding in the surrounding rock. Coupling possibilities across the ring joints and the absorption of moments in the longitudinal joint hinges by eccentric normal force transfer contribute to the ring load bearing capacity.

To avoid cross joints, the lining segments are usually installed offset from ring to ring. Cross joints should be avoided in general or are only permissible to a limited extent.

3.1.2 Ring geometry

In determining the ring inner diameter, care must be taken to ensure that sufficient access tolerance is provided for. In Europe a tolerance radius for the shield drive of R = ±10 cm is usually allowed for, i. e. the diameter of the tunnel is made 20 cm greater than the required internal structural boundary. In particular with long tunnels of over 10 km the measurement tolerances and in some cases the breakthrough conditions can require an additional allowance. With two-pass lining the tolerance requirements can be reduced in some cases.

The segment thickness is based on static and structural factors (e. g. sealing details, durability) and is generally between 15 and approx. 75 cm. With one-pass lining with compression joint strips the thickness should not be under 30 cm.

Depending on the diameter, the ring width is approximately between 0.75 and 2.50 m.

For curve drives tapered rings are used. The required tapering (k) can be calculated with the following formula:

$$k = \frac{Ø_A \cdot b_m}{R}$$

with:

k	tapering (difference of maximum to minimum ring width)
$Ø_A$	outer diameter of the segmentring
b_m	mean ring width
R	minimum curve radius

A correction curve drive in the event of failed drives must be taken into consideration. The correction curve radius should be at least 20 % less than the smallest desired curve radius horizontally and vertically.

Because the tunnel boring machine never follows the intended curve exactly, tapered segment rings should also be used for straight tunnel projects. This is especially true when using intermediate layers in the ring joints, as these are unevenly pressed together by varying jacking pressure. For straight tunnel sections the correction curve radius should be chosen according to the control options of the tunnel boring machine (for example $R_{Correction}$ = 400 m).

It should only be planned to use straight rings (parallel rings) as special rings, for example when steel segments are used in the region of later crosscuts.

It must also be taken into consideration that with offset longitudinal joints the tapering cannot be fully exploited because the maximum/minimum can only be arranged within the parameters of the existing longitudinal joint offset in the ring.

The tapering should be planned on one side and on the rear side of the segment ring in the direction of tunnelling, as this is the only way the new ring being built can immediately correct with the entire tapering.

The ring position of the new ring being constructed should always be chosen so that the front side of the ring ends up as centered as possible in the tailskin and the advance differences of the thrust cylinders are as small as possible.

To avoid having to install the key segment below the side wall, left/right rings are frequently used Here the maximum/minimum ring length is arranged 90° from the key segment axis. Although the modern segment erectors and today's press controls are able to easily install the key segment in the lower shield area and the logistics are somewhat easier to perform with the "universal ring", left/right rings do not constitute a disadvantage: if the supplied ring type does not

"fit", it can be used like a universal ring, and the key segment can be installed in the lower ring region.

3.1.3 Design of the segmental ring

The ring division must be matched to the press assembly of the tunnel boring machine. With segment rings that are installed offset, this means that even distribution of the presses across the extent of the TBM is provided for. The presses should always press on the individual segment at points designated for this. The split tensile reinforcement and any intermediate layers are installed specifically at these points to avoid damage to the segments.

In order to avoid bending moments in the presses and eccentric force application to the segment, the radius on which the presses are arranged in the machine should correspond to the axis radius of the load transfer surface of the ring joint.

Every second segment ring should be installed offset to the previous ring by half or a third of the segment handling length. This prevents continuous longitudinal joints across multiple segment rings (cross joints) that are detrimental to the support and sealing effect of the segmental lining.

3.1.4 Principle of ring building

In ring building the segments of the new ring being built must be placed against the most recently built ring so they are free floating. It is important to ensure that the ring joint surface of the segment has contact across the entire surface (avoid tilting) and the gasket is completely compressed with the respective thrust cylinders. When putting the next segment in place each time, it must be ensured that the longitudinal joint seals are also completely compressed by the segment alignment device (erector) and the bolted connection. Any type of guide rails (shift bars), or other fixtures in the tailskin should be avoided.

In hard rock in particular a jacking pressure ring is frequently used. With this concept, in the tailskin the segment ring must be put down on permanently installed rails before the completely built ring is pushed against the last built ring.

3.2 Joint design

The specifications are for one-pass, sealed lining segment systems. For two-pass systems the specifications apply mutatis mutandis.

3.2.1 Joint types

Applicable for all joints:

- Concentration of the load-transferring contact surfaces to the areas that are secured by means of constructive reinforcement, i. e. the surfaces (edges and corners), which cannot be secured by means of constructive reinforcement must be relieved by appropriate geometric shaping (recesses, chamfers)
- Avoid notches and notch effects in the load-bearing joint area
- Sufficient edge distances in the arrangement of the sealing frame for secure absorption of the pretensioning forces
- If there is a local increase in concrete compressive strength in accordance with the concept of partial surface pressures, split tensile forces occurring must be covered by conventional rebar or steel fiber reinforcement.
- Impact of manufacturing and installation tolerances

a) Longitudinal joints
Via the longitudinal joints, essentially the ring interface forces resulting from external and internal influences are transferred. In addition to this, the pretensioning forces required for the compression of the sealing frames must be applied and absorbed here.

b) Ring joints
In the ring joints the longitudinal forces from tunnelling are transferred between the rings and the coupling forces. The uneven load transfer through control forces during course corrections by the TBM must be accounted for in measurements.

When designing ring joints the following must be especially observed:

- Consideration of joint liners and their compressibility in the ring geometry
- If the thrust cylinders come to lie in the region of the longitudinal joint, it must be ensured that the press shoes do not act directly in the longitudinal joint region of the joint.

3.2.2 Joint shapes

a) Longitudinal joints
Four joint shapes are available:

- Flat joint
- Tongue/groove joint
- Convex-convex joint
- Concave-convex joint

For the one-pass segment ring the flat joint has prevailed. No decisive simplification can be achieved in ring building with a tongue and groove design. A reinforcement of the tongue and groove elements is hardly possible because of the required concrete cover. This means reliable absorption of the coupling forces in the tongue and groove construction cannot be guaranteed. There is the risk that in the event of assembly inaccuracies the tongue edges come to lie on the groove edges and that in compressing the ring in the tailskin or grouting the annular gap the groove edge tears off. When "guiding rods" are used (plastic rods axially inserted into the longitudinal joint) there is not usually such a risk because in the event of major displacements the rods shear off due to their low strength.

With rounded joint constructions, although higher compressive stress can be absorbed, only a small bending moment can be transferred via the joints, so that altogether the ring can be moregreatly deformed. With convex–convex joints ring building is also much more difficult.

In the longitudinal joints no intermediate layers are provided for.

b) Ring joints
The following joint shapes are available:

- Flat joint
- Tongue/groove joint
- Flat joint with additional centering or coupling elements such as cam and pocket, dowel or centering cone

For the one-pass segment ring the flat joint has prevailed. Additional centering and coupling elements may be provided for. These can be dowels, centering cones, reinforced or unreinforced cam and pocket toothings.

In places where cam and pocket coupling is used, strips of bituminous material (e. g. Kaubit strips) can be inserted to achieve a defined force deformation behavior for the radial coupling of the segmental rings. For the transfer of great coupling forces the cam and pocket connections must be reinforced. In order not to compromise the water tightness of the structure it must be ensured that when exceeding the load bearing capacity of the coupling the cam is sheared off before the pocket edge is damaged. Plastic dowel or spherical coupling elements have also proven themselves.

The tongue and groove constellation in the ring joint places increased demands on ring building because in the case of slightly offset rings spalling often occurs during tunnelling. It is generally only used in very poor subsurface conditions.

To compensate for irregularities, intermediate layers of hard fiberboard material or plywood should be installed in the ring joints. Plastically deformable intermediate layers (for example tiles made of bituminous material) should not be used for this purpose as they are greatly deformed plastically under load and cannot maintain the intended spacing. It is also possible to dispense with intermediate layers. In this case, however, greater accuracy in manufacturing the segments must be ensured.

With planned transfer of the longitudinal forces without intermediate layers increased demands on the ring joints' flatness apply. Areas in which no force is to be transferred must be protected by chamfers.

3.2.3 Connections

The connections in the joints are generally required only during ring building, especially for the pretensioning of the compression joint strips, and the advancement of the tunnel boring machine. After setting of the annular gap grout or after installation of about 10 rings this function is usually no longer needed and the bolts can be removed. In traffic tunnels, the bolts must be removed in the area over the track or roadway to prevent bolts from falling out during later operation.

Permanently remaining bolts, for example in the area of transitions to in situ concrete and connections to the tunnel must be secured against loosening and protected against corrosion.

As a temporary connection, inclined bolts with plastic dowels have proven particularly useful. They are easy to assemble, represent an elastic connection and can be easily removed again.

In exact ring building, plug dowel joints in the ring shorten the installation time and simplify the reinforcing, but can be difficult to decommission again. The use of centering cones can make sense.

On some projects (for example North-South Line Amsterdam, Brescia Metrobus, Metro C, Rome) bolt connections were dispensed with and the restoring force for the sealing frames assured by means of high tensile strength dowel connections.

In the longitudinal joints, inserted longitudinal rods/guiding rods can prevent the segments slipping away from each other during ring building.

3.3 Mountings in the segmental ring

With *two-pass* tunnel lining, any mountings that may be required (e. g. for the catenary or signals) are installed in the in situ concrete inner shell. No special mounting hardware is required for the segment ring.

With *one-pass* lining, later mounting options must be taken into account in the planning phase already.

Fundamentally the following mounting options are available:

- Installation of anchor rails (laying in the segment mould)
- Installation of steel mounting plates (laying in the segment mould)
- Subsequent dowelling of the mountings

When installing anchor rails or mounting plates it must be ensured that the intended position in the tunnel is secured. With tapered, rotatable rings in particular the anchoring must be installed all round or a predetermined position on the ring provided for during ring building. Consideration must be given to the required edge distances (to the ring and longitudinal joints).

In the planning it must be ensured that the spacing of the mountings is matched to the width of the rings. If there are changes in the components to be mounted after installation of the relevant segment rings, consideration must be given to the existing installed components. The position of the anchor rails or mounting plates generally also affects the geometry of the suction plate of the erector.

When the mountings are dowelled later it is possible to more flexibly address the requirements of the fitters regarding the necessary fixing components. To prevent hitting and severing the segment reinforcement when drilling the dowels, dowel lanes must be specified and coordinated with the reinforcement. Dowel lanes must be marked on the inner segment surface or the dowels drilled with the help of drilling jigs.

With all mountings the auditability later in the course of site inspections must be taken into consideration. For road tunnels, chloride contamination is a major problem, so the relevant material specifications must be observed. For large loads, for example fans, mounting directly onto the rock can also be considered, in which case the segment is perforated ("buttonhole"). This type of design is only possible, however, with relatively benign hydrogeological conditions.

3.4 Manufacturing tolerances

3.4.1 Fundamental considerations

The design tolerances are manufacturing tolerances of the individual segments and segmental rings. Access tolerances of the tunnelling machine, installation tolerances of the segment ring in the tunnelling machine and deformations of the segment ring during the advance and afterwards need to be considered separately.

Tolerance specifications are used to limit deviations from the planned segment geometry. Deviations may only be permitted to an extent that damage from tension peaks in the segment and leaks due to insufficient compression of the sealing profiles is sufficiently unlikely.

In this sense, the permissible degree of the deviations is actually dependent on several different factors:

- Stress level with planned geometry
- Utilization and deformation characteristics of the sealing profile
- Main segment dimensions (length, width, thickness, and radius).

The contractually predefined tolerances specify the permissible deviations of the segments produced from the nominal geometry.

Deviations from the nominal geometry can only be accepted if they do not result in damage due to unrecognized influences and the water tightness of the ring is not restricted.

Reasons for the strict tolerance requirements are:

- Geometric sensitivity to inaccuracies and distortions of individual segments
- High load factors from earth, water and grouting pressure on the segment ring
- Jacking forces during tunnelling
- The load transfer takes place only in limited areas (partial surface load)
- Damage cannot always be detected (for example, on outer side of ring)
- Repairing damaged segments is costly and time-consuming

3.4.2 Measurements for the determination of tolerance compliance

To determine compliance with manufacturing tolerances, in addition to the necessary measurements on individual segments, measurements on the complete segmental ring are also useful. The measurement frequency and the type of measurements need to be established in the construction contract. The measurement results must be passed on to the client. The measurement location (e. g. roofed hall with temperatures between 15 and 20°C) should be specified in the construction contract. If manufacturing tolerances are exceeded in any measurement, all segments produced after the last measurement (with compliant tolerances) must be remeasured working backwards from the most recent. All segments within the tolerances should be accepted, all segments exceeding the tolerances must be considered separately.

At the initial inspection of the formwork, lining segments are produced from all moulds and measured in three dimensions. The fit of the ring joint can be tested by building up two rings (without installed sealing frame) on top of each other.

A ring diameter and circumference measurement on the upper ring is not useful because the upper ring can only be built up relatively imprecisely.

After the start of production, the 50th ring produced from every formwork mould should be remeasured. The next measurements should be performed after every 100 fillings, unless otherwise provided for in the construction contract

3.4.3 Tolerance requirements

The manufacturing tolerances are specified for ring inner diameters ≤ 8.0 and ≥11.0 m. For diameters between 8.0 and 11.0 m, the tolerance values can be linearly interpolated and rounded up to 1/10 mm.

When the segments are installed in the tunnelling machine and in the course of the advance of about the first 10 rings, there are often deviations from the nominal position of the segment. Things to be watched out for include, among other things, the ovalization of the ring, the floating of the invert segments and the emergence of offsets between the individual segments.

The installation tolerances depend on the future use of the tunnel (required clearance gauge) and the segment design, and must be specified by the designer individually for each project in consultation with the client.

For the joint offset no more than 10 mm should be allowed. The permissible ovalization of the ring depends much on the diameter and the number of individual segments per ring, but should be less than 0.5 % of the internal diameter in each case.

The total of all tolerance values, including access tolerance, must be limited to the extent that the required clearance gauge is always adhered to.

3.4.4 Exceeding the manufacturing tolerances

If the planned loading is small, additional loading as a result of deviations is fundamentally more likely to be absorbed without damage than by an already high degree of utilization of the segment. The same applies with regard to seal tightness: A sealing profile deliberately compressed more

No.	Manufacturing tolerance	Ring size (inner diameter)	
		≤ 8,0 m	≥ 11,0 m
1.	**Longitudinal joints tolerance (based on the load transfer surface)**		
1.1	Longitudinal joint deformation	± 0,3 mm	± 0,5 mm
1.2	Angular deviation of the longitudinal joint	± 0,5 mm	± 0,7 mm
1.3	Addition rule for 1.1 and 1.2:	± 0,6 mm	± 0,9 mm
2.	**Overall segment deviations (based on the median plane)**		
2.1	Segment width	± 0,5 mm	± 0,7 mm
2.2	Segment thickness	± 3,0 mm	± 4,0 mm
2.3	Segment arch length	± 0,6 mm	± 0,7 mm
2.4	Inner radius of each segment	± 1,5 mm	± 2,5 mm
2.5	Difference of the diagonal length of a segment to the target length	± 1,0 mm	± 2,0 mm
2.6	Vertical spacing of the fourth segment corner from the plane formed by the other three corners	± 5 mm	± 8 mm
3.	**Sealing groove**		
3.1	Sealing groove width	± 0,2 mm	± 0,2 mm
3.2	Sealing groove depth	± 0,2 mm	± 0,2 mm
3.3	Position of sealing groove axis	± 1,0 mm	± 1,0 mm
4.	**Flatness of the contact zones**		
4.1	Longitudinal and ring joint	± 0,3 mm	± 0,5 mm
5.	**Tolerances on the entire segment ring**		
5.1	Outside diameter	± 10 mm	± 15 mm
5.2	Inside diameter	± 10 mm	± 15 mm
5.3	Outer circumference (measured at three heights)	± 30 mm	± 45 mm
6.	**Position of the fixing components**		
6.1	Erector cones	± 2 mm	± 2 mm
6.2	Spiral pockets and bushings	± 1 mm	± 1 mm

Table 1: Tolerances on individual segment and the entire segment ring

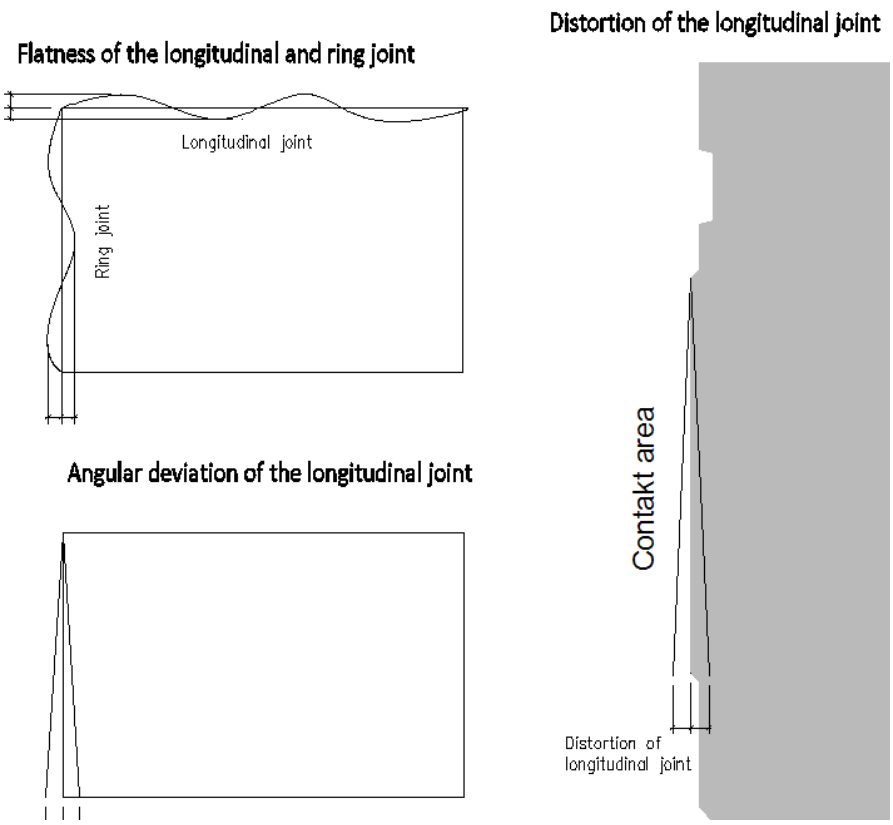

Figure 2: Manufacturing tolerances on manufactured segment of one-pass constructions – Installation tolerances

than necessary can still be tight against the surrounding water pressure if it is less compressed as a result of deviations.

If segments have already been produced outside the tolerance requirements, they can be used if the compatibility can be demonstrated. Possible measures when permissible tolerances have been exceeded are described below:

a) Exceeding the segment width tolerance

If the ring mirror surface does not result in a correct plane because the segment width tolerance has been exceeded, the segments can be used e. g. in areas with low projected tunnelling forces. For this, a static verification must be performed.

b) Exceeding the angle of longitudinal joint conicity/ longitudinal joint distortion

If the load transferring surfaces in the longitudinal joint are opened as a result of exceeding the tolerance value of the longitudinal joint distortion angle, the existing ring normal force pressurizes the load transferring surface until equilibrium is established. The ring normal force is then transferred over a smaller area, which is therefore subjected to higher loads. Again, it is advisable to install the incorrect segments in areas of lower loading. The split tensile reinforcement must be dimensioned to the higher tension.

c) Calculation of contact zone deformation under external loading

The contact zone of adjacent segments can be detected by calculating the deformations.

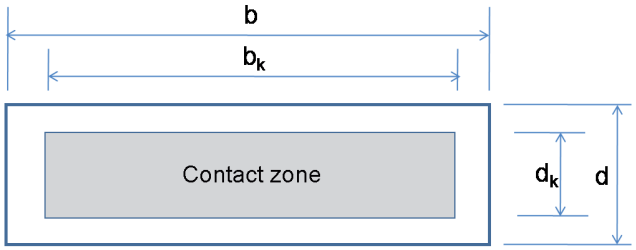

Figure 3: Planned contact zone in the longitudinal joint

Deformations in partially pressurized longitudinal joints:

- b Segment width
- b_k Width of the contact surface
- d Segment thickness
- d_k Thickness of the contact surface
- l Segment length
- α Opening angle of the incorrect longitudinal joint before application of the load
- N Ring normal force
- E Concrete modulus of elasticity (modulus of elasticity actually measured after ≥ 28 days)
- x Width of the deformed longitudinal joint

Possible hinge rotations after installation and the effect of loading must be realistically assessed and taken into account in the calculation.

Instead of a linear diffusion of tension in both directions *x* and *d*, a non-linear tension block can be assumed the resultant of the block must match the resultant of the tension triangles in both directions.

Verification:

(1) $\delta_L = \tan\alpha \cdot x$; $\quad x = \delta_L / \tan\alpha$

(2) $\delta_L = N \cdot l / (E \cdot x \cdot d)$

(3) $\delta_L = [N \cdot l \cdot \tan\alpha / (E \cdot d)]^{1/2}$ (1) in (2)

(4) $\sigma_{LK} = 2 \cdot N / (x \cdot d)$

(5) $\sigma_L = s_L \cdot d / d_K \cdot b / b_K$

(6) $\sigma_{LK} \cdot \gamma_F < \sigma_{Rdu}$ (see Chapter 5.6.1)

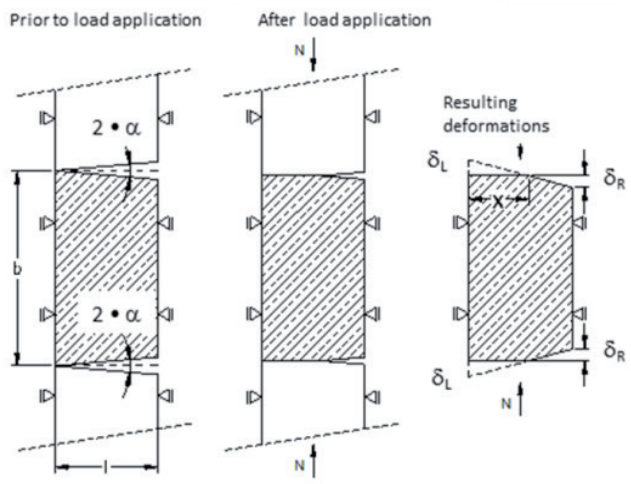

Figure 4: Pressurized longitudinal joints

e) Neighborhood relations

One way to compensate exceeded tolerances is to sort the segments in such a way that exceeded tolerances of adjacent segments cancel each other out.

This requires considerable effort to sort the segments in the segment store and for transport into the TBM. This option greatly restricts the ability to combine different segments and must therefore be approved by the client.

If the executing company can demonstrate a secure supply chain, however, this combination option is possible. A data recording system for the stored segments is absolutely necessary for this.

3.5 Notes for the design

3.5.1 Concrete cover

On the surfaces a minimum concrete cover of c_{min} = 40 mm must be maintained, on the end faces and in local areas

(for example bolt channels) the minimum concrete cover is $c_{min,red}$ = 20 mm.

The tolerance allowance of the concrete cover Δc is determined according to the production conditions and the quality control. As a guide, Δc = 5 mm can be assumed.

Increasing the concrete cover may be required for reasons of durability (exposure classes according to DIN EN 1992-1-2 [8]). Because of the associated structural disadvantages (including reduced statically effective height, poorer enclosure of the split tensile forces), increased concrete cover should be carefully weighed up by the draft author and alternative measures examined.

3.5.2 Reinforcing spacing

Typical reinforcing grids are in the range of between 100 mm and 150 mm. Larger bar spacings are possible, but have a negative effect on the calculated crack widths. After the reinforcing cage has been lifted into the mould, it must be possible to locally reach through the upper layers of steel to fix built-in parts in the mould. Clear openings in the reinforcing cage of at least 90 mm · 120 mm must be provided for this purpose.

3.5.3 Minimum reinforcement

A grid reinforcement of d = 10 mm, a = 150 mm is generally recommended as the minimum reinforcement for the segments.

In Section 5 the ZTV-ING for road tunnels [3] additionally requires a minimum reinforcement of d = 10 mm, a = 100 mm on all segment surfaces.

In Ril 853.4005 [1], surface reinforcement of at least 0.15 % per direction on all surfaces is required for railway tunnels. For segment thicknesses of 35 cm this corresponds to the requirement described in the first paragraph.

4 Sealing of the segment joints

4.1 Fundamentals

The following statements apply to one-pass linings, in which the sealing function is handled solely by the segment shell. With two-pass linings the sealing function is handled completely by the inner shell or by a geomembrane, resulting in different or even no demands on the sealing tightness of the outer shell.

The sealing tightness of tunnel linings made of precast reinforced concrete parts is determined almost exclusively by the sealing tightness of the joints. The standard solution for sealing the segment rings are EPDM (Ethylene propylene diene monomer) sealing profiles (gaskets) arranged circumferentially on the end faces. When mounting the segments, the sealing profiles of adjacent segments are pressed against each other in pairs and at the same time on their contact surfaces with the concrete. Appropriate design of the segment end faces in conjunction with a sealing profile designed for the particular task should ensure that after completion of the segment shell all joints are completely sealed without gaps. The complete absence of gaps is the obvious prerequisite for any sealing measure. Because the sealing performance of the EPDM profiles, which are not bonded to the concrete and not welded to each other, is based solely on contact pressure, it is imperative that sufficient contact pressure to handle the expected water pressure is consistently present on all parts of the entire segment circumference. This applies both to the two concrete grooves as well as the joint between the sealing profiles.

All key components of the seal design must be coordinated in such a way that the sealing task at hand is performed in compliance with the defined installation tolerances.

4.2 Choice of the sealing profile

Wherever possible, proven sealing profiles from the various manufacturers are used. In this way the cost of development, testing and approval can be saved, and at the same time there is cost and planning certainty right from the start.

The development of sealing profiles is the task of the manufacturer. Generally, however, a multiple iteration process is gone through here with the involvement of the other project participants, construction company, planner, client with their experts, test engineer, test institutes and material testing centers.

Shaping and vulcanization of the sealing profiles made of EPDM synthetic rubber takes place during extrusion. The rectilinearly produced profiles are cut to size and in a further vulcanization process corner mouldings are added to form the sealing frame. The approval of the sealing profile for the particular project is based on the successful completion of the required tests.

After the planned compression, sealing profiles should still have a remaining voidage, even in the corners of the frame, of about 10 %. This proportion is distributed across numerous elongated, separate chambers that are created during profile extrusion. The elastic properties of the sealing profiles are mainly based on the deformation of the ribs remaining between the cavities, with simultaneous reduction in the cavity volume. Once the cavities are completely compressed, the stiffness of the profile increases abruptly and there are high spreading forces. This state is outside the regular area of application and must not occur in the structure because of the associated segment damage.

Sealing profiles that are already inserted into the formwork and concreted into the segment with foot anchors have already been used for individual projects but have yet to prove themselves in construction practice. This may be a way to simplify the attachment of sealing strips and improve sealing.

4.3 Mode of action of the segment seal

In the finished segment tube the following leaks in the joint sealing system are possible:

- Contact surface between sealing groove and gasket
- Contact surface between opposite sealing profiles
- Joint between different sealing frames on segment corners.

As a result of the compression of the sealing profile during ring building, both the continuity of the seal must be produced and contact stress achieved at all potential subsurface watercourses, which ensures that the projected water pressure can be withstood. This target is not only for the ideal case of absolutely correct quality and geometry, but also for all expected deviations in the production of components and in assembly. In particular these are:

- Dimensional tolerances of the segments including sealing groove
- Groove base: freedom from cracks, voids and porosity, no concrete nests
- Ring building tolerances and ring deformations
- Dimensional tolerances of the sealing profile and frame
- Weight or rigidity tolerances of the sealing profile
- Deviating mechanical behavior of the frame corners
- Height difference due to longitudinal offsetting of adjacent sealing frame corners
- Unplanned expansions and compressions as well as detachment from the sealing groove during ring building
- Eccentric contact of the sealing profiles (lateral offset)
- Incomplete compression of the sealing profiles.

Of these possible deviations, in accordance with the STUVA recommendation [62] or TL/TP-DP (Technical terms of delivery and technical test specifications for sealing profiles) [42] only the latter two are systematically reproduced in the leak test. Otherwise, compliance with the tolerances is assumed. The possible influence of all remaining deviations and the influence of the relaxation of the sealing profile are ultimately covered by the fact that the test pressure is set higher than the actual water pressure to be withstood.

4.4 Typical tests of sealing profiles

Regarding the requirements for the sealing frame and the sealing profile, in Section 3 under 8.2.2 the ZTV-ING, Part 5 [3] applicable to road tunnels refers to the "Technical terms of delivery and technical test specifications for sealing profiles" (TL/TP DP) of the German Federal Highway Research Institute (BASt) [42]. The Ril 853 [1] governing railway tunnels follows this provision in module 4005 under (13). Consequently all data on requirements and tests can be found uniformly in the TL/TP DP. See here for details.

In the following a number of special aspects of the most important tests are discussed:

The distance between the deepest points of two opposite sealing grooves is referred to as the minimum groove base distance when the associated segments are frictionally pressed against each other until concrete contact or until maximum compression of the intermediate layer. In this position, the greatest compression and therefore the greatest restoring force of the sealing profile are achieved.

The force-displacement behavior of a sealing profile is tested on two 200 mm long pieces in equally long steel groove shapes the same as the concrete groove of the segment. The test extends from the initial deformation to the minimum groove base distance of the real segment, if relevant also to the steel surface contact of the groove shape. The tests are usually carried out in a materials testing laboratory, completely independent of the leak tests. The different equipment and the groove base distances used as a reference must be considered when evaluating the results.

Leak tests can be performed on steel or concrete specimens. Working with concrete specimens is time consuming and prone to failure, so that practically only tests on steel specimens are still carried out. The geometric situation is simulated on a T-joint in the laboratory, whereby, as on the ring joint, a straight piece of sealing profile is pressed against the end of a longitudinal joint.

In several series of tests, each with a specific offset distance, the water tightness for different groove base distances is tested by gradually increasing water pressure. Ultimately decisive is the result of the test constellation meeting the set requirements. These requirements are bindingly regulated, but can be defined related to the project.

An adequate seal is best achieved when the sealing profiles are compressed without an offset on the minimum possible groove base distance. This case is, however, unrealistic and is generally not tested.

4.5 Bolting

When using compression joint strips, usually temporary bolting or dowelling of the ring and longitudinal joints is necessary, from the installation of the segments to the hardening of the annular gap mortar (see Chapter 3.2.3). The bolting / dowelling must mutually brace adjacent segments against the restoring force of the sealing profile.

4.6 Concrete spalling adjacent to the sealing groove

When designing the segment it must be ensured that an adequate distance is planned from the outer edge of the sealing groove to the outer edge of the segment (40 to 50 mm, depending on the restoring force).

In the mathematical proof of protection against spalling of the concrete adjacent to the sealing groove, usually the tension arising in the sealing profile with the minimum groove base distance is taken as the load on the groove edge. This generally provides adequate protection.

A laboratory test called for in the TL/TP DP, on the other hand, regularly leads to failure. This is due partly to the test apparatus, partly to extremely unfavorable test conditions. To cover the sum of different possible tolerance level crossings the sealing profile is compressed even more than in testing the force-displacement behavior. Such tests are unrealistic and should be ignored in the suitability test of the sealing profile.

With reference to the TL/TP DP, in Ril 853 the Deutsche Bahn (German Railways) has already specifically excluded the spalling test.

4.7 Dimensional and weight tolerances of the sealing profile

Compliance with the standard manufacturing tolerances for the geometry of the extruded profiles is often not enough to ensure consistent component behavior. Fluctuations in the degree of filling i.e. the void fraction are critical, as they result in considerable variations of the deformation behavior and thus of the restoring forces. Weighing the sealing profile has been found to be an effective way to check this. This should be done both in production during regular quality checks, as well as when carrying out leakage and force-displacement tests.

4.8 Long-term behavior of the sealing profile

To ensure the water tightness achieved during construction is maintained in the long term, two conditions must be met:

- Material stability of the sealing profile
- Maintaining the minimum required compression.

The tests to be performed are listed in the TL/TP DP. However, explanations are missing here on the value of the individual tests in the long-term prognosis. Ultimately the tests must allow an extrapolation to the end of the intended service life of e. g. 100 years. There is still a need for research and regulation in this respect. It has become standard practice to verify water tightness in an accelerated test for a level of water pressure increased by a factor of 2.0.

4.9 Frame corners

Frame corners are always the critical point in the assembled segmental shell. The risk of leaks and of spalling is greater between the corners than at any other point. The difficulty in the elimination of these risks is that the appropriate measures run counter to each other. Against leakage particularly strong compression tends to help, against spalling as little compression as possible. When designing the frame corners it must be taken into account that through the vulcanization process during insertion of the corners, material can easily get into the cavities of the extruded profile, unintentionally making it more rigid locally. In addition, there is usually some excess material on the segment corners created during assembly, which also increases the restoring force generated. In the TL/TP DP, the force-displacement behavior of the frame corner is queried separately, with the addendum "hardening". No requirements are mentioned, however If the restoring forces are not to exceed those of the sealing profile, the corner piece must be designed differently to the normal profile. It can even be comb-shaped or provided with openings.

4.10 Water tightness requirements

A completely watertight tunnel is not achievable with the one-pass segment ring. Even if the client generally requires a watertight tunnel and the contractor is obligated to repair in case of leaks, small amounts of residual water must be reckoned with. Without giving up the fundamental demand for water tightness, provisions for this case should be formulated in the construction contract. A distinction should be made here between individual ingresses and the total water accumulation over long tunnel sections, but also according to the location of the water leakage. Both the permissible residual amounts of water and the measures to reseal and remove the water need to be regulated.

Running or dripping water ingresses are not normally permitted in traffic tunnels. In railway tunnels it is imperative that dripping on current-carrying installations is prevented.

In the design phase the planner must assume that to the greatest extent possible a watertight tunnel will be produced. Nevertheless, design options must be provided for to easily remove dripping water if necessary. This purpose is served, for example, by a dovetail resealing groove on the inner side of the ring.

In addition to the ingress of residual water, in tunnels with traffic drag water is carried in and in the case of fire, firefighting water has to be removed. In longer tunnels considerable condensation can occur in the summer. A drainage pipe with inspection shafts should always be planned at least in traffic tunnels.

5 Structural planning

5.1 Subsoil properties (geology, hydrology)

The geotechnical investigations should always be carried out on the basis of DIN 4020 [23]. The determination of characteristic values, the presentation and evaluation of the geotechnical investigation results and the conclusions, recommendations and instructions should be geared to the (expected) future segment system early in the planning stage already.

Because the segment ring already has its final rigidity shortly after installation, rock deformations are largely confined to the area of the tunnel face and the TBM. Unlike working with shotcrete, with segmental lining, load redistribution in the rock around the tunnel can only be expected to a small extent at the most. For tunnels in hard rock with high rock load and for systems with pea gravel blowing as a substitute for annular gap grouting specific approaches must be developed for each individual case.

With mechanized tunnelling with segmental lining a comprehensive subsoil investigation before the detailed design is of great importance, because later during tunnelling the segment thickness cannot be adapted to changed influences.

Table 2 lists a few key geotechnical parameters required for the calculations. They must be determined for all expected subsoil types and if necessary supplemented according to the specific project.

It is useful to show the anticipated subsoil conditions in a geotechnical longitudinal section and assign them to corresponding tunnelling/lining categories.

If the rings are pressed behind with grout, the segmental ring is immediately prestressed against the rock by the annular gap mortar under the grouting pressure applied. Annular gap grouting also has a positive effect on the final state and may possibly be reflected in the form of improved ring bedding.

When compressible annular gap fillings are used the rock loadings can be reduced according to the deformability of the ring or the filling material.

5.2 Influence of the annular gap filling on the calculations

If the segment is backfilled or blown behind with pea gravel, settling of the filling material and poor bedding of the ring above the side wall must be reckoned with, which often leads to unwanted deformations of the segmental ring. For one-pass segmental lining grout should always be used. If the rigidity of the annular gap material is significantly less than that of the rock, the radial bedding modulus must be reduced accordingly for graphical calculations.

Graphical calculation		Slab calculation (Mohr-Coulomb)		Slab calculation (Hardening-Soil)	
Young's Modulus	E_s	Modulus of elasticity	E	Reference Young's modulus	$E_{s,ref}$
Density	γ/γ'	Poisson's ratio	ν	Reference triaxial modulus	$E_{50,ref}$
Lateral pressure coefficient	k_o	Density	γ/γ'	Un-/reloading modulus	E_{ur}
Water pressure	p_w	Friction angle	φ	Reference tension	σ_{ref}
		Cohesion	c	Stiffness exponent	m
		Dilatancy angle	χ	Poisson's ratio	ν
		Tensile strength	f_t	Density	γ/γ'
		Water pressure	p_w	Friction angle	φ
		Lateral pressure coefficient	k_0	Cohesion	c
				Dilatancy angle	χ
		If necessary:		Tensile strength	f_t
		Rock mechanical parameters		Water pressure	p_w
				Lateral pressure coefficient	k_0
				Shear factor	R_f

Table 2: Required geotechnical parameters for the static calculations

The strength of the grouting mortar should be only slightly higher than that of the surrounding soil to prevent substantial normal force components being removed from the annular gap mortar in the final state. This would mean that the mathematically determined normal force included in dimensioning is not reached in the segment.

Although the favorable effect of the lateral pressure of the annular gap grouting is present in principle, it is not generally considered in calculation.

5.3 Action and action combinations – Dimensioning concept

The European standards DIN EN 1990 [4], DIN EN 1991 [6], DIN EN 1992 [8] and DIN EN 1997 [11] quoted in this Chapter always apply in conjunction with the associated National Annexes [5], [7], [9] and [12].

The dimensioning of the segmental lining should be based on DIN EN 1997-1 in conjunction with DIN 1054 [17] as the overarching standard. The design concept shown in detail below is essentially the procedure in Guideline 853 for railway tunnels.

5.3.1 Permanent actions

- Actions from the rock
- Water pressure
- Dead weight of the segmental lining and all other incorporated components
- Actions from tunnel installations
- Actions from prestressing measures
- Loads continuously impacting on the site surface and impacts from adjacent cavities
- Actions from possible subrosion and suffosion occurrences (for example karst, sinkholes)
- The jacking forces from tunnel boring machines (TBMs) acting on the lining during normal tunnelling operations
- Actions from shrinkage and creep (see DIN EN 1991-1-6 and 1992-1-1) can be neglected in the segmental ring (segments are largely cured before installation)

5.3.2 Regularly occurring variable actions

- Characteristic actions according to DIN-EN 1991-2 for traffic in the tunnel and traffic routes over the tunnel
- Although temperature changes are generally considered to be regularly occurring variable actions, they are, however, to be regarded as a special case, since they only generate constraint forces.
- Aerodynamic actions caused by the traffic in the tunnel can generally be neglected in a configuration with precast reinforced concrete segments, but for tunnel installations they must be taken into account.

5.3.3 Rarely occurring actions

Rarely occurring traffic loads and transient actions during construction.

- Rarely occurring traffic loads include for example impacts from vehicles on the site surface away from transport routes

Transient actions during construction include:

- Temporarily acting loads of tunnelling machines (for example jacking pressures set to the maximum for the advance impacting the lining), construction equipment, scaffolding, construction materials and construction components
- Grouting pressure during grouting (annular gap grouting)
- Actions from compressed air, where they act unfavorably.

Temporarily acting action from changes to the site surface (for example, excavations or embankments) and from adjacent cavities (for example tunnelling performed later) can generally be counted among the rarely occurring actions unless they are to be classified as permanent actions because of the duration and frequency of the conditions.

5.3.4 Accidental actions

- Temperature actions in the case of fire
- Earthquake/seismic actions
- Accidental actions from tunnel installations (for example, failure of the catenary in railway tunnels)
- Flooding of the tunnel in case of flooding via the portals
- Impact loads (generally applies only to components that are transverse to the direction of travel)

5.3.5 General notes on verifications of load-bearing capacity

For the segmental lining the verifications must be carried out in the limit states UPL, STR and GEO-2 according to DIN 1054 [17]. With the exception of special cases (for example leaning tunnel in unstable slopes), verifications in the limit state GEO-3 (slope or embankment failure) are not relevant for tunnels. For verifications in the limit state STR and GEO-2, additionally DIN EN 1990 can be applied with regard to actions from traffic and temperature (see below). For the resistances here the material parameters and partial safety factors specified in DIN EN 1992-1-1 apply. The segmental lining is designed for the design situations BS-P, BS-T and BS-A according to DIN 1054.

a) Verifications in the limit states UPL according to DIN 1054

For tunnels, verification of sufficient buoyancy safety (limit state UPL) is primarily of interest.

Here A_k is the hydrostatic buoyancy, $\gamma_{G,dst}$ the partial safety factor for unfavorable permanent actions in LS 1A, Q_k the characteristic value of possible unfavorable variable vertically upward directed actions, $\gamma_{Q,dst}$ the partial safety factor for unfavorable variable actions in LS 1A, $G_{k,stb}$ the lower characteristic value of favorable permanent actions and $\gamma_{G,stb}$ the partial safety factor for favorable permanent actions in LS 1A.

For the verification of buoyancy safety, for tunnel tubes not lying completely in the groundwater, for the final state the highest expected water pressure *during the period of use* of the tunnel should be planned for and for the construction state the highest expected water pressure *during construction*. For a subsequent replacement of the roadway of traffic tunnels the partial safety factors for the design situation BS-A may be used for the verification "without roadway".

b) Verifications in the limit states STR and GEO-2 according to DIN 1054

Experience has shown that a consideration of the temperature changes within the concept of DIN 1054 is problematic. According to DIN 1054, for verification in the limit states STR and GEO-2 a partial safety factor of $\gamma_Q = 1.5$ should be assumed for the design situation BS-P, which compared with the previous global safety concept would lead to significantly less favorable results. Therefore, in the context of the action combination outlined below (see below), special provisions are recommended for the coefficients of the temperature changes.

It is also suggested not to consider the coefficients for the actions from traffic according to DIN 1054, but according to DIN EN 1990.

The following action combination should therefore be used as the basis for the design situations BS-P and BS-T according to DIN 1054 (corresponds to the permanent and transient design situation according to DIN EN 1990):

$$\underset{1)}{\sum_{j\geq 1}\gamma_{G,j}\cdot G_{k,j}}+\underset{2)}{\gamma_{Q,1}\cdot Q_{k,1}}+\underset{3)}{\sum_{i\geq 1}\gamma_{Q,i}\cdot\psi_{0,i}\cdot Q_{k,i}}$$

1) Permanent actions G_k according to DIN 1054
2) Dominant variable action (leading action): For traffic, the partial safety factors according to DIN EN 1990 apply. For temperature the following applies:

   $\gamma_Q = 1{,}5$ when the internal forces with the stiffness (EI) in the state II are determined, as an approximation $EI_{II} = 0.6\ EI_I$ may be assumed here

   $\gamma_Q = 1{,}0$ when the internal forces are determined with the stiffness in state I

   For other geotechnical variable actions, the partial safety factors according to DIN 1054 apply.
3) Accompanying variable actions (accompanying actions): For traffic the combination factors according to DIN EN 1990 apply. For temperature $\psi_0 = 0.8$ (partial safety factors as in 2) applies. For other geotechnical variable actions, the factors according to DIN 1054 apply.

Accordingly, for the design situation BS-A according to DIN 1054 (corresponding to the accidental design situation according to DIN EN 1990) the following action combination is recommended:

$$\underset{1)}{\sum_{j\geq 1}\gamma_{G,j}\cdot G_{k,j}}+\underset{2)}{A_d}+\underset{3)}{\gamma_{Q,1}\cdot\psi_{1,1}\cdot Q_{k,1}}+\underset{4)}{\sum_{i}\gamma_{Q,i}\cdot\psi_{2,i}\cdot Q_{k,i}}$$

1) Permanent actions according to DIN 1054
2) Design value of an accidental action (for example, fire, impact).
3) Dominant variable action (leading action): For traffic and temperature $\gamma_Q = 1.0$ applies. For traffic, the combination factors according to DIN EN 1990 apply. For temperature $\psi_1 = 0.6$ applies. For other geotechnical variable actions, the factors according to DIN 1054 apply.
4) Accompanying variable actions (accompanying actions): For traffic and temperature $\gamma_Q = 1.0$ applies. For traffic, the combination factors according to DIN EN 1990 apply. For temperature $\psi_2 = 0.5$ applies. For other geotechnical variable actions, the factors according to DIN 1054 apply.

In the event of fire, special load combinations apply.

5.3.6 Serviceability verifications

In accordance with DIN 1054, verifications in the serviceability limit state (SLS) generally refer to deformations or displacements to be complied with. In addition, it is pointed out in the standard that in individual cases other criteria may be relevant.

In connection with the design of a reinforced concrete segmental lining, the crack width verification in particular is of importance. For this, the following requirements are proposed on the basis of DIN EN 1990 and DIN EN 1992-2.

For the crack width verification the internal forces should be determined with the stiffness of the rod elements in state I. For the action combinations the following equation applies (see DIN EN 1990, common combination):

$$\underset{1)}{\sum_{j\geq 1}G_{k,j}}+\underset{2)}{\psi_{1,1}\cdot Q_{k,1}}+\underset{3)}{\sum_{i>1}\psi_{2,i}\cdot Q_{k,i}}$$

1) Permanent action according to DIN 1054
2) Dominant variable action (leading action): For traffic, the combination factors according to DIN EN 1990 apply. For temperature $\psi_1 = 0.6$ applies.
3) Accompanying variable actions (accompanying actions): For traffic, the combination factors according to DIN EN 1990 apply. For temperature $\psi_2 = 0.5$ applies. For other geotechnical variable actions, the combination factors according to DIN 1054 apply.

The permissible calculated crack widths can be calculated according to the exposure classes according to DIN EN

1992-2 in conjunction with the accompanying National Annex. In general, the crack widths are to be limited to $w_k \leq 0.2$ mm.

For traffic structures the requirements of ZTV-ING [3] or Ril 853 [1] apply.

The determination of the internal forces can also be performed with non-linear material behavior. This also applies to the load-bearing capacity and serviceability verifications.

5.4 Determination of internal forces – Calculation method

The structural behavior of the tunnel lining subjected to bending is mainly determined by the supporting effect of the surrounding soil. Only in special cases with unusual loads or extremely low bearing capacity soils must the tunnel lining made up of individual segments bear load as a rigid ring. In these cases the coupling of the rings to each other in the ring joint is of crucial importance for the load transfer.

The calculation for the tunnel lining can be done using both the truss model and the continuum model.

When calculating as a bedded continuous member the supporting effect of the subsoil is usually only simulated using bedding tongues acting normally on the members. For reasons of numerical stability, a small tangential bedding can be assumed.

The following assumptions apply to the bedding:

- Assumption of a linear elastic radial bedding with a beam gap all around the cross section. Planning a beam bedding is not permissible. For tunnels in soft ground with little overburden, generally in the 90° area around the crown no bedding is ever planned [53]
- Choice of the bedding modulus k_R as a function of the curvature of the system line of the segment shell (system radius R_{Sys}):
  $k_R = E_S / R_{Sys}$
- Tangential bedding and tangential loads are usually not planned due to the shear flexibility of the fresh grouting mortar. In special cases, such as with unbalanced load, it can be useful, especially for load cases added later (for example, one-sided wreckage load, construction and excavation) to consider a tangential bedding. It must then be limited by means of the max. potential friction.

Geometric deformations, for example through installation tolerances, must be taken into account in the calculation, or if necessary assumed to be lying on the unfavorable side.

In the calculation with a 2D continuum model the tunnel lining is also shown as a truss – in a 3D continuum model correspondingly as a shell. The behavior of the subsoil can be determined more accurately using a continuum model and corresponding constitutive laws. For this purpose it is necessary to realistically mirror all structural elements (tunnel shell, interaction of the segments, annular gap grouting, soil) in order to realistically register the effects resulting from them and their interaction with each other.

5.4.1 Truss model

For a calculation using the truss model the tunnel lining is mapped as a bedded continuous member.

To take into account the torsional rigidity in the longitudinal joint and to detect the resulting moment transfer, non-linear torsion springs are arranged in the computational model at these locations The associated non-linear spring characteristics reproduce the moment in the longitudinal joint as a function of the existing torsion and the effective ring normal force. The determination of these spring characteristics is usually after the calculation model of *Leonhardt/Reimann* [31]. This calculation model originally developed for concrete joints of bridges has also proven itself for lining segments, as has been demonstrated in corresponding experiments.

Depending on the planned structural behavior and shape of the ring joint, the statically effective coupling of rings one behind the other in the ring joint is reproduced using non-linear coupling elements. The spring characteristics for these coupling elements should take into account the slip in the joint and the flexibility of the existing joint filler. They are determined with the help of tests. Depending on the stage of construction, in addition to the coupling from interlocking adjacent rings, coupling effects from friction due to the advance jacking forces must be taken into consideration.

When considering adjacent rings under the assumption of the above-mentioned couplings in the ring joints, the deformations of the individual rings are similar, whereby the bridging of the concrete joints by the adjacent segments leads to a stiffening of the system and an accompanying increase in the bending moments.

In spite of the coupling, because of the slip in the coupling elements i.e. the tongue and groove, there is a certain mobility in the ring joint as radial shear deformation, which allows torsion in the longitudinal joint.

A possible static model for a modeling of two coupled segmental rings is shown in Figure 6. For the calculation of the rings, depending on the program system, the rings can be

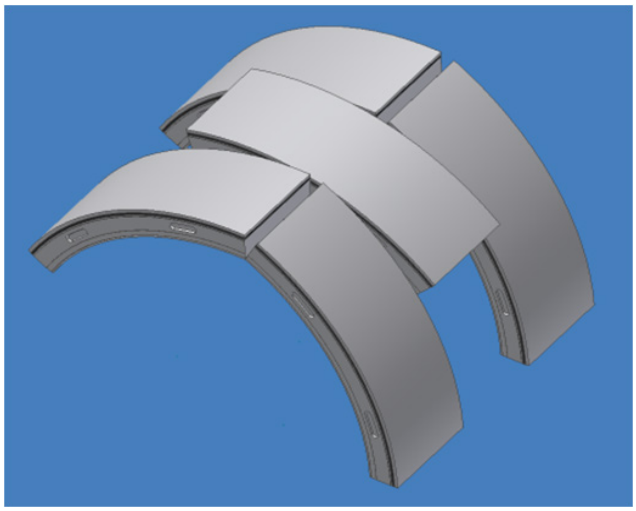

Figure 5: Different deformation of individual segments (greatly exaggerated)

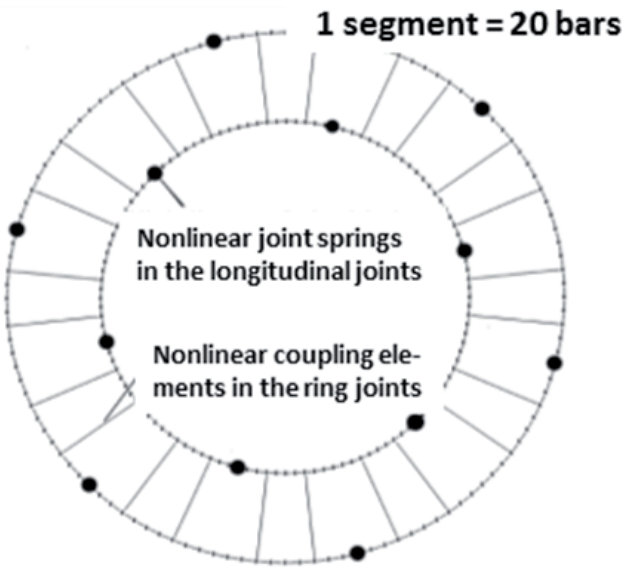

Figure 6: Illustration of the segmental lining by two truss rings (different diameters expanded for illustration purposes only)

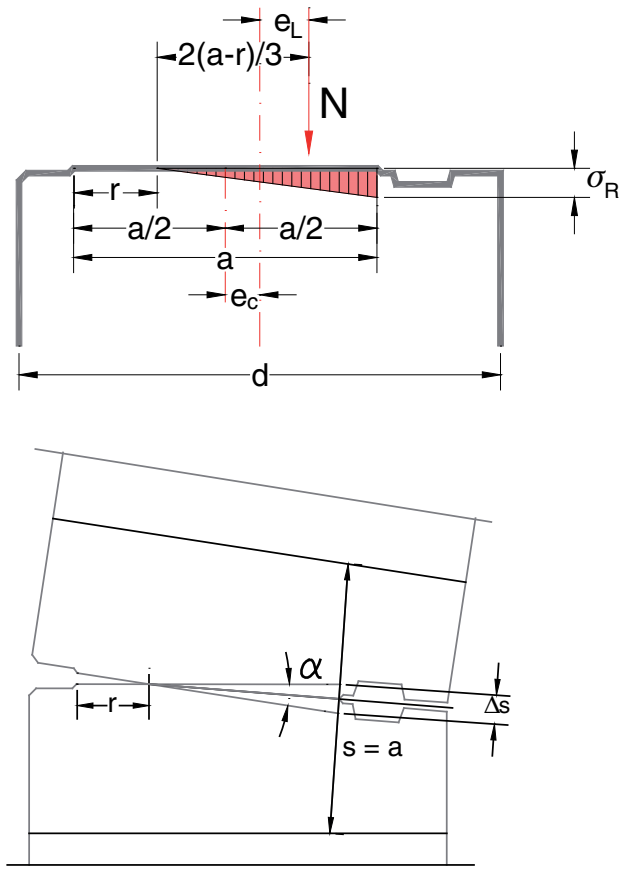

Figure 7: Approaches and terms for estimating the torsional resistance of concrete hinges

reproduced as spatially consecutive rings or more simply as rings in a plane with an almost identical diameter.

In the following the names and formula relationships from DIN EN 1992-1-1 [8] are used to determine the torsional stiffness in the longitudinal joints.

The torsional resistance of a hinge is expressed by a restoring moment which produces an eccentricity *e* in the hinge.

The following relationships are the basis for the formulas:

- a — Width of the hinge neck
- r — gaping joint on the tension side $r = a - 2 \cdot N / \sigma_R$
- e — total eccentricity; $e = e_L + e_c$
- e_L — eccentricity of the normal force; $e_L = M / N$
- e_c — eccentricity of the hinge neck
- s — length of the region involved in the deformation in the circumferential direction (the length corresponds approximately to the width of the hinge neck a) s = a
- Δs — change in length of the deformation region at the edge with maximum edge stress σ_R
- N — normal force
- M — moment
- E — modulus of elasticity of concrete (because the loads are applied immediately, in general the modulus of elasticity cannot be mitigated due to creep)
- α — Torsional angle
- σ_R — Edge stress $\sigma_R = \frac{2 \cdot N}{3 \cdot \left(\frac{M}{N} - \frac{a}{2}\right)}$
- m — restoring moment obtained, $m = M / (N \cdot h_c)$,

According to [41], [57] it follows that:

$$\alpha = \frac{\Delta l}{a - r} = \frac{\sigma_R \cdot a}{E \cdot (a - r)}$$

$$\alpha = \frac{8 \cdot N}{9 \cdot (1 - 2m)^2 \cdot a \cdot E}$$

With these formulas the restoring moment can be specified as a function of the torsional angle α. For practical calculation, it is useful to approximate the non-linear curve with a polygon.

The rigidity of the non-linear coupling elements in the ring joint of adjacent rings is determined by the *geometric* configuration of the coupling elements and the inserts or materials of the coupling elements used. As an example a cam and pocket coupling with inlaid Kaubit strips is shown in Figure 9.

Friction coupling

Before a mechanical coupling (via mechanical coupling elements such as cam / pocket or dowel connections) takes effect in the ring joints, in the region behind the TBM at least, a friction coupling becomes effective between the segment rings. The friction coupling must be set taking into account the geometry and stiffness of the intermediate layers and their friction factor or shear resistance under the assumption of effective jacking forces to determine the maximum bending moments.

As a result of temperature changes, creep deformation and plastic deformation in the ring liners, friction coupling is usually slowly reduced again, so that a complete failure of the friction coupling must be reckoned with in the final state.

5.4.2 Continuum calculation

In a continuum calculation the interaction of the tunnel shell with the soil is not detected through the bedding and the specification of slack loads, as in the truss models, but through the discretization of the soil itself. This also includes the fundamental possibility of better mirroring of the non-linear stress-strain behavior of the soil.

In the mirroring of the tunnel lining as continuous members, a bowl or as a continuum, it is necessary to also reproduce the load bearing mechanisms of the interaction of the individual segments explained in detail under truss modeling. If a coupled ring system is to be mirrored, a spatial continuum model with shell elements to simulate the segmental lining is recommended.

For control purposes the continuum calculations should always be checked for plausibility by simple analytical calculations. They are only of limited use for the segment design.

To determine the actions from rock pressure and to calculate ring deformations under special actions, a continuum calculation can provide relatively realistic results.

Among other things, it is particularly advantageous in the following situations:

- Consideration of stress states in the subsurface, where the principal stress directions vary considerably from the Cartesian coordinate directions, such as where there are high individual loads from buildings or traffic loads, excavation, undercutting of slopes or embankments
- Driving past components in the subsurface, such as slurry walls, bored piles and sheet piles, anchorages, sensitive foundations or lines
- Consolidated subsurface
- Inhomogeneities in the subsurface, especially in the presence of ground layers of low stiffness and/or strength in the area of the tunnel
- Consideration of overconsolidation in the underground, excavation relief-related elevations in the invert or stress-strain dependent material behavior
- Increased horizontal stresses in the subsurface
- Highly fissured rock
- Crosscuts with load-bearing coupling elements, partial bedding removal by excavation, ice loads. This assumes three-dimensional modeling of subsurface and segmental lining
- Determining settlement and stabilizing, settlement reducing measures

5.5 Determination of the internal forces and stresses from the construction process

5.5.1 Split tensile load resulting from jacking forces

During tunnelling the TBM supports itself with the tunnelling force via the presses on the ring joints of the segment rings already built. Depending on the geometry of the ring joint, high partial surface pressures develop under the jack shoes. The partial surface pressures and the resulting split

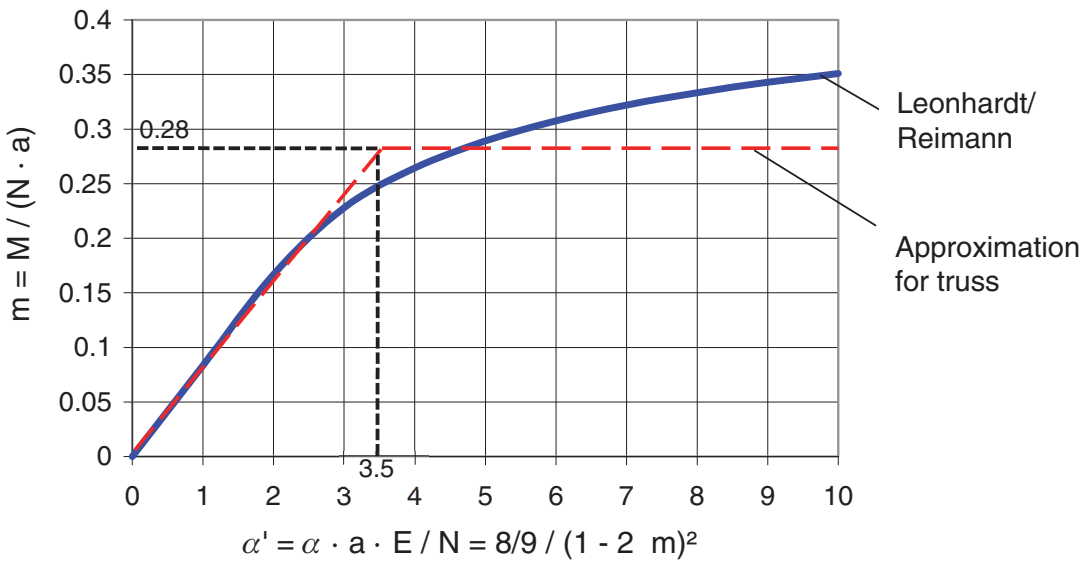

Figure 8: m-α' relationship (according to [34], or [61], as well as a bilinear approximation)

tensile forces in radial and circumferential direction must be verified and covered in accordance with the specifications in DIN EN 1992. In the verifications a difference can be made between standard values of the jacking forces and extraordinary jacking forces for infrequent greater control movements. The verifications can be done for the different design situations with the respective safety factors.

5.5.2 Slab stress due to misalignment or exceeded tolerances in the ring joint

In the course of ring building, as a result of tolerances but mainly due to assembly inaccuracies, misalignments of adjacent segments can occur, so that the ring appearance is no longer even. Depending on the size of the offset and the type of joint inserts (plywood or hardboard), the inserts may not be able to bridge the offset and as a result of the associated tensile stress of the slab there may be damage to the segments (see Figure 10).

For the design it is difficult to specify realistic values for a possible offset, since this is greatly dependent on the ring building and large values lead to very large reinforcement cross sections being required. Here it is useful to define project-specific limits, to dimension the segments according to these and to compensate for larger values by inserting intermediate layers or other measures during ring building. The ring joint plane of the last ring built should be regularly measured, approximately every 10th ring, and deviations from the plane determined. Should the ring deviate at any point by more than about 2 - 3 mm from the ideal plane, an ideal plane of the ring joint must be produced again.

5.5.3 Stress from transport, storage and installation processes

a) Storage

In general, segment rings are stored in a stack one above the other. During storage of the segments it is important to make sure the bearing blocks and intermediate layers between the stacked segments reliably prevent them from touching each other or the storage area. The bearing battens must be aligned exactly (flatness, securing of the position by stops) and the segments placed in precisely the planned position. With inclined battens / bearing blocks there is the risk that the segment undergoes internal torsion due to creep and can no longer be installed in a precise position.

The bearing stress (segment stack) must be statically verified or specified on the basis of static calculation.

b) Transport

During transport, all risk of accidental touching must be prevented. If damage to the segments is found in the TBM after delivery, it must be established where this damage occurred and the situation remedied. All transport damage must be documented.

Before the segments are installed it must be clarified with the construction supervision whether the defective segments can be installed or must be replaced.

c) Stresses from installation processes

Stresses resulting from the installation processes must already be taken into account during planning of the segment rings. When using central erector mounts, segments must be measured for the resulting bending moments.

5.5.4 Splitting tensile from the restoring force of the seal groove

The splitting tensile in the concrete that develops under the groove base surface as a result of the restoring force of the sealing profile can be simply determined as follows (Figure 11).

Compression force of the sealing profile:

P = sealing profile restoring force [kN/m]

$$d_S \cong 2 \cdot d_R + d_D$$

Resultant split tensile force according to [51]:

$$Z_S = 0{,}25 \cdot P \cdot (1 - d_D / d_s)$$

The existing reinforcement cannot really be used for absorbing split tensile forces due to its location (concrete cover to the outer edge of the segment and to the joints). It

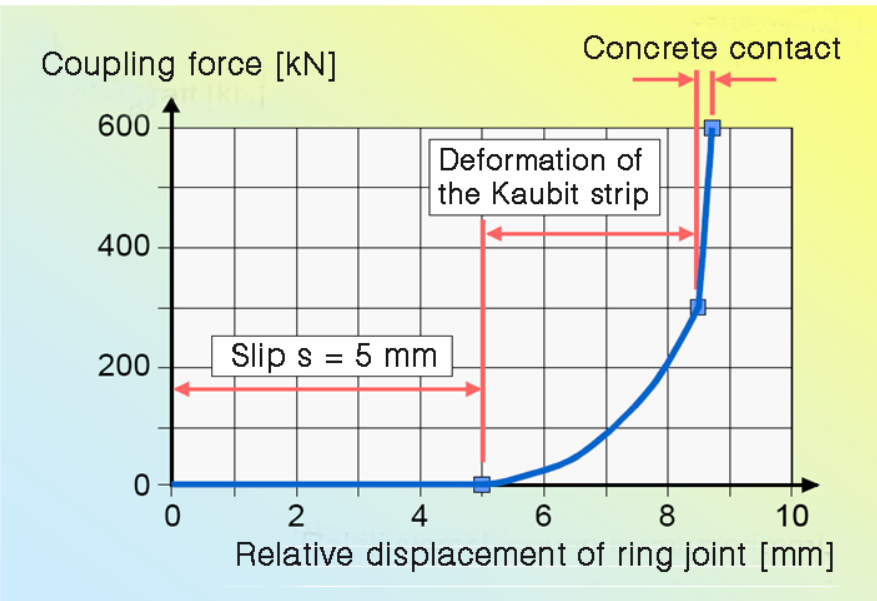

Figure 9: Non-linear coupling in the ring joint. Coupling force as a function of relative deformation

must therefore be verified that the splitting tensile can be absorbed by the concrete without reinforcement. According to [51] Figure 3.6 the following applies:

$\sigma_0 = P / (b \cdot d_S)$

→ gives the stress ratio σ_y / σ_0 and from that σ_y

5.6 Individual verifications of the segment joints

5.6.1 Permissible concrete compressive stress at partial surface pressure

As a result of conventional joint designs, actions in the ring joint as well as in the longitudinal joint are applied as partial surface loads. The concrete compressive stresses and the resulting split tensile stresses must be verified.

According to DIN EN 1992-1-1 the following applies to designing for partial surface load:

$$\sigma_{Rd} = f_{cd} \cdot \sqrt{\frac{A_{c1}}{A_{c0}}} \leq 3{,}0 \cdot f_{cd}$$

$$f_{cd} = \alpha_{cc} \cdot \frac{f_{ck}}{\gamma_C}$$

A_{c0}	Load area (hinge neck area, load transfer surface in the ring joint)
A_{c1}	mathematical distribution area
α_{cc}	= 0,85
$\gamma_c = \gamma_{c,\,red.}$	= 1,35 for finished parts with factory production and continuous monitoring

For segment joints with partial surface pressures a large number of tests were carried out in the past. The tests for the 4th Elbe Tunnel tube are an example for these (see [55], [56], [57]). All tests show very high load capacities. In some cases it may therefore be useful to conduct separate trials to demonstrate for higher load bearing capacities.

As long as no systematic experimental studies are available, to be on the safe side the partial surface load according to DIN EN 1992-1-1/ NA [10] can be used for segment joints as an approximation, whereby the basic conditions of load area, distribution area and dispersion geometry must be observed. Helical reinforcement of the same thickness and width as the segment must be planned. The reinforcement in segment width must be distributed over the height of the load dispersion.

Another option, as an alternative to the previous paragraph, is to plan partial surface pressures on the longitudinal joints beyond the ratio $\sqrt{A_{c1}/A_{c0}} \cdot f_{cd}$ up to max. $3 \cdot f_{cd}$ if the two transverse strains in the load introduction area according to Figure 12 remain limited to max. 0.1 ‰/γ_c. Mathematically a uniform, linear-elastic material behavior and a Poisson's ratio ν=0.2 for concrete should be planned for [64].

It must be verified:

$$\varepsilon_q = \frac{N_{Ed}}{E_c \cdot A_{c1}} \cdot \nu \leq \frac{0{,}1‰}{\gamma_c}$$

With:

$\gamma_c = 1.35$

N_{Ed}	total joint force
$A_{c1} = d_2 \cdot b$	distribution area on the lower dispersion edge
E_c	modulus of elasticity

Split tensile effects must always be absorbed with reinforcements. The load introduction area along the longitudinal joints must be reinforced with at least 1% of the concrete area $A_{c2} = d_2 \cdot h$.

a) Design of the partial pressure stress in the longitudinal joint

As the key pressure transmission area, the hinge joint width d_k is reduced by twice the eccentricity (see Figure 13).

Verification of concrete stress:

$$\sigma_d = \frac{N_{Ed}}{b_1 \cdot d_1} < \sigma_{Rd} \text{ (σ_{Rd} according to Chapter 5.6.1)}$$

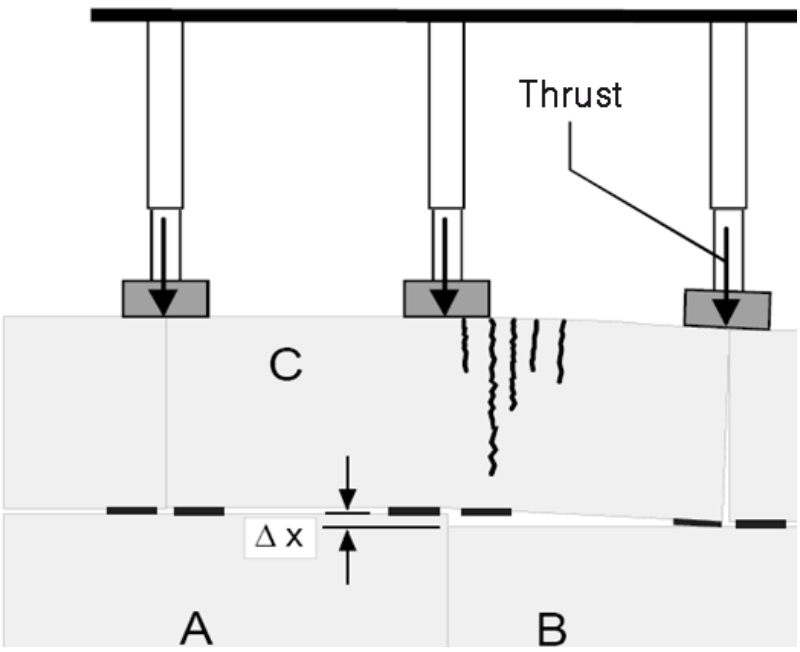

Figure 10: Damage from displacement in the ring groove

b) Verification of split tensile reinforcement in the longitudinal joint

In addition to the absorption of the concrete compressive forces, the split tensile stress in the longitudinal joints must be verified. To this end the split tensile reinforcement for the maximum stress from normal forces and associated moments are determined. [34] can be the basis for this.

Verification can be carried out under the assumption of force transfer by means of tension block.

For an eccentrically acting load (e > d / 6), in addition to the split tensile forces (F_{Sd}), edge tension forces ($F_{Sd,R}$) and secondary tensile forces ($F_{Sd,2}$) also occur.

The following applies to the split tensile force:

$$F_{Sd} = 0{,}25 \cdot N_{Ed} \cdot (1 - d_1 / d_s)$$

The split tensile forces are determined for the maximum normal force N_{max} and associated eccentricity *e* and for the maximum eccentricity e_{max} and associated normal force N from the calculation of the non-linear moment-torsion relationship in the longitudinal joints.

Required split tensile reinforcement:

$$\text{req. } a_S = F_{Sd} / (f_{yk} \cdot \gamma_S) \text{ [cm²/m]}$$

$$F_{Sd,R} = N_{Ed} \cdot (\frac{e}{d} - \frac{1}{6})$$

$$F_{Sd,2} \approx 0{,}3 \cdot F_{Sd,R}$$

c) Structurally possible joint torsion in the longitudinal joint

In addition to the structural verifications of the longitudinal joint the possible joint torsion must be checked.

With the aid of the calculated joint torsion (for example from a continuous member calculation), the structural compatibility of the torsion with the joint geometry, an adequate sealing effect when opening the groove on the outside, and when opening on the inside the increase in the restoring forces in the sealing profile and thus concrete pressing, splitting tensile and shear stress can be verified.

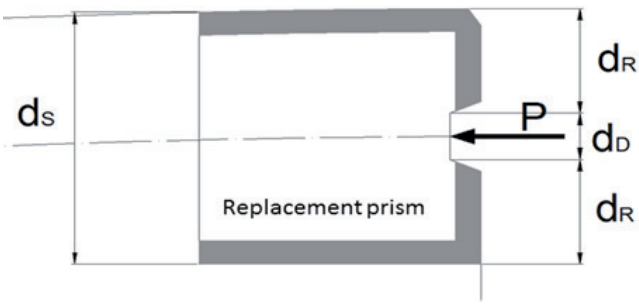

Figure 11: Detail from joint with replacement prism for verification of seal groove

d) Shear force in the hinge

Because the segment hinges are not in situ concrete hinges, the ratio Q to N can be evaluated using a friction model.

According to EN 1992-1-1, even with very smooth joints the friction coefficient between concrete and concrete must be planned with at least $\mu = 0.5$. From this follows, for the maximum ratio of Q to N, the minimum certainty against sliding of:

$$\text{min. } \eta \geq 0{,}5 / (Q / N)$$

Required certainty η:

Load case "normal state": $\eta \geq 2$

Load case "abnormal stress": $\eta \geq 1{,}5$ (for example, tunnel fully overflowed with minimum ring normal force)

e) Verification of partial surface pressure in the ring joint

As a result of the jacking forces from TBM tunnelling the ring joints must be verified. For the verification of the partial surface pressure and the determination of the split tensile an eccentricity *e* of the jack shoe must be taken into account.

Partial surface pressure according to DIN EN 1992-1-1:

$$\sigma_d = \frac{N}{A_{c0}} < \sigma_{Rd} \quad (\sigma_{Rd} \text{ acc. to Chapter 5.6.1})$$

The split tensile verification is done according to DIN EN 1992-1-1 (see Chapter 5.6.1b)).

f) Load transfer of the coupling forces

If coupling forces are generated in the ring joint with a tongue and groove construction, cam and pocket or dowel connections, these must be verified. An approach for verification is given in [53]. If necessary, the absorbable coupling forces can be determined from tests.

5.6.2 Verification of connections

In the assembly state during ring building, temporary bolting in the longitudinal joints fulfills the function of counteracting the restoring forces of the sealing profile until the surrounding soil or the annular gap grouting prevent joint opening.

The compression of the sealing profiles in the ring joint is carried out primarily by the thrust cylinders, whose preload force exceeds that of the bolts many times over. Here the bolts are intended to prevent opening of the joints during ring building during the removal of individual jacks.

Neither the bolts in the longitudinal joints nor in the ring joints are needed after the installation of additional rings. They are removed and can be used again (see Chapter 4.5).

Permanent bolting is only installed at the start and finish area and if necessary in the region of crosscuts to permanently accommodate the restoring forces of the sealing profile.

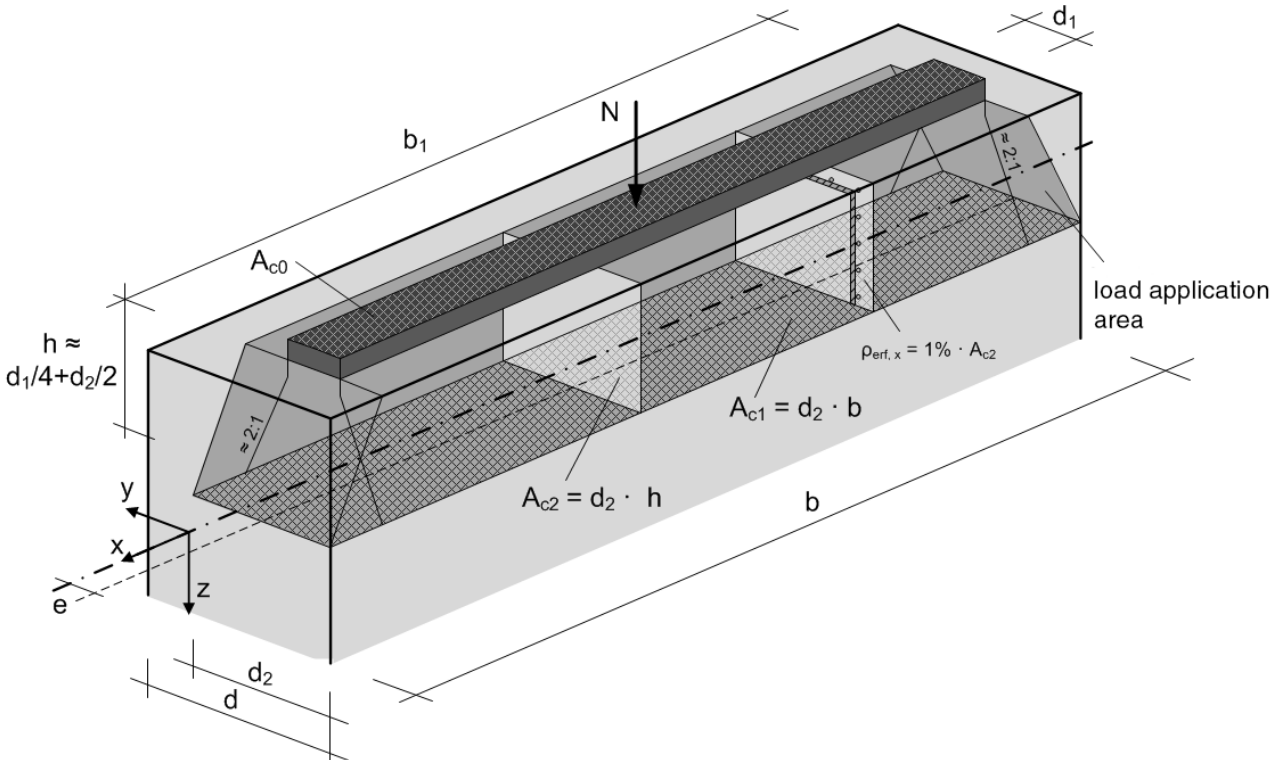

Figure 12: Schematic diagram of load dispersion across the segment thickness at raised partial surface pressure with definition of the mathematical distribution areas

The sealing profile encloses a segment along its circumference. The restoring force per joint P_i can be specified with

$$P_i = p \cdot L_{Joint}$$

The load bearing capacity of bolts and dowels should be sized to 2.0 times the restoring force P_i of the sealing frame. Here only bolt load share acting in the direction of the seal may be projected.

It must also be noted that the preload force F_V of the bolts is greater than the restoring force P_i for the profile and less than the bolt yield stress F_S, so that the bolts do not plasticize.

5.6.3 Verification of the longitudinal joint on the key segment

The longitudinal joints of standard lining segments are formed radially. This ensures that the ring normal force is always perpendicular to the longitudinal joints and no output drive components need to be mounted. In this way it is possible to make the joints flat without toothing or dowelling. In the key segment longitudinal joints, because of the greater circumferential length on the outer side and the assembly, a radial design results in an increase in the required installation path in the direction of the advance. As a remedy, the joint is usually made somewhat steeper, in the direction of the parallels to the segment axis. A vertical joint (longitudinal joints parallel to the segment axis) should always be avoided, because external actions push the key segment to the inside and a parallel arrangement of the joints cannot prevent sliding inwards.

With the form deviating from the radial direction an output drive component works as planned in the longitudinal joints. This can have the effect that the joint is not capable of safely transferring away the rock and water pressure acting on the stone from outside. The longitudinal joint of the key segment can therefore be designed with tongue and groove toothing or with a guiding rod. The load transfer of

Concrete compressive strength class			**C35/45**	**C40/50**	**C45/55**	**C50/60**
Cylinder strength	f_{ck}	[N/mm²]	35.0	40.0	45.0	50.0
Concrete compressive strength for the design	f_{cd}	[N/mm²]	22.0	25.2	28.3	31.5
Maximum partial surface pressure (3.0 · f_{cd})	σ_{Rd}	[N/mm²]	**66**	**76**	**85**	**95**

Table 3: Compressive strength for partial surface pressure in joints

the toothing must be verified in the same way as with the ring joint.

5.7 Peculiarities in the use of steel fibers

5.7.1 General

Concrete is known to have high compressive strength, while the tensile strength is much lower, and because of its great dispersion, to be on the safe side, is not projected mathematically in stability analyses.

The mixing of steel fibers into a base concrete creates a construction material with certain material properties, in particular in the tensile area: steel fiber reinforced concrete. Ideally the fibers are evenly distributed spatially and oriented in all spatial directions, i.e. without preference for a specific direction.

Steel fibers can give the base concrete greater ductility and significantly improve post-cracking behavior. Tunnel lining segments made of steel fiber reinforced concrete are more robust than conventionally reinforced segments, particularly with regard to corner and edge spalling from manufacturing and installation conditions. The fibers are distributed right up to the peripheral area and structurally reinforce the edge zones, in contrast to a conventionally reinforced segment, where the edge zone (concrete cover) is generally unreinforced.

Depending on the bending stress of the tube, segments can be designed and produced as pure steel fiber reinforced concrete segments or also in combination with conventional reinforcement (see Figure 14).

When used for segments as so-called macro fibers, the fibers typically have lengths of about 40 to 60 mm. The ratio of the fiber length L to the fiber diameter D (substitute diameter with a rectangular fiber cross section) is defined as slenderness. The greater the fiber slenderness, the more individual fibers are distributed in the concrete with the same fiber content, and thus the better the effectiveness of the fibers in post-cracking. With increasing fiber slenderness, however, the risk of concrete segregation and so-called “balling” increase. For use in segments a slenderness L/D of about 50 to 80 should therefore be maintained.

In order to improve the composite behavior of the fibers in the concrete matrix, they are typically provided with end anchoring elements in the form of hooks, upward bends or surfaced heads. Structuring of the fiber surface can also favorably improve the composite behavior.

The fiber properties must be matched to the base concrete with the aim of achieving the greatest possible level of post-cracking ductility. For this purpose, sufficient pull-out resistance is necessary on the one hand, on the other hand-tearing of the fibers must be avoided by means of appropriate tensile strength of the wire.

In order to achieve any effect of the fibers at all in the concrete, a fiber content of at least 25 kg/m³ should be maintained. In practice, fiber contents of 30-50 kg/m³ have prevailed. Higher fiber contents (80 kg/m³ or more) are possible with the appropriate concrete technology and with careful processing, but are not considered here as a special case.

To improve fire behavior, steel fibers can be used in combination with polypropylene (PP) fibers.

Because when steel fibers are used concrete, covers are not maintained and the steel fibers are also close to the surface, use in adverse exposure conditions (e. g. road tunnels with salt spreading) is usually not possible or problematic.

5.7.2 Mode of action of the fibers

With the above-mentioned fiber contents of about 30 to 50 kg/m³ the behavior of the concrete under compression (pressure area) is changed only slightly. Stiffness (modulus of elasticity) and compressive strength remain virtually unchanged; in rock fall areas (pressure) the energy capability increases.

With tensile stresses a difference must be made between the state before and after cracks arise. With the onset of tensile stress steel fiber reinforced concrete with macro fibers initially behaves like concrete without fibers and the tensile strength is practically not affected by the addition of the fibers before the first crack occurrence. While a plain concrete has only a very low post-cracking energy capability – in tests the corresponding stress-crack opening relationship (σ-w relationship) shows a comparatively short, steeply dropping branch – through the addition of steel fibers a decisive improvement can be achieved here: Through the choice of the type and dosage rate of the fibers, a substantially increased post-cracking energy capability with corresponding post-cracking tensile strengths can be achieved.

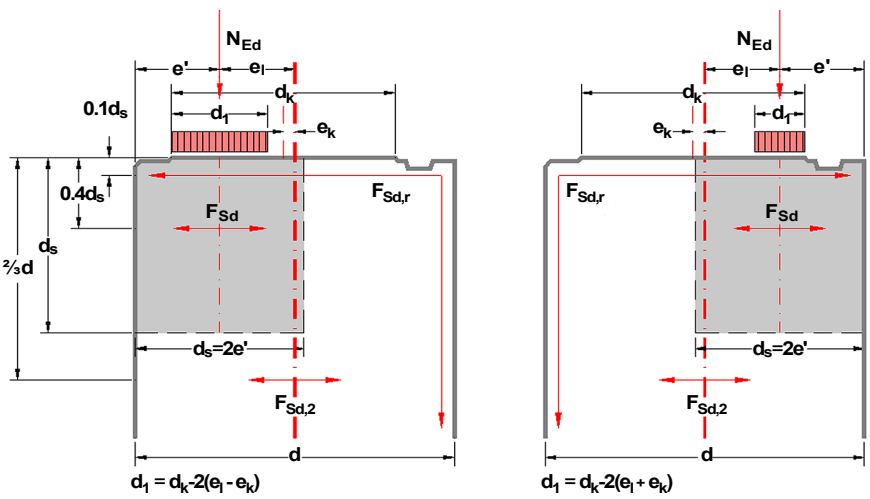

Figure 13: Segment joint with load eccentricity and split tensile stress

Figure 14: Conventional segment reinforcement (left); segment with steel fibers (right)

Other properties are improved by the addition of steel fibers, such as resistance to shock loads (transport and installation conditions of the segment) and mechanical wear; the latter can be significant in the design of water tunnels with corresponding transport of solids.

Ideally the fibers should be uniformly dispersed in the concrete matrix. The fibers are thus so scattered that continuous electrical contact of the fibers between each other does not occur. The change in electrical resistance compared to plain concrete is thus barely noticeable.

5.7.3 Experience with steel fiber reinforced concrete segments

In the meantime, several tunnel projects with steel fiber reinforced concrete lining segments have been completed. With no claim to completeness, these include:

- Channel Tunnel Rail Link (CTRL), London, United Kingdom
- Heathrow baggage tunnel, London, United Kingdom
- District heating tunnel, Copenhagen, Denmark
- Jubilee Line, London, United Kingdom
- Docklands Light Rail, United Kingdom
- Subway Lot 34, Essen, Germany
- Metro M9, Barcelona, Spain (design and construction with steel bars, client requirement: addition of 30 kg steel fibers per m³ of concrete structurally)
- Metro Line 4 and 5, Sao Paulo, Brazil
- Hofoldinger tunnel (water tunnel) in Munich
- Temporary railway station segments, subway Wehrhahn line Dusseldorf

5.7.4 Basis of calculation

Steel fiber reinforced concrete has been the subject of intensive research and development work for many years. With the release of the DAfStB Guideline Steel Fiber Reinforced Concrete [37][32], the gap to DIN 1045-1 or EN 1992-1-1 was filled and a consistent set of rules for the design of steel fiber reinforced concrete and steel fiber reinforced concrete in combination with reinforced concrete (i.e. conventionally reinforced concrete) is available. The Guideline version adapted to the requirements of EN 1992-1-1 is expected to be officially adopted by the building authorities in Germany in early 2014 [37][32].

The Guideline follows an approach determined by material behavior: the post-cracking material behavior of steel fiber reinforced concrete is ascertained using small-scale experiments from which characteristic values and basic parameters are determined. From the fundamental values the so-called performance classes L1 and L2 are defined. The calculatory and design parameters for defined stress-strain curves are also determined from the fundamental values. These stress-strain curves for steel fiber reinforced concrete are incorporated into the usual calculation and design of reinforced concrete structures according to DIN 1045-1 and EN 1992-1-1 for the purposes of improving the flexural, shear and punching shear load capacities or crack width limitation.

As a result of his static calculation the design engineer determines the required construction material properties by specifying the performance classes L with L1 (post-cracking bending tensile strength for small deformations) and L2 (post-cracking bending tensile strength for larger deformations) or in combination with conventional reinforcement of the steel fiber reinforced concrete.

The Guideline *Steel Fiber Reinforced Concrete* is primarily geared to the needs of the standard building and industrial construction sector. The design of the full cross-section of the tunnel lining segment for longitudinal force with bending/shear should be performed based on the Guideline for Steel Fiber Reinforced Concrete. It represents the current state of the art in Germany.

For segment-specific questions, special investigations (approvals in each individual case) may also be necessary.

5.7.5 Determining properties of the concrete in tests

The classification of steel fiber reinforced concrete in the performance categories L1 and L2 is based on the results of a 4-point bending test of beam-shaped specimens according to [37], Part 2, Annex O – Test to determine performance categories. The definition of the concrete composition including fiber type and quantity is the responsibility of the manufacturer of steel fiber reinforced concrete.

Steel fibers according to DIN EN 14889-1 Fibers for Concrete – Part 1: Steel Fibers [22] are to be used. Usually steel fibers from cold drawn wire are used in segment production.

5.7.6 Calculation notes

Segments of steel fiber reinforced concrete are best suited for tunnels with low stress, especially low bending stress, and greater thickness of the tunnel lining segments. The design is carried out for longitudinal force with bending and shear in accordance with the Guideline *Steel Fiber Reinforced Concrete*. For the calculation of internal forces, usually non-linear methods or theory of plasticity methods are needed to enable rearrangements in the system.

In addition to the verification of the longitudinal joints in the final state, often the stress caused by thrust cylinder loads that result inhigh split tensile stresses in the thickness direction of the segments and slab stresses (cf. Chapter 5.5.1) proves to be key. Here there is often an additional input of conventional reinforcement (reinforcement combination).

In order to limit the bending and slab stress on the individual segments, the ratio of the developed length in the circumferential direction to the segment width should not be too large.

Slab stresses from thrust cylinder loads act only for a short time and thus represent a transient action during construction. Any cracks that may occur here are generally completely overpressured in the final state by the ring normal force as a result of annular ring grouting pressure and/or water pressure. In order to enable the closing of these cracks from slab stresses as far as possible, the mathematically calculated crack width must be limited. The limiting of the crack width can be verified with the help of the Guideline *Steel Fiber Reinforced Concrete*.

Major advantages of fiber reinforcement are the mathematical limitation of crack widths and the increased rearrangement potential of the ring by the development of mathematical, plastic joints.

6 Structural fire protection

6.1 Introduction

The requirement, nature and extent of structural fire protection for a tunnel lining is always to be considered in association with the operational protection measures (e. g. traffic management and control, possibilities to drive into safety/evacuation zones, escape routes design, fire detection, smoke removal, ventilation, cooperation with emergency services) in accordance with the relevant regulations and determined accordingly.

In the relevant regulations, ensuring adequate stability and if necessary also serviceability (water tightness, limitation of permanent deformations) during and after a fire are named as the key protection goals of structural fire protection in tunnels.

6.2 Actions

Measurements in fire tests in tunnels and the subsequent evaluation of real tunnel fires show that tunnel fires differ from fires in buildings both by the height of the maximum temperatures reached and on the other hand by the extremely rapid temperature rise at the beginning of the full fire.

For the description of the thermal actions, usually temperature-time curves are defined for the fire gas mixture. Figure15 shows the temperature-time curves of relevant regulations.

6.3 Ways of ensuring structural fire protection

The various ways of ensuring structural fire protection according to the current state of the art are discussed in detail in [1], [58] and [59]. In the following the most important points from these are summarized. Specifically the following measures are involved:

- By cladding with fire protection panels or fire protection plasters, which act as an additional heat insulation layer, the inner reinforcement layer can be prevented from being heated substantially over 300°C. Compliance with this criterion ensures the stability of the tunnel construction during the fire and that major permanent deformations after the fire are avoided.
- Through the use of concrete with high fire resistance (for example, by the addition of PP fibers) the concrete cover can act as a thermal insulation for reinforcement with correspondingly low spalling. Verification must be carried out by means of large-scale fire tests on a representative section of the tunnel lining, through mathematical proof of stability, taking into account the expected spalling in case of fire, or a combination of the two.

6.4 Fire protective claddings and fire tests

6.4.1 Fire protection plasters

Because of their fiber content, fire protection plasters are relatively soft and elastic and have limited crack-bridging properties. Harmful cracks in the concrete can therefore not be transferred to them and not recognized in the regular structure inspections that are to be carried out. Mounting elements for signage, tunnel control systems, etc., penetrate the plaster finish. In these areas, special designs are necessary for fire protection and for load transfer.

To ensure the protective effect of fire protection plasters, sufficient adhesion to the structure by means of spray plaster, adhesive or plaster base must be ensured.

Plaster coverings have a service life of 25 to a maximum of 35 years. With an assumed useful life of the tunnel of 100 years the plaster covering must be replaced two or three times.

6.4.2 Fire protection panels

With a panel covering, the mounting is part of the protective system, as it must not lose its functionality during the fire, in order to prevent the panels falling off. Fire tests are necessary to verify the insulating effect of the panel covering and the load bearing capacity of the mounting. Specially adapted panel coverings must be provided for in the vicinity of tunnel installations.

Similar to the fire protection plasters, the life of panel coverings is 25 to a maximum of 35 years, so the covering must be replaced two or three times within the lifetime of the tunnel. Particular attention should be paid to the attachment of the fire protection boards from the viewpoint of corrosion resistance. Fire protection panels hide the underlying concrete areas from inspection or structural examination. Their use is therefore to be viewed critically.

6.4.3 Concrete with high fire resistance

Recently adequate structural fire protection has been verified in various traffic tunnels by leading fire tests on representative sections of the tunnel lining. In general the concrete was upgraded in fire protection terms by the addition of polypropylene fibers (PP fibers) to minimize spalling in case of fire. In this case mono- or multifilament PP fibers should be used with a round cross-section and a smooth surface. The fiber length should be within a range of 2 mm to 12 mm and the diameter in a range of 12 µm to 35 µm.

As of March 30, 2012 it was specified in the notes to ZTV-ING, Part 5 Section 1 and 2 (closed and open construction) that for increased structural fire protection for new road tunnels, execution of the inner shell with polypropylene fiber reinforced concrete (PP fiber reinforced concrete) should always be projected. 2 kg of PP fibers per m³ of concrete should be added. The fibers should have a length of 6 mm and a diameter of 0.016 to 0.020 mm. Because there is a reference to Section 1 in ZTV-ING, Part 5, Section 3 (Mechanized shield tunnelling method) in the Chapter “Structural Fire Protection”, the above information should be taken into account.

In the fire chamber the specimens are subjected to the projected temperature-time curve (see Section 6.2). According to current knowledge, segments with the dimensions and

the concrete composition as in the subsequent tunnel are used as specimens. In addition, the predicted state of stress in the segment is approximately set by means of horizontal and radial presses. With small specimens and those without stress, significantly less spalling can occur in the tests than can be expected in reality.

If spalling remains low in the test under the real conditions described above and the reinforcement is not unacceptably overheated, this can generally be viewed as a criterion for adequate structural fire protection.

Otherwise the tests in accordance with DIN EN 1363 Part 1 and Part 2 [20], [1] and [58] are performed.

A structure inspection or structure examination is perfectly possible with this type of design.

6.4.4 Conclusion

Although fire protective coverings are fundamentally suitable for ensuring structural fire protection, as explained above, they have a number of disadvantages In particular these are the very restricted possibilities for inspection of the tunnel construction and the significantly shorter service life compared to the tunnel itself.

In special cases, in the event of fire the water tightness of the tunnel must be guaranteed if otherwise serious damage can occur and the restoration of the serviceability of the structure is associated with considerable costs and time involved (for example in underwater tunnels). When fire protection coverings are used, water tightness – with the segment thicknesses usual in road construction (≥ 30 cm) – is definitely maintained. But the maintaining of water tightness can also be verified with fire tests or mathematical methods. Spalling must then be limited by a suitable concrete composition so that the maximum temperature is not harmful in the area of the reinforcement. Project-specific requirements must be specified in this case Because of the narrow joint gaps the temperature increase is generally not critical for the sealing profile on the outer side.

6.5 Mathematical studies

The segments can be verified according to DIN EN-1992-1-2. Another method for the verification of the segmental rings during and after a fire is shown in Ril 853.

During design and in the concrete mix already, steps should be taken to ensure that the least possible spalling occurs in the event of fire.

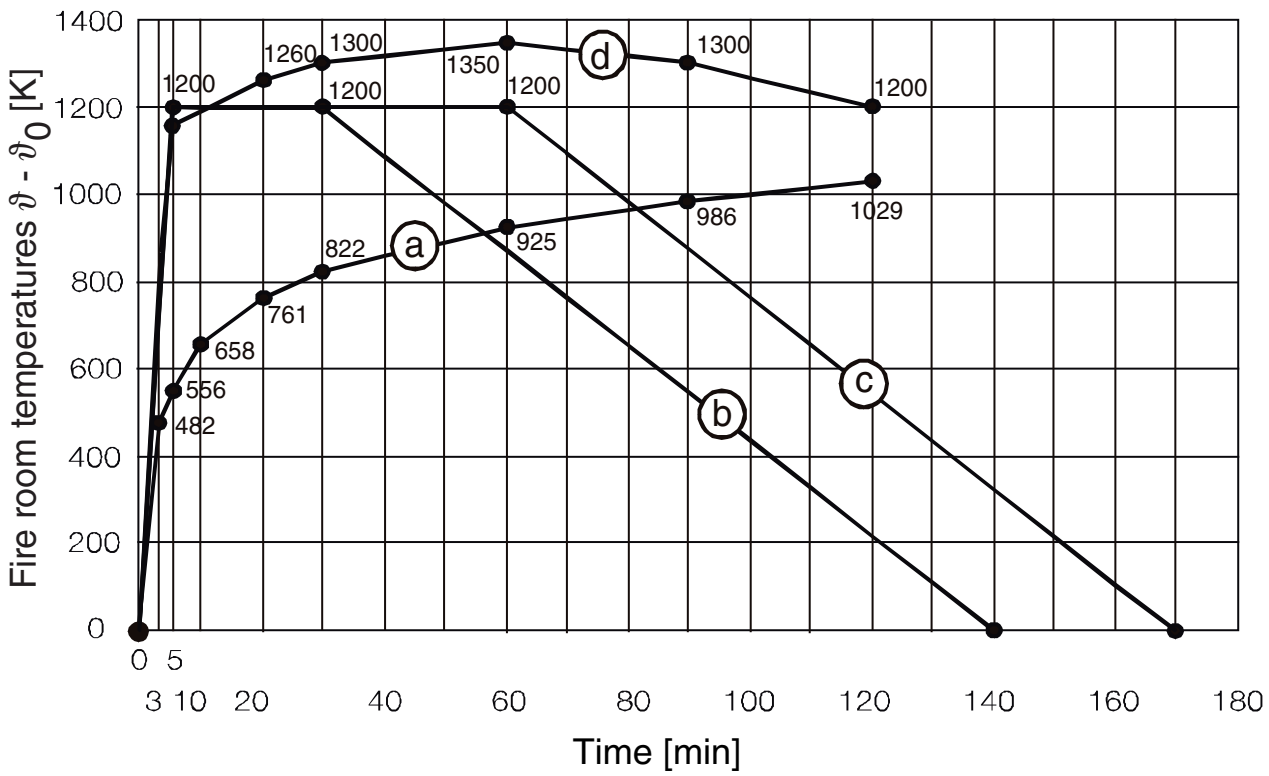

Figure 15: Temperature-time curves of relevant regulations (a: ETK, b: ZTV-ING, c: EBA, d: RWS)

7 Durability

7.1 Requirements

The durability of the tunnel structure assumes its planned load bearing capacity and serviceability – with reasonable repair expenses – over its entire useful life. Service lives of 100 years or more are common Inspection and repair options are usually available only to a small extent. This is especially true for the ground contact surfaces, seals and side surfaces no longer accessible after installation. The following requirements must always be met:

- Load bearing capacity of the ring and its individual components
- Water tightness against water under pressure
- Avoidance of spalling, which can limit serviceability (e. g. road safety), but can also be relevant to load bearing capacity
- Avoidance of excessive degradations such as corrosion and aging damage in the materials concrete, reinforcing steel (structural steel or fiber materials) or sealing and mounting components

The following two sections cover only the classical segmental lining with segments as precast reinforced concrete parts or precast parts made of steel fiber reinforced concrete. With regard to the specific characteristics of structural steel segments in installation, corrosion protection, transitions, etc. reference is made to additional literature ([2], [21], [43]).

7.2 Aging mechanisms

Reinforced concrete segments are exposed to ongoing aging from processes attacking concrete and steel (see [60], [61]). The individual mechanisms occur mostly in combination and may reinforce each other. They include:

- Carbonation of the outer sides in ground contact or the airside surfaces
- Sulfate attack due to sulfate-containing water or subsoil with dissolving or driving effect
- Chloride attack from de-icing salts (for example, in portal vicinity), saline water environment, possibly the effects of fire and corrosion of reinforcing steel triggered by it
- Mechanically abrasive wear stress of the inner surfaces and edges, including unplanned events (e. g. also from tunnel cleaning)
- Degradation from thermal stress in climatic changes, such as frost-thaw cycles in portal vicinity
- Contact corrosion of reinforcing steel with stainless steel components of durable longitudinal bolting is usually not significant

Unplanned cracking and spalling under compulsion effects or mechanical loads have a negative effect on the processes of aging and should be avoided in favor of a closed concrete structure with low porosity. Such defects can occur at corners, edges, the ring joints toothing (cam/pocket tongue/groove) or the longitudinal joints.

With the usual concrete strengths for tunnel lining segments the depassivation front of carbonation (pH values of <9) usually remains within the normal concrete cover values over the useful life. In contrast, under unfavorable conditions penetration depths of chloride-containing waters with chloride ion concentration relevant to reinforcement corrosion can also be markedly higher than traditional concrete cover values, which needs to be considered in the segment design.

7.3 Recommendations to improve durability

The following marginal conditions are recommended in terms of improved durability tunnel lining segments made of reinforced concrete or steel fiber reinforced concrete:

- Use of a normal strength concrete at the upper limit of the strength spectrum (usual: C40/50). As the lower barrier this must provide adequate strength properties compared to the planned stress, but at the same time as the upper barrier have sufficient deformation or energy capacity. In the event of unplanned marginal pressures during installation or transport, high-strength concretes tend more towards brittle edges and corner spalling. Subsequently repaired damaged areas from spalling or too wide cracks are often weak points in terms of durability.
- A dense concrete structure with low porosity is desirable particularly in the areas of concrete cover. This must be ensured by:
  - the concrete technology (low w/c values, tiered grading curves, etc.)
  - suitable production in the factory, usually with closed steel formwork (compaction, adequate curing, protected storage). The curing of the outer side of the segment is of special importance because here, as a result of the concreting process and top closing shuttering flaps, air pockets can gather (absorbent forming systems at the tops or manual treatment and removal of segregated surface concrete)
  - Adhering to stripping times
  - transport, storage and installation that avoid damage (avoidance of cracking and subsequent repairs)
- As a rule concrete cover should not be less than min c = 40 mm on the outside and inside. A tolerance allowance of 5 mm geared to the production of finished parts with higher quality standards must be considered, which must be particularly adhered to for the outer shell that lies on top at the production site. In the case of strong chloride or sulfate attack, in some cases increased concrete cover is necessary [60]. At the end faces (ring and longitudinal joints) locally reduced concrete cover values to min. c = 20 mm are acceptable if loads are to be absorbed near the surface, so that there is no cracking and spalling at the seals.
- Use of a securely fixed reinforcement cage – fixed with wire mesh or local spot welding – in compliance with the spacing requirements of the concrete cover and mounting parts. Industrialized prefabrication of partial elements from list mats and computer-aided manufac-

turing make sense. Avoidance of unnecessary transportation.

- Avoidance of unplanned mechanical loads (overloading, local damage) and unplanned exposures (e. g. chloride- or sulfate-containing backwater or leakage water) by continuous structure inspections and maintenance during operation.
- Limiting of mathematical crack widths (ZTV-ING Part 5 Section 3 No. 8.2.1 (5): For segments generally 0.2 mm, for pressurized groundwater on the wetted side 0.15 mm).
- Inclusion of additional installation parts and anchorage connectors (anchoring of pipes, fittings, electrification, etc.) in the planning for durability.

7.4 Peculiarities in the use of steel fibers

The steel fibers can corrode with a correspondingly aggressive environment, corrosion is, however, limited to the near-surface region. Due to the small fiber diameter, the corrosion products do not lead to bursting of the concrete matrix and the corrosion does go very deep.

The corrosion of the steel fibers on the concrete surface can potentially be an aesthetic problem, but is otherwise acceptable.

According to the application limits of the Guideline *Steel Fiber Reinforced Concrete*, in an aggressive environment (exposure classes XS2, XD2, XS3 and XD3) an engineer-driven durability design for the lifetime of the segment must be created.

For road tunnels, however, the great penetration depth of chloride measured results in a significant durability problem.

8 Peculiarities of two-pass lining

In Germany inner shells are rarely still used as a secondary lining. Even with a two-pass lining the segment ring must be able to absorb all loads. Only the verification regarding water pressure can be dispensed with (for example with segments without sealing) in the event of potential drainage impact during construction.

Advantages of two-pass lining:

- When using a foil seal a completely water-tight tunnel is achieved.
- The segment ring can be planned as a simplified economical ring (for example no design for subsequent excavation and construction), which often also does not need to be water-tight.
- The mountings in the tunnel (anchor rails, dowels, steel plates) can be made more cheaply. The planning of the exact mounting points can be done later (just before installation of the inner shell).
- Fire protection is ensured by the inner shell. After a fire the inner shell can be replaced.
- The crosscuts, ventilation and rescue tunnels and shafts, and the transition to the portals can be made more easily.

Disadvantages of two-pass lining:

- The inner shell can usually only be made after the end of tunnelling of each tube. This requires a longer construction period and results in additional costs.
- If the segment shell must absorb the loads of rock and water pressure alone for a long time, after installation the inner shell only gets the loads from dead weight and fixtures. Since usually only a small normal force is present in the shell, larger shrinkage cracks can occur.
- With subsequently occurring loads, for example from excavation or construction, the distribution of the loads on the outer and inner shell cannot be clearly defined.
- The exact location of leaks is difficult to determine after installation of the inner shell.
- Verification of whether a shear connection exists between the outer and inner shell or also the verification that no shear connection exists is difficult to carry out. If a shear connection between the inner and outer shell is mathematically needed, so far no satisfactory structural solution is known to create the shear connection.

9 Special designs (crosscuts, steel segments, transition to open construction)

9.1 Crosscuts

9.1.1 Introduction

Crosscuts in tunnel tubes with segmental lining serve as escape tunnels between two tubes or as emergency exits, a connection to stairways, or as service rooms. The crosscuts are usually made using shotcrete, less commonly with pipe jacking. The formation of the crosscuts itself has few peculiarities. In contrast, the transitions between segmental lining and crosscut are problematic in structural and static terms, which will be exclusively discussed in the following. A similar problem also often occurs with shaft connections, niches, emergency and breakdown bays and pump sumps.

9.1.2 Placement of the crosscut opening

The optimum formation of a crosscut opening greatly depends on the existing marginal conditions (cross-section of the main tunnel and cross-cut, geometry of the segmental lining and location of longitudinal joints, production and lining of the crosscut, required passageway opening, pipelines and cables, rock type, water pressure, sealing concept for the crosscut, number of crosscuts, construction schedule, requirements for corrosion and fire protection, etc.). The upper and lower edges of the crosscuts and their transitions should be within the segment tunnel if possible. It is advantageous if the height of the crosscut axis coincides approximately with the height of the tunnel axis of the segment tunnel.

Fundamentally it is possible to plan special segmental rings with steel segments in the crosscut area, or to install normal segment rings (possibly with increased reinforcement and additional boltings/dowellings) from which the crosscut opening is removed or cut out.

If special segmental rings are planned, it is advantageous to plan the arrangement of crosscuts in the area of parallel rings of uniform width. With tapered rings the location and order of the rings must first be determined or limited. The key segment should be on the side opposite the crosscut opening. To reduce the number of special segments, a mirror-image arrangement of the segments in the crosscut area is desirable in both tunnel tubes It should be noted that this means that in both tubes in the area of the special segments the possibility of TBM course correction is lost or limited.

Should freezing of the ground from out of the segmental tunnel occur, the static verifications should take into account the arrangement and location of the ice lances when forming the crosscut and the segments as well as any ice pressures acting on the segmental tunnel.

9.1.3 Support of the segments

The segment rings are permanently interrupted in the area of the crosscut opening. In the final state the normal forces

Figure 16: Steel segments around a crosscut opening

are generally transferred away via an in situ concrete frame or a frame made of steel or cast iron segments. Because an in situ concrete frame can only be produced after the break-out of the crosscut opening, this solution additionally requires temporary support of the segments during construction. This can be done with steel rings, profile girder trestles or frames transverse to the tunnel axis ("hedgehog"). It is also possible to plan bolting or dowelling of the segments in the ring joints with the help of special connecting structures in the concrete segments.

If segment frames or dowelling or bolting are used as support during and after construction, the bedding of the load-bearing rings in the side wall must be ensured at all stages of construction.

If the entire junction area is iced or solidified with DSV or injections, then the temporary support can potentially be replaced by this ground stabilization or the load to be supported can be reduced to the dead weight of the segments and a loosening pressure.

In the calculation it must be taken into consideration that the load impact and bedding are no longer present at the opening, and possibly beyond, which disrupts the load bearing system of the segment ring.

9.1.4 Steel segment frames

Special segments made of steel must have the ring width of standard segments, if necessary smaller segments must be supplemented with additional special elements to make up the full ring width. Bolting of the ring and longitudinal joint must correspond to the concrete segments. The longitudinal joints must also be matched to the concrete segments. In an extension of the TBM jacks the steel segments must be stiffened accordingly. Because of the tailskin seal the outer diameter of the special segments must correspond to that of the standard rings, the inner diameter can be made the same or greater.

In the choice of the inner diameter the requirements regarding corrosion and fire protection must be clarified in advance. For corrosion protection coatings, an increase in the metal sheet thickness or a concrete casing are commonly used. For fire protection, special plasters, fire protection panels or concrete casing come into question. In order not to restrict the clearance gauge, when concrete casing and fire protection panels are used the inner diameter of the special segments is usually increased.

Usually special segments also have circumferential elastomer profiles as a seal. Therefore a seal groove must be formed corresponding to the concrete segments. Internal corner cantilevers are not possible. It is also important that the sealing profile is not damaged when lining the filling segments.

The steel segment frames are also used during construction for supporting the segmental tube. This requires sufficient lateral bedding of the rings. The required bedding width depends on the load, the cross-section of the main tunnel, the width of the transition frame and the surrounding geology.

At the latest before lining the filling segments in the later crosscut opening, the individual steel segments are joined together with high tension bolted connections to form a rigid frame. This requires corresponding mounting holes.

9.1.5 Bolting or dowelling in the ring joints

When special segments are arranged the segments can be frictionally bolted or dowelled in the ring joints above and below the crosscut opening. As a result of the coupling the normal forces of the interrupted segment rings can be transmitted to the adjacent rings.

Such structures can be designed both solely for the construction stage and for the final state. If they are merely for load transfer during construction, in the final state the ring forces of the segment must be absorbed by an in situ concrete collar within the opening (bracket). If the connections are projected for the final state, special requirements must be made regarding fire protection and corrosion protection.

Since the load transfer in the ring joints between the adjacent rings results in a high local stress, usually special precautions are taken for the load introduction into the concrete segments and the reinforcement designed accordingly. The load on these special segments usually requires a high reinforcement content.

Depending on the geotechnical and geometric marginal conditions, in addition to the forces in the tangential direction (normal forces in the ring direction), forces in the radial direction (transverse forces in the direction of the segment thickness) also occur at the coupling points in the ring joint. The latter often determines the size of the load bearing capacity, and thus the possibility of using such a construction.

9.1.6 Steel structures

Steel frame around opening

Steel frames around a crosscut opening are placed either inside the main tunnel cross-section or in the central area of the segment shell.

The placement within the cross-section determines the introduction of force via brackets or similar from the segmental lining into the support structure. In addition, the structure must be installed frictionally (potentially preloading of the struts), the deflection of the bars must be taken into account and the bedding be ensured in the case of curved struts. If the main tube consists of tapered rings, the tunnel describes a spatial curve. This must be considered in the design of the frame and the bracket.

Steel rings

Steel rings within the clearance gauge of the segment tunnel for the temporary support of a segmental tube are only suitable for small loads because they are very soft and require adequate bedding. Structurally, the rings must be positively connected to the segment (mortar cushions, wedges, etc.).

Profile girder trestles

Profile girder trestles have greater load bearing capacity than steel rings. The arrangement of the struts should be matched to the construction work (passage opening, track). Maintaining a specific track level is especially important for rail operations. In the formation of steel structures the assembly process and the possible weight of the individual parts will depend on the available equipment. Safety restraints alongside tracks must be generally secured against vehicle impact.

Statically the concentrated load introduction is often problematic in the frame corners. A combination of steel rings and profile girder trestles is also possible.

Hedgehog structures

If the steel rings are formed as a rigid, rectangular support frame with allround supports for longitudinal members, one speaks of hedgehog structures. One or two hedgehogs are usually arranged to the side of the crosscut opening and the segment shell is supported in the region of the crosscut with longitudinal profile girders. The longitudinal beams rest on the support frame and can often be pretensioned against it with hydraulic presses. The individual option of preloading and readjustment make it a very convenient solution. It was a standard design in the early days of segmental lining. For cost reasons it is rarely used today.

9.1.7 In situ concrete frames

In situ concrete frames at the transition between segmental tunnel and crosscut are often used as the final support of the segmental tube. The height and the segmental division of the main tube and the height of the crosscut are decisive for the structural design. In addition to the clear opening height, above and below the opening there must be a sufficient bracket height for supporting the segment rings. Problems are sometimes caused by necessary cable conduits or drainage pipes in the invert that weaken the lower bracket.

For steel segment frames the in situ concrete frame together with the inner shell of the crosscut serve as unyielding bedding.

With the two-pass lining, the in situ concrete inner shell with openings produced in advance usually serves as support for the segmental tube in the crosscut area during and after construction.

9.1.8 Creating the crosscut opening

Fillers seal off what will later be the crosscut opening during the advance and are then removed. The opening is usually sealed with steel segments. Concrete elements are also possible, however. When planning a crosscut opening the removal of the fillers needs to be considered already.

It is also possible to create the opening in normal reinforced concrete segments using tangential core bores or saw cuts along the opening contour.

9.1.9 Seal connections

When planning the seal connection between crosscut and segmental lining the amount of water pressure and the type of sealing of the crosscut are key. It is possible to line the crosscut with an inner shell made of impermeable concrete or without additional sealing using plastic liners.

A technical possibility for sealing is gluing the plastic liner of the crosscut onto the appropriately prepared outer side of the lining segments outside the crosscut opening and additional fastening with a loose-fixed flange construction. This solution has the disadvantage with concrete segments that the segment outer side is usually rough and curved in one direction and the clamp construction crosses several segment joints. These joints must be cleaned and filled to the depth of the sealing profile to avoid underflow of the clamping construction. Backfilling with special mortar is recommended only at low water pressures. In any case, an additional grouting hose should be put in place. For higher pressures, a PU resin filling can be considered. Here, however, there are substantial problems with joint filling overhead. PU also does not adhere to the elastomeric seal.

If steel segments are arranged around the crosscut opening, a loose flange with a joint strip or a protruding steel flange can also be mounted on the outer side or end face of the segment.

Loose-fixed flange constructions can generally be used only for water pressure up to about 3.5 bar.

Between the main tunnel and the crosscut *differential settlement* is generally possible. When a reinforced concrete frame is formed the expansion joint between the main tunnel and crosscut is advantageously arranged between this and the standard cross-section of the crosscut.

9.1.10 Safety seals

Safety seals of the crosscut openings against water intrusion during construction are partly required by clients and are very expensive. The seals must be dimensioned for water pressure and are therefore very heavy. On the other hand, they must be quick and easy to open in case of danger. The preload force for the seal is generally produced by the water pressure. Laterally sliding emergency bulkheads have been used (Weser Tunnel) or folding or dropping doors placed above the opening (Westerschelde Tunnel).

9.2 Steel segments

9.2.1 Introduction

In the past, “steel” segments were mostly produced as cast iron segments made from nodular cast iron. Despite the steel-like properties of nodular cast iron, these are not steel components. Today, increasingly steel segments are made from rolled steel sheets which are welded to form a segment. Steel segments are generally used where, due to the load or the geological conditions the tunnel lining is exposed to extreme stress, which can no longer be absorbed by reinforced concrete segments.

9.2.2 Formation

Steel segments welded from rolled sheet metal usually consist of an outer shell plate, which forms the watertight shell of the tunnel lining. On the inside web plates are arranged in the circumferential direction and in the longitudinal direction of the tunnel, so that a kind of cassette segment is created. Together with the shell plate the web plates arranged circumferentially absorb the ring forces consisting of normal force, moment and shear force. The web plates arranged in the longitudinal direction of the tunnel are used for the passage of the normal forces in the longitudinal direction of the tunnel, for example, jacking forces from the TBM.

Both in the longitudinal joints and in the ring joints, the steel segments are joined by means of bolts. Depending on the number and the preloading of the bolts the connections can be made rigid and shear resistant.

In a segment ring either only single reinforced concrete segments can be replaced by steel segments (see Chapter 9.1.4) or the entire ring can be formed from steel segments.

The seal between the steel segments is analogous to reinforced concrete segments, with a sealing frame located in a seal groove.

9.2.3 Production

Depending on the process, in the production of steel segments marginal conditions result that must be taken into account at the planning stage.

The individual plates are first cut and then welded together to form segments. Welding results in stresses and distortion in the sheets and the entire segments. For this reason the final outline is formed only after welding, by milling. The segments are aligned in such a way that as little material as possible is milled. The holes for the bolts are also drilled in this step. This ensures that the segments fit together exactly.

When choosing the plate thicknesses the amount for milling must be taken into account and also a certain tolerance must be considered. It must be ensured that after milling the statically set minimum thickness of the plates is maintained.

9.2.4 Installation

The installation of steel segments is a lot more complicated than the installation of reinforced concrete segments. This is due to the low tolerances for bolting, which force very exact ring building. The installation of the numerous bolt connections is very time consuming. All bolts must be tightened to their required preload. This lowers tunnelling performance considerably. Usually special adapter plates are required for the installation of the steel segments with the erector.

Because of the way the individual segments are produced, offsets can occur on the inner side between adjacent segments, although the bolt connections fit together exactly and thus the sealing profile is ideally matched.

9.3 Transition to open methods of construction (stations, portals)

9.3.1 Introduction

Stations, portals and other special structures are usually produced as in situ concrete structures. To make a tight connection between the segmental lining and the situ concrete,

Figure 17: Flange construction at the transition to in situ concrete, e. g. Katzenberg Tunnel

a special transition structure is required. This is usually accomplished by means of sealing joint strips. Fundamentally it must be differentiated whether the seal construction should be accessible and replaceable from the outside, or whether it should be integrated into the in situ concrete structure and no longer accessible.

9.3.2 Replaceable seal constructions

Externally accessible and replaceable seal constructions can be accomplished only with the help of a clamp construction and an omega joint strip. For this purpose, complex loose-fixed flange constructions are required. Appropriate fixed flanges must be arranged both on the segment lining side and on the in situ concrete structure side for this. With the help of a loose flange a joint strip is attached at both ends.

For corrosion protection, the flange structures usually have to be made of stainless steel.

Because such constructions are technically very complex and usually no deformations are expected between connection block and segmental tunnel, they are usually dispensed with.

For fire safety reasons, the joint strip must usually be protected against the effects of fire with the help of appropriate fire safety equipment (fire protection mats).

9.3.3 Permanent seal constructions

Constructions in which a joint strip is embedded directly into the situ concrete are more suitable. On the segment lining side the seal construction should be flanged onto the sealing frames of the adjacent segment ring. The free end of the joint strip generally ties into the in situ concrete construction made of impermeable concrete. Alternatively, the joint strip can also be connected with an external sealing foil.

To accommodate any possible shifts between in situ concrete construction and segmental lining, the joints between the segmental lining and in situ concrete structure should be formed as an expansion joint. Appropriate compressible materials and joint strips that can absorb the movements should be used for this purpose.

Special fire safety precautions are not generally required because the joint strip is adequately protected by the in situ concrete.

As with any joint construction, appropriate grouting hoses should be put in place for any potentially required resealing later.

10 Sets of rules, standards and publications

10.1 Sets of rules and standards

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Appendix

A.1 Notes on the production of segments in a precast plant

For the production, storage and transport of the segments a project-based QM and testing plan should be created and used for each tunnel project. This QM plan contains the specifications of the client and the contracting company for the durable, fault-free and certified tested production and delivery of the segments.

- For the production of segments the following conditions are generally required:
- Released implementation plans (segment design) as well as formwork, reinforcement and detailed plans
- Contract review defining all requirements
- Decision on production by subcontractors or in-house production
- Decision on production in a field production facility or in a stationary precast plant

A.2 Segment production

The QM plan for segment production should address the following points:

Stationary production – Steps

- Cleaning and oiling of the formwork
- Inserting the reinforcement, closing the formwork and mounting installation parts
- Final inspection of the formwork before concreting
- Concreting and compaction
- Opening and cleaning the counter formwork
- Stripping and smoothing the segment back
- Concrete curing (up to stripping)
- Lifting off the segment

Carousel production – steps deviating from stationary production

- Concreting
- Prestorage
- Heat tunnel

Curing

- Fresh concrete temperature
- Temperature of the production site
- Temperature profile

Interim storage / Maturing storage

- Supports and interim storage battens
- Storage time and necessary concrete maturity
- Handling and transportation equipment
- Protection against drying out and drafts
- Tolerance control
- Joint control
- Concrete repair

Concrete repair

- Cracks
- Minor damage and air voids
- Damage to the segment outer side to the reinforcement
- Damage to the segment inner side to the sealing joint with small dimensions
- Damage to the segment inner side to the sealing joint with large dimensions
- Refurbishment concept and documentation

Open air storage

- Foundation and stability
- Supports and interim storage battens
- Space requirements
- Handling and transportation equipment
- Configuration of the segment stack
- Weather protection against snow and ice
- Protection against water and moisture with seals with hydrophilic profiles

Materials

- Concrete
  - Mix design and initial testing
  - Materials such as aggregates, binders, additives, admixtures
  - Synthetic fibers
  - Concrete supply and equipment
- Reinforcement
  - Steel bars
  - Steel fibers
  - Concrete cover and spacers
- Installation parts
  - Dowels
  - Other installation parts
- Equipment
  - EPDM sealing frame
  - Joint sealing strips (for example TOK tape or foam rubber strips)
  - Hard fiberboard as a ring liner
  - Guide rods
  - Other equipment materials
  - Adhesive for equipment materials
- Release agents
  - Curing agents
  - Materials for concrete repair

Quality assurance / testing

- Test plan
- Factory acceptance and quality testing segment moulds
- Commissioning production plant
- Internal and external monitoring of the concrete
- Quality control of the reinforcement cages
- Incoming inspection and quality assurance of the suppliers
- Ongoing control of formworks
- Segment measuring
- Sample ring
- Documentation / traceability of segments
- Delineation of responsibility

Occupational Safety

- Noise
- Concrete contact
- Dust
- Handling hazardous materials
- Handling equipment

A.3 Tunnelling

The construction operation requirements of the segments from delivery on the site until installation in the tunnel are defined in the QM plan of the shield manual.

All design, static and construction operation issues for tunnelling must already be considered during technical processing. These include, for example:

- Interim storage on site
- Transport to the installation location
- Interaction segment lining and shield drive
- Ring building
- Annulus grouting
- Repair of damage