6 The tunnel lining

6.1 General

The tunnel lining has to permanently guarantee structural safety, durability and serviceability for the entire duration of the use of the tunnel. It supports the interior against the surrounding ground, forms a barrier against the penetration or emergence of water, transfers the internal loads from installations and traffic and, depending on the design of the TBM, may serve as an abutment for the thrust cylinders. The design and constructional detailing of the lining has to meet the requirements of the tunnel use, the acting loads and the conditions imposed by the construction process.

Temporary support with shotcrete and rock bolts is only an option with a gripper TBM. This type of support is dealt with in Maidl: “Hardrock Tunnel Boring Machines” [203].

The boring process normally demands a circular cross-section. The internal radius is determined by the use and the resulting requirements, such as a structure gauge that has to be maintained in transport tunnels or the required hydraulic cross-section in water or ventilation tunnels.

The dimensioning of the lining is decided depending on the structural actions, which mainly come from ground and water pressure. On account of the circular cross-section of the tunnel and the loading, which is not normally radially symmetrical, the system and support lines rarely coincide. This results in a transverse bending action on the tunnel lining in addition to compression, which can lead to the installation of structural reinforcement. The water pressure acting on the lining is influenced both by natural conditions and by the waterproofing concept. In tunnel systems subjected to water under pressure, the natural water conditions are restored after the completion of tunnelling. In this case, the lining must be designed to resist the entire water pressure. In tunnel systems not subjected to water under pressure, the water is drained so that no water pressure can build up.

The machinery used has a great influence on the possible types of lining. If a open gripper TBM is used, temporary support can be provided with shotcrete and an inner lining of in-situ concrete can be concreted later. If a shield is used normally, an immediately load-bearing segment lining will have to be used.
6.2   Construction principles for the tunnel lining

6.2.1   Single-layer and Double-layer construction

The lining of tunnels can consist of one layer (single-pass) or two or more layered construction [185], [189], [196].

In double-layer construction, the individual layers are constitutionally and functionally separate. The outer lining is installed as the tunnel advances and is designed to provide immediate support for the excavated cavity against the expected ground pressure. There are normally no serviceability requirements and thus no waterproofing requirements. These are complied with for the lifetime of the tunnel by the second inner layer installed as a permanent lining. For tunnels subject to water under pressure, the inner lining is designed to resist the applied water pressure. The inner lining also has to permanently support the ground pressure if the structural stability of the outer lining cannot be guaranteed for the lifetime of the tunnel. This is the case, for example, when aggressive groundwater, which can damage concrete, causes rotting of the outer lining. The inner and outer layers of construction are normally constructionally separated, for example by foil, in order to keep the inner lining free from indirect actions. In waterproofed tunnels, the waterproofing membrane undertakes this function.

Single-layer constructions can either be real single-layer solutions fulfilled by one construction system or composite solutions, in which two or more layers undertake the requirements on the lining with the individual layers contributing to the resistance of external loading as a composite (Figure 6-1). The first category includes, for example, tunnels with a single-layer segmental or extruded concrete lining and also tunnels in stable rock, which require no support for structural purposes but are provided with a smooth internal finish such as in-situ concrete for aesthetic or operational purposes. The second category includes, for example, tunnels whose lining consists of a composite of shotcrete applied for temporary support and a subsequently concreted bonded inner lining to complete the tunnel support system.

For both variants, the single-layer or composite cross-section must ensure structural safety and serviceability, particularly concerning waterproofing of the tunnel tube, for the entire period of use.

Figure 6-1 Definition of single-layer tunnel construction [185]
As the installation of precast segments and the application of shotcrete are both possible for a TBM-driven tunnel, the whole range of single and multi-layer tunnel construction types is available. There are also new developments using steel fibre reinforced concrete. Table 6-1 gives a schematic overview of the already used application possibilities.

Table 6-1 Matrix of possible lining construction types

<table>
<thead>
<tr>
<th>Inner layer or single-layer construction</th>
<th>Shotcrete</th>
<th>In-situ concrete</th>
<th>Segments</th>
<th>Extruded concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer layer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shotcrete</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Segments</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extruded concrete</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Single-layer construction</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

The question as to whether single or double-layer construction is better is primarily determined by economic aspects. But the risks for the construction of a waterproof tunnel also have to be considered. The construction of a segmental lining as the final tunnel support and lining is already standard worldwide for pressurised shield tunnelling. But for a hard rock TBM tunnel, the matter is not so clear-cut. A single-layer lining is only the economic option under certain conditions.

Comparisons of tenders for a number of major transport projects in Switzerland have shown that double-layer construction is still 5% to 10% cheaper because the production costs are lower due to thinner segments, less reinforcement and less stringent precision requirements. Better advance rates can be achieved due to the shorter ring building time and the annular gap can be filled by stowing pea gravel instead of relatively expensive grouting, which is required to compress the gaskets in the longitudinal joints of the segments, among other reasons.

### 6.2.2 Watertight and water draining construction

In order to deal with the presence of water in the ground, there are two basic possibilities: the groundwater can be collected by drainage and led away, or the tunnel can be made watertight all round and resist water under pressure. Figure 6-2 shows the functional principles of these two methods through the example of a single-layer segment lining (left) and a double-layer cross-section with in-situ inner lining (right).

In drained tunnels, the tunnel vault is made watertight to protect the interior from water penetration. This can be achieved by a plastic waterproofing membrane hung in front of the inner lining or the construction of the vault as a waterproof concrete structure. The groundwater flows around the technically waterproof tunnel lining into the drains at the sides, where it is collected and carried away. This system is also known as drainage pipes with umbrella waterproofing and is suitable for percolating water or water under pressure. As no hydrostatic pressure can build up around a drained tunnel, the tunnel lining only has to be designed to resist ground pressure.
A disadvantage of tunnel systems that drain water away is the sometimes heavy expense for the maintenance of the drainage system due to encrustation and sintering, resulting in high operating costs. In order to maintain their function, drainage pipes should be flushed regularly. Recent investigations have shown that the use of low-elution shotcrete, constructional alterations to individual components of the drainage system and alterations to the overall system, like for example the exclusion of air by backing up the water, can reduce the problem of sintering [198].

Tunnel systems that drain water have an impact on groundwater conditions and thus the ecological system by lowering the groundwater table [184]. It may therefore be a requirement for environmental protection reasons to construct a waterproof tunnel without any effect on groundwater conditions after the completion of the tunnel.

Since the 1960s, the use of improved materials (plastic waterproofing membranes, plastic waterstops, waterproof concrete, new grouts etc.) have enabled the construction of tunnels with all-round waterproofing against water under pressure [258].

While single-layer, watertight segmental lining are now standard technology for shield tunnels, the proportion of the total number of tunnels with in-situ lining constructed to resist water under pressure is very low. For example, a survey of experience with tunnel waterproofing in Switzerland investigated altogether 239 projects, of which 233 were designed to resist seepage water and only 6 against water under pressure [310], [258].

In a study of the experience with waterproofing systems in German road and rail tunnels, altogether 9 tunnels with waterproofing against water under pressure were
analysed. In summary, the results showed that the contractually required waterproofing classes had not been achieved straight away without additional measures. In systems with plastic waterproofing membranes, localised leaks were often caused by damage during the installation of reinforcement. This was, however, often only detected in the form of visible damp patches after the first exposure to water under pressure, which made subsequent repair measures necessary, often extensive and made difficult by the continued water pressure. With a single-layer segment linings, waterproofing can be impaired by defective installation of segments resulting in damage in the form of heavy cracking or spalling.

Experience shows that not even two-layer waterproofing systems make it possible to ensure the required waterproofing without additional measures. A concept should therefore be produced for tunnels intended to resist water under pressure at the design stage to enable the subsequent improvement and repair of the waterproofing system with some prospect of success, even under water pressure.

### 6.3 Segmental lining

#### 6.3.1 General

Segments are precast elements, which are installed in a ring to serve as tunnel lining. The particular feature of a segment lining is the high degree of jointing, in addition to the segments themselves. The joints can be differentiated into longitudinal joints between the segments in a ring and ring joints between the rings.

![Segments for single- and double-layer construction](image)

**Figure 6-3** Segments for single- and double-layer construction
The use of segments is essential in TBM tunnelling if the gripping of the machine into the rock mass in order to produce the thrust forces is not possible due to insufficient rock strength. In such cases, the thrust forces are resisted by the already installed lining, which then works as an abutment in the direction of the tunnel axis. This requires immediately available load-bearing capacity, which cannot be provided by a shotcrete or in-situ concrete lining.

Figure 6-3 shows the spectrum of construction possibilities for segments for single- and double-layer construction in tunnelling.

Segments are usually installed using an erector in the protection of the tailskin of the TBM or braced directly against the rock mass behind the shield. In a subsequent working step, the annular gap remaining between the segment ring and the sides of the excavation is filled or grouted with suitable material through appropriate openings in the segments or through the tailskin. This limits the loosening of the surrounding ground, enables continuous transfer of the external ground pressure into the lining and provides the bedding required for the stability and structural safety of the tunnel tube.

Concrete segments are standard today and have mostly superseded steel and cast iron segments or tubbings for cost reasons. For further information about the use of steel and cast iron for tunnel linings, see [83], [143], [183], [196].

Specifications for segmental linings, which ensue from the local geological and hydrological conditions and also process-related and economic aspects, have led to numerous different construction variants for concrete segments.

The thickness of segments is determined according to structural and constructional criteria. The minimum thickness is mostly determined by the need to transfer the thrust cylinder forces and the resulting load-bearing area of the thrust pads. The usual thickness is 20 to 50 cm. Larger tunnel cross-sections also require thicker segments, for example segments 60 cm thick were required for the fourth tube of the Elbe Tunnel.

The width of concrete segments varies between 1.0 and about 2.0 m, with a current tendency to wider segments due to production developments in formwork technology and in the technology of transporting and installing segments. This enables quicker tunnelling and the reduction of joint lengths. But the increasing width of segments also concentrates more secondary loading in the joints resulting from production and installation tolerances and thus leads to a worsening of the cracking and spalling problem. Increased width of segments also reduces the “margin” for driving round curves and increases the necessary stroke of the thrust cylinders.

Segments should be reinforced around the ring to resist bending from external loading. Nominal reinforcement in both directions is also recommended to ensure serviceability. The splitting tension resulting from the thrust cylinder loading the ring joints should also be covered with appropriate reinforcement. This also applies for the transfer of eccentrically acting compression forces in the longitudinal joint.

6.3.2 Constructional variants

6.3.2.1 Block segments with rectangular plan

This variant is the most commonly used form, with a ring being built of five to eight single segments and a keystone. The rectangular geometry results in flat ring joints, and each ring
alone is stable and load-bearing. The wedge-shaped keystone is generally smaller than the other segments and is installed last. This allows the closing of the ring by inserting the keystone along the tunnel direction. The spreading action can produce a pressurising of the segment lining around the ring.

It is advantageous for structural reasons to produce all the segments with as similar size as possible, i.e. the keystone has about the same opening angle as the other segments. But for ring installation, a smaller, easily handled keystone is better. It should be investigated on each project, which system is more advantageous. A large keystone is becoming ever more accepted.

The use of block segments with a rectangular plan has become the norm for single-layer, watertight tunnels. Waterproofing is ensured by an all-round gasket profile, which fits into a groove intended for it in the longitudinal and ring joints. In addition to the provision of sealing gaskets, reliable waterproofing requires high quality installation of the ring while minimising secondary actions or excessive stiffness of the segment tube. The latter is normally effected by offsetting the longitudinal joints of adjacent rings (Figure 6-4). This reduces on the one hand the deformation capability of the tube by interlocking to mechanically bond adjacent rings (Section 6.3.3.2) and on the other hand eases the problem of waterproofing crossing joints.

A quite different procedure for keystone installation is the five-piece segment lining with keystone at the bottom (Figure 6-2 b), which is usual in Switzerland. The joints between the segments are not waterproofed, but are supplemented by an inner lining with waterproofing foil in-between. The ring installation sequence is as shown in Figure 6-5: first, the two invert segments are installed and then the side segments. These have to be laid on slewing carrier rollers, because the segments are not bolted to each other and no holding force is available from the thrust cylinders during ring installation. Then the crown segment is installed from below with the erector. The erector stays in place to maintain the position. Then the invert joint is widened using dowels inserted into the openings provided in the invert segments and the straight keystone is inserted into the gap at the bottom. Finally, the widening of the invert segments is slackened and the no longer required erector and the support rollers are removed, causing the crown segment to settle slightly. The segment ring is now in its final position and the thrust reaction ring for the thrust cylinders can be moved forward again.
The advantages of this method are the avoidance of excessive secondary loading due to violent insertion of the wedge-shaped keystone and the short time needed for ring building of 15 to 20 minutes. The disadvantages are the lower installation precision and the resulting spalling of the edges of the segments.

In general, a tunnel alignment is a three-dimensional curve, which the TBM has to follow as precisely as possible. The ring being installed has to follow the direction taken by the TBM without damage occurring due to contact of the shield skin on the lining [7]. This
would result in a one-sided opening of the ring joint in the curve. This is, however, not permissible for a single-layer tunnel with waterproofing requirements, as it could cause the gaskets to lose their function. In order to enable driving around curves without opening the ring joints, rings are formed with a taper on one side. Two basic systems can be used:

- When a tapered universal ring is used, any angle can be obtained through the appropriate rotation of the ring. The advantage is the lower formwork and logistics effort through the use of only one ring type, which is a decisive advantage in segment production. When offset longitudinal joints are specified, however, it should be noted that a compromise is often necessary regarding the rotation of the ring for the optimal steering of the shield. A further disadvantage of the universal ring is that the keystone position varies. If the keystone is in the invert, then ring assembly has to begin with the segment in the crown, which in this case can only be held in position by applying the thrust cylinders. This has to be taken into account in the design of the TBM, as additional measures are necessary to protect the crew in the erector area.
- The production of a number of ring types as right-, left-turning and parallel rings can maintain uniform geometry of the longitudinal joints with a defined keystone position. The disadvantage is the relatively high logistical complication and the resulting higher segment production costs.

The use of block segments with conventional shield machines normally demands the coupling of the excavation and ring assembly operations. This means that excavation can only continue after the installation of a ring is complete. This limitation results primarily from the limited travel of the thrust cylinders.

The desire for a continuous installation sequence has led to the development of the spiral segment, which has sometimes been used in Berlin and Stuttgart (Figure 6-6). This variant has not, however, become established.

![Figure 6-6](http://example.com/figure6-6.png)  
*Figure 6-6 Spiral segment, Berlin underground, 1965/66 [196]*
6.3.2.2 Hexagonal segments

Hexagonal segments were first used as long ago as 1961 for the construction of the Happurg water tunnel [196]. This type of segment is being increasingly used today as the outer layer of a two-layer tunnel system, but also for single-layer solutions, particularly when a double shield TBM is used [113], [182], [288], [287]. Because of the hexagonal shape of the individual segments, there is no continuous ring joint in this system, as this is offset by a half segment width between adjacent segments. The mechanical interlocking of the ring joints also results in an altogether stiffer tube compared to rectangular block segments without offset longitudinal joints. A ring built of hexagonal segments can consist of altogether four segments in smaller diameters, with the invert and top segments and the side segments opposite each other (Figure 6-7).

A significant economic advantage of this segment system is that ring construction only requires one type of segment. This leads to considerable cost savings in segment production compared to the use of rectangular block segments. Only the invert segment is often constructed with differences from the standard segment for operational reasons.

Disadvantages of this variant result from the size of the segments with increasing diameter and the resulting transport and assembly problems. Hexagonal segments are therefore preferably used for smaller diameters up to 4.50 m, although larger diameters are possible, as demonstrated by the Plave II and Doblar II pressure water tunnels in Slovenia, which are both of 6.98 m diameter [287].

6.3.2.3 Rhomboidal and trapezoidal segment systems

The desire to use mostly automated processes for segment installation has led to the development of segment systems with jointing dowels and guiding rods [294]. This is intended to reduce secondary loading during installation by optimising the segment geometry and by installing guiding rods in the longitudinal joints as well as centring dowels in the ring joints to achieve a high precision of assembly and ring quality.
6.3 Segmental lining

Figure 6-8 shows the segment system used for the construction of a single-track rail tunnel in Paris [294]. The segment ring consists of a trapezoidal invert segment, four rhomboidal segments and a trapezoidal keystone. The angled longitudinal joints of the segments mean that the sealing gaskets of the segments only come into contact in the last few centimetres of installation movement. However, angled joints lead to kinematic lack of fit and stresses when a ring is deformed in its plane by a curve.

The ring joints are connected with three Conex plastic dowels per element (Figure 6-9) and one per keystone. Precise installation is ensured by 5 cm wide guidance grooves in the longitudinal joints. This system was also used successfully on a rail tunnel in Milan.

6.3.2.4 Expanding segments

In stable and relatively dry ground, ring construction can also be undertaken behind the shield. The ring is then expanded against the excavated ground and assumes a stable position. No further filling or grouting of the annular gap is required as long as the tunnel can be excavated with a uniformly round excavation profile.

Figure 6-9 Conex Lining System, dowelled segments, Passante Milan (Mayreder) [196]
a) Plastic dowel
b) Dowels prefitted in a segment
Expanding segments were originally developed for use in London Underground construction in clay with a long stand-up time [162]. Figure 6-10 shows a typical cross-section, which was installed in large numbers on the British side of the Channel Tunnel. The spreading of the segment ring is determined by how far the wedge-shaped keystone is inserted. This has a smaller width than the remaining segments [16].

This lining system enables short ring building times and thus high advance rates. One major disadvantage is that each ring assumes a different geometry, which can be associated with corresponding offsets at the joints. As a result of the relatively large twisting of the longitudinal joints, expanding segments are not normally suitable for single-layer, waterproof construction.

**6.3.2.5 Yielding lining systems**

According to the model representation used with shotcrete construction, the convergence of the excavated cavity leads to the formation of a so-called rock mass ring, which contributes to bearing the ground pressure. The time of installation of the support is therefore of particular significance, as this determines the share of the load falling on the lining. The earlier the support can be installed, i.e. the less time the rock mass can relax through deformation, the larger is the load the support has to resist. It should, however, be noted that depending on the geological conditions, it is also possible that the ground pressure can increase further with increasing deformation and softening of the rock mass.

A segmental lining is immediately load-bearing and relatively stiff in bending, which provides immediate resistance to deformation of the rock mass after the passage of the shield machine and the filling of the annular gap. This can lead to extremely high loading under high overburden or in squeezing rock, which in extreme cases could lead to the failure of the lining.
For this reason, various attempts have been undertaken to develop yielding lining systems, which permit controlled convergence of the sides of the excavation. The measures can be differentiated into methods concerning the filling of the annular gap and methods concerning the longitudinal joints.

The use of a special grout for the filling of the annular gap can provide yielding support in combination with a segment lining. This can be a mixture of Styropor beads and sand. Particularly suitable could be the use of Styropor beads surrounded by cement paste, which would solve the problem of separation. Figure 6-11 shows the deformation potential of a Styropor-sand mix.

Figure 6-11 Trials of yielding stowed fill with high deformation potential [255]

Figure 6-12 Yielding construction of a longitudinal joint using plastified steel tube [248]
The yielding of a segmental lining can also be accomplished by the use of compressible inserts in the form of steel or plastic profiles. Figure 6-12 shows diagrammatically how convergence can be permitted by the plastic deformation of a steel tube inserted along the joint. The compression force in the lining is also limited by the transverse compression that can be resisted by the pipe in the plastic state.

A continuation and improvement of this principle is shown in the detail of a yielding joint construction (Figure 6-13). The yielding element in this detail is a plastic hose filled with water under pressure, which is grouted after the deformation of the rock mass has declined. Overloading of the segments can be prevented by valves in the water outlet pipe, which open at defined water pressures. The compression of the segment ring is enabled by the reduction of the volume of the hose due to water discharge.

Another proposal is for the use of a closed, plastically deformable plastic element (Figure 6-14), which also meets the requirements for waterproofing. This element, which takes up almost the entire face of the joint, consists of chambers filled with compressible air-entrained concrete. The load-deflection behaviour of the system can be adjusted by changing the details of the chamber system.

The use of compressible air-entrained concrete for filling the annular gap should also be able to yield with a set deflection.

In a shaft at the Ibbenbüren coal mine, a segmental lining was constructed with Meypo yielding elements in the longitudinal joints. For the construction of the shaft, the effective overburden corresponded to a depth of 1,650 m, which increased in operation due to further coal removal to be equivalent to a depth of about 2,000 m.
The tunnel lining shown in Figure 6-15 consists of eight segments with eight longitudinal joints whereas four are detailed as yielding joints. The cross-section has a clear diameter of 8.5 to 9.5 m and a support resistance of over 1,000 kN/m². The yielding around the circumference is 30 cm per yielding element, corresponding to about 4% of the total circumference.

The yielding mechanism of the Meypo yielding elements is shown in Figure 6-16. The essential components are the shear ring with a hardened shear pin to ensure the transfer of shear forces and the yielding plunger, which folds up in waves under compression loading.
The working curve of the yielding elements shows nearly ideal plastic behaviour. Up to about 85% of the maximum load, the element is stiff, with the load resistance being maintained with further plastic deformation until the last few millimetres of travel.

The effectiveness of the yielding lining system has been demonstrated with deflections of up to 17 cm [17]. The first application did, however, show that the cost of the process is too high for normal tunnelling. A further proposal is therefore the inclusion of a reusable plunger, which can be removed after the convergence has died down and the longitudinal joints have been concreted and used again for ring installation behind the face (Figure 6-17). Hydraulic cylinders are used as yielding elements. The transfer of shear forces is ensured by a trussed articulation system, which is also reusable. This system has not yet been tried in practice.

6.3.3 Joint details

Because of the construction of each ring out of segments and the construction of the lining out of rings, the degree of joints in the tunnel tube is relatively high. The joints are either longitudinal joints running parallel to the tunnel axis or radial ring joints, and these have different functions and construction. The suitability of the chosen joint detail with regard to load-bearing, risk of spalling and waterproofing should if possible be demonstrated in appropriate test series [29], [52], [261], [262].

6.3.3.1 Longitudinal joints

The longitudinal joints transfer axial ring forces, bending moments from eccentric axial forces and shear forces from external and sometimes also internal loading. This occurs mostly through the contact at the contact surfaces, and in some cases also through the bolting of the longitudinal segment joints. In the usual precast concrete segment system, the longitudinal joints are hinges or partial hinges (concrete hinges) from the structural point of view with a limited capacity to transfer bending moments.

The engineer responsible for detailing can essentially consider three different groups of joint types for the detailing of the longitudinal joints. Longitudinal joints can have

- two flat contact surfaces
- two convex contact surfaces
- convex/concave contact surfaces.

A further variant is the tongue and grooved detail, which however is normally constructed as a hinge with flat contact surfaces.
6.3 Segmental lining

Longitudinal joints with flat contact surfaces

A detail with flat contact surfaces as shown in Figure 6-18 geometrically prevents free rotation of the segments. Thus the longitudinal joints can transfer not only axial compression force and shear force (through friction) but also bending moments, which reduces the moments in the segments.

The rotation of the longitudinal joints takes place at the contact surfaces through elastic and plastic compression strains. Figure 6-19 illustrates the basis for the determination of resistance to rotation. Because only compressive stresses can be transferred, equilibrium can only occur when the resultant of the external forces R acts inside the cross-section.

In order to prevent the introduction of compressive stresses at the outer edge of the cross-section, outside the core surrounded by reinforcement, the contact surface is normally reduced. The width $b$ of the reduced thickness at the joint is normally $1/3$ to $1/2$ of the total segment thickness. The splitting tension resulting from the introduction of concentrated compressive stresses has to be taken into account and covered by sufficient reinforcement.

The reduction of the thickness of the reduced section leads to a higher rotation capability of the longitudinal joints. This is of particular significance for single-layer waterproof tunnel linings, as the rotation capability has to be limited to prevent the sealing gaskets “breathing”.

![Flat longitudinal joint detail](image)

**Figure 6-18** Flat longitudinal joint detail

![Stress along section A-A](image)

**Figure 6-19** Relationships for the determination of the resistance to rotation at flat joints [153]
The construction of the longitudinal joints with flat detail offers advantages during segment installation in that the offsets resulting from the inevitable imprecision in installation do not normally lead to concrete spalling.

**Longitudinal joints with two convex contact surfaces**

With flat contact surfaces, the splitting tension loading increases with increasing rotation due to the narrowed contact surfaces. If the axial compressive forces are large, there is a danger of concrete spalling at the outer edges, which could extend into the gasket area in single-layer waterproof linings. If the compressive forces and the angle of rotation are very large, the convex joint detail shown in the diagram in Figure 6-20 is recommended, in which the width of the contact area is not dependent on rotation angle [16].

Figure 6-21 shows the scope of application for flat and convex joints depending on the compressive force and the angle of rotation. The diagram was produced by evaluating tests.

The radius of curvature of the convex surfaces depends on segment thickness, the magnitude of the loads acting and the permissible angle of rotation. The detailing of the curvature radii must consider various aspects. If the radius is too small, the area through which the loads are transferred is reduced and the splitting tension is worsened. If the radius is too large, the rotation capability of the segments is limited.

During ring building, this system is not stable because there is no ring compressive force and no resistance to rotation. Suitable measures (e.g. bolting) should be undertaken to ensure that the ring does not collapse during construction.

![Figure 6-20](image1.png)  
**Figure 6-20** Longitudinal joint with convex contact surfaces in the Great Belt Tunnel [16]

![Figure 6-21](image2.png)  
**Figure 6-21** Scope of application for flat and convex longitudinal joints [16]
Longitudinal joints with convex-concave contact surfaces

Longitudinal joints with convex-concave contact surfaces as shown in Figure 6-22, which are also referred to as hinged segments, generally have a high rotation capability of the segments. In order to reduce the friction resistance and to provide more play during the installation of the segments, the radius of curvature of the concave surface is normally detailed larger.

For constructional detailing, a large angle of rotation makes it necessary to ensure that unwanted contact surfaces at the edges of the joint are avoided, which could result in spalling due to the concentrated introduction of compressive stresses. The edges of the concave side of the joint are particularly at risk because it is not practical to provide enough reinforcement at this location. In order to avoid damage to the edges, the central part of the longitudinal joint surface is normally detailed as a hinge.

The convex-concave joint detail leads to greater stability of the ring during installation, which is why this detail is preferred for use with expanding segments [16]. The centring effect represents an aid to assembly.

Hinged segments are mostly used for two-layered tunnels, as the waterproofing of the joints in single-layer waterproof construction has not been successfully solved [163].

Longitudinal joints with tongue and groove

Joints with tongue and groove (Figure 6-25) offer good guidance for assembly and with flat contact surfaces transfer axial forces, moments and shear forces. Because the sides of the groove cannot be reinforced effectively, there is a risk of concrete spalling if the available play is only slightly exceeded.

A special form of tongue and groove joint is the one-sided tongue/groove, i.e the inside-face spur. This is normally only used for small keystones in order to prevent them slipping out.

6.3.3.2 Ring joints

The plane of the ring joints lies at right angles to the tunnel axis. The loading on it comes mostly from the introduction and transfer of the thrust cylinder forces during construction. If the deformation patterns of two adjacent rings are different and the deformation is hindered, additional coupling forces (shear forces) occur in the ring joints.
The load from the thrust cylinders is introduced into the face of the ring plane through thrust pads to increase the support area and transferred through the segment into the next ring joint. Because flat contact in the ring joint cannot be assumed due to the unavoidable inaccuracies in segment assembly, there are normally contact zones at points, which load the segment as a deep beam. In order to avoid impermissibly high stresses and the resulting formation of longitudinal cracks, intermediate spacers are inserted to define the load transfer in the ring joint. These are glued centrally in the ring joint and should ideally be located exactly one behind the other in order to enable a straight flow of force in the longitudinal direction (Figure 6-23). The material used is rubber bitumen or hard fibreboard. Any deviations in the location of the load distribution boards should be covered by additional radial reinforcement.

As the height of the load introduction surface does not extend over the whole thickness of the segment, the loading from the thrust cylinders results in splitting tension, which should be covered by additional reinforcement.

**Flat ring joint detail**

The most simple ring joint detail is the flat, level joint as shown in Figure 6-24. Each ring is load-bearing on its own and there is no interaction between the rings, at least as a design assumption. The coupling is solely through friction, and the time-dependent decrease of the elastically stored prestress caused by the thrust cylinder forces, for example due to concrete creep, should be taken into consideration.

The flat ring joint provides no assistance for the assembly of the segments. This can be provided, for example, by the provision of plastic dowels as centring cones (see Figure 6-9). This is not normally intended to provide a mechanical coupling for shear transfer. This can be implemented with permanent bolting, as was used for example in the Great Belt Tunnel (Figure 6-24).

**Tongue and groove systems**

Various joint details are possible in order to simplify ring assembly and also to provide mechanical coupling of adjacent rings. Particularly for single-layer watertight segment construction, the deformation of the joints and offset joints should be kept as small as possible.
One method is to construct the ring joint as a tongue and groove system. The tongue typically occupies more than half of the segment thickness and has a height of 10 to 25 mm. In order to enable the defined transfer of the coupling forces, coupling strips of rubber bitumen can be provided in addition to the boards to distribute loading from the thrust cylinders. This is illustrated in Figure 6-25.

Reinforcement of the tongued and grooved element to resist the coupling forces is difficult to implement while keeping the required concrete cover. Assembly inaccuracies and the resulting secondary loading can rapidly lead to damage to the ring joint. In order to minimise such damage, the groove is made larger than the tongue. The available play is normally only a few millimetres and is quickly taken up by production and installation tolerances.

In addition to the detail with tongue and groove, convex-concave detail of ring joints is also known, as shown in Figure 6-26. In this case also, the edges of the concave surface are at risk of damage during installation.
Pin and socket systems

In contrast to tongue and groove, pin and socket systems provide coupling at points, e.g. at the quarter points of the segment (Figure 6-27). This can limit secondary loading resulting from assembly tolerance in the ring joint to the location of the pin. The coupling forces are, however, locally concentrated, which would be distributed along the joint in a tongue and groove detail. According to local conditions, the coupling locations can be heavily loaded in operation.

As the pin is normally thicker than a tongue would be, it can be reinforced to a certain degree. The dimensioning of the height of the pin should be planned to ensure that in case of failure, the pin would shear off and not the edge of the socket, which ensures continued waterproofing.

Figure 6-27 Ring joint with a pin and socket system
6.3.4 **Steel fibre concrete segments**

The external actions on a tunnel lining often lead to compression loading with only slight eccentricity, which would not require reinforcement for structural reasons. But the provision of nominal reinforcement is normally specified and necessary. In such cases, steel fibre concrete offers a suitable and economic alternative to conventional reinforcement [196].

Steel fibre concrete is a relatively ductile construction material with a high working capacity. The crack-distributing effect of the fibres in concrete is ideal for the required waterproofing of a single-layer segment lining. The positive effect on the cracking behaviour under the typical bending and compressive loading on a tunnel lining is particularly noteworthy [69], [99], [224], [230].

A further important advantage of the use of steel fibre concrete is the strengthening of the fragile corners and edges of the segments, which cannot be adequately reinforced conventionally due to the required cover [51]. The extent of damage at such locations can be significantly reduced.

Due to the industrial production methods used, higher fibre contents can be provided than in in-situ concrete. A typical fibre content would be 60 to 80 kg/m$^3$ with fibre lengths of up to 60 mm.

6.3.5 **Filling of the annular gap**

The process of shield tunnelling with segmental lining leaves a gap between the excavated ground and the lining, termed the annular gap. This has to be filled with a suitable material in order to provide the appropriate bedding for the segment tube and to ensure a uniformly distributed transfer of the loading from ground pressure and also to counter any loosening of the surrounding ground.

6.3.5.1 **Filling with gravel**

On shield tunnelling in hard rock, the annular gap is normally filled with pea and closely graded gravel (Figure 6-28), which is blown in (stowed), for example, by a normal dry shotcrete machine [286]. The filling of the annular gap should be undertaken as soon as possible after ring closure. This requires the appropriate openings to be provided in the segments for the hoses.

The pores in the gravel fill can then be grouted with fluid mortar in a subsequent working stage, in order to prevent the permeable fill acting as a drain.

6.3.5.2 **Mortar grouting**

In tunnels in ground with less stability, the annular gap is grouted. The necessary grouting pressure is matched to the prevailing ground and water pressure. As the grout is not normally taken into account in the verifications of structural safety of the tunnel support, no particular requirements are placed on its strength. But the stiffness must reach at least that of the surrounding ground in order to justify the assumed modulus of subgrade reaction.
In order to be pumped successfully, the grout must be capable of flowing sufficiently. When the grout is injected into the annular gap, a part (depending on the ground properties) of the mixing water is lost into the surrounding ground, which activates the grain skeleton of the grout as a support medium. At the same time, the loss of filter water represents a volume loss for the fill material, the quantity of which should be limited by using a mix with the lowest possible water content and high solid material content.

Good compaction can be achieved by adding fine material such as fly ash. Cement is normally used as binder to ensure rapid stabilisation of the grain skeleton. The hardening behaviour and strength gain have to be selected so that the grout in the hoses can be injected without problems even after long stoppages, in order to limit the requirement for flushing and cleaning work to a minimum.

The grout can be injected through openings in the segments or through the grout lines in the tailskin. For grouting through the segments, the lockable openings are fitted with threaded connections for the grouting hoses. A further possibility is the provision of plastic backflow valves integrated in the segments.

As a precondition for tunnelling with little settlement, grouting should be undertaken as near behind the shield as possible. Particularly when the ground has little or no stand-up time, no voids should be permitted to remain behind the shield tail for collapsing ground. The development of high-performance shield tail sealing systems, such as modern plastic seals or steel brush seals, has enabled the grouting of the annular gap directly through the shield tail. This means that the annular gap created with the advance of the shield can be filled immediately and the ingress of soil prevented.
6.3.6 Measures to waterproof tunnels with segment linings

Single-layer tunnel linings are mostly subject to waterproofing requirements. Transport tunnels have to be secured against the penetration of seepage water or formation water under pressure, while water tunnels have to limit the loss of water. As a segmental lining has a high degree of joints, the effort required to ensure waterproofing is relatively large.

6.3.6.1 Gaskets

In most single-layer transport tunnels with segmental linings in hard rock and loose ground, the penetration of formation water or groundwater is prevented by the provision of continuous gaskets in the longitudinal and ring joints. The closing of the segments compresses the butting gaskets and seals the joint (Figure 6-29). The contact pressure of the sealing frames has to exceed the water pressure acting on one side. The concrete surface of the groove must be free of air holes, in order to prevent water bypassing the gasket.

The compression behaviour of the profile and the detail of the groove must be matched to each other to prevent concrete spalling behind the groove due to splitting tension. The relationships between joint opening and compression force and between testing pressure and joint opening are shown in Figure 6-29 through the example of a profile from the manufacturer Dätwyler.

Figure 6-29 Elastomer sealing band
In the ring joints, the required contact pressure is applied by the introduction of the forces from the thrust cylinders and is stored elastically. In the longitudinal joints, the sealing profiles are compressed by the axial compression force from ground and water pressure. “Breathing” of the sealing frame during construction is prevented by temporary bolting, and Figure 6-30 shows some possible variants. Near the portals and at crosscuts, the bolting is permanent.

Sealing materials used at the moment are natural rubber, plastics, elastomers, neoprene, silicon and swelling rubber (Hydrotite etc.), which are subject to stringent durability requirements. Considering the possible period of use of the tunnel, the functionality of the seal must be preserved for 100 years, including the consideration of any relaxation and ageing effects. As shown in Figure 6-31, the compression is reduced to about 70 % of its original value through relaxation, depending on the composition of the sealing material [115].
6.3.6.2 Grouting

Another way of ensuring the required waterproofing is to reduce the flow of incoming formation water or the outflow of water from the tunnel by filling the joints in the surrounding ground by grouting.

For the construction of the Evinos Tunnel, a water tunnel with a single-layer lining of hexagonal segments (Figure 6-32), this method was successfully used to limit the water loss to the quantity specified in the contract. A grouting plan was designed with contact grouting of the fine-grained gravel fill in the annular gap followed by systematic consolidation grouting of the surrounding ground.

The joints have to be adequately sealed so the required grouting pressure can be applied. For this purpose, the longitudinal and ring joint are mortared over. As the grout is injected, the filtering out of the excess water from the grout presses this into the joints so that the full grouting pressure can be applied and the joints are completely filled and load can be transferred over the full area [288].

6.3.7 Production

Segments are normally produced in specialised precast concrete works. On larger tunnel projects, it can be more economical to set up a production facility on site, as for example at the Channel Tunnel and the Belt Tunnel, and the areas required for this need to be taken into account in the planning of the site facilities. Particularly on large projects, reliable supply of segments requires detailed planning and logistics.

Steel formwork is the only option in order to comply with the dimensional requirements for segments. The precision specifications for the production of segments are determined by the intended waterproofing function and to minimise secondary constraint loading. Progress in formwork technology has made possible formwork tolerances similar to me-
chanical engineering. For rail tunnels in Germany, the stringent dimensional specifications of the DS 853 [62] apply, as illustrated by excerpts in Table 6-2. This specification has often been included in contract documents on international projects.

### Table 6-2 Dimensional tolerances for segments [62]

<table>
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<tr>
<th>Segment width</th>
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<td>Segment thickness</td>
<td>± 2.0 mm</td>
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<tr>
<td>Segment arc length</td>
<td>± 0.6 mm</td>
</tr>
<tr>
<td>Longitudinal joint flatness</td>
<td>± 0.3 mm</td>
</tr>
<tr>
<td>Ring joint flatness</td>
<td>± 0.3 mm</td>
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<tr>
<td>Twist angle in the longitudinal joints</td>
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<td>Taper angle of the longitudinal joints</td>
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The maintenance of tolerances should be checked regularly at the shortest possible intervals in order to be able to spot warping of the formwork during production as soon as possible. Exceeded tolerances could result in unplanned constraints to the segments during assembly and in service. These can reach a magnitude, which cannot be resisted by the concrete or reinforcement in the concrete. If it proves impossible to maintain the tolerances in practice, the effects on the segments should be investigated.

The taper of the longitudinal joints can be mentioned as an example. With an increasing angle of taper, the uniform introduction of the load over the width of the segment assumed in the structural calculations can no longer be guaranteed. This leads to eccentric load introduction into the joint, which could have to be compensated with additional reinforcement.

Quality assurance in precast production of segments should be verified in the production phase through a suitable quality assurance programme with a quality assurance handbook and associated working instructions.

### 6.3.8 Damage

Most damage to segments is caused during the construction phase. This can result in the formation of single cracks or even large-scale spalling. The cause of such damage is mostly the occurrence of impermissibly large contact stresses resulting from high thrust loads combined with production and installation tolerances in the segments resulting in a geometrical lack of fit. The segment design should be investigated for unwanted contact joints through geometrical and kinematic studies in the design phase.

Figure 6-33 shows an example from the El-Salaam siphon, a drinking water tunnel under the Suez Canal, with spalling of the longitudinal joint of the adjacent segment to the keystone, which was to some extent due to the unsuitable constructional detailing of the longitudinal joint with a spur between the keystone and the adjacent segment.

If segments are only used as excavation support behind the TBM and as the outer lining of a tunnel, damage can be regarded as uncritical unless the structural stability of the segment is endangered or the resistance and transfer of the thrust forces is impaired. In such cases, repair of even large-scale damage can be omitted.
When the lining is a single layer of segments with waterproofing function, damage is however critical if it impairs the serviceability or the waterproofing. In such cases, repair of the damage is essential, often requiring extensive work, the cost of which should not be underestimated.

There follows a description of some causes of damage to single-layer waterproof segment systems during segment assembly, on application of the thrust forces, in the shield tail and after the segment has left the shield with appropriate repair measures.

**6.3.8.1 Damage during ring building**

Clumsy assembly of rings with the erector is the most frequent source of damage to the concrete surface and gaskets during ring building. Damage is often also caused as the keystone is inserted due to the limited space available. The longitudinal joints of the new ring being assembled are not normally fully pressed together by the erector and the connection bolts so that the ring appears to be too large and the normally tapered keystone can only be inserted with great force. If the tolerances are inadequate or if the ring assembly is imprecise, this can cause wedging and unwanted contact at the sides, leading to concrete spalling. This needs to be borne in mind in design and construction.

**6.3.8.2 Damage while advancing the machine**

After the ring has been assembled, the thrust cylinders again apply the required thrust force. As the last ring to be assembled is not completely within the shield skin, i.e. is not yet bedded, each individual segment has to bear the axial force from the thrust cylinders independently, as there is only a limited load-bearing action of the ring. This effect can be worsened by one-sided thrust forces resulting from steering curves or correction radii.

Excessive thrust forces can sometimes also cause longitudinal cracks in the central third of the segment. Such cracks are often only noticed due to water ingress or damp patches two to three rings behind the shield but are have mostly been caused immediately after the first application of thrust force. Such damage occurs more often when segments are supported in a statically indeterminate system with more than two load transfer points per
segment than with a statically determinate system. This is due to the fact that just slight assembly inaccuracies lead to partial ineffectiveness of a support and the segment without abutment is thus loaded in bending by the thrust cylinders. Even heavy reinforcement against tension resulting from bending cannot support the high thrust cylinder forces if a support point is ineffective.

This effect can be avoided by meticulous ring building with intentional compression of the ring joints of the last ring to be assembled. While the ring is being assembled, the thrust cylinders are retracted. At the same time, however, sufficient axial force must be maintained in the ring joint by the bolts to create enough friction to prevent the segments moving against each other. Only load transfer plates placed exactly in the line of the thrust cylinder forces can transfer the force from segment to segment without damage, as shown in the “column model” (Figure 6-23).

6.3.8.3 Damage in the shield tail seal

If the segment ring is not centred in the shield tail, the contact bar of the tailskin in front of the shield tail can come into contact and apply concentrated loading to the lining and attempt to push the segment ring into a central location in the shield tail. If a ring is installed eccentrically to the shield tail, then it will be forced into the central position by the seal as the shield tail seal slides past it. If this movement is prevented by the geometry of the concrete, for example with a pin and socket or tongue and groove joint detail, then damage can be caused to the segment in the shield tail.

This type of damage can be minimised if, for example, tapered segment rings are used and always installed so that the ring centreline is centred as exactly as possible in the shield tail. A frequent problem in practice is that a ring is incorrectly installed and the eccentricity to the shield tail is actually magnified.

It is essential to constantly monitor the clearance in the shield tail and control the ring assembly programme in order to prevent any dangerous increase of the clearance. It has to be pointed out that it is still the usual practice to measure the clearance in the shield tail manually. Local conditions and pressure of construction schedules can often lead to this not being checked often enough, which is only human. The only solution is the use of automatic measuring systems. These often prove unsuitable in practice due to local conditions, but the equipment is constantly being improved (serviceability). Manual measurement should, however, be history.

Continuous monitoring and control and careful analysis is the only way of avoiding damage.

6.3.8.4 Damage after leaving the shield

After leaving the tailskin, the segment ring is loaded by the pressure of annular gap grouting and the prevailing ground and water pressure. The resulting deformation can show a type of “trumpet effect”. The loads acting on the ring in this construction state are quantitatively the highest loads in the entire sequence of temporary and permanent loading. A further unfavourable circumstance is that the back part of the ring is still largely unbedded in the protection of the shield tail and is only completely loaded as the machine advances.

Extreme rotation of the segment ring can occur as it emerges from the tailskin, which can lead to the failure of corners of the contact surfaces.
Such rotation can be limited by careful ring assembly with planned compression of the longitudinal joints while they are still in the shield tail. In addition to the constructional details, balanced and simultaneous grouting of the annular gap is an absolute precondition for the avoidance of this problem. The data from annular gap grouting should be recorded and evaluated continuously. Control and analysis of possible damage can be used to optimise the construction process.

It is also possible that the segment ring in the area of unhardened grout becomes oval under flotation, which can lead to impermissible deformation with concrete-to-concrete contact and spalling. The properties of the grout should be selected to avoid this. Continuous control of segment deformation can be used to determine the cause of damage.

After leaving the shield tail, the segment rings are also loaded by the concentrated load from the wheel sets of the first backup in the area where the grout is still soft. If the location of the joints is unfavourable or the grouting of the annular gap is defective, the load of the backup must be carried by the joints, which can lead to displacement and severe damage to the joints. The load from the first backup carriage should therefore be spread as much as possible and be as far from the shield tail as possible.

6.3.8.5 Repair of damage

As long as the stability of the structure is not endangered, damage to the internal surfaces of the lining can be repaired relatively easily. Repair mixes based on artificial resin have proved successful for concrete repairs. Large areas should be filled in with shotcrete after careful removal of the affected or damaged concrete layers. The affected concrete can best be removed by high-pressure water jetting. If the damage extends through the entire depth of the layer and could have damaged the external waterproofing or its supporting concrete, the lining will have to be broken out completely.

Waterproofing defects are the most common source of damage, and can also lead to expensive long-term damage. When elastic joint sealing compounds are used, grouting through the lining to the external surface has proved successful. If the damage is restricted to the joint, which more often affects the keystone, then a thin injection lance can be pushed between the gaskets. The selection of grout depends on local conditions. Cement paste, sodium silicate and plastics have been used successfully.

Swelling (hydrophilic) rubber is also used for the repair of waterproofing defects. Swelling rubbers expand their volume many times on contact with water, resulting in the contact pressure required for waterproofing when the expansion is restricted. The provision of a second inner waterproofing groove for the insertion of swelling rubber profiles can provide for this eventuality.

6.4 In-situ concrete lining

6.4.1 General

In-situ concrete lining in TBM tunnelling are mostly used as the inner layer of a two-layer construction in combination with an outer support lining of shotcrete or segments. The construction and function is essentially the same as in-situ concrete linings in conventional rock tunnelling [183], [197].
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