Building Tomorrow's Society

Bâtir la Société de Demain

Fredericton, Canada

June 13 – June 16, 2018/ *Juin 13 – Juin 16, 2018*

TUNNEL SEGMENT GASKET DESIGN – SOLUTIONS AND INNOVATIONS

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Abstract: Watertightness of tunnels must be ensured during design and construction to prevent water infiltration and minimize maintenance and repair costs, maintain operational safety, and protect inside equipment. In one-pass segmental lining system, watertightness is guaranteed by segments and gaskets placed between segments joints. In this paper, a procedure is provided to select gasket materials, solutions for different working water pressures, appropriate safety factor considering relaxation, and gasket profiles considering size of tunnel, tolerances and required construction gap/offset. Watertightness tests, gasket load-deflection tests, and details of gasket groove design are discussed. Gasket short-term behavior was provided in terms of a load-deflection curve, and discussion is made on design of connection systems for maximum gasket load in this curve or in a less conservative approach after short-term relaxation. Gasket groove design is briefly explained with a focus on simulation of impact force in a gasket groove as a hydrostatic distribution. New developments in gasket systems are introduced including anchored gaskets and most recently developed fiber anchorage technology for gaskets; soft corner solutions to eliminate point loading using pin-based cavities; and new repair method for post sealing of segment joint based on direct drilling and injection through joint sealing gasket.

1 INTRODUCTION

Watertightness of tunnels must be ensured during design and construction in order to prevent water infiltration, minimize maintenance and repair costs, maintain operational safety, and protect mechanical and electrical equipment inside tunnels. One-pass segmental lining system nowadays is the most commonly-used system in TBM bored tunnels. In these tunnels, the watertightness is guaranteed by the individual components of the support system, namely precast concrete segments and gaskets placed between segments and ring joints. As shown in Figure 1, gaskets are positioned around individual segments like a frame and primarily near the lining extrados to provide the joint tightness.

The technical solutions that engineers need to implement to design segment gasket and achieve the watertightness requirements may vary depending on project specific circumstances. The important factors for design and application of tunnel sealing gaskets are the water pressure, safety factor, size of tunnel and consequently size of segments, gap and offset between segments, and tolerances. All these factors are discussed in this paper. Load-deflection response of gasket profiles tested according to national guidelines is explained. Gasket groove design is presented by a simplified simulation of impact force in gasket groove as a hydrostatic pressure distribution. Latest developments in gasket systems are introduced.

Figure 1: Gaskets positioned near the lining extrados to ensure watertightness at joints

2 GASKET MATERIALS

Recommended materials for segment gaskets are Ethylene Propylene Diene Monomer (EPDM) rubber compounds which have replaced the formerly used Chloroprene gaskets. EPDM compounds guarantee a life span of more than 100 years, and economically and technically most suitable material to withstand climate and groundwater with varying water composition. EPDM rubber compound is stable enough not to react with the environment or deteriorate in contact with other materials, such as concrete, grease, injection materials and ground and groundwater anions, cations, heavy metals, volatile and semi-volatile organic compounds. EPDM elastomer resistance to some of the substances that may found in some specific grounds such as hydrocarbons, oils and tar are limited. However, in such cases, often due to low concentrations of these substances and also the embedment of gaskets in the segments joints, EPDM elastomer gasket contact with such substances does not raise any significant concern. An alternative elastomer material which offers a better resistance to hydrocarbons, oils and tar is a Chloroprene Rubber/Styrene Butadiene Rubber (CR/SBR) compound. However, CR/SBR compound offers much lower or no resistance to most of other substances such as acids, has serious application issues in ground water with a PH value of 2, much weaker resistance to aging and weathering effects, and weaker behavior with regard to stress relaxation over service life a tunnel. Gasket relaxation has a significant effect on long-term waterproofing performance, and resistance against water and gas permeability. Therefore, EPDM elastomer is recommended as the most suitable material for segment gaskets. In order to provide the desired characteristics, several material-specific requirements must be met for the gasket to perform as intended. One of these properties is hardness of the rubber compound. The BSI PAS 8810 requires a maximum shore hardness of 75 according to ASTM D2240 (2015), whereas the German STUVA (2005) and French AFTES (2005) recommendations call for a maximum hardness of 85. Other important properties include tensile strength and elongation according to ASTM D412 (2016) which are recommended to be higher than 1700 psi and 300%, respectively.

3 WATER PRESSURE AND GASKET DESIGN

The most important parameter for design of gaskets is the maximum water pressure. Depending on the expected water pressure in the tunnel, different solutions and different gasket profiles are selected. The first gasket generation could only withstand a maximum water pressure of 3 bar. Today, with the advance of technology and limited offset between adjacent segments due to more accurate segment erection inside TBM, water tightness of up to 10 bar is often achievable with a standard mono-extrusion EPDM gasket profile. As shown in Figure 2, water tightness between segments will be created through the compression of gaskets developed during the assembly process of the segments.

For higher requirements and higher water pressure, two main solutions are available. First solution includes a composite seal combining two different sealing technologies of EPDM compression gasket and a hydrophilic seal. As shown in Figure 3, this solution can be provided by the application of co-extruded gaskets with hydrophilic layer, composite profiles with hydrophilic cord, or designing a composite solution with separate hydrophilic seal next to the standard EPDM gasket. Figure 4 shows effect of the hydrophilic insertion on improving sealing performance of a composite EPDM gasket in terms of resisting higher water pressure after several days of immersion in water. The hydrophilic cord swells under water pressure and can act as an extra backup of the EPDM profile. Note that tests with co-extruded gaskets or hydrophilic swelling cord gaskets do not influence the test results in a short term, as the hydro-swelling takes longer than 24 hours to react. About 50% of the swelling occur within 7 days, nearly 100% of swelling occurs within 30 days. To measure the positive influence of hydro-swelling layers, long-term watertightness tests have to be carried out. Second solution includes two sealing gaskets, one near the extrados and one near the intrados of the segment, providing double the security for the waterproofing performance. When used in combination with sealing profile connecting bars between the extrados and intrados gaskets, isolation chambers can be created that help confine any localizing leakages thus permitting precise repairs by grout injection methods. A look at reference projects with double gaskets shows that in half of these projects no connecting gasket bar was used. In projects with connecting gasket bar, except for one project that cross connecting bars were vulcanized at the gasket manufacturing plant, the connecting gasket bars were glued in place at the segment precast plant. Care needs to be taken to the fact that the watertightness of double gasket system is defined by the higher capacity of the two gaskets, not by the sum of both gaskets' capacity (BSI PAS 8810, 2016).

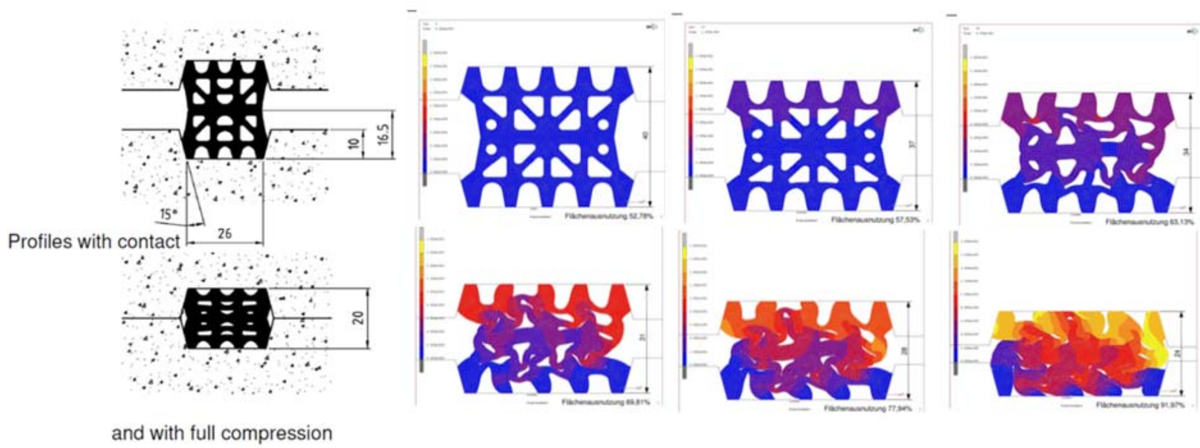


Figure 2: Water tightness between segments created through gasket compression

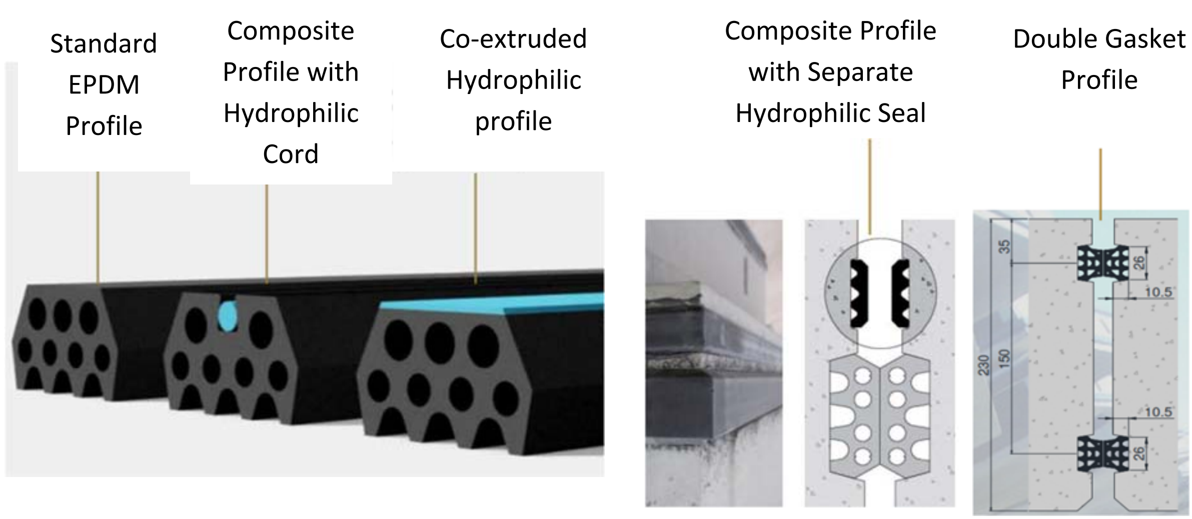


Figure 3: Water tightness between segments created through gasket compression

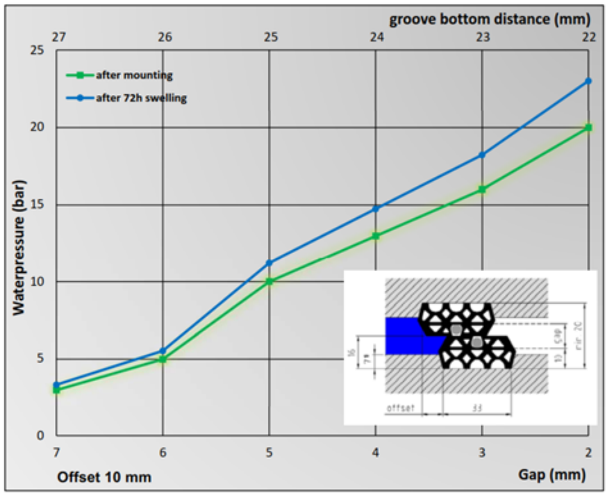


Figure 4: Effect of hydrophilic swelling cord on improving sealing performance of a composite EPDM gasket in terms of resisting higher water pressure after several days of immersion in water

4 GASKET RELAXATION AND FACTOR OF SAFETY

In addition to the expected water pressure in the tunnel, specifications have to define the watertightness performance of a sealing gasket and thereby include a safety factor that takes rubber relaxation effects into account. To get a long-term post construction performance, it is crucial that the gasket profile and rubber compound uphold the designed reaction force to withstand the applied water pressure even years after its application. The majority of the relaxation occurs in the first months after installation. The relaxation can be tested with so-called accelerated aging tests using an accelerated procedure with elevated temperatures to get results within a reasonable timeframe (Figure 5). Most of specifications ask for a minimum residual compressive stress of 60% after 100 years. This means a safety factor of 1.67 (1/0.60=1.67) is the minimum factor of safety for gasket profiles. Considering the relaxation effects of rubber and design life of most of tunnels from 100 to 120 years, a safety factor of two is advisable to ensure that the gasket is able to withstand the design pressure in the long term. As the geometry of the gasket profile has a significant impact on the relaxation behavior of a sealing gasket, such aging tests have to be carried out independently for every gasket profile.

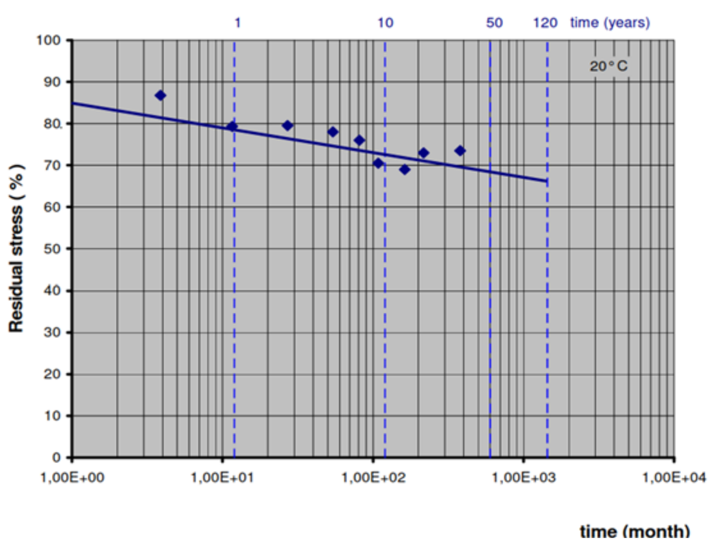


Figure 5: Typical long term relaxation test results according to ISO 11346 (2014)

5 GASKET DESIGN BASED ON SIZE OF TUNNEL AND TOLERANCES

The width of gasket profile depends on the size of tunnel as segment thickness is a function of tunnel diameter itself. Following gasket profile widths are commonly used with regard to the tunnel diameter as current industry practice.

- Tunnel Diameter < 4m, Gasket Width = 20mm
- 4m < Tunnel Diameter < 7m, Gasket Width = 26mm
- 7m < Tunnel Diameter < 11m, Gasket Width = 33 or 36mm
- 12m < Tunnel Diameter, Gasket Width = 36 or 44mm

Note that in specific cases, a more conservative requirement (i.e. a wider segment profile) may be requested by the owner. Gasket size is also related to erection tolerances which in turn depend on tunnel diameter, segment size, and the connection system. Bolt and dowels as the two typical connection systems allow for different gap and offset tolerances during the segment erection process. Gap openings and offsets are illustrated in Figure 6. The connection system with bolts usually allows offsets up to 15mm, which can be reduced to 5mm when precisely applied. Dowels, however, are the connection system with reduced tolerances. Note that reducing the tolerances has a major impact on the design of gasket system. With the smaller offset range that gasket needs to cover, a gasket profile with smaller width can be selected. Also, due to reduction of gasket offset, gasket resistance pressure is often increased. In addition to smaller and less costly gasket profile, other advantages of sealing system with reduced tolerances include:

- Reduction of TBM erector forces (~50%)
- Reduction of induced forces in connectors (~50%) and in turn reduction in size of connectors
- Reduction of designed space for gasket and connection systems

Most of tunnel project specifications allow for 5 mm gap and 10 mm offset for segment gaskets. Dowels can easily provide this requirement. However, bolts are the predominant connection system in longitudinal joints, and contractors tend to change the conditions to higher gap and especially higher offset values to avoid an additional time and labor needed for very precise application of connections to such low tolerances. A review of 50 international projects show that while the gap opening between segment gaskets ranges from 2-7 mm, in 30% of these projects the contactors selected to use a gap of more than 5 mm. Also with offsets between gaskets ranging from 5-20 mm, contractors have chosen an offset of more than 10 mm in 46% of these projects. While engineers design the gaskets for specified gap and offset in the project specifications, they are also encouraged to consider possible larger gaps and offsets with potential cost saving during construction due to faster erection and construction time comparing to gasket and connection materials itself.

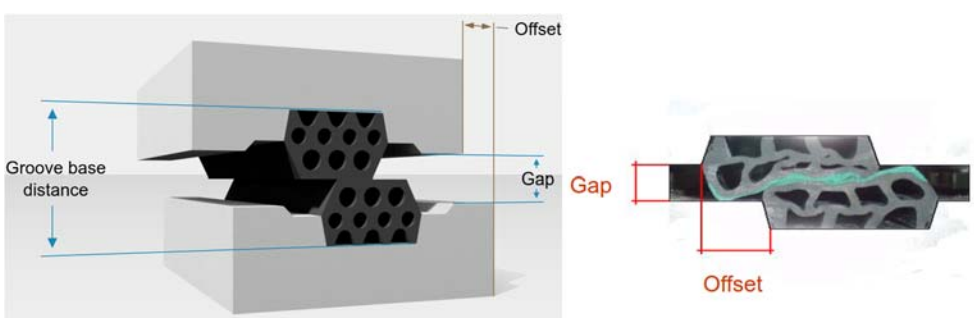


Figure 6: Illustration of gap opening and offset before and after compression

Watertightness tests using gaskets can be performed on steel or concrete specimens. However, working with concrete specimens is time consuming and prone to failure. Practically only tests on steel specimens are currently carried out. Following STUVA (2005) recommendations, as shown in Figure 7, the tests are performed on a T-joint setup in the laboratory, simulating a simplified situation at a circumferential joint with straight pieces of gasket profile pressing against each other at the end of a longitudinal joint. Gaskets must ensure the watertightness under all possible gaps and offsets. Therefore, it is necessary to run the watertightness tests with different gaps and offsets. For every offset value (0 – 20 mm), the test has to run through a range of different gaps. For every gap, the water pressure is built up in steps of 1 bar and is hold there for 5 minutes until the profile shows leakage. The recording of all leakage pressures under different gaps and offsets leads to the watertightness-gap diagram shown in Figure 8. Gasket's resisting pressure corresponding to designed gap and offset in the watertightness-gap diagram should be higher than maximum factored working pressure.

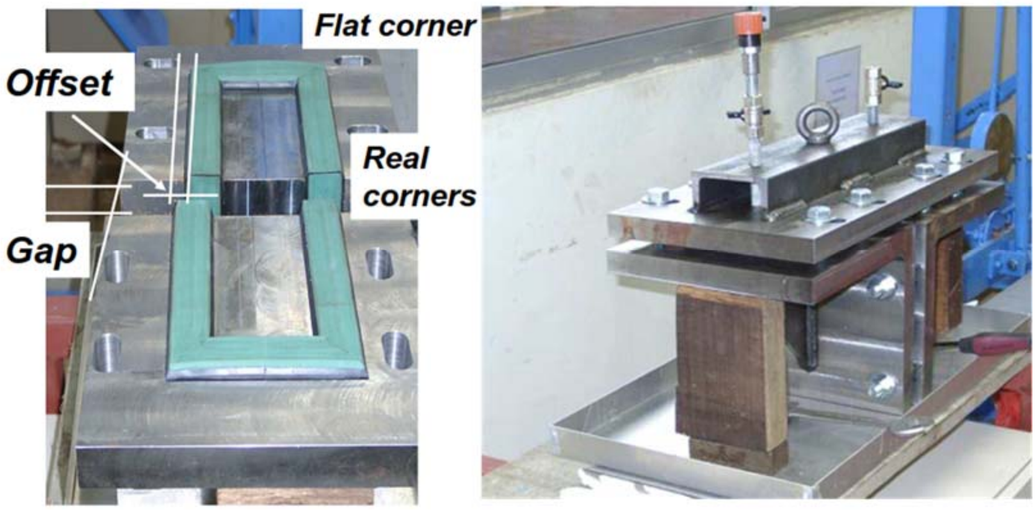


Figure 7: T-joint watertightness test setup for segment gaskets recommended by STUVA (2015)

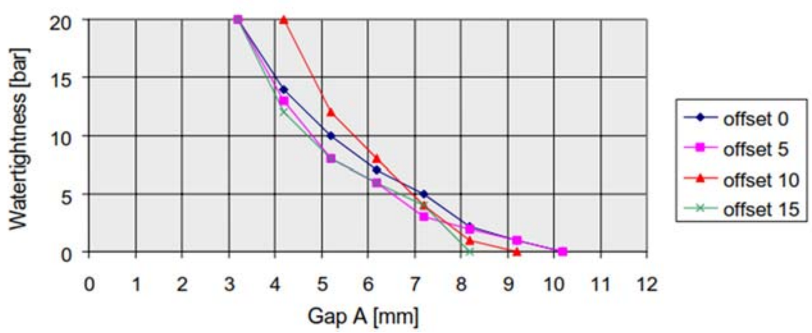


Figure 8: Typical watertightness-gap diagram

6 GASKET LOAD-DEFLECTION

Gaskets, on one hand, should be able to withstand the water pressure on a long-term perspective. Considering the relaxation effect, gasket's compressive force should be higher than factored working pressure. On the other hand, if the reaction force is too high, a strong erection force should be applied to properly compress the segments. With a high compression force, there is a risk of cracking in the concrete groove and at edge of segments that may lead to water penetration underneath the gaskets causing durability and serviceability issues in the lining. In addition, connection systems are designed based on the initial reaction force of gaskets. Therefore, gasket short-term behavior should be also provided in shape of a load-deflection curve which depends on the compound, the shape of gasket profile and required gap and offset. As shown in Figure 9a, in this curve, deflection is represented by the gap. Connection systems can be designed for maximum load in this curve corresponding to zero gap. In a less conservative approach, maximum reaction force of gaskets after a short-term relaxation within 5 minutes (as in Figure 9b) can be used for design. Note that 5 minutes is approximately a minimum time for connectors to start acting against compressive force of gaskets because of required time for segment erection and removal of TBM thrust jack forces.

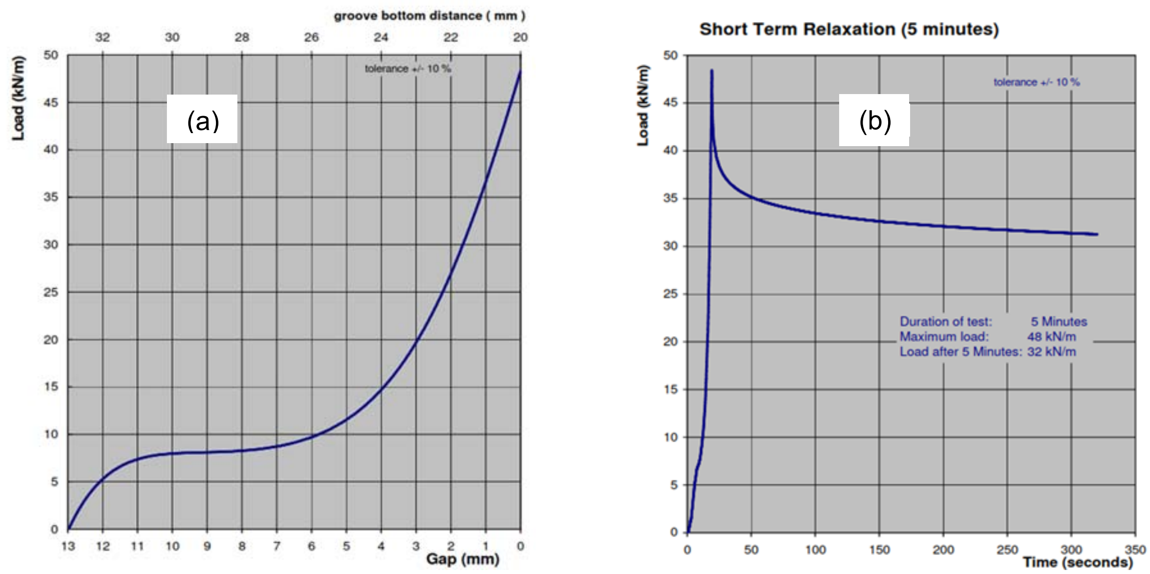


Figure 9: typical gasket load-deflection (reaction force) test results (a), short-term relaxation diagram (b)

7 GASKET GROOVE DESIGN

The watertightness further depends on the groove geometry. Angle and groove depth have to be designed with respect to the selected gasket. To avoid spalling of concrete, it is crucial that the net volume of the rubber can be housed within the groove when the tunnel segments are fully closed (gap=0). To achieve that, the net volume of gasket profile in cross section should be slightly and some percentage smaller than groove cross section (approximately 90% of cross section). In that way, even in case of very high TBM jack forces applied onto the segment joints, there will be enough space for the gasket to fit into the groove. However, practical experiences from projects with narrow and deep grooves and high TBM jack forces show that spalling cracks are still generated near segment corners despite of fulfilling above-mentioned criteria on volume ratio. This is often related to the fact that EPDM rubber is an incompressible material. When compressed, the applied force, R, will strongly deform the gasket profile and close the hollow body. When reaching its full compression (no voids), the applied force will be evenly spread (p) onto the groove flanks and the groove bottom, similar to hydrostatic pressure. Therefore, the spalling force (P1 or P2 on Figure 10) at the flanks is directly depending on the groove depth and width. Nonetheless, shear area of concrete resisting the lateral spalling force for both groove types is practically the same (a≈b). This leads to the conclusion that the danger of spalling increases with a deeper gasket groove and a flat profile design is more favorable.

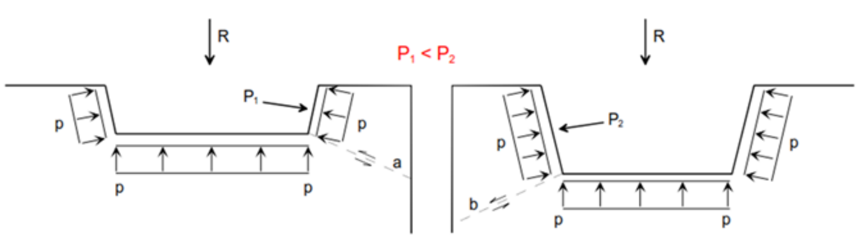


Figure 10: Simplified distribution of impact force in gasket groove as p, similar to the hydrostatic pressure.

8 NEW DEVELOPMENT IN GASKET SYSTEMS AND REPAIR METHODS

Conventional gasket systems include design of gasket groove in the segment molds, so that after casting, gasket can be placed into the groove and glued with contact adhesive and brush or using a spray gun and a pneumatic pressing frame. In this gasket system, also referred to as glued gasket, gluing of gaskets is carried out to ensure that they remain in their grooves during segment handling, storage and especially erection. The main issue with this system is the low bond strength of glued gaskets to the segments to prevent gasket coming loose especially during key segment installation. Recently, an alternative solution has been developed using anchored gaskets to meet high waterproofing requirements and provide much higher bonding strength against gasket pull-off from the segment. As shown in Figure 11, this gasket system is equipped with footed legs as special anchorage pieces underneath which is directly embedded in concrete in the process of segment production. Attention must be paid that the anchored profile corners are precisely positioned, the anchored feet always pointed upward and the sealing lips are positioned tightly alongside the steel counter surface. In this system, the seepage path of any penetrating water with this system is prolonged and the gasket is held safely in place during installation (ÖVBB, 2011). In addition to safer bond to segments, this gasket system has several other advantages over glued gasket systems such as: better waterproofing performance due to less failure on concrete groove side; no risk of gasket falling off the segment during outside storage due to insufficient gluing, weathering, and frost during outside storage; better working conditions and higher safety for segment production staff due to abolition of solvents used in tunnel gasket adhesives; and saving of costs of adhesives, gluing procedure and equipment.

Note that for all types of gaskets, coating with a lubricant is recommended to avoid damage to the gasket through shearing at the groove base and in order to reduce the friction between segments during installation especially the key segment. Such excessive frictional force, if not reduced by lubricating the gasket, is directly transferred to concrete segments and may cause damage. This is even more crucial with anchored gaskets as with this system the gasket material has to be mitered and vulcanized at the joint corner in gasket manufacturing plants. This can form a high point of the harder material and therefore lack of lubrication of the corners when erecting segment rings may lead to spalling cracks.

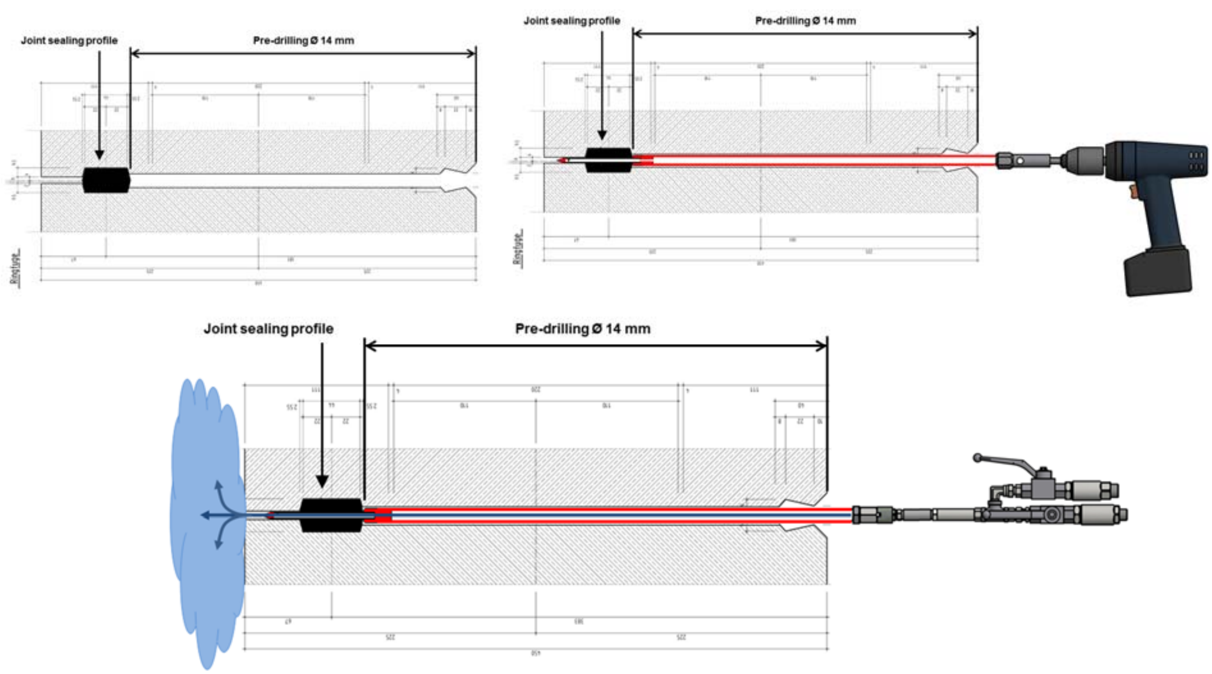
Another major development is design of the gaskets at the corners. Most of the manufactures now provide prefabricated corner solutions with reduced stiffness of the corner element. This technology provides soft corners and reduces risk of spalling of concrete at the segment corners.

Figure 11: Anchored gaskets fixed into concrete segment during segment production without using glue.

The most recent innovation in the gasket design is the use of fiber anchorage technology. The principal is the elimination of footed legs in anchored gaskets and application of plastic fibres as anchoring element (Figure 12). This new technology, similar to regular anchored gasket system, offers an additional pull-out resistance comparing to conventional glued gasket system. In addition, it provide several advantages over anchored gasket including: easier handling; improving the fixation in longitudinal direction; reduced risk of spalling; no possibility of wrong installation (anchored feet up or down), more economic packaging, easier repair procedure because of perfect groove bottom (no holes from the anchored feet) and no possibility for air entrapment in the anchorage area.

Figure 12: Latest developments in segment gasket using fiber anchorage system.

New repair concepts for post sealing of segment joint has been recently provided. Leaking joints inside segmentally lined tunnels is a well-known issue which is often caused by displacement of gasket profile during installation of concrete segment. Another common reason is lack or loss of compression force on gaskets due to an unprecedented increased gap between the segments faces. Damaged concrete segments and cracked concrete edges due to eccentric forces during TBM jacking forces are among major causes of leakage near joint sealing gaskets. This very recent repair method is based on direct drilling and injection through joint sealing gasket (Kirschke et al. 2013). Four major steps for this repair method (shown on Figure 13) include: Step 1—Pre-drilling Ø14 mm to the joint sealing profile; Step 2—drill and push injection needle through the entire joint gasket; Step 3—Injection using accelerated injection material; Step 4—removal of extension tube. The injection needle remains in the joint gasket. Among main advantages of this repair system is efficient injection procedure with less time, material and labor cost; less drilling work with no significant damages on concrete and steel reinforcement; and injection works only at leaking areas.



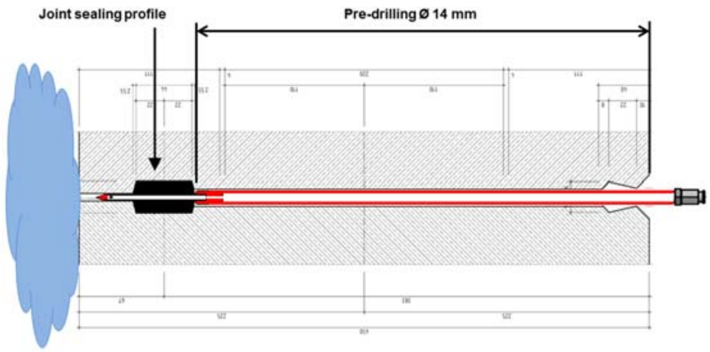


Figure 13: Four major steps of recently developed repair method of controlling groundwater inflow using injection through gaskets in leaking segmentally lined tunnels (Kirschke et al. 2013)

9 CONCLUSION

Major design factor for segment gaskets include gasket materials, gasket profile for designed water pressure, gasket relaxation and factor of safety, gasket profile width, and expected erection tolerances including gap and offset. Load-deflection response and short-term relaxation diagram are required for design of connection systems. Gasket groove can be designed by a simplified simulation of impact force in gasket groove as a hydrostatic pressure distribution. Latest developments in gasket systems include anchored gaskets and recently-developed fiber anchorage technology which is based on the elimination of regular footed legs and use of fiber for anchorage, development of gaskets with soft corners, and new repair method for post sealing of segment joint based on direct drilling and injection through the gasket.

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