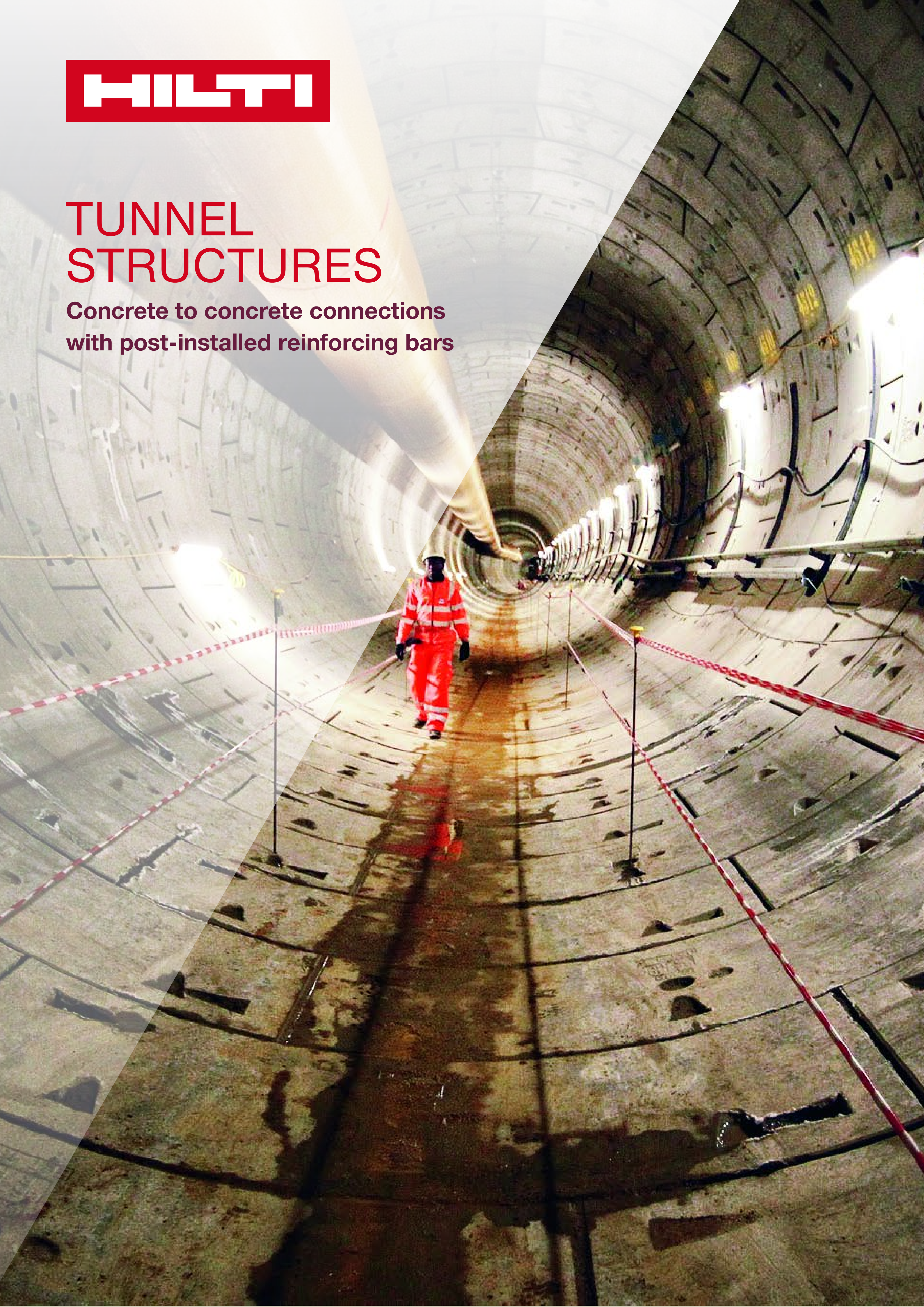
HILTI

TUNNEL STRUCTURES

Concrete to concrete connections with post-installed reinforcing bars



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1. INTRODUCTION

Concrete work in underground structures is often difficult due to space restrictions and/or cross-section geometry. For example, in many tunnels suspended ceilings are installed to create separate chambers for longitudinal ventilation. It is nearly impossible to create this in one construction step with the inner lining. In the end, any concrete element that has to be connected to the lining, resulting in a monolithic connection such as walkways, suspended ceilings, vertical track dividers and corbels, must be done in a subsequent process and may result in a post-installed rebar connection. **Figure 1** provides a schematic overview of possible concrete to concrete connections in tunnels by connecting cast-in-place concrete, prefabricated concrete units or UHPFRC structures with the concrete lining or within the components themselves.

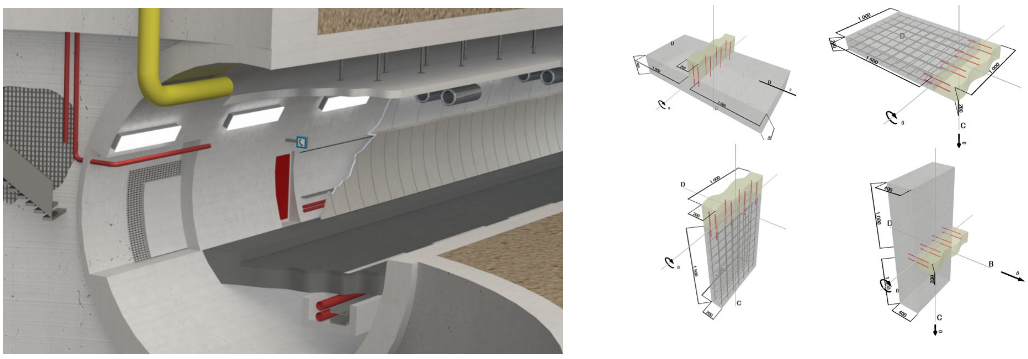


Figure 1
Example of possible concrete to concrete connections using post-installed rebars in tunnels; wall to slab connection, slab extension, wall extension and slab to wall connections.

To realize concrete-to-concrete connections in tunnels with post-installed rebar, chemical injection adhesives are preferred over the traditional bagged cement grout because of their ease of use and quality of application by providing a complete installation and cleaning system to minimize installation errors. There are numerous systems readily available in the market with different or similar product and performance characteristics covered in European Technical Assessments (ETAs). However, if not dealing with post-installed rebar systems every day one may find it difficult to understand what kind of technical boundary conditions are considered in case of these different ETAs and what kind of product should be used for the design of such post-installed rebar connections.

It is the intention of this article to provide an overview of the use of post-installed rebar in concrete-to-concrete connections in tunnels. It should be noted that this paper does not distinguish between the different tunnel types (rail tunnel, road tunnel, utility tunnel, etc.) in detail but focuses on the technical requirements of post-installed rebar connections in general.

2. GENERAL

The post-installed rebar systems for concrete-to-concrete connections in tunnels are in general selected based on structural considerations and are typically designed and detailed by a structural engineer. A detailed technical design is needed because post-installed rebar failures can lead to safety hazards and significant economic loss.

The design establishes whether the requirement of the ultimate limit state (ULS) and serviceability limit state (SLS) are met. At the ultimate limit state, it must be verified that the design values of actions do not exceed the design value of the fastening resistance. The serviceability limit state includes requirements for limiting deformation or requirements on durability as corrosion, chemical attack, temperature and other factors that may occur in tunnels. The following aspects need to be considered in the analysis of the ultimate limit state and serviceability limit state for post-installed rebar connections:

1. Type of action (static [short-term vs. long-term], fatigue, seismic, shock and fire)
2. Corrosion
3. Design life
4. Applicable design code or guideline

Additional economical or quality aspects may be considered already in the design or the specification by, for example, specifying proof loading or test loads.

3. POST-INSTALLED REINFORCING BARS IN TUNNELS – DEFINITION

A post-installed rebar connection consists of a reinforcing bar (rebar) installed with chemical adhesives in holes drilled into the existing concrete. The reinforcing bars connect the new and existing concrete by casting the new elements against the existing structure after the chemical adhesive is hardened (**Fig. 2**). A post-installed rebar connection can be used equivalent to a straight bar cast in concrete if the adhesive is qualified accordingly. An example is shown in **Figure 3** for the connection of a corbel to the tunnel lining. A post-installed rebar application can be characterized as follows:

(a) Post-installed reinforcing bars are straight or can be equipped with hooks or heads on the cast-in end and are necessarily straight on the post-installed end (**Fig. 2 and Fig. 3**).

(b) Post-installed reinforcing bars, in contrast to adhesive anchors, are often installed with small concrete cover ($2\phi < c < 3\phi$, where ϕ is the reinforcement bar diameter and c is the concrete cover). This geometrical boundary condition can be given by the individual geometry of the pre-cast concrete segments of the tunnel lining in case of a TBM driven tunnel. In such cases, the strength under tension loading of the post-installed rebar connection is typically limited by the splitting strength of the concrete (as characterized by splitting cracks forming along the length of the bar).

(c) Post-installed reinforcing bars are typically not designed to resist direct shear loading, compared with rebars designed as bonded anchors or concrete overlay connections (shear dowels). In case of post-installed rebar, shear is typically transferred by a roughened surface between existing and new concrete (**Fig. 2**).

(d) Post-installed reinforcing bars are in general embedded as required to “anchor” their design stress σ_{sd} using the required anchorage length and splice length provisions of Eurocode 2: “Design of concrete structures - Part 1-1: General rules and rules for buildings” **[1]**. In order to achieve ductility of the structure, the design stress is often close to the design yield strength.

(e) Also the basic provisions for the anchorage length regulated in the EOTA Technical Report 069 with improved bond-splitting behavior **[2]** as compared to EN 1992-1-1” **[1]** can be applied. Under such conditions, failure can be governed by steel failure of the rebar under tension or concrete related failure modes. EOTA TR 069 **[2]** is a combination of reinforced concrete design and anchor design in which several boundary conditions must be considered when using this design approach. For more details concerning the application and the design concept of EOTA TR 069 see **[3]**.

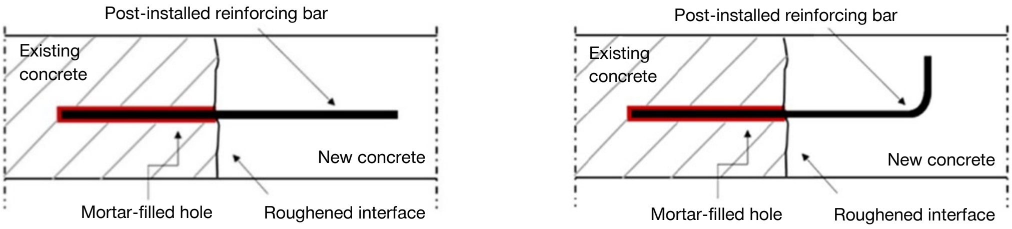


Figure 2
Post-installed reinforcing straight or hooked bar (typ.) **[4]**

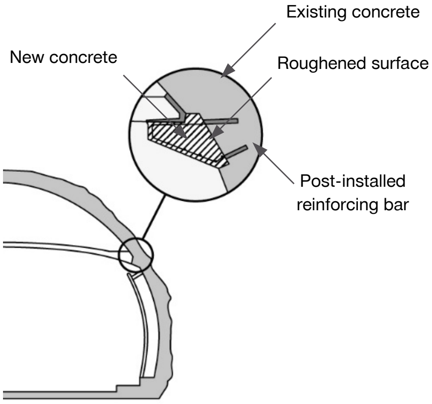


Figure 3
Post-installed rebar connection (corbel to tunnel lining)

3.1 Application range

Post-installed reinforcing bars are typically used to create a monolithic connection between new concrete elements and the existing tunnel lining. Post-installed reinforcing bars are used in both retrofitting of tunnels and in new construction and are suitable for a wide range of applications in tunnel construction.

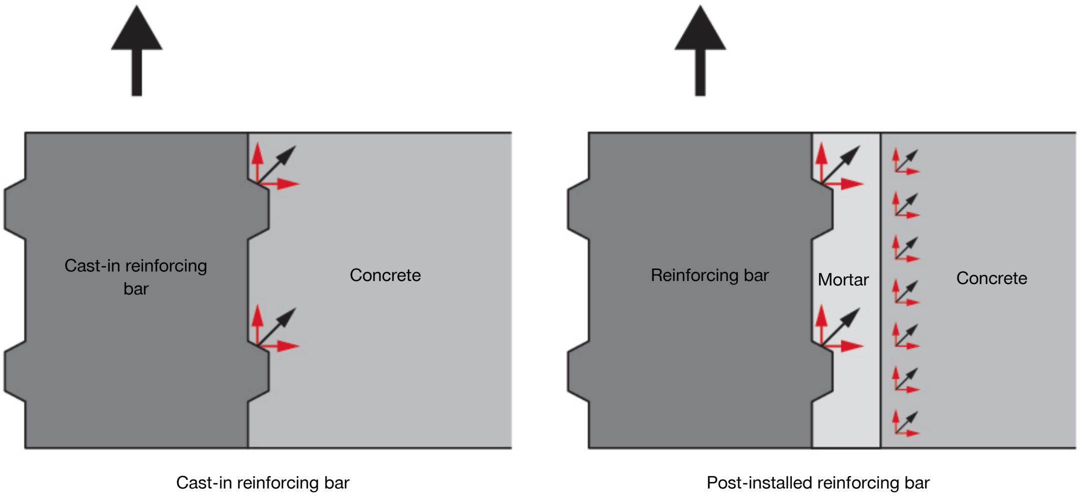
Examples of common applications of post-installed reinforcing bars in tunnel construction are:

- Opening of tunnel lining and partly closing due to installation of edge reinforcement
- Reinforcement of concrete whaler/ diaphragm wall
- Securing and positioning of reinforcement steel meshes
- Replacement of misplaced cast-in rebar couplers
- Moment resisting connection of corbel and tunnel lining for intermediate slab
- Concrete-to-concrete connection of concrete foundation with tunnel lining (may also be designed as shear-dowel application according to EOTA TR 066 [5])

Above-mentioned applications usually require the placement of a large number of bars with often close spacing. To help avoid drilling through or damaging existing reinforcing bars in the tunnel lining, reinforcing detection equipment, such as the Hilti PS 250 or Hilti PS 1000 scanning systems, can be used.

4. STATIC DESIGN OF POST-INSTALLED REBAR CONNECTIONS

Figure 4
Schematic load-carrying mechanism of deformed reinforcing bars



Although the load-carrying behavior of cast-in rebar in concrete is not identical with a post-installed rebar, the basic load transfer of an acting tension force into the concrete is similar. Both cast-in and post-installed rebar generate a rotationally symmetric stress pattern around the bar. Equilibrium is provided by the hoop stresses (tangential) in the concrete. Same failure modes of cast-in and post-installed rebar can be observed. The rebars can fail by steel rupture, pullout/bond failure and splitting failure. The only difference is that for post-installed reinforcing bars, the tension loads are transferred by mechanical interlock from the reinforcing bar's ribs to the mortar and via bond (combination of adhesion and micro keying) from the mortar into the concrete member whereas for cast-in reinforcing bars, the tension loads are directly transferred from the rebar to the base material (**Fig. 4**).

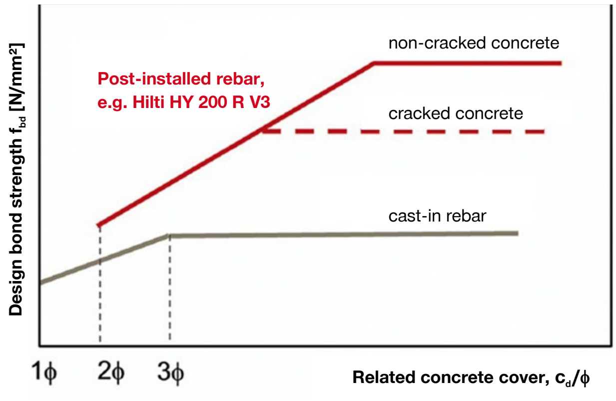
Until 2018 the EOTA Technical Report 023 "Assessment of Post-installed Reinforcing Bar Connections" **[6]** provided guidance for verifying that post-installed reinforcing bar connections installed with a specific mortar system exhibit comparable behavior to cast-in-place reinforcing bar connections in terms of load and displacement behavior under several environmental conditions. Since 2018 EOTA TR 023 **[6]** has been replaced by EAD 330087-00-060 "Systems for post-installed rebar connections with mortar" **[7]**. As a result, a post-installed reinforcing bar system assessed by **[6]** results in at least comparable bond strength and comparable displacement behavior as cast-in-place reinforcing bars taking into account the influencing factors stated in the EAD 330087. Due to this core philosophy, the design of post-installed reinforcing bar connections can be done according to the provisions for cast-in-place reinforcing bars according to EN 1992-1-1 **[1]**. Usually, the application range of post-installed rebar is limited to:

(a) Overlap joints of rebar connections for slabs and beams and overlap joints at a foundation of a column or wall by means of a non-contact splice. In this case the tension loads are transferred between adjacent bars via compression struts. The tension forces generated by the hoop stresses are taken up by the stirrups or transverse reinforcement, respectively, in the splice area.

(b) Simply supported beams and anchoring of reinforcement to cover the line of acting tensile forces

To overcome these limitations an EOTA Technical Report (EOTA TR 069 **[2]**) was developed and published in 2019.

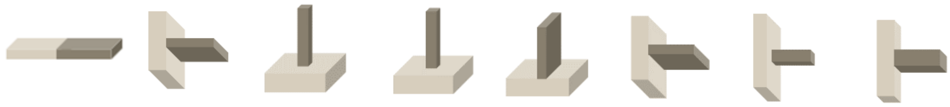
Figure 5
Design bond strength as a function of the related concrete cover, schematically



EOTA TR 069 **[2]** allows to design moment-resisting post-installed rebar connections without the execution as a lap splice according to EN 1992-1-1 **[1]**. EOTA TR 69 **[2]** is utilizing the bond splitting behavior of post-installed rebar systems taking into account the concrete cover in the design equations. According to **Figure 5** the value of the minimum concrete cover is greater than 2ϕ (where ϕ is the diameter of the reinforcing bar). Post-installed rebar systems (e.g. Hilti HIT HY 200 R V3) exhibit significantly higher bond-splitting behavior than cast-in-place bars of equivalent bar diameter and anchorage length. This behavior can be qualified and assessed according to EAD 332402-00-0601 “Post-installed reinforcing bar (rebar) connections with improved bond splitting behavior under static loading” **[8]**. It should be noted that the testing is extensive when compared to post-installed rebar connections that are limited to the design according to EN 1992-1-1 **[1]** where only the comparability of the post-installed rebar with a cast-in rebar is verified. However, both EADs (EAD 330087-00-0601 **[7]** and EAD 332402-00-0601 **[8]**) provide safeguards to restrict post-installed reinforcing bar systems that exhibit very low stiffness or brittleness compared to a cast in bar.

The allowable concrete-to-concrete connections taking into account connection type, allowable forces, design method, required EADs and covered load cases as shown in **Figure 6**.

Figure 6
Allowable concrete-to-concrete connections taking into account connection type, allowable forces, design method, required EAD and covered load cases



	1	2	3	4	5	6	7	8
Connection as…	Splice	End-Anchorage	End-Anchorage	End-Anchorage				
Forces and Moments	Yes	Forces only	Predominant compression or Strut & Tie models	Yes				
Examples	All members connected via a splice (extension, slab to wall, etc.)	Simply supported beams or slabs	Wall/column to foundation	Column to foundation	Wall to foundation	Slab to wall	Beam to wall	Beal to column
Applicable design method	Eurocode 2 / Eurocode 8			EOTA TR 069				
Required EAD	EAD 330087-0			EAD 332402				
Load cases	Static, sustained loading, fire, 50 years, 100 years, seismic			Static and sustained loading, 50 years, 100 years, seismic				

5. FATIGUE DESIGN OF STRUCTURAL POST-INSTALLED REBAR CONNECTIONS IN TUNNELS

When a high-speed train is entering or passing through a tunnel, a complicated system of pressure waves develops and propagates through the tunnel and in addition the concrete foundation may be exposed to repeated loads. The resulting loads during train-tunnel passage may play an important role in the structural design of concrete-to-concrete connections. Material fatigue is relevant not only for high-speed train tunnels but also in road tunnels designed for an additional operational loading due to the wind pressure and suction caused by the moving vehicles, especially when entering the tunnel.

The authors see an increasing demand on fatigue-approved solutions in tunnels, especially in rail tunnels with high to very high load cycles over the service life of the connection. Unfortunately, while the research in case of anchors in concrete loaded under fatigue gained importance in the last decades, research on post-installed rebars under fatigue loading is rather limited. As a result, current design **[10]** and assessment provisions **[11]** for post-installed anchors in concrete include provisions for fatigue whereas qualification and design provisions for post-installed rebars loaded under fatigue are not existing. Therefore, the following discussion has to be seen as a possible approach to tackle post-installed rebar applications under fatigue. A simplified method is provided in the following. The actions to be used in design may be obtained from national regulations or in absence of them in the relevant parts of EN 1992-1-1 **[1]**.

As a simple and conservative approach, fatigue is verified if the following equation is fulfilled:

Steel failure:

$\Delta N_{Ed} < \Delta N_{Rd,E,n}$

where ΔN_{Ed} = design fatigue action

$\Delta N_{Rd,E,n}$ = design fatigue resistance of the post-installed rebar for pulsating or alternating load taking into account the required number of load cycles

In cases where actions consist of a combination of a non-negligible lower cyclic load and a fatigue relevant part, it is necessary to determine the influence of the lower cyclic load on the fatigue resistance. This is achieved by using the Goodman diagram which is in general available for rebars. In absence of such a diagram, ΔN_{Ed} shall be replaced by $\Delta N_{Ed,simple}$ as follows:

Concrete cone or pullout failure:

$\Delta N_{Ed,simple} < k_{fat,red} \cdot R_d$

where $\Delta N_{Ed,simple}$ = simplified fatigue design action

$k_{fat,red}$ = Reduction factor for fatigue in case of bond and concrete failure taking into account the number of load cycles

R_d = design static resistance

For a simplified design in case of pullout and concrete cone failure, all loads are assumed to be fatigue relevant ($\Delta N_{Ed,simple} = N_{Ed} + \Delta N_{Ed}$). It is obvious that in case of low percentage of the fatigue load compared to the static value, this approach may yield to relatively conservative results. With this approach a normal "static" PROFIS Rebar calculation may be performed applying the reduction factor for fatigue in case of bond and concrete failure taking into account the number of load cycles.

5.1 Proposed method for evaluating the reduction factor in case of concrete cone failure when applying the logic of EOTA TR 069 [2]

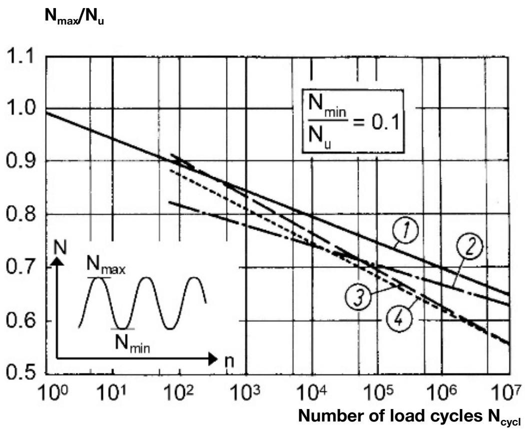


Figure 7
Comparison of S-n_{cycl} curves corresponding to concrete cone failure with S-n curves for other failure modes; curve 1: concrete cone breakout, curve 2: bond failure, curve 3: concrete under uni-axial tension, curve 4: concrete under uni-axial compression, taken from **[12]**

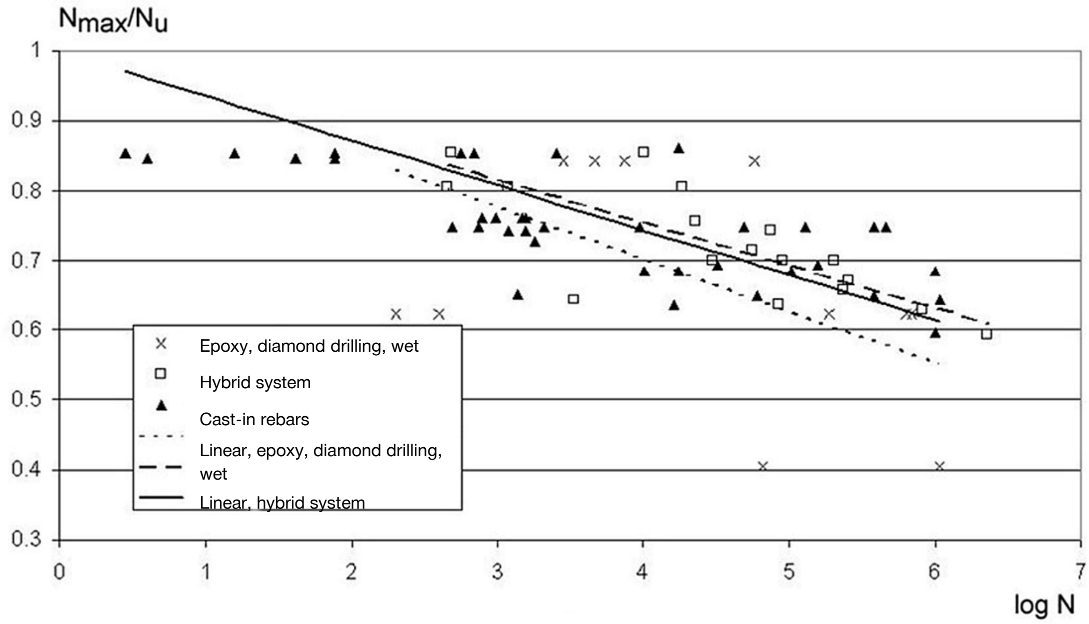
EOTA TR 069 **[2]** covers the design of concrete-related failure modes under static loading. To apply the same design concept for fatigue loading, a reduction factor for concrete related failure modes needs to be considered. Typical concrete related failure modes under tension loading are pull-out failure, concrete cone failure and splitting failure. The relative capacity of headed studs as a function of load cycles (S-n_{cycl} curve) is shown in **Figure 7** for concrete cone breakout, bond failure and concrete under both uni-axial tension and compression. **Figure 7** can be also transferred to reinforcing bars causing concrete splitting failure as expected in the design philosophy of EOTA TR 069 **[2]**. It is assumed that the fatigue strength for concrete related failure modes is at least equal to the fatigue strength of concrete subjected to uni-axial tension. This assumption is justified limiting the maximum fatigue load to 50% of the average static failure load and the number of load cycles to n = 107 ($k_{fat,red,CC}$ ~ 0,5 for n = 107).

5.2 Proposed method for evaluating the reduction factor in case of pullout failure when applying the logic of EC2 [1] and EOTA TR 069 [2]

Research on the fatigue behavior of the bond between steel element and mortar or mortar and concrete is limited **[12]**. Spot testing is presented in **[13]**. Test parameters were chosen in such a way that pullout failure occurred. The results indicate that, in principle, the behavior found with cast-in-place reinforcing bars also applies to threaded rods anchored with resin. The ratio of N_{max}/N_u is shown in **Figure 8** as a logarithmic function of the number of load cycles at failure for specific epoxy and hybrid systems. For comparison, the results of tests with cast-in bars are shown as well. The fatigue strength at two million load cycles (log N = 6.3) is approximately 60% of the short-term bond strength ($k_{fat,red,bond}$ ~ 0,6 for n = 2 · 106).

In conclusion, the fatigue design bond strength of a post-installed reinforcing bar system is not provided in an ETA due to missing regulations on the design and qualification side. For simple cases, it may be reasonable to apply assumptions in design considering the material behavior under fatigue loading of concrete, bond and steel.

Figure 8
Ratio N_{max}/N_u as a function of number of load cycles at failure [13]



6. SEISMIC DESIGN OF STRUCTURAL POST-INSTALLED REBAR CONNECTIONS IN TUNNELS

Historically, underground utilities have experienced a low rate of damage during earthquakes than surface structures for a given intensity of ground shaking because the imposed ground strains are lower at higher depths. However, tunnels may suffer from damage due to earthquake loading by showing lining cracks, shear failure of lining, tunnel collapses caused by slope failure, portal cracking, leaking and deformation of sidewall/invert damage **[14]**, **[15]**, **[16]**, **[17]**. It was found that for peak ground accelerations (PGAs) equal to or less than about 0.2g, ground shaking caused minor damage. For PGAs in the range of about 0.2–0.5g, some instances of slight to heavy damages were observed, whereas for PGAs larger than 0.5g there were many instances of slight to heavy damages. This may lead to the need - based on the project specification - that the concrete-to-concrete connection may also be designed considering seismic conditions. It should be noted that upfront of such a seismic design the effects of ground motion on the underground structure by determining the additional loading imposed by ground shaking and deformation must be assessed and special requirements for reinforcement detailing may be followed.

With EAD 330087 **[18]** a qualification process for post-installed rebar is existing that allows a design according to EN 1998-1 “Design of structures for earthquake resistance” **[19]**. The assessment of post-installed reinforcing bars under cyclic (seismic) loading is conducted following the same logic adopted in the case of static loading. The performance of the system in the case of pullout (bond) and splitting failure is compared and related to the performance of cast-in bars by means of comparing and assessing the bond strength degradation of a post-installed bar system with the number of cycles.

In conclusion, the seismic design bond strength of a post-installed reinforcing bar system $f_{bd,seis}$ that can be used in combination with the requirements of EN 1998-1 **[19]** is provided in the related ETA. Additional bond efficiency factors $k_{b,seis}$ (reduction factor) may be applied to the design bond strength taking into account the drilling systems and borehole conditions.

7. REQUIREMENT FOR 100 YEAR DESIGN LIFE

Nowadays there are more and more requests from owners or operators of tunnels for an extended service life from 50 years to 80, 100 or even 200 years. The authors believe that this is a rapidly growing international demand also on post-installed rebar applications. However, it should be noted that the design life should not be confused with the service life. The service life relates to the period that the tunnel is expected to be in operation. In contrast, the design life represents the period on which the statistical derivation of transient loads is based on. The requirement for a service life and/or design life of 100 years is based on the goal of minimizing maintenance requirements and to help that the investment is spent in a rational way.

The variant of the EAD 332402-00-0601-v01 **[9]** provides the answer to an extended working life for post-installed reinforcing bar connections of 100 years. This EAD is also the basis for Hilti to provide engineering judgments for a working life of 120 years. The biggest difference in the assessment for an extended working life in comparison to a working life of 50 years is that the long-term test is modified from a 50-years bond-strength estimation to a 100-years projection (120-years projection as an engineering judgment outside of the EAD).

However, it is important to note that the design life assessment in **[9]** is limited to the bond between mortar and concrete (bond strength) by providing bond strength values for 50 years and 100 years. The durability of the steel element (rebar) and the surrounding concrete is not considered within the scope of the European Assessment Document. Consequently, the EAD assumes that the material specific parameters of the concrete and the steel are not negatively influenced by the design life. Important is the definition of the correct exposure class in the tunnel projects, maximum water cement ratio, minimum cement content and consequently the required nominal concrete cover of the reinforcing bars for an extended working life.

In conclusion, the 100-year design bond strength $f_{bd,PIR,100y}$ of a post-installed reinforcing bar is provided in the related ETA. The design process is equal to the design for 50 years by replacing the bond strength of 50 years $f_{bd,PIR,\ 50y}$ with the 100-year design bond strength $f_{bd,PIR,100y}$. Additional bond efficiency factors k_{br} (reduction factor) may be applied to the design bond strength taking into account the drilling systems and borehole conditions.

8. FIRE

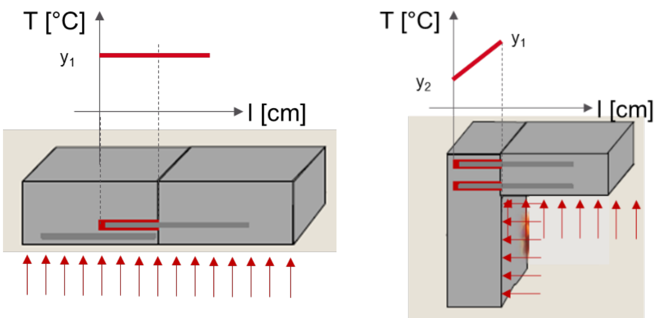
When post-installed reinforcing bar connections are part of a fire-rated assembly (floor, roof, etc.), it is important that the fire resistance of the connection is evaluated using test data for the time-dependent reduction in bond strength associated with typical geometries and time-temperature loading protocols. These elements are designed and constructed to provide a specific period of fire resistance (R), typically rated for 30, 60, 90, 120, 180 or 240 minutes.

In general, the capacity of post-installed reinforcing bars is reduced when exposed to fire. The bond-strength degradation is highly product dependent. Main parameter is the composition of the used adhesive material (inorganic or organic such as vinyl ester or epoxy). Consequently, if post-installed reinforcing bars are part of a fire-rated assembly it is important to know the time-temperature dependent reduction in bond strength to properly design the connection.

The bond strength of post-installed rebar subjected to fire is assessed on European level based on tests according to EAD 330087-00-0601 **[7]**. The European Technical Assessment (ETA) provides an equation to calculate the design value of the bond resistance under fire $f_{bd,fi}$. The bond resistance in the cold condition is multiplied with a reduction factor under fire exposure. The bond resistance in the cold condition depends on concrete class, rebar diameter, drilling method and bond conditions according to EN 1992-1-1 **[1]**. In case the temperature along the post-installed rebar is known, the anchorage length can be calculated according to EN 1992-1-1 **[1]** using the temperature-dependent bond strength $f_{bd,fi}$.

The determination of the temperature in the mortar layer is easier in case of equal distance along the length of the post-installed rebar to the flamed surface (**Fig. 9a**). A constant temperature distribution can be assumed that depends on the exposure time and concrete cover. In case of varying distance, the determination of the temperature along the length of the post-installed rebar is only possible with the help of numerical analyses (**Fig. 9b**). The bond strength is not affected along the entire anchorage length. The load is transferred in regions with lower temperature where no decrease of bond strength takes place.

Figure 9
Simplified temperature distribution in the mortar layer depending on the location of the rebar relative to the flamed concrete surface



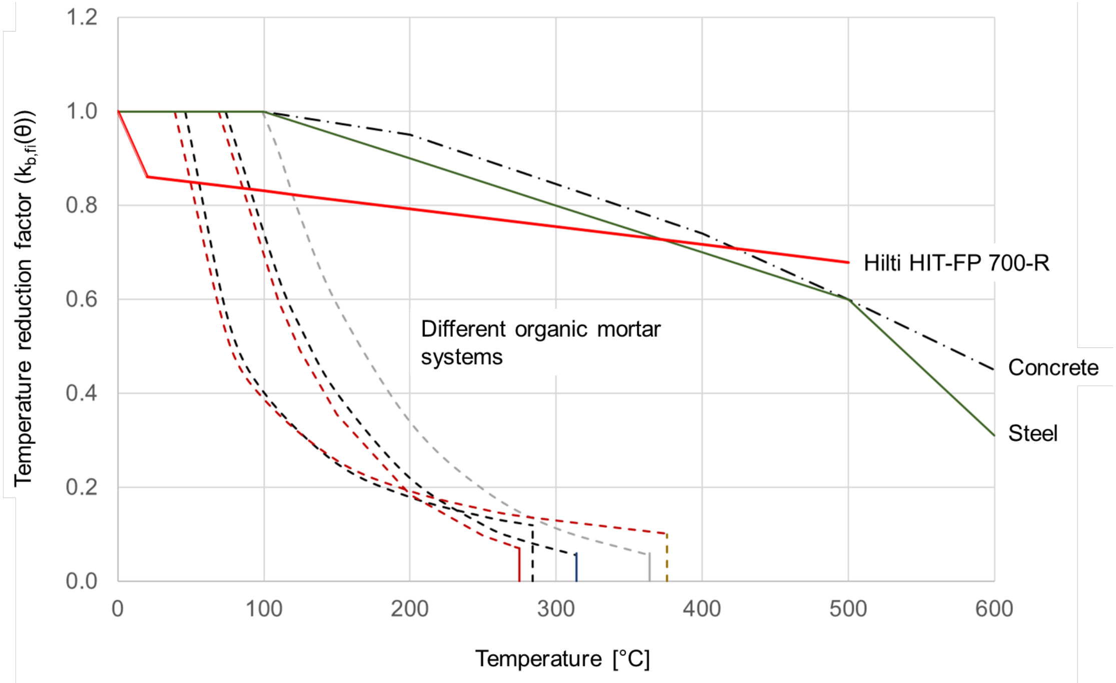
a) Post-installed rebar located parallel to the flamed concrete surface

b) Post-installed rebar with uneven temperature distribution along the length of the bar

The requirements for the fire load case in a tunnel can be different depending on the application and type of tunnel. To minimize the damage in case of a fire event, the temperature on the concrete surface and the temperature in the reinforcement should be limited. Note, both the concrete and steel temperature depend on several parameters (e.g. exposure time, concrete cover, protection of concrete member). Based on the experience of the authors and as a simplification, the following temperature limitations should be used: concrete surface (200°C to 380°C) and reinforcement (250°C to 300°C). In case of higher temperatures on the concrete surface, fibers of polypropylene or steel should be incorporated into the concrete. However, it is noted that at such high temperatures organic adhesive material is showing a very low bond strength $f_{bd,fi}$ which is only 10-20% of the bond strength in cold condition f_{bd}. Especially for applications in which the rebar is parallel to the flamed concrete surface the impact is more pronounced which often leads to challenges in design.

To overcome this challenge, Hilti developed an injectable inorganic calcium-aluminate-based cement for post-installed rebar connections, named Hilti HIT-FP 700-R. Compared to organic mortar systems, which show no residual capacity at 500°C, Hilti HIT-FP 700-R has been tested up to 500°C (932°F) and experiences a very low reduction of its bond capacity compared to concrete for which a reduction of 40% is assumed at 500°C, see **Fig. 10**.

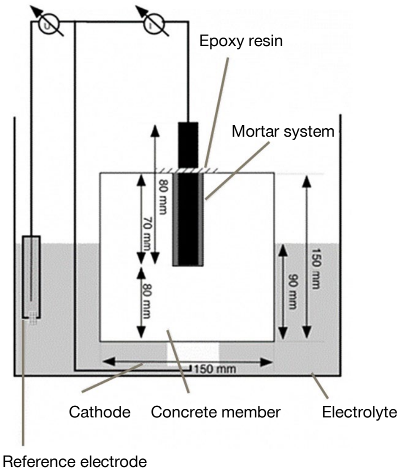
Figure 10
Reduction factor under fire exposure $k_{b,fi}(\theta)$ for Hilti HIT-FP 700-R compared to several organic mortar systems in the market and concrete (example: concrete strength class C20/25))



9. CORROSION

Concrete is an alkaline material and under normal conditions corrosion of cast-in reinforcing bars is prevented by passivation of the bar surface. However, when concrete undergoes carbonation, its decreased pH value can break the passivation film and allow corrosion. Furthermore, accelerated corrosion rates (pitting corrosion) are observed if the concrete is contaminated with chlorides. Consequently, the qualification of systems for post-installed rebar connections with mortar includes a specific test for the susceptibility of the system to long-term bar corrosion.

Figure 11
Test setup to assess the long-term rebar corrosion **[6]**



After curing of the mortar, a concrete member with an embedded post-installed rebar is immersed into a container filled with artificial tap water (sodium sulphate and sodium bicarbonate) while each rebar is connected to a cathode, see **Fig. 11**. The current between the rebar and the cathode is determined by measuring the potential drop while additionally, the corrosion potential of each rebar is measured by a voltmeter. The measured current flow and the potential are plotted as a function of the time (duration of the test for at least 3 months). The measured current flow and the potential must be below a certain limiting value. In addition, a visual inspection of the rebar after the test takes place to identify signs of corrosion products. If the requirements are fulfilled, the post-installed rebar connection is assessed as comparable with the corrosion resistance of cast-in-place rebars. Consequently, it can be said that post-installed rebars installed with a qualified system should exhibit similar corrosion rates to cast-in-place bars installed in the same concrete.

The Swiss Association for Protection against Corrosion (SGK) was given the assignment to evaluate the corrosion behavior of fastenings post-installed in concrete using the Hilti HIT-HY 200-R V3 and Hilti HIT-RE 500 (V4) injection systems to provide further information about the corrosion behavior in addition to the “pass/fail” criteria according to the related European assessment document.

The results can be summarized as follows:

Hilti HIT-HY 200-R V3

- The Hilti HIT-HY 200-R V3 system in combination with reinforcing bars can be considered resistant to corrosion when they are used in sound, alkaline concrete. The alkalinity of the chemical mortar helps to ensure the initial passivation of the steel.
- If rebar is installed in chloride-free concrete using Hilti HIT-HY 200-R V3, in the event of later chloride exposure, the rates of corrosion are about half of those of rebar casted-in concrete.
- In concrete containing chlorides, the corrosion behavior of Hilti HIT-HY 200-R V3 corresponds to that of cast-in rebar. Consequently, the use of unprotected steel in concrete exposed to chlorides is not recommended because corrosion can be expected after short exposure times.

Hilti HIT-RE 500 V4

- If the Hilti HIT-RE 500 V4 system is used in corrosive surroundings, a sufficiently thick coat of adhesive significantly increases the time before corrosion starts to attack the steel.
- The Hilti HIT-RE 500 V4 system may be used in carbonated concrete containing chlorides if a coat thickness of at least 1 mm can be ensured. In this case, only the unprotected steel in the new part of the concrete joint is critical.
- In none of the cases investigated previously rusted steel (without chlorides) showed signs of an attack by corrosion, even in concrete containing chlorides.

Neither during this study an acceleration of corrosion was found at defective points in the adhesive nor there is any reference to this effect available in literature.

10. HILTI PRODUCT BASKET FOR POST-INSTALLED REBAR CONNECTIONS IN TUNNEL CONSTRUCTION

Depending on the requirements - e.g., type of action (static [short-term vs. long term], seismic, fatigue and fire), corrosion, design life, design concept, installation - different products are offered by Hilti. Every product has its strengths but also its limitations. **Figure 12** shows the product portfolio Hilti is offering for anchoring post-installed rebar. The overview provides guidance on the selection of the product. Hilti is also providing a software to design post-installed rebar (Hilti PROFIS Engineering) that allows for a faster and safer design of post-installed reinforcement connections.

Figure 12 Overview of Hilti products used for post-installed rebar connections in tunnels

Product name	HIT-FP 700	HIT-RE 500 V4	HIT- HY 200-R V3	HIT-CT 1
ETA-Rebar (EC2, static and quasi -static, 50 years design life)	Φ 8-40	Φ 8-40	Φ 8-80	Φ 8-25
ETA-Rebar (EC2, static and quasi -static, 100 years design life)	Φ 12-40	Φ 10-40	Φ 10-40	-
ETA-Rebar (TR069, static and quasi-static, 50 years design life)	-	Φ 8-40	Φ 8-32	-
Seismic assessment for EC2	No	Yes	Yes	No
Max. fire temperature [°C]	> 500	152	275	376
Reduction at max. fire temperature	0%	≈ 80%	≈ 95%	≈ 90%
Working time at 21°C	20 minutes	30 minutes	9 minutes	4 minutes
Curing time at 21°C	10 days	7 hours	60 minutes	75 minutes
Pre-load time at 21°C	5 days	-	-	-
Installation temperature [°C]	+5 to +40	-5 to +40	-10 to +40	-5 to +40

Simplified overview, details can be found in the relevant ETA. Pre-load time: 75% of final performance indicating the time when scaffold can be removed (available as Hilti technical data)

11. ON SITE TESTING TO SUPPORT IMPROVING INSTALLATION QUALITY OR DESIGN ASSUMPTIONS

If a post-installed rebar system carries an ETA and is installed according to the manufacturer's instruction for use (IFU) in a base material within the scope of the assessment, there is no need to verify the performance with on-site testing. There are only two reasons why on-site testing in tunnel construction is performed:

1. In cases where the base material is not covered in the ETA non-destructive (proof loading) or destructive tests can be performed to determine the design resistance. One example is the use of concrete with a mix composition that is outside of the scope of the qualification according to the related European Assessment Document (EAD).
2. To enable customer to control and potentially validate the quality of installation of the post-installed rebars, non-destructive tests can be performed on the job site (proof tests).

In case of **non-destructive loading (proof loading),** a tension load is applied to the rebar. The customer must select the appropriate load level depending on requirements. But in any case, loading on the system should not be so high as to result in damage (e.g. in the form of yielding or permanent slip). Proof loads should be defined by the responsible engineer and maintained long enough – for non-destructive testing it's normally minimum 60 seconds holding the proof load – to guarantee no rebar movement. Proof loads are set as a percentage of the tension capacity of the post-installed rebar, not as the design tension load.

Note that, depending on the embedment depth to diameter ratio and the steel grade, the proof load might lead to yielding of the reinforcing bar. In any case it should be verified that the proof load does not exceed 80% of the nominal yield stress of the rebar.

Proof loading equipment is arranged with sufficient spacing to the post-installed rebar to observe movement due to incorrect installation. If proof load is used to determine the design resistance, loading equipment is arranged with close spacing to the post-installed rebar to avoid failure of the base material. Hilti provides a complete on-site testing engineering service with appropriate testing equipment and a service for the customer for evaluation of the result/full documentation.

In case of **destructive loading** a tension load is applied to the rebar up to failure. The failure is typically characterized by yielding of the steel or pullout failure of the rebar.

However, it is noted that on site testing (neither non-destructive or destructive loading) cannot replace approval testing to assess the suitability of the product. Also onsite testing does not serve to conclude on product performance between different products (product A is better than product B).

12. SUMMARY

Post-installed rebar connections are important in tunnel construction to connect new concrete elements (e.g. ceiling- or floor connections) with the existing concrete structure. Knowledge about the different technical application conditions but also selecting the right post-installed rebar system is crucial. It is the intention of this paper to provide relevant background information about concrete-to-concrete connections in tunnels realized with post-installed rebar and give guidance for the selection and design of the post-installed rebar system.

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