ITAtech Guideline for Radially Installed Bolts In Tunneling - Subgroup Bolts & Arches

ITAtech Sub-Activity Group Bolts & Arches

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1 >> Introduction

The excavation in conventional tunneling is typically supported by radial bolts, reinforced shotcrete and if required by steel arches or lattice girders. Radially installed bolts reinforce the surrounding ground and create a so-called supporting arch around the excavation. Thus, radial bolts are an essential part of the primary support in tunnel construction and must be chosen carefully to suit the expected ground conditions.

There is no bolt covering all demands and therefore decision criteria are necessary to define the most suitable bolt type(s) at the design stage. This requires knowledge about various characteristics of bolt types, installation methods, areas of application, ground conditions and activation modes. After the selection, individual types must be clearly defined in tender documents, so that both the contractor's offers are comparable, but also the originally designed measures are installed during construction to ensure safe, stable, and cost-optimized excavation processes.

To enable this process, this document describes common radial bolt types, their characteristics and properties, advantages, and disadvantages as well as safety and quality concerns.

1.1. OBJECTIVE

The goal of this guideline is a compilation of selection criteria for bolts, which should be considered during design stage. These are complemented by properties of bolting systems and bonding agents, detailed descriptions of common bolting systems and installation procedures, criteria for and types of corrosion protection and quality management for bolts as well as testing of bolt properties. This information is intended to assist the designer as well as underground engineer to choose the technically most appropriate bolt type(s) for each expected ground condition and to set minimum requirements for chosen bolt types ensuring a high level of safety during construction.

1.2. DOCUMENT STRUCTURE

After the introductory part of this document, which includes descriptions of load bearing components and material of bolts as well as definitions, the primary focus is set on selection criteria for bolts (chapter 4). Two matrices summarize the criteria to guide the selection of bolts.

Another key part of this document is chapter 6 that gives a detailed description of common bolting systems used in tunneling. Focus is set on system components, installation steps, activation modes as well as advantages, disadvantages, and limitations for each bolt type.

Each bolting system consists of several components, which must be properly specified in tender documents. To be able to achieve unambiguous tender documents, the minimum specification for each component is recommended (chapter 7).

This part is followed by descriptions of the different types of installation (chapter 8) and bonding agents (chapter 9).

Corrosion protection is an essential issue for permanent bolting. Chapter 10 describes not only methods of corrosion protection, but also a way how to define the corrosion potential of the environment.

Quality assurance becomes more and more important in tunneling. Hence, chapter 11 covers the following topics: system tests, monitoring during manufacturing and installation as well as testing after installation.

Chapter 12 provides a general approach to include innovative products into the design and chapter 13 presents sample clauses for tender documents.

1.3. USE OF REFERENCES

The references used in this document are limited to international or national standards or codes respectively (ISO, ASTM, EN, DIN, ACI, etc.). These are commonly known to the industry and are to be considered as an example not superseding national standards or local regulations, where applicable.

2 >> Bolts as Part of Ground Support

Ground support generally comprises elements such as bolts, steel arches, lattice girders, sprayed concrete, combined with mesh or fibers and other support elements, which carry the predicted loads. The principal objective in the design of a bolting system is to reinforce and stabilize the ground.

Apart from spot bolting in fair ground conditions, bolts in tunneling are typically installed in a systematic radial pattern. The design depends on the ground conditions, the type and size of excavation and the service life requirements.

2.1. LOAD BEARING COMPONENTS

This chapter is meant to introduce and describe the load bearing components of a bolt.

Tendon

The tendon is the main load bearing element of a bolt which transmits tensile load along the axis of the bolt. Typically, it is a solid or hollow bar, but other shapes of cross sections (profiles) are possible as well. The surface can be smooth, structured (threads, ribs, etc.) or feature discrete anchorage points.

Note: This document does not cover wire strands (cable bolts) because they are not commonly used in tunneling.

Coupling

Couplings are used to connect tendon sections to achieve the required bolt length.

Bolt head

The bolt head is an assembly which typically consists of a plate and a fastening element attached to the near end of the tendon.
Plates are in contact with the ground surface either directly or via a layer of shotcrete or another intermediate structure. Additional washers may be positioned in between fastening element and plate to improve the load transfer between the two or to accommodate for boreholes not being rectangular to the ground surface. Fastening elements transfer the load from the plate into the tendon. Protective caps may be used to improve the resistance against corrosion.

Expansion shell

Expansion shells are anchorage elements connected to the tendon. They are mounted at the far end of the tendon and expand typically via a leaf-and-wedge system.

Bolts equipped with expansion shells can serve as mechanical bolts. Alternatively, some mechanical bolts can be grouted afterwards to improve the load transmission and to provide corrosion protection.

Accessories

Note: Accessories are non-load bearing components and are of minor importance in tunneling.

Spacers (Centralizers) (Figure 1) are used to centralize the bolt in the borehole to ensure that encapsulation with cement or resin grout has a minimum and ideally uniform thickness around the bolt. Spacers sit on the bolt and have several distance pieces (fins) on the outer circumference. Most spacers are not fixed on the tendon and can move along the bolt to the next coupling, which stops further movement. Spacers can be made of steel or plastic.

A conical **bottom cap** (Figure 1) has no structural function but is useful for the insertion of tendons into the borehole. It has the same function as a pointed top at rebar bolts.

Manchette **injection sleeves** (Figure 1) are used for cement or resin injection under pressure for waterproofing and ground improvement. A manchette injection sleeve in combination with a packer allows to execute localized repeated injections on the same sleeve.

2.2. BASE MATERIALS

Steel

Steel is the most used material for bolt tendons and load bearing components. Depending on bolt type and application area, various steel grades are in use. The governing factors for selection of a steel grade are forming capacity, a defined load-deformation behavior, and cost-effectiveness. Furthermore, the selected steel grade must comply with requirements for corrosion protection.

Glass Fiber Reinforced Polymer (GFRP)

(G)FRP reinforcing elements consist of a high number of continuous, orientated, inorganic fibers, typically embedded in a polymeric matrix. As they occupy the largest volume fraction (50-80%) and have an elastic modulus much higher than that of the matrix, fibers are the principal stress-bearing constituent, while the resin transfers stresses among fibers and protects them against environmental influences and damage during handling. Fibers are commonly made of glass or aramid, but other materials such as carbon and basalt are emerging.

FRP composite materials considered in this document are limited to GFRP bolt (bar and hollow bar) manufactured using thermosetting resins and glass fiber. This choice is related to the specific application of the guideline to tunneling.

Note: The use of a polyester matrix is allowed only for temporary structures because the water content in concrete pores may be responsible for the degradation of the polymeric matrix. (CNR-DT 203/2006). For permanent bolts Epoxy or Vinyl ester must be used as matrix.

Geometrical, mechanical, and technological properties of GFRP reinforcement basically depend on fiber and resin type, constituent volume fractions, production parameters, shape, and surface texture. The characteristics of the bolt surface influence the bond properties between GFRP bolts and bonding agent.

Figure 1. Spacers with five fins (left side), conical bottom cap (middle), and injection sleeve (right side).

$A_{5.65}$ [%]: As defined in EN ISO 6892-1: 2009: Permanent elongation of the gauge length after fracture, expressed as a percentage of the original gauge length.

Note: The index refers to a formula which determines the reference gauge length: A5 has an original gauge length of 5,65 $\sqrt{S_0}$ where S_0 is the original cross-sectional area of the sample.

A_{gt} [%]: As defined in EN ISO 6892-1: 2009: Total elongation (elastic elongation plus plastic elongation) at maximum force, expressed as a percentage of the original gauge length.

A_t [%]: As defined in EN ISO 6892-1: 2009: Total elongation (elastic and plastic) of the gauge length at failure, expressed as a percentage of the original gauge length.

Automated installation: Installation of supporting measures performed without any manual work.

Bolt: A reinforcing member used to stabilize ground. The main intention is to increase the capacity of the ground to carry loads in shear and tension itself.

Bolt head : Assembly of the piece of the tendon which sticks out of the borehole, the nut, the face plate, and any additional washers. The bolt head transmits the load that the ground surface applies to the plate into the bolt.

Bond strength: The adhesion of the bonding agent to a reinforcement element, or to other surfaces.

Bonding agent: Material to fill the annulus between bolt and borehole wall with a certain strength to transfer load.

Borehole: A longitudinal opening created in the ground for bolt installation.

Cementitious grout: Hydraulic cement based bonding agent.

Composite: A combination of one or more materials differing in form or composition on a macroscale (ACI 440.1R-2006).

Continuously bonded: Bolt is cement or resin grouted over its entire length.

Continuous friction: Bolt provides frictional resistance over its entire length.

Conventional installation: Also referred to as manual installation. Installation of a bolt into a pre-drilled borehole, e.g. a multiple-step installation process, involving manual interaction.

Convergence: Shortening in distance in a cross section usually measured between two points on tunnel walls, such as wall-to-wall convergence and/or roof-to-floor convergence.

Corrosion: Corrosion is the reaction of a material with its ambient environment, causing a measurable change in the material (e.g. rust), which can lead to function impairment of a component or system.

Corrosion potential: Electrode potential difference, e.g. measure for mitigation of electrons in the presence of an electrolyte; used as parameter in estimating corrosion damage and detection.

Corrosion protection: Minimization or slowing down of corrosion by the application of e.g. coatings or cathodic protection.

Coupling: Couplings are used to extend tendons by connecting tendon sections.

Cycle time: Entire duration of one working cycle in conventional tunneling including excavation, mucking, hauling and installation of support.

Discrete mechanically anchorage: Bolt is fixed at the far end of the borehole with one defined anchor point.

Durability: The ability of a material to resist cracking, oxidation, chemical degradation wear and/or the effect of foreign object damage for a specified period under specified environmental conditions.

Dynamic impact: A sudden impact to a reinforcement element, caused by the propagation of seismic waves caused by either blasting, sudden release of ground strain energy, or sudden dislocation of large quantities of ground.

Dynamic bolt: A bolt that can respond to dynamic impact without premature failure. Such dynamic bolts may work via energy-absorbing mechanisms like elongation, mechanical interaction of bolt components, or interaction between bolt, grout, and ground.

ε_{fu} [%]: Design rupture strain of FRP reinforcement (ACI 440.1 R-2006).

Electrolytic galvanizing: Also known as electrogalvanization. Coating of ferrous metal parts with a layer of zinc by immersing in an aqueous bath with dissolved zinc ions, which are reduced by applying electricity onto the metal (cathode).

Elongation: As defined in EN ISO 6892-1: 2009: Increase in the original gauge length at any moment during the tensile test.

Energy-absorbing capacity: The capability of a reinforcement element to absorb energy by e.g. elongating, sliding, a domed face plate flattening, or mechanical parts interacting. The energy-absorbing capacity of a bolt may be described by the maximum energy the element can absorb, or by the energy absorbed for a given displacement. The maximum energy a bolt can absorb is reached just prior to failure.

Face plate: A flat or domed, typically square, rectangular, or round plate with a hole that allows for the tendon to pass through.

Fastening element: Load bearing element mounted on the near end of a bolt. It can either be a nut screwed onto the tendon or an attached bushing acting as shoulder to the plate. The fastening element transfers the load from the plate into the tendon.

3 >> DEFINITIONS

Fiber: Fine thread-like natural or synthetic object of mineral or organic origin.

Note: This term is generally used for materials whose length is at least 100 times its diameter (ACI 440.1 R-06).

Fiber content: Amount of fiber present in a composite.

Note: This usually is expressed as a percentage volume fraction or weight fraction of the composite (ACI 440.1 R-06).

F_f [N/mm²]: Stress in FRP reinforcement in tension (ACI 440.1 R-06).

F_m [kN]: The actual ultimate load (maximum force) is the value of the maximum load obtained in a tensile test of a specific sample.

$F_{m, nom}$ [kN]: As defined in EN ISO 6892-1: 2009. The index "nom" refers to the nominal ultimate load specified for the product by the supplier typically a (fractile) minimum value.

$F_{p0.2}$ [kN]: The actual yield load (yield force) is the value of the load at which yielding occurs obtained in a tensile test of a specific sample.

$F_{p0.2.nom}$ [kN]: As defined in EN ISO 6892-1: 2009. The index "nom" refers to the nominal yield load specified for the product by the supplier typically a (fractile) minimum value.

Note: This value refers to the point in the stress-strain curve where 0.2% of permanent elongation occur (Rp0.2). In some occasions the value at 0.1% permanent elongation is used (Rp0.1).

Fractile value: A statistical denomination describing the value of a distribution for which some fraction of the sample lies below.

FRP/GFRP: Composite material consisting of continuous fibers impregnated with a fiber binding polymer, then molded and hardened in the intended shape (ACI 440.1 R-06).

FRP/GFRP matrix: Materials that serve to bind fibers together transfer load to the fibers and protect them against environmental influence and damage due to handling.

Ground (ref. to bolting): Soil or rock mass surrounding the bolt and its zone of influence with regards to load transfer.

Ground support: Elements intended to maintain the stability of excavations.

Grout: Pumpable (fluid) bonding agent either based on resin or cement.

Grouting: Filling a borehole with grout to provide a bonding agent in between the ground and the tendon. Filling of voids and cracks around the borehole is a collateral effect.

Hollow bar: A tendon which has a tubular cross section typically with a continuous thread on the outer surface.

Hot-dip galvanizing: Coating of ferrous metal parts with a layer of zinc by immersing into a bath of molten zinc at a temperature of around 450 [°C].

Injection: Filling of voids and cracks of the ground aiming at improving the ground stability and/or sealing it against water ingress.

Mechanized installation: Installation of supporting measures performed with mechanical devices controlled by operators.

Mesh: An arrangement of interlocked steel or GFRP rebar groups that are normally perpendicular to each other. Typically, mesh is used as reinforcing element in shotcrete.

Normal load [kN]: Load or load component that is acting in the tendon's longitudinal axis. In combination with bolts a normal load is typically a tension force.

Polyester resin: Unsaturated, synthetic, thermosetting resin.

Pre-tensioned (active): The supporting effect of pre-tensioned bolts is primarily activated by an active tensioning / elongating with hydraulic jacks or torque wrench.

Pull test (in-situ / field test): System test to verify the anchorage and/or bolt capacity by applying a tensile load on the installed bolt.

Rebar: Reinforcing steel element with circular cross section with a smooth, ribbed, or corrugated surface.

Reinforcement (reinforcing) element: An element (tendon, mesh) that strengthens the reinforced material (e.g. ground) by taking longitudinal and shear forces.

Resin: Polymeric material that is rigid or semi-rigid at room temperature, usually with a melting point or glass transition temperature above room temperature (ACI 440.1 R-06).

R_m [N/mm²]: Tensile Strength as defined in EN ISO 6892-1: 2009: stress corresponding to the maximum force Fm.

Rock burst: Rock bursts are the result of brittle failure of rock, causing it to collapse rapidly with subsequent violent spalling of rock, releasing dynamic (kinetic) energy to the support system.

Rock mass: A large and indistinct body of solid earth materials, containing features on the scale of jointing, folding, schistosity, etc. The term would not be used to describe a rock only the size of a hand specimen.

Rotary-percussive: Drilling method combining both rotation and percussion in drilling, ratio depends on the ground type, tools used and type of rock drill.

$R_{p0.2}$ [N/mm²]: Proof (yield) Strength as defined in EN ISO 6892-1: 2009: stress corresponding to the yield force $F_{p0.2.}$

Note: This value refers to the point in the stress-strain curve where 0.2% of permanent elongation occur ($R_{p0.2}$). In some occasions the value at 0.1% permanent elongation is used ($R_{p0.1}$).

Sacrificial drill bit: Drill bit used only to drill one single hole. The drill bit is typically mounted on a self-drilling bolt and remains in the borehole as sacrificial bit.

Seismic events: Any kind of ground vibration caused by blasting, geomechanical failure mechanisms, or an earthquake.

Self-drilling: Simultaneous drilling and bolt installation, where the tendon with the sacrificial drill bit acts as drill rod.

Semi-automated: Installation method where part of the installation process is automated supervised by the operator.

Semi-mechanized: Installation method where part of installation process is done with mechanical devices controlled by the operator.

Service life: Expected lifetime or acceptable period of use in service of a ground support item.

Shear lag: During a tensile test on a GFRP bar the innermost fibers are not subjected to as much stress as those outermost fibers, i.e. the distribution of strain inside the GFRP bar is not uniform.

Shear load [kN]: Load or load component that is acting perpendicular to the tendon's longitudinal axis.

Sherardizing: Also, known as vapor or dry galvanizing. Coating of ferrous metal parts with zinc dust at temperatures between 300 [°C] and 500 [°C], whereby the zinc evaporates and diffuses into the steel surface forming Zn-Fe phases.

SN-Bolt: Rebar type bolt named after the place Store Norfors where this bolt was reportedly used first.

Sprayed concrete / shotcrete: Concrete sprayed onto a structure surface, such as tunnel walls, to help support the ground.

Spalling: Superficial failure of surface sheets or plates (fragments) of brittle rock under compression at high-stress contact points.

Squeezing: The occurrence of squeezing is directly associated with the capacity and stiffness of the support as well as the deformations of the ground due to construction. The maximum work envelope of lining can be used to determine whether equilibrium between ground and a conventional support is possible or squeezing conditions occur.

Stable borehole: The borehole remains in sufficient shape until the bolt installation is finished.

Stress corrosion cracking: Corrosion due to crack formation of a metallic material in a corrosive environment. Ductile metals subjected to a tensile stress fail due to stress concentrations within the structure, caused by e.g. manufacturing or excessive loading.

Swelling ground: A ground that increases its volume by a physico-chemical reaction when exposed to water (associated with montmorillonite and gypsum).

Temporary support: Service life of less or equal than two years or service life sufficient to maintain load-bearing capacity over the construction period.

Tendon: Longitudinal element of the bolt which stretches into the depth of the borehole providing the ground with additional capacity regarding tension and shear load.

Tensile test (laboratory): Product test to verify the load capacity of a load bearing element by applying tensile load. Can also be done in a model rock to estimate a product property, for example the anchorage capacity.

Thermosetting resin: Class of resin that, when cured by application of heat or chemical means, changes into a substantially infusible and insoluble material (ACI 440.1 R-06).

Thixotropic behavior: A reversible behavior of gels or fluids that liquefy when they are agitated or pumped (shearing) and reset after being allowed to stand.

UCS [N/mm²]: Uniaxial compressive strength is defined as maximum stress in a sample under uniaxial loading conditions.

Unstable borehole: Borehole collapses (caves in) during or after drilling or deforms that it is not in a shape allowing a proper bolt installation.

Un-tensioned (passive): Ground movements activate the supporting effect of un-tensioned bolts.

Vinyl ester resin: Class of thermosetting resins containing ester of acrylic, methacrylic acids, or both, many of which have been made from epoxy resin (ACI 440.1 R-06).

W/C ratio: Is the ratio of the weight of water to the weight of cement in cementitious grout.

Water-bearing borehole: Boreholes where water is flowing in through the borehole.

4 >> Abbreviations

$A_{5.65}$, A_{gt}, A_t	Different elongation values (see definitions)
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
cm	Centimeter
CNR	Consiglio Nazionale delle Ricerche / National Research Council
DIN	Deutsches Institut für Normung e.V. / German Institute for Standardization Registered Association
ε_{fu}	Rupture strain (see definitions)
EN	Europäische Normen / European Standards
f_f	Stress (see definitions)
F_m, $F_{m, nom,}$ $F_{p0.2,}$ $F_{p0.2, nom}$	Different load values (see definitions)
(G)FRP	(Glass) Fiber reinforced plastic
GPa	Gigapascal
hr	Hour
ID	Inner diameter
ISO	International Organization for Standardization
kJ	Kilojoule
kN	Kilonewton
m	Meter
mm	Millimeter
MPa	Megapascal
N	Newton
R_{el}, R_m, $R_{p0.1}$, $R_{p0.2}$	Different strength values (see definitions)
sec	Second
UCS	Uniaxial compressive strength
°C	Degree Celsius

Tunnels can be driven in changing ground conditions. For this reason, there are one or more suitable types of bolts. Bolt selection depends on the ground in which installation is performed. Ground conditions must be investigated carefully during the design phase. It is recommended that within the contract the owner classifies the excavation sequence and method, and the corresponding support measures, by definition of a classification system (excavation and support classes) for different ground conditions. The classification system can be based on international or national standards, or on project-specific basis.

In the following, common types are described to simplify and optimize the selection process. Key parameters are summarized in a table.

5.1. CLASSIFICATION OF BOLT TYPES

Bolt Properties

Load transfer mechanism

Load is transferred between ground and bolt in the following ways:

- **Discrete mechanically anchored systems** transfer load at two discrete points namely the bolt head and the anchorage point.
- **Continuously bonded systems** transfer the load from a reinforcement element (tendon) inside a borehole bonded by a bonding agent that fills the annulus between the bolt and the borehole wall over the entire length of the tendon.
- **Continuous frictionally engaged systems** transfer the load directly from the ground to the bolt by frictional forces over the entire length of the reinforcing element.
- **Possible combined systems** of the above-mentioned load transfer modes. In case special properties are required the use of a specialty bolt is considered (chapter 6.4).

Insertion

Insertion can be done in one step, simultaneously during drilling **(self-drilling),** and/or in a separate step after drilling the borehole **(in pre-drilled boreholes)**.

Note: Installation in pre-drilled boreholes can only be performed under stable borehole conditions.

Note: Cased drilling is not seen as an alternative in tunneling due to low productivity.

Activation

The activation of bolts can be basically achieved in three different ways.

- After installation, a bolt can be **pre-tensioned** by applying tension to the tendon before deformation occurs.
- It can be **tensioned at the bolt head only,** which means that the bolt is partly tensioned by tensioning the nut after installation and afterwards by ground movements due to stress redistributions of the construction.
- An **un-tensioned** bolt is activated by ground movements only.

Note: Pre-tensioning is not commonly used in tunneling.

Shape of tendon

Cross section and surface properties are key factors for the installation method and bonding mechanisms. Possible cross sections are:

- **Solid bar:** typically installed in pre-drilled boreholes with the bonding agent inserted or injected before bolt goes into the borehole.
- **Hollow bar:** typically installed in self-drilling mode. The hollow core being used for flushing and consecutively for injecting the bonding agent.
- **Profile:** either hydraulically expandable or using the spring effect of the material.

The surface can be smooth, structured (threads, ribs, etc.) or feature discrete anchorage points.

Tendon material

Typically, two categories of materials are used for tendons and bolt heads in tunneling.

- Steel
- GFRP

Resistance to Shear

Bolts are activated and used as tension elements. However, in ground conditions where the dominant failure is block failure bolts may get loaded by shear. In these cases, the shear capacity is based on the cross-sectional area as well as the material properties.

If the design allows shear displacement to a certain extent, friction-based bolts can be considered. In case shear displacements are not allowed, other bolt types must be applied to block shearing mechanisms or to increase normal forces in shear planes.

Note: On equal cross sections, steel can resist significantly higher shear loads than GFRP.

Note: Bolts are already loaded so not all their capacity can be activated as shear load capacity (combined forces).

Note: In general, friction-based bolts can accept higher shear displacements at lower shear resistance compared to rebar or hollow bar steel bolts with comparable load capacity.

Bonding agent

The bonding agent can either be **resin** or **cement** based.

- Inner load transfer capacity is defined by the load that can be transferred between bolt and bonding agent. It is influenced by the surface of the tendon as well as the properties of the bonding agent (chapter 9).
- Outer load transfer capacity is defined by the properties of the bonding agent as well as the condition of the borehole wall and the properties of the surrounding ground.

Energy absorbing ability

An installed bolt system may be subjected to energies released from the ground. This applies in:

- Swelling ground, caused by the volume increase by physico-chemical reactions.
- Squeezing ground, caused by the release of strain energy from ground failure mechanisms, resulting in closure of the excavation.
- Rock burst, where the release of accumulated elastic strain energy in highly stressed rock may cause a violent failure of brittle rock masses after excavation.

Bolts in tunneling are commonly loaded in the elastic range. The minimum requirement for elongation in these cases is an A_{gt} of minimum 5%.

In the following conditions bolts with special characteristics may be used coping with:

- High convergences within a long period of time: (cm/month, in this document further referred to as “slow convergences”) - swelling ground
- High convergences within a short period of time: (cm/hr, in this document further referred to as “fast convergences”) - squeezing ground
- Dynamic impacts (m/sec) - rock burst.

5 >> Classification & Selection Criteria

		MECHANICALLY ANCHORED	BONDED BY BONDING AGENT		
		EXPANSION SHELL TYPE	CEMENTICIOUS GROUTED (SN TYPE)	RESIN GROUTED (SN TYPE)	SELF-DRILLING HOLLOW BAR
Load transfer mechanism	Discrete mechanically anchored	✓			
	Continuous grout / chemical grout		✓	✓	✓
	Continuous frictionally engaged				
	Possible combined systems				
Insertion	During (self-) drilling				✓
	In pre-drilled holes	✓	✓	✓	✓
Activation	Pre-tensioned	✓		✓	
	Tensioned (face plate only)	(✓)	✓	✓	✓
	Un-tensioned		✓	✓	✓
Tendon shape	Solid	✓	✓	✓	
	Hollow bar / tube / profile				✓
Tendon material	Steel	✓	✓	✓	✓
	GFRP				
Bonding agent	No bonding agent	✓			
	Cartridge based		✓	✓	
	Grouted prior to bolt insertion (pre-grouted)		✓	✓	
	Grouted after insertion of bolt (post grouted)				✓
Yielding ability	Yielding Agt≥5% elongation	✓	✓	✓	✓
	Energy absorbing		✓	✓	

Table 1. Classification matrix of commonly used bolt types – bolt properties.

✓ Yes

(✓) Yes... with limitations or dependent on the used type.

FRICTION BASED		COMBINED SYSTEMS; MECHANICALLY ANCHORED AND GROUTED	DEFORMABLE / ENERGY ABSORBING	GFRP BAR	GFRP HOLLOW BAR
WATER EXPANDABLE FRICTION BOLT	SELF-DRILLING FRICTION BOLT				
(✓)		✓	(✓)		
		✓	✓	✓	✓
✓	✓		✓		
		✓	(✓)		
	✓		(✓)		(✓)
✓		✓	✓	✓	✓
		✓		(✓)	(✓)
		(✓)		✓	✓
✓	✓		✓	✓	✓
		✓	✓	✓	
✓	✓		(✓)		✓
✓	✓	✓	✓		
				✓	✓
✓	✓				
				✓	✓
			(✓)	✓	✓
		✓	(✓)	✓	✓
(✓)	✓	✓	✓		
	✓		✓		

Decision Criteria

Borehole condition
Stable boreholes allow an installation of bolts into pre-drilled boreholes, **unstable boreholes** require use of self-drilling solutions (or cased drilling). Use of self-drilling bolts generally leads to a reduction in cycle time. **Water bearing boreholes** or continuous flow of ground water also have an influence on the selection of bolt and bonding agent.

Number of basic installation steps
Time constraints are related to either immediate support and/or quick installation procedures. Immediate support refers to the shortest possible delay between start of installation and full capacity whereas quick installation refers to productivity.

Principle ground conditions
See introductory part of chapter 4.

Working characteristics
The **time of activation** refers to the time an installed system requires to achieve its full capacity. It is divided into **immediate load bearing capacity** after installation and **load bearing capacity after / during curing** of the bonding agent.

Resistance to shearing (see definitions)

Response to convergences.

Vibrations caused e.g. by blasting works can influence the performance of certain bolt systems, for example mechanical anchors where the expansion shell might become loose. Grouted bolts and friction bolts are generally not much affected.

Economy
The economic feasibility of a chosen bolting system or its economic feasibility as temporary or permanent support should be investigated. Total costs of ownership: Optimization of cost / benefit ratio

Environment
Environmental compatibility with local regulations including disposal.

Other factors
The service life refers to the durability of the system over the required project time without losing a defined minimum capacity. Relevant factors are depending on environmental influences. Important factors are the choice of material and corrosion protection system (chapter 10).

Safety
Mechanized or automated installation procedures are preferred methods and therefore recommended since they are a significant improvement of safety.

		MECHANICALLY ANCHORED
		EXPANSION SHELL TYPE
Borehole condition	Stable	✓
	Collapsing (unstable)	
	Water bearing	✓
Number of basic installation steps *1)		3
Principle ground conditions *2)	Soft	
	Hard	✓
Working characteris-tics	Immediate load carrying	✓
	High resistance to shearing	
	Squeezing / high convergences	
	High resistance to vibrations	
Economy & environment	Justifiable for temporary support	✓
	Environmentally sensitive material	

	BONDED BY BONDING AGENT			FRICTION BASED		COMBINED SYSTEMS; MECHANICALLY ANCHORED AND GROUTED	DEFORMABLE / ENERGY ABSORBING	GFRP BAR	GFRP HOLLOW BAR
	CEMENTICIOUS GROUTED (SN TYPE)	RESIN GROUTED (SN TYPE)	SELF-DRILLING HOLLOW BAR	WATER EXPANDABLE FRICTION BOLT	SELF-DRILLING FRICTION BOLT				
	✓	✓	✓	✓	✓	✓	✓	✓	✓
			✓		✓		(✓)		(✓)
		✓		✓	✓	(✓)			
	4	4	3	3	1	4	4	4	4 (3)
	✓	✓	✓				(✓)	✓	✓
	✓	✓	(✓)	✓	✓	✓	✓		
		(✓)	(✓)	✓	✓	✓	(✓)		
	✓	✓	✓	✓	✓	✓	(✓)		
	✓			(✓)	✓		✓		
		✓		✓	✓	✓	(✓)		
	✓	✓	✓	✓	✓			✓	✓
		(✓) *3)						(✓) *4)	(✓) *4)

Table 2. Classification matrix of commonly used bolt types – decision criteria.

✓ Yes

(✓) Yes... with limitations or dependent on the used type.

***1)** Basic installation steps: drilling, insertion of grout/resin/cartridges, insertion of bolt, expanding, post grouting, assembly of bolt head.

***2)** Soft: Load transfer by continuous grout or chemical bonding only.

Hard: All load transfer mechanisms possible.

***3)** If the resin is not cured.

***4)** Depending on standards and regulations applicable for the site.

6 >> Common Bolting Systems

This chapter describes the most common bolt types used for ground support in tunneling. Based on the load transmission mechanism, the following categories can be defined:

- Discrete mechanically anchorage
- Continuously bonded
- Continuous friction
- Combination of above mentioned and other

Note: Advantages and disadvantages mentioned in this chapter are not sorted according to importance.

6.1. DISCRETE MECHANICALLY ANCHORED BOLTS

Mechanically anchored bolts are probably the oldest form of ground reinforcement used in underground excavation. Given that the ground is hard enough to provide a good grip for an expansion shell which is attached to the end of the bolt, this mechanism will usually allow the bolt to be pre-tensioned up to a defined portion of the nominal yield load.

Tensioned bolts are effective in retaining loose blocks of rock near the excavation surface. These blocks may have been loosened by intersecting joints and bedding planes in the ground, or they may have been created by effects from blasting. Since the disintegration normally does not stretch very far into the ground, the support is only required to hold up the dead weight of the loose material. Tensioning of mechanically anchored bolts requires the consideration of a safety factor against the yield load.

Expansion shell type bolt

The most common type of mechanically anchored bolts is the expansion shell bolt. This bolt type is designed for moderately hard to hard rock conditions that can transfer bolt forces locally at the expansion shell. The two mechanisms by which the shell is anchored against the borehole wall are friction and interlock. These bolts are usually used in massive and blocky rock conditions.
An expansion shell bolt consists of an expansion shell that transfers the bolt forces into the ground, a tendon, and a bolt head that typically consists of a plate and a nut.

Expansion shell bolts are installed in cleaned pre-drilled holes with a specified diameter. Typically, these holes are drilled by using rotary-percussion and the drill steel as well as the drill bit are removed from the hole after drilling. The expansion shell bolt is then inserted into the bore hole and a wedge, attached to the tendon, is typically pulled or screwed into a conical expansion shell forcing it to expand against the borehole walls. After fixing the bolt to the borehole wall the bolt head is pre-tensioned by a wrench with a defined torque as stated in the design.

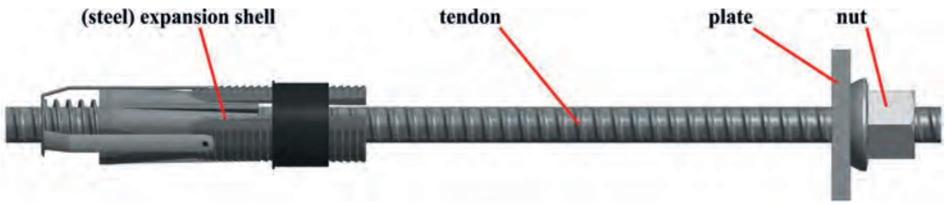


Figure 2. Typical system components of an expansion shell bolt.

	Drilling of a borehole in accordance with the specifications of the supplier
	Insertion of the assembled expansion shell bolt into the borehole – the expansion shell fits tight into the borehole
	Pre-tensioning via impact wrench or adequate tools

Table 3. Installation procedure for an expansion shell bolt system.

So, expansion shell bolts are activated at first by pre-tensioning and secondly by a gravitational movement of kinematically free blocks. After activation of the bolt forces can immediately be transferred between the bolt head and the expansion shell.

During activation, the entire bolt tendon is elongated equally so local higher deformations (block movement at a joint do not decrease its capacity.

Advantages:

- Fixation in upward direction by default
- Immediate load-bearing capacity after installation
- Nuts and couplings must not compromise the specified load bearing capacity of the system (otherwise it must be stated in the product specification)
- Bolt can be pre-tensioned
- Default corrosion protection measure is sacrificial corrosion
- Can be used in water-bearing boreholes
- Un-problematic installation

Disadvantages:

- Limited use in soft ground conditions
- Stable boreholes only
- Difficult to install reliably
- Must be monitored and checked for proper tensioning
- Sensitive on seismic events like blasting
- Can be used just temporarily unless corrosion protected and/or post grouted
- Generally no self-drilling installation
- Bolt length is limited to available space in the tunnel

Limitations

- Limited to use in moderately hard to hard rock
- Unstable boreholes
- Soft ground.

6.2. CONTINUOUSLY BONDED BOLTS

Continuously bonded bolts respectively grouted bolts are fully encapsulated by their bonding agent. The bonding in the borehole is accomplished by grouting where pumpable cementitious or resin-based grout is pumped into the borehole first, starting from the bottom of the borehole. The bolt is then driven into the fresh grout. Another common method is the use of polyester resin cartridges. Resin cartridges are installed into pre-drilled boreholes. A spinning bolt is pushed through the cartridges, mixing catalyst with mastic thus activating the grout. Alternatively cement cartridges can be used.

Fully grouted rebar bolts (SN-bolts)

Due to their simple design and application, SN-bolts are the most common bolt type in tunneling.

A fully grouted rebar bolt consists of a tendon mostly pointed at the far end, either with a continuous thread or with a threaded end, to carry nut, (washer,) and plate.

Fully bonded rebar bolts are installed in cleaned pre-drilled boreholes with a diameter clearly larger than the bolt diameter. Then grout is pumped into the borehole by using a hose or an injection lance starting at the bottom of the borehole. Alternatively, resin or cement cartridges are pushed or typically in mechanized installation shot into the borehole by compressed air. Afterwards, the assembled rebar bolt is pushed into the grout or through the resin cartridges. When using cartridges, the components must be mixed by rotating the rebar as specified by the supplier. After curing of the bonding agent, the bolt head can be tightened. Although several steps must be performed, installation is simple which may be an explanation why this bolt type is used so often.

Fully bonded rebar bolts are activated by excavation induced deformations of the ground. Relative movements between ground and rebar result in a load transfer via the bonding agent so grout and/or resin curing time has an influence on the load transfer and activation respectively. In case relative movements between ground and bolt occur at an early stage to a large degree (squeezing ground conditions) it may happen that grout is disrupted in its hardening process. If this occurs, special rib distances can be recommended to improve load transfer from ground to bolt and vice versa.

Note: A change to resin cartridges might not make sense in case of squeezing ground conditions because the borehole walls deform as well so either the cartridges cannot be pushed into the deformed borehole or the borehole is too large, and the installed resin cannot ensure a fully bonded rebar bolt.

Advantages:

- Reliable support in hard rock and soft ground conditions
- Unaffected by seismic events like blasting
- Load bearing capacity after and/or during curing of the bonding agent
- Nuts and couplings must not compromise the specified load bearing capacity of the system (otherwise it must be stated in the product specification)
- Bolt can be pre-tensioned (applies for resin cartridge only)
- Default corrosion protection measure is sacrificial corrosion

Disadvantages:

- Stable boreholes only
- No self-drilling installation
- Bolt length is limited to available space in the tunnel
- Additional measures required to fix in upward direction
- Bolt cannot be pre-tensioned
- Possible limitations in water bearing boreholes (flow rate may be critical)
- Full encapsulation is difficult to check and maintain

Limitations:

- Unstable boreholes

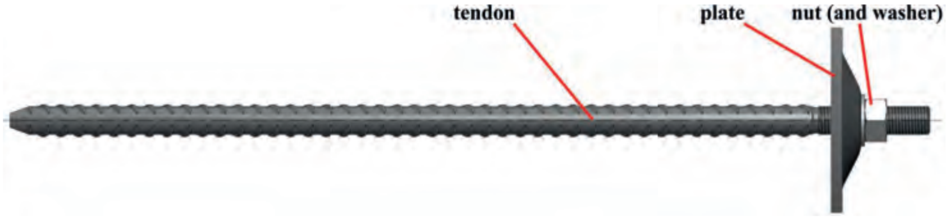


Figure 3. Typical system components of a fully grouted rebar bolt.

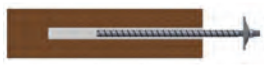
	Drilling of a borehole in accordance with the specifications of the supplier
	Grouting of a borehole by using a hose or an injection lance starting at the bottom
	Insertion of the bolt into the grout
	Tightening of bolt head

Table 4. Installation procedure for a fully grouted rebar bolt.
Note: For upwards inclined bolts, additional wedges may be used to fix the bolt in position during the curing time.

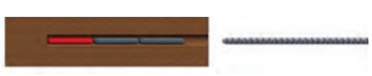
	Drilling of a borehole in accordance with the specifications of the supplier
	Filling of borehole with cartridges. (A fast-setting cartridge at the bottom of the borehole is recommended.)
	Simultaneously spinning and advancing the bolt through the cartridges. Rotation speed and duration as specified by the supplier
	Tightening of bolt head

Table 5. Installation procedure for a rebar bolt bonded by cartridges.
Optional: The bolt can be pre-tensioned after curing time of fast setting cartridge at the bottom of the borehole.
Note: Cartridges are usually used for bolts up to a length of 4 m due to difficulties in installation.

Self-drilling hollow bar bolt

Self-drilling hollow bars have been designed as a bolting solution for unstable borehole conditions such as sand, gravel, silt, clays, and soft to medium fractured rock formations. This system is widely used in geotechnical and underground applications such as bolts, soil and rock nails, micropiles, ground anchors, radial systematic bolting, face stabilization, and roof support.

A self-drilling hollow bar system for a typical tunneling application consists of a sacrificial drill bit, one or more threaded hollow bars, couplings, and a bolt head.

Hollow bars are commonly installed by utilizing a sacrificial drill bit with a self-drilling, rotary percussive drilling method. During drilling, the hollow bars are used as drill rod and can be extended by couplings. After drilling the designed length, the last hollow bar is disconnected from the drill rig and the bolt is grouted by pumping grout through the inside to the far end. This process is continued until the grout flows out from the annulus between borehole wall and hollow bar at the near end of the bolt. After curing of the grout, the near end is fixed to the primary lining by mounting the bolt head. A self-drilling hollow bar works as an “all in one” tool for drilling, flushing, grouting and finally acts as bolt.

Fully grouted hollow bars are activated by excavation induced deformations of the ground. Relative movements between ground and hollow bar result in a load transfer via the bonding agent so the grout curing time has an influence on the load transfer and activation respectively.

Compared to self-drilling hollow bars, conventional bolts generally have the disadvantage that, when being installed in poor ground conditions, unproductive time is spent on measures such as: retrieving expensive drill tools from collapsed boreholes, repositioning the drill feed to clean collapsed boreholes, inserting the grout hose to the borehole bottom, grouting the borehole, and inserting the bolt with the assistance of the feed system of the drill rig.

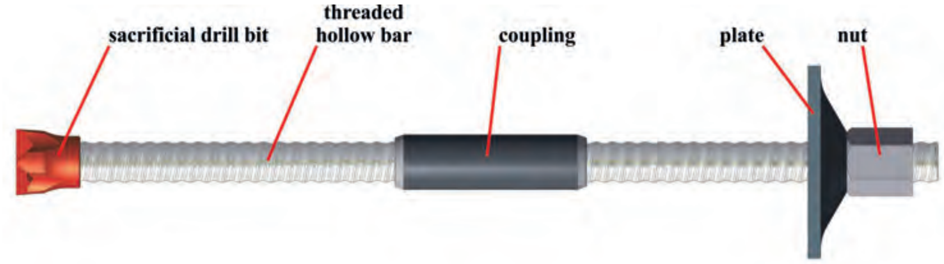


Figure 4. Typical system components self-drilling hollow bar bolt in tunneling.

	Assembly of the hollow bar and connection to the rock drill.
	Rotary percussive self-drilling installation without casing; single-use drill bit and hollow bar drill steel, water or air mist flushing (*)
	Extension of the hollow bar by using couplings
	Uncoupling from the drill rig, subsequent grouting using a post-grouting adapter
	Assembly of bolt head construction (plate and nut)

Table 6. Installation procedure for a self-drilling hollow bar system.

(*) In unconsolidated ground conditions, self-drilling hollow bar bolts can also be grouted simultaneously while drilling using a rotary injection adapter. This tool is placed between shank adapter and hollow bar. Grout is injected as flushing medium during drilling at a higher water/cement (w/c) ratio. The final grouting must be done in accordance with chapter 9.1.

Note: Simultaneous grouting can only be recommended for horizontal or downward directions.
Note: For upwards inclined bolts, additional wedges may be used to fix the bolt in position during curing.

Advantages:

- Reliable support in hard rock and soft ground conditions
- Stable and unstable boreholes
- Unaffected by seismic events like blasting
- Self-drilling installation process
- Bolts can be extended during installation
- Load bearing capacity after and/or during curing of the bonding agent
- Nuts and couplings must not compromise the specified load bearing capacity of the system (otherwise it must be stated in the product specification)
- Default corrosion protection measure is sacrificial corrosion
- Un-problematic installation

Disadvantages:

- Additional measures required to fix in upward direction
- Bolt cannot be pre-tensioned
- Possible limitations in water bearing boreholes when using cementitious grout (flow rate may be critical)

Limitations:

- No technical limitations

GFRP Bolts

GFRP is widely used in geotechnical and underground applications such as radial bolts, soil nails, micropiles, ground anchors, radial systematic bolting and face stabilization.
GFRP bolts consist of a corrugated GFRP bar and a bolt head. Optionally the tendon can be equipped with a conical bottom cap. If required GFRP bars can be extended using metal couplings.

GFRP bolts are either installed the same way like SN bolts in pre-drilled holes, or the GFRP bar is inserted in an un-grouted borehole. Afterwards the annular gap can optionally be sealed by a packer or sealing device. The bar is then grouted by pumping the bonding agent through a grouting hose from the near end to the bottom of the borehole. Grouting is performed vice versa in case of downward inclined boreholes. This process is finished and the annular gap is filled when the bonding agent flows out from vent hose.

Fully grouted GFRP bolts are activated the same way as fully grouted rebar bolts (SN bolts). Alternatively, GFRP bolts can be tensioned with a torque wrench. A steel bolt head required if a hydraulic jack is used for pre-tensioning.

Compared to steel bolts, GFRP bars have a low unit weight, and they are easy to cut. GFRP bars are characterized by a low electrical conductivity which means that they are not sensitive to electric stray current.

Advantages:

- Reliable support in hard rock and soft ground conditions
- Unaffected by seismic events like blasting
- Bolts can be extended during installation
- Load bearing capacity after and/or during curing of the bonding agent
- Bolt can be pre-tensioned (for example by using resin cartridges)
- High resistance to aggressive environments
- Low electrical conductivity
- Low unit weight
- High ultimate tensile strength

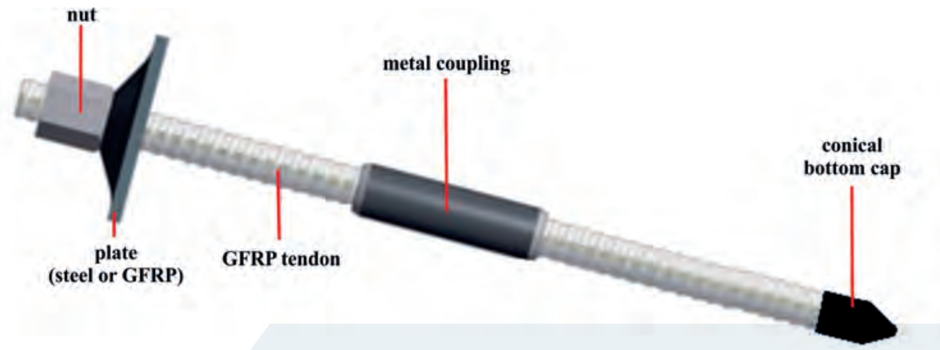


Figure 5. Typical system components GFRP bolt.

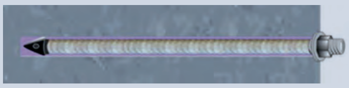
	Drilling of a borehole in accordance with the specifications of the supplier
	Insertion of the bolt into the borehole and sealing by packer or sealing device
	Grouting of annular gap through injection hose
	Mounting of bolt head.

Table 7. Installation procedure for GFRP Bolts.

Note: GFRP rebar bolts can also be installed the same way as mentioned in the rebar bolt section.

Note: For upwards inclined bolts, additional wedges may be used to fix the bolt in position during curing time.

Disadvantages:

- Stable boreholes only
- No self-drilling installation
- Additional measures required to fix in upward direction
- System load bearing capacity is defined by the performance of nuts and couplings
- Possible limitations in water bearing boreholes (flow rate may be critical)
- Full encapsulation is difficult to check and maintain
- Low compression resistance
- Limited torsion resistance

Limitations:

- Unstable boreholes

GFRP Hollow Bar

GFRP hollow bars have the same application area and installation method as GFRP bars.

System components are the same as described in the GFRP bar section except that the tendon is a hollow bar. Additionally, tendons can be equipped with injection sleeves.

Installation of GFRP hollow bars is performed in the same way as for GFRP bar except for the grouting procedure that is performed through the hollow core of the bar. Use of an injection sleeves allows localized injection of bonding agent.

Fully grouted GFRP hollow bars are activated the same way as fully grouted rebar bolts (SN bolts).

Compared to steel bolts, GFRP hollow bars have the same advantages as mentioned in the GFRP bar section.

Advantages:

- All the ones of GFRP bars
- Localized grouting when using injection sleeves in combination with packers

Disadvantages:

- All the ones of GFRP bars
- Limited use in self-drilling application (self-drilling GFRP bolts only – no percussion)

Limitations:

- Unstable boreholes

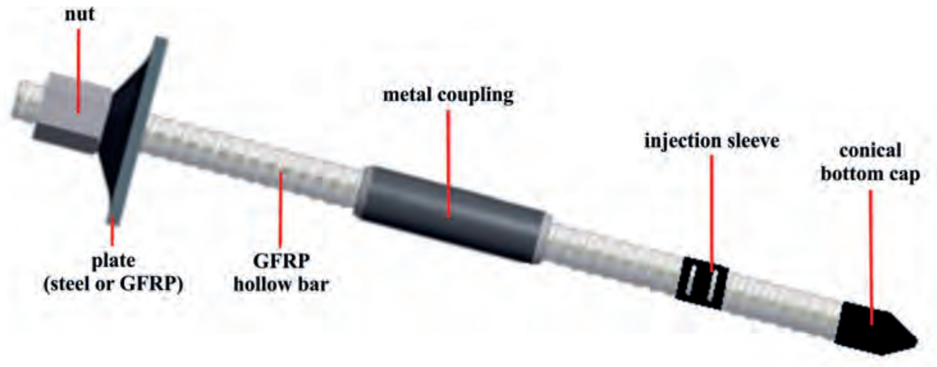


Figure 6. Typical system components for a GFRP bolt constituted by hollow bar.

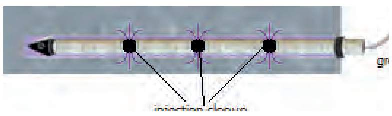
	Drilling of a borehole in accordance with the specifications of the supplier
	Insertion of hollow bar by coupling tendons until the designed length.
	Grouting using a post-grouting adapter through the hollow bar. The optional injection sleeves allow for localized injection of bonding agent.
	Mounting of bolt head

Table 8. Installation procedure for GFRP hollow bars.

Note: For upwards inclined bolts, additional wedges may be used to fix the bolt in position during curing time.

6.3. CONTINUOUS FRICTION BASED BOLTS

Friction based bolts do not require mechanical anchoring devices or bonding agents. For these bolts, the friction resistance to sliding is generated by a radial force against the borehole wall over the entire length of the bolt.
The three most common friction-based bolt types used are:

- Water expandable friction bolts: the mechanism is based on friction and mechanical interlock.
- Friction stabilizer type bolts prevent the bolt from sliding up to about half the ultimate tensile strength of the steel tube. The pure friction bolt can thus accommodate large displacements without failing. This technology is not common in tunneling but widely used in mining. Therefore, a description is omitted.
- Self-drilling friction bolts work the same way as friction stabilizers, but their steel tubes are heavier, and the friction generated is higher, so their bearing capacity is at the level of water expandable friction bolts.

Water expandable friction bolts

Water expandable friction bolts are commonly used in the mining industry for medium-term support and in tunneling for systematic radial reinforcement in hard rock conditions.

They consist of an end bushing, a profile, and a bolt head. The profile is expanded by water pressure to transmit friction to the ground and to create a mechanical interlock to the ground.

Water expandable friction bolts are installed in cleaned pre-drilled holes with a diameter specified by the supplier. Then the installation chuck is connected to the bushing head. Afterwards the profile is expanded with the aid of a high-pressure water pump (200-300 bar) to create the mechanical interlock and the friction to the borehole wall. After expansion of the profile to the shape of the borehole the chuck can be decoupled, and the installation is completed.

The bolt can be activated immediately after installation by relative movements between the tube and the ground.

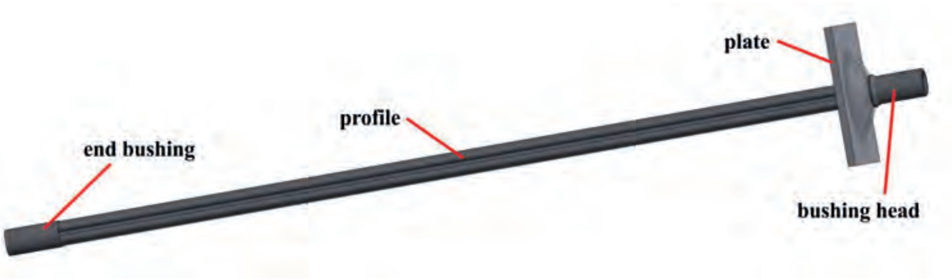


Figure 7. Typical system components of a water expandable friction bolt.

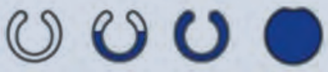
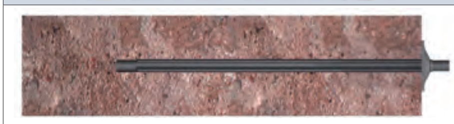
	Drilling of borehole in accordance with specifications.
	Connection to the installation chuck and insertion of the bolt.
	Expansion of the tendon with high-pressure water.
	Expansion process of the profile.
	De-coupling from the chuck after the profile is expanded.

Table 9. Installation procedure water expandable friction bolt.

Advantages:
- Reliable support in hard rock conditions
- Unaffected by seismic events like blasting
- Bolts can be extended during installation
- Fixation in upward direction by default
- Immediate load-bearing capacity after installation
- Nuts and couplings must not compromise the specified load bearing capacity of the system (otherwise it must be stated in the product specification)
- Can be used in water-bearing boreholes
- Un-problematic installation

Disadvantages:
- Limited use in soft ground conditions
- Stable boreholes only
- Bolt cannot be pre-tensioned
- No self-drilling installation
- Thin wall thickness makes it sensitive to corrosion if not coated

Limitations:
- Unstable boreholes
- Ground conditions, which do not permit transmission of friction

Self-drilling friction bolt

Self-drilling friction bolts have been developed based on the concept of conventional friction stabilizer bolts. Compared to standard friction bolts, self-drilling friction bolts consist of improved load-bearing elements and are installed self-drilling (one-step) by using a sacrificial drill bit and special rock drilling equipment.

A self-drilling friction bolt consists of a single use (sacrificial) drill bit, an improved slotted steel tube as tendon, a plate and multiple-use drilling equipment (drill steel and impact adapter).

A self-drilling friction bolt is usually installed by hydraulic rotary-percussive drilling. The drilling of the borehole and the installation of the bolt is performed simultaneously. This means that the impact adapter distributes the drilling energy via drill steel to the drill bit as well as to the end of the friction bolt so both parts are driven forward at the same time. After drilling and installing the bolt respectively the drifter with the impact adapter and the drill steel moves backwards and the installation is finished.

The bolt can be activated immediately after installation by relative movements between the slotted tube and the ground.

The described one-step installation procedure allows rapid installation of radial bolt pattern in critical unsupported tunnel sections. Because all system components of the bolt can be prepared on the drill arm in already supported tunnel sections before the installation starts it is possible to install this type of bolt without human beings exposed to unsupported tunnel sections.

Advantages:

- Reliable support in hard rock conditions
- Stable and unstable boreholes
- Unaffected by seismic events like blasting
- Self-drilling installation process
- Fixation in upward direction by default
- Immediate load-bearing capacity after installation
- Can be used in water-bearing boreholes
- Un-problematic installation

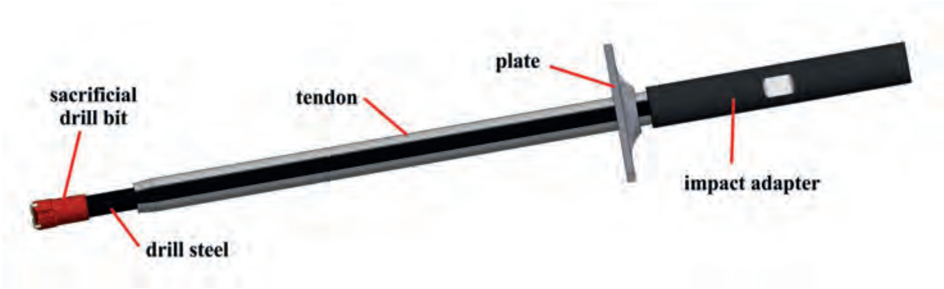


Figure 8. Typical system components self-drilling friction bolt.

	Assembly of all system components on the drill arm
	Simultaneous rotary-percussive self-drilling installation process
	Drilling until the designed depth
	Retraction of drill steel and impact adapter

Table 10. Installation procedure self-drilling friction bolt.

Note: An additional expansion element may be applied to increase bonding between ground and bolt in case the requested pull-out force cannot be achieved.

Disadvantages:

- Limited use in soft ground conditions
- Bolt length is limited to net feed length of the boom
- Bolt cannot be pre-tensioned
- Thin wall thickness makes it sensitive to corrosion

Limitations:

- Ground conditions, which do not permit transmission of friction

6.4. COMBINATION OF ABOVE-MENTIONED AND OTHER BOLT SYSTEMS

In addition to the mentioned bolt types in the previous chapters, various other "niche" types are used in tunneling.

Mechanically Anchored and Fully Grouted Bolts

These systems basically combine the benefits of discrete anchored bolt systems and a post grouted bonding which also serves as corrosion protection

After an installation of a discrete mechanically anchored bolt, the grout is injected into the collar end of the hole and the return pipe is extended for the length of the borehole. Grout injection is stopped when the air has been displaced and grout flows from the return tube. The tendon can additionally be corrosion protected.

These bolt types are used in applications where immediate support and enhanced corrosion protection is required.

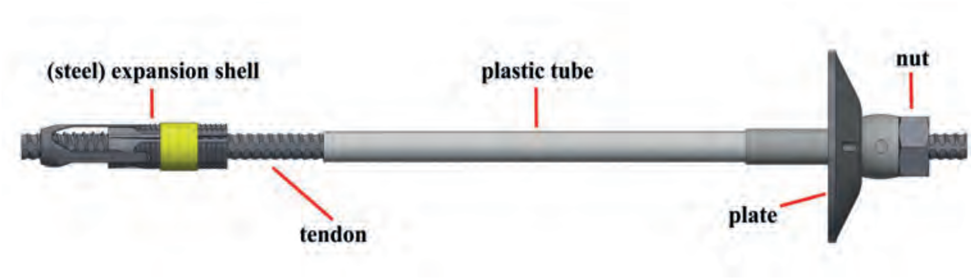


Figure 9. Example for a combined system bolt (expansion shell + fully grouted).

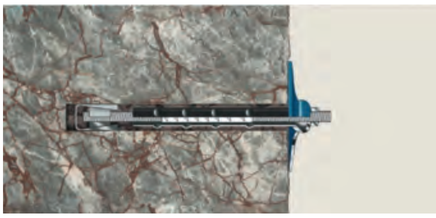
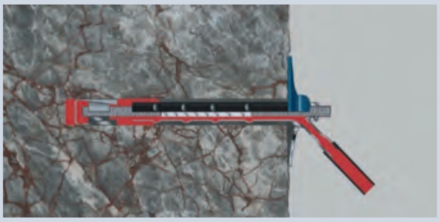
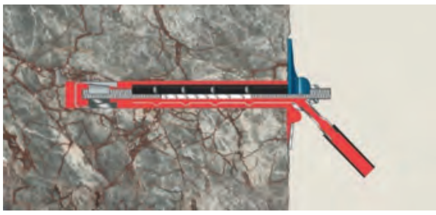
	See installation of an expansion shell bolt.
	Connection of an injection adapter to grouting adapter of the bolt. Grout flows forward on the inside of the sleeve.
	Grouting until the annular gap is filled up and the backflow is seen.

Table 11. Installation procedure combined system bolt.

Advantages:

- See expansion shell bolts.
- The possibility to grout around the rebar in a controlled way for corrosion protection.

Disadvantages:

- Correct installation requires close attention and supervision.

Limitation:

- Unstable boreholes

Bolts with Enhanced Energy Absorbing Ability

In conditions with high convergences, deformation-tolerable bolts are required to achieve proper ground reinforcement while in ground conditions exposed to dynamic impacts bolts with enhanced energy absorbing ability are required.
Note: Brittle failure of ground due to overstress requires a support system (bolts, mesh, shotcrete) and is therefore not part of this guideline.

Bolts for high convergences within a long period of time

Ground conditions which are characterized by delayed large deformations due to physico-chemical processes is initiated by water. This affects the choice of flushing media and type of bonding agent. Since no additional water should be introduced into the ground drilling technologies with air-flushing and resin as bonding agent are recommended.

To cope with the expected deformations, the bolt system should be characterized by high ductility of the tendon or special bolt systems with adequate response mechanisms should be employed.

Note: Friction based, and mechanically anchored bolts cannot be recommended because the described conditions are mostly associated with a high clay mineral content reducing the transferable friction force.

Note: High ductility of tendons can be defined by higher Agt values (plastic elongation at maximum load) and additional definitions of A or At values (elongation at failure). The required specifications need to be adapted to the conditions on site. The availability of respective products must be checked.

Bolts for high convergences within a short period of time

Tunneling in squeezing ground is characterized by early and large deformations (decimeter range). Cementitious bonding agents harden while relative movements between bolt and ground occur causing a negative impact on the inner bond strength. Changes in the rib distance as described in chapter 11.1 result in an optimized inner bond strength.

Additionally, the large deformations may require bolt systems with a high ductility. Alternatively, bolts with adequate response mechanisms that can absorb deformations at higher load levels can be employed.

Note: Friction based, and mechanically anchored bolts cannot be recommended because squeezing ground conditions are mostly associated with a high clay mineral content reducing the transferable friction force.

Note: High ductility of tendons can be defined by higher Agt values (plastic elongation at maximum load) and additional definitions of A or At values (elongation at failure). The required specifications need to be adapted to the conditions on site. The availability of respective products must be checked.

Note: Normally deformations in squeezing ground are associated with overloaded zones reaching far into the ground so long bolts (9m and more) are recommended depending on the expected conditions.

Note: For safety reasons, ductile bolt heads working as load indicators are recommended.

Bolts for dynamic impacts

Recent developments have addressed the shortcomings of traditional bolt systems to handle elongation and energy-absorption. Thus, bolt systems were developed that are especially designed to absorb energy that is released in highly stressed rock. Energy bolts may rely on different energy-absorbing mechanisms, e.g. stretching of smooth or de-bonded sections of steel or the ploughing of end anchors through either a bonding agent or a sleeve.

Bolts responding based on elongation properties of steel.

One example of steel-stretching energy bolts are deformable bolts. The tendon has a limited number of anchorage points and de-bonded sections in between. Anchor points are firmly fixed in the bonding agent that fully encapsulates the bolt, while the de-bonded sections will elongate, thus absorb energy.

Water expandable dynamic bolts are installed in similar ways as standard water expandable bolts and absorb energy similar as described above.

Bolts responding based on mechanical and/or frictional interaction.

Friction stabilizer bolts can accommodate large displacements without substantial failure. Once the load bearing capacity of the bolt is reached, it slides within the borehole in terms of a controlled failure mode. For applications in tunneling, heavy-duty friction stabilizer bolts with an increased outer diameter and wall thickness comparable to the already mentioned self-drilling friction bolts are recommended.

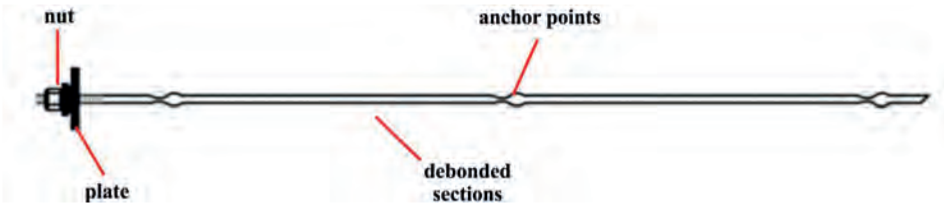


Figure 10. Typical system components deformable bolt.

To meet design requirements, it is fundamental to have a clear and common understanding regarding the products and specifications being tendered. The following material properties and geometry of the tendon, bonding agent, and bolt head have been identified to be considered as key parameters.

7.1. GENERAL

All specifications must refer to the performance of the finished product in sellable condition as close as possible to the installed state.

It is taken for granted that the load bearing components of the system (filler bushing of expandable friction bolt, collar of friction bolt), the coupling, and the expansion shell can carry and transmit the nominal yield load of the system. It must be specified separately if their capacity is lower because that becomes the limiting factor for the entire system.

In technical specifications, a 5% fractile value must be specified for yield load and elongation, which means that at least 95 % of test results must meet or exceed this value, to be able to ensure product quality and reliability of the specification.

7.2. TENDON

Steel tendon

All bolts must have the following minimum parameters specified: (compare to Figure 11)

- Cross-section [mm²]
- yield load; $F_{p0.2.nom}$ [kN]
  - 5% fractile value
- Elongation;
  - A_{gt} [%] for bars and hollow bars (elongation at maximum load). Otherwise $A_{5,65}$ [%] according to ISO 6892 where A_{gt} is not applicable (elongation at failure load)
  - A_{gt} must be ≥ 5% for tendons
- Bond Strength [N/mm²]
- Shear load resistance if required

Note: The cross section of steel tendons is typically back calculated by its weight and length.

Note: Although still used, the ultimate load cannot be recommended as design parameter for the load bearing capacity of a bolt.
Note: It must be specified which elongation is stated, A_{gt} or $A_{5.65}$ or other.

Note: To avoid sudden brittle failure of a support member, a minimum elongation A_{gt} of 5% is required (ductile failure) - health and safety requirement.

Note: A definition of steel grade is not necessary because the yield stress (f_y) can be calculated by yield load / cross section.

Note: A definition of shear load resistance is only required if shear load on the tendon is expected.

Product specific specifications:

- Expandable friction bolt:
  Yield load (YL), elongation, and shear load resistance must be specified for a bolt expanded to borehole diameter (chapter 11)

Note: The specified loads for bolts do not guarantee that this load can be transferred into the ground.

GFRP tendon

All bolts must have the following minimum parameters specified: (compare to Figure 11)

- Equivalent cross-sectional area [mm²] (CNR DT 203/2006 – Appendix B 6.1)
- Tensile strength: f_{fu} [N/mm²] [ACI: 440.3 R-12]
  - 450 [N/mm²] - 1,000 [N/mm²] (current range commercially available)
- Tensile modulus of elasticity [N/mm²]
- Bond strength [N/mm²]

Note: The glass content of the GFRP tendon is a direct consequence of requested tensile strength and modulus of elasticity.

Comparison of mechanical properties of steel and GFRP

Figure 11 illustrates the mechanical behavior of different steel grades and GFRP samples under tensile load.

As can be seen, the blue lines representing steel samples show an elastic-plastic behavior. The elastic part is characterized by a straight increase in stress over strain until the nominal yield stress is reached. This is the point where the values R_{el}, $R_{p0.1}$ and $R_{p0.2}$ are very close to each other. After this point the stress increases slowly while the strain increases over-proportionally indicating plastic behavior.
Compared to this characteristic the green area representing the GFRP samples shows a flatter, straight increase of stress over strain. This indicates the elastic behavior of GFRP up to failure without ductile, plastic behavior. Due to the absence of plastic behavior the design value is defined differently. For GFRP the nominal ultimate stress (f_f) is defined at a maximum strain value of 2% elongation.

The red line is representing the behavior of a high strength steel sample. This type of behavior without a significant plastic deformation at least up to an A_{gt} of 5% is unwanted for steel due to the risk of sudden failure.

The inclination of the straight increase determines the modulus of elasticity which for steel is 4 to 7 times higher depending on the glass fiber content in the GFRP. Thus, activation of steel tendons is faster compared to GFRP. This means that a longitudinal, relative movement of ground around the bolt must be higher by about the same factor to induce the same stresses into GFRP.

It is also obvious that the maximum stress of GFRP can be higher with the right fiber content than the one of steel. Thus, at comparable cross sections, GFRP bolts are activated at higher relative movements.

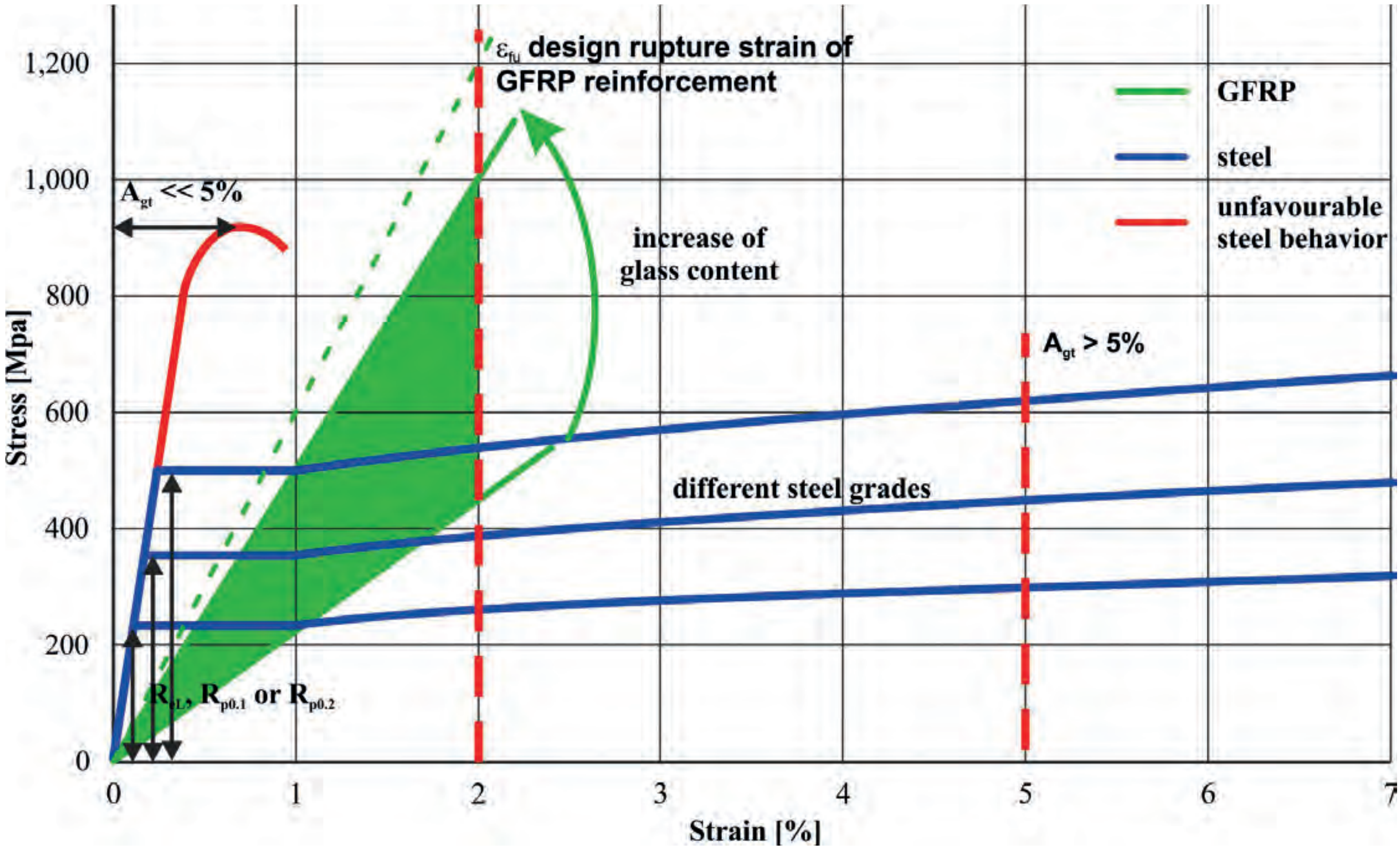


Figure 11. Comparison of typical stress-strain curves for steel and GFRP. Colored areas show the bolt working within the design criteria. Failure must occur at higher strain values than marked (2% for GFRP, 5% for steel).

7.3. BOLT HEAD AND COUPLING

Bolt heads and couplings govern the load capacity of a bolt. It is therefore important that it is clearly stated in case they cannot carry the nominal yield load, or the nominal ultimate load as specified by the supplier.

All bolt heads must have the following minimum parameters specified:

Nuts / rings / bushings

- Load capacity if it is less than the nominal ultimate load of the tendon.
- For nuts: the width across flats and whether they should be domed.

Note: For fully grouted or frictional bolts it is not required that nut/ring/bushing carry the nominal ultimate load, but at least the nominal yield load.

Plates

- Geometry (round, square, rectangular) and shape (flat or domed)
- Load capacity if it is less than nominal ultimate load of the bolt.

Note: A domed plate can act as a load indicator since excessive load will be visible by the deformation of the dome.

Bolt head assembly

- Load capacity bolt head (interaction tendon-plate-nut)
- Additional washers
- Protective caps if required (steel or plastic)

Couplings

The following must be specified:

- Load capacity if it is less than the nominal yield or nominal ultimate load of the bolt.

Note: Couplings in between steel tendons must not compromise the nominal load of the system.

Note: Couplings and nuts of GFRP bolts typically have a lower load capacity as the tendon. The capacity of connections and nuts is a function of coupling / nut length and coupling / nut system (only mechanical or mechanical plus glue).

7.4. Bonding Agent

The following criteria must be specified for bonding agents.

CRITERION	UNIT	CEMENTITIOUS BULK	CEMENTITIOUS CARTRIDGE	RESIN BULK	RESIN CARTRIDGE
Chemical description	[-]	✓	✓	✓	✓
Geometry (diameter, length)	[-]		✓		✓
Early strength 1)	[MPa]	✓	✓	✓	✓
Final strength after setting/curing (UCS) 1)	[MPa]	✓	✓	✓	✓
Bending tensile strength	[MPa]			✓	✓
Setting/curing time	[min]	✓	✓	✓	✓
Shrink factor	[-]	✓	✓		
Creeping	[-]	✓	✓		
Applicable temperature range	[°C]	✓	✓	✓	✓
Durability	[-]	✓	✓	✓	✓
Shelf life and storage conditions	[-]	✓	✓	✓	✓
Grain size	[mm]	✓	(✓)		
W/C ratio or mixing ratio	[1]	✓		✓	
Pumpability	[-]	✓		✓	
Flammability	[-]			✓	✓
Heat dissipation	[-]	(✓)	(✓)	✓	(✓)
Chemical resistance	[-]	✓	(✓)	✓	(✓)
Environmentally hazardous	[-]	✓	✓	✓	✓

Table 12. Bonding agent criteria.

✓ Yes

(✓) Yes... with limitations.

1) Preferably, a setting curve or table describing the development of the strength (UCS) over time is provided.

7.5. CORROSION PROTECTION

In many tunneling applications, corrosion protection is not required due to the limited design lifetime of bolts during the excavation process (e.g. temporary support). Since effects of corrosion might be dramatic, basic information is provided in this document EN 12501-1&2.

If corrosion protection of bolt components is required, the following parameters must be specified:

- **Corrosion potential (low, medium, or high):** this information eliminates or enhances use of certain bolt systems and corrosion protection measures.
- **Steel:** Possible corrosion protection methods are sacrificial corrosion protection, encapsulation by bonding agent, duplex coatings, double corrosion protection, hybrid methods. For each method, a relevant technical standard as well as minimum protective layer thicknesses must be specified.
- **GFRP:** Degradation (corrosion) protection methods are commonly related to the raw material mixture of the matrix. Relevant technical standards must be defined for the mixture to protect all components from all identified degradation possibilities.

Further information on this topic can be found in Chapter 10)

7.6. BOLT PROPERTIES FOR TECHNICAL SPECIFICATIONS

			MECHANICALLY ANCHORED	BONDED BY BONDING AGEN	
			EXPANSION SHELL TYPE	CEMENTICIOUS GROUTED (SN TYPE)	RESIN GROUTED (SN TYPE)
Tendon	Length	[mm]	✓	✓	✓
	Diameter, cross section, wall thickness	[mm / mm²]	✓	✓	✓
	Yield load	[kN]	✓	✓	✓
	Elongation (A_{gt} or ε_{fu})	[%]	✓	✓	✓
	Bond strength	[N/mm²]		✓	✓
	Modulus of elasticity	[GPa]			
	Impact energy	[kJ]			
	Corrosion protection	[yes + method / no]	✓	✓	✓
	Applicable standards	[-]	✓	✓	✓
Bonding agent	Type (resin, cement, bulk, cartridge)			✓	✓
	Final strength	[MPa]		✓	✓
	Strength development	15 min, 24 hrs, 48 hrs		✓	✓
	Applicable standards	[-]	✓	✓	✓
Plate	Dimensions	[mm]	✓	✓	✓
	Shape	round, square, domed, flat	✓	✓	✓
	Load resistance	[kN]	✓	✓	✓
	Applicable standards	[-]	✓	✓	✓

Table 13. Bolt properties for technical specifications.

✓ Yes

(✓) Yes... with limitations or dependent on the used type.

[1)] *By the use of a vinyl-ester or epoxy matrix (CNR-DT 203/2006)*

NT		Friction Based		Combined Systems; Mechanically Anchored and Grouted	Deformable / Energy Absorbing	GFRP Bar	GFRP Hollow Bar
	Self-Drilling Hollow Bar	Water Expandable Friction Bolt	Self-Drilling Friction Bolt				
	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓
	✓			✓	✓	✓	✓
						✓	✓
					✓		
	✓	✓	✓	✓	✓	(✓) 1)	(✓) 1)
	✓	✓	✓	✓	✓	✓	✓
	✓			✓	✓	✓	✓
	✓			✓	✓	✓	✓
	✓			✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓

Note: Steel grades are considered irrelevant since the mechanical performance of the finished product is specified. Each cold forming process during production influences the mechanical properties of steel.

Installation of all commonly used bolts can be performed manually, mechanized and automated. The midterm target is to fully replace manual installation with mechanized and automated installation to improve both safety and productivity.

To ensure proper installation and performance of bolts, the installation procedures recommended by the supplier must always be observed.
Bolt installation methods can be classified as in the following sub-chapters.

8.1. INSTALLATION STEPS

- Drilling of borehole
- Insertion of bonding agent into the borehole
- Insertion of tendon into the borehole
- Extension of tendon with couplings
- Grouting or expansion (expansion shell / water inflatable friction bolt)
- Mounting of bolt head
- Pre-tensioning

Note: Not all steps are required for each bolt type.

Note: The activation of bolts can start with pre-tensioning but is usually induced by the subsequent relative ground movements.

8.2. MODE OF INSTALLATION

Bolting can be differentiated by the drilling method:

- Pre-drilling: supporting element is installed into the ground after the drilling process.
- Self-drilling: supporting element is inserted into the ground simultaneously to the drilling process.

Alternatively, the timing of the grouting can also be used for differentiation:

- Immediate grouting: grouting is done during bolt installation.
- Post grouting can be done any time after installation.

Note: The timing for grouting depends on ground conditions.

8.3. BOREHOLE STABILITY

- Stable borehole allows the installation of all bolt types.
- Unstable borehole (borehole collapses (caves in) during or immediately after drilling): - Requires the use of self-drilling bolt types to get the tendon in place.

Note: Cased drilling is not seen as an alternative in tunneling due to the low productivity.

8.4. NUMBER OF INSTALLATION STEPS (INSTALLATION TIME)

The number of installation steps as per chapter 8.1 can be associated with installation time.

Note: Not all installation steps must necessarily be performed for all bolt types.

8.5. COUPLED SYSTEMS

Space constraints or the limitation in feed length require bolts to be extended in length (coupled).

8.6. DEGREE OF MECHANIZATION OR AUTOMATION

Drill rigs and handheld drilling equipment are examples of mechanization as well, but both are common standard worldwide, so they are classified under manual here to have a better differentiation from improved techniques.

- Manual: Drilling of the borehole with a drill rig or a handheld drilling equipment, insertion and/or grouting/expansion of bolt performed manually.
- Semi-mechanized: Drilling by drill rig, at least one of the above-mentioned steps is done mechanized and controlled manually.
- Fully mechanized: All installation steps are done mechanized and controlled manually.
- Semi-automated: Individual steps of installation processes are triggered and afterwards performed automatically.
- Automated: Once the process is triggered all installation steps are performed automatically.

8.7. BOLTING IN MECHANIZED TUNNELING

There are two types of default ground support used in mechanized tunneling: precast concrete segments or a combination of bolts, steel arches, lattice girders, mesh, and shotcrete, etc.

When using concrete segments as a lining the TBM will hold the ground in place until the ground is supported by the segmental lining. Due to the installation of segmental lining subsequently after the excavation, additional systematic/ radial bolting is rather the exception. However, in some challenging ground conditions additional ground improvement and/or temporary support is required even if segmental lining is used.

The TBM types providing space and access for additional radial bolting are so-called open tunnel boring machines (open/main beam/ gripper type). These machines are typically not used to install segmental lining, and the area behind the cutter head remains open for ground access. In open TBMs, access to the ground is facilitated due to several design innovations, including:

- Shorter front shields
- Retractable shields
- Installation of ground support immediately behind the front shield

From today's safety aspect, when open TBMs are used, early installation of support is a top priority to protect people and equipment.

Bolting devices in open TBMs are rigid or telescopic. The devices are mounted close behind the cutter head so bolts can be installed in a radial pattern. Bolting also allows for additional radial exploration drilling, drainage and injection works as well as fixing of steel mesh for subsequent application of shotcrete.

Apart from open TBMs, bolting in TBM driven tunnels is also used in areas of cross passages, junctions, widened tunnel cross-sections (emergency lay-byes, bus-stops), portals, etc. In addition, it should be mentioned that most roadheaders nowadays are also equipped with bolting devices.

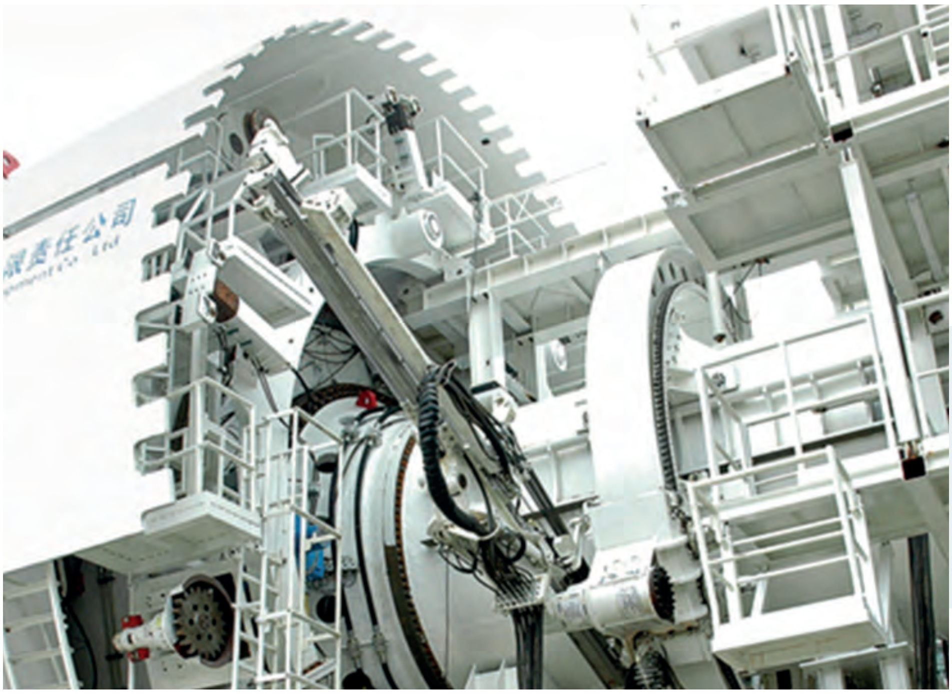


Figure 12. open TBM with drilling equipment.

Common bolts in TBM tunneling

The most significant criteria for bolts used in open TBMs is the possibility to extend tendons in case the required bolt length exceeds the available net length of the drill feed. To avoid multiple manual installation steps, like exchanging of drill steel with the bolt tendon and vice versa, self-drilling solutions are preferred and recommended.

9 >> Bonding Agents & Grouting

Bonding agents are used to fill the annular gap between borehole wall and tendon. They are available in bulk or as cartridges. There are two basic types of bonding agents:

- Bonding agent based on cement, water, aggregates and preferably with additives to achieve certain properties.
- Bonding agent based on chemical components such as resin and aggregates.

A bonding agent is required for all types of continuously or partially bonded systems to transfer the load between the ground and the reinforcement element or tendon.

Note: Grouting with bulk material should be done either through a hollow bar or by using an injection lance / hose to fill the hole from the far end (toe).

9.1. CEMENTITIOUS BONDING AGENTS

Cementitious grout is based on cement and aggregates preferably with additives such as accelerators, plasticizers, volume stabilizers etc. mixed with water at a specified water/cement ratio of typically less than 0.45. The mixture cures hydraulically and final strength is defined to be achieved after 28 days.

In tunneling a cementitious bonding agent is typically used in bulk.

Evaluation of the environment

As a first step, ground conditions must be analyzed:

- In the presence of groundwater with high content of sulfides, the use of C_3A free cement is required to ensure full strength of the cement is developed and maintained.
- If the pH value is < 7, the use of special cementitious grout is required.

Note: It is not recommended to use pure Portland cement due to shrinkage and curing time. Anchor mortars typically include additives and admixtures compensating for these deficiencies.

General Criteria

The following must be observed:

- Water used for the admixture affects the quality and durability of the grout and needs to fulfill the requirements as per the supplier's recommendation and standard regulations.
- Modulus of elasticity (after 28 days) must be lower than 20,000 [N/mm2].
- Strength requirements should be in line with EN 447.
- Length variation should be less than 2.0‰ after 28 days.
- Volumetric change should range between -1% and +5% within 24 hours as per EN 447.
- The grout should start to solidify/cure as soon as possible after injection.

The ratio of water and bonding agent (w/c factor) should not exceed 0.45 and should always be recorded.

- To simplify the checking of the w/c ratio in-situ, the grout producer should be committed to specify the gross density of freshly mixed grout.
- The grout should show thixotropic behavior.
- The maximum grain size is depending on the bolting system e.g. inner diameter of injection hose, annulus between borehole and bolt, flushing hole diameter of sacrificial drill bits, etc.
- Typical requirements for a pumpable grout:
  - Nominal hose ID: 25mm
  - Hose length: ≥ 50m
  - Pumping height: ≥ 10m
  - Pressure: ≤ 30 bar
- Where the risk of freezing temperatures exists, the air void content should be greater than 6% to ensure frost resistance.

Cementitious grouting equipment

For cementitious grouting equipment, there are different mixing and pumping technologies. The combinations of technologies and their main features are shown in Table 14.

Batch mixing	Piston pump		
Batch mixing	Screw pump		
Cont. mixing	Screw pump	Single shaft	
Cont. mixing	Screw pump	Split machine	

Batch mixing	Piston pump		
Batch mixing	Screw pump		
Continuous mixing	Screw pump	Single shaft	
Continuous mixing	Screw pump	Split machine	

	Grouting pressure			Grain size		Data recording *3			Flow rate		Delivery behavior	
	< 10 bar *1	10-50 bar *2	> 50 bar	< 4 mm	> 4 mm	Volume	Pressure	Water	Variable	Unchangeable	Pulsating	Continuous
	✓	✓	✓	✓	✓	✓	✓		✓		✓	
	✓	✓		✓		✓	✓		✓			✓
	✓	✓		✓		✓	✓			✓		✓
	✓	✓		✓		✓	✓	✓	✓			✓

Table 14. Combinations of technologies for cementitious grout.

✓ Yes

(✓) Yes... with limitations or dependent on the used type.

***1** Typical for fully grouted rebar bolts

***2** typical for self-drilling bolts

***3** separate device required

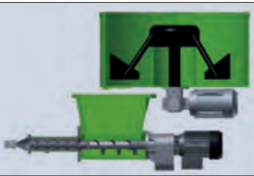
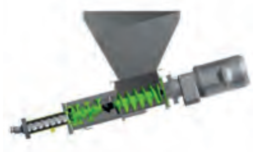
		+ high pressure pump + manual admix of additives possible - labor intensive - large and heavy
		+ manual admix of additives possible - labor intensive - large and heavy
		+ most popular in tunneling + compact machine + easy to operate + not labor intensive
		+ grout consistency (w/c ratio) control + process security + easy to operate + not labor intensive-

Table 15. Working schemes, advantages and disadvantages for grout pumps.

Cement Cartridges

Cement cartridges consist of a cementitious compound encased in a perforated package which, when immersed in water, will allow controlled wetting of contents, forming a thixotropic grout. The cartridge is then inserted into the hole and the bolt is pushed in.

Advantages:

- Convenient and easy-to-handle cartridge form
- Faster curing compared to standard cement grouts
- Controlled setting times
- Simple activation by immersion in water
- No special grouting equipment required.

Disadvantage:

- Manual wetting
- Quality control
- Dry storage conditions mandatory.

Limitations:

- Long bolts (> 4m)
- Water bearing boreholes.

9.2. RESIN BONDING AGENTS

Resin grouts are generally two component systems which, when properly mixed and installed, typically cure within minutes to the full strength. The grout should completely fill the annulus between bolt and borehole wall, quickly and securely bonding the bolt into the borehole. Resin grout is not a glue – if the two surfaces are pulled away from each other, the grout will offer relatively little resistance.

In tunneling typically resin cartridges are used.

Resin Cartridges

A resin cartridge is a two-compartment hose containing typically a polyester resin composition (mastic) in one compartment and a catalyst composition in the other. When the cartridge is used the separation between the two compartments is broken and the two components are mixed together. The catalyst causes the resin to harden at a controlled and pre-selected speed. Hardened resin bonding agent securely bonds the bolt into the borehole.

The skin or sheath of the resin cartridge is plastic which is strong enough to contain and protect the contents during manufacturing, storage and handling, yet it is punctured up easily by the bolt in the borehole, to completely release the two components and not interfere with the contact between the set resin and the ground and the bolt, respectively.

Advantages:

- Easy usage
- Fast setting
- High long-term strength
- Automated installation available

Disadvantages:

- Higher material cost compared to cementitious grout
- Cannot be recommended in fractured rock
- “Finger gloving effect”
- Storage temperature condition
- Difficult quality control (mixing time, borehole vs bolt diameter for manual or semi-mechanized installation procedures)
- Handling of hazardous chemical components.

Limitations:

- Collapsing boreholes
- Bolt length (> 4m)
- Shelf life.

Methods of Installation

Manual: Cartridges are manually inserted into the borehole and moved to the far end by using a loading stick. The bolt is then inserted and simultaneously spun and pushed forward so that it breaks both compartments of the cartridges and mixes mastic and catalyst. Bolt advance rate, rotation speed and duration as recommended by the supplier must be observed. For bolt installation, typically a handheld jackleg or another spinning device is used.

Automated: The installation process is either semi-automated (the steps of the process are triggered manually) or fully automated (the full cycle of installation is triggered). The cartridges are shot to the far end of the borehole using pneumatic pressure. The bolt is then inserted and spun by the drill rig.

Bulk injectable resin

Bulk injection resins come in two components and are designed specifically for underground environment in which they are to be used.

Advantages:

- No “finger gloving effect”
- Fast setting
- High long-term strength
- Unlimited availability of grout (voids and cracks)
- Suitable for long distance pumping

Disadvantages:

- Higher material cost compared to cementitious grout
- Storage temperature condition
- Time consuming set-up when not automated
- Handling of hazardous chemical components.

Limitations:

- Shelf life.

Method of Installation

The two components are stored in separate containers and are typically pumped through a static mixer into the borehole either via a hose or through a hollow bar. Depending on the required ratio of mastic and catalyst the volume flow may vary for both components.

- Design considerations
  - Bolt length
  - Bolt diameter
  - Borehole diameter
  - Full encapsulation (minimum length of encapsulation)
  - Tensioned / pre-tensioned
  - Temperature

9.3. PACKERS AND BOREHOLE PLUGS

A packer is an auxiliary tool for injection and sealing. Packers for bolts are commonly designed as single packer (one packer at the borehole collar) and mounted around the tendon and expanded against the borehole wall. Afterwards, the annulus and surrounding fractures and voids is injected with grout under a certain pressure.

In case an injection under pressure is not required (e.g. the grout must just be kept inside the borehole), so-called borehole plugs are used for sealing of the annulus in the collar region.

Advantages:

- Injection of the annulus under pressure
- Additional ground improvement by injecting fractures and voids
- Can be used in water-bearing boreholes.

Disadvantages:

- Time-consuming procedure.

Figure 13. Exemplary packers and borehole plugs.

9.4. GROUT SOCKS

Grout socks are geosynthetic sleeves primarily used for containment of grout in highly fractured ground, voids, or similar. They are placed typically over the entire length of rebar steel or GFRP bolts and sealed on the bottom (toe) in case of grouting and on the collar in case of injection. Grout socks are grouted or injected under a controlled pressure with grout. Grout socks allow typically for leakage of surplus water, featuring an enhanced curing process of cement grout.

Advantages:

- Prevention of grout loss, improvement of bonding
- Can be used in water-bearing boreholes

Disadvantages:

- If prepared on-site additional manual working steps
- Cost

Limitation:

- Not applicable in collapsing boreholes

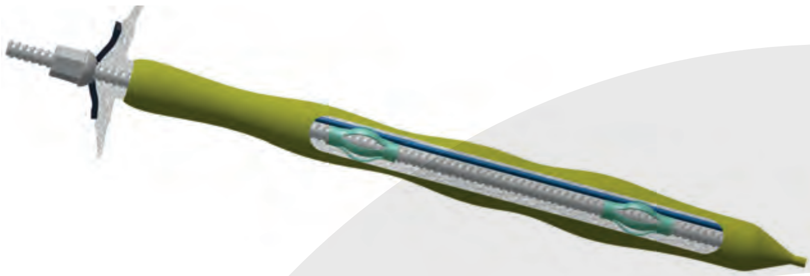


Figure 14. Schematic sketch bolt with grout sock (yellow).

Typically temporary ground support in tunneling does not require a corrosion protection system.

Note: For GFRP systems, corrosion is typically described as degradation.

10.1. CORROSION POTENTIAL AND AGGRESSIVE ENVIRONMENT

Prior to any project-specific design considerations for corrosion protection systems, a on site assessment of the corrosion potential of the ground, the ground water and other potentially influencing factors such as stray current must be accomplished. As project-specific information may be rather limited at an early design stage, this evaluation can be conducted based on common criteria for stress corrosion of metallic materials in soils (reference standards EN 12501-1 and EN 12501-2). The corrosion potential may either be:

- Low,
- Moderate, or
- High.

Typical physical and chemical soil parameters for the evaluation of the corrosion potential of the ground are summarized in the table 16.

Note: Default application range: pH-values from 5-8. At pH values < 5 for blank and galvanized steel and at pH values > 8 for galvanized steel, the corrosion potential of the next higher corrosion class must be assigned.

Note: Temperatures < 10°C generally show lower corrosion potentials; temperatures > 20°C generally show higher corrosion potentials.

Note: If criteria for "high" are exceeded, the service life can be considered as highly limited.

Ground parameter	Corrosion potential		
	Low	Medium	High
Ventilation	Moderate to very good	Poor to moderately good	Very poor to poor
Ground structure	Predominantly sand and gravel-sustainable (coarse to medium dispersed)	High proportions of silt and fine sand (medium to finely dispersed)	Possibly high proportions of organic substances and clay (finely dispersed); industrial waste, de-icing salt
Water content	Low (drainage capable)	Generally average	Generally high
Neutral salt content	Low	Possibly increased	High
pH value	pH value		
Specific soil resistivity in [Ωm]	> 70	10 to 70	< 10

Table 16: Common parameters for the evaluation of corrosion potential (EN 12501-1 & EN 12501-2).

10.2. METHODS FOR CORROSION PROTECTION

From a global perspective, various methods for corrosion protection based on national/regional/global regulations or standards are used. Those different methods use the following typical types: blank, galvanizing, galvanizing and coating or encapsulation (bonding agent). The following table summarizes typical methods for corrosion protection of steel bolts, followed by a short description. GFRP-based systems are not included in this table and will be covered in chapter 10.3.

Corrosion protection method	Description	Examples	Installation mode
Sacrificial corrosion protection (considered loss of cross-section due to corrosion of the load-bearing element)	No additional surface corrosion protection measures	All solid bolts; hollow bars; mechanical anchors; friction bolts	Self-drilling and installed in pre-drilled boreholes
	Galvanizing: sacrificial cover with zinc		
Encapsulation by bonding agent	Defined layer of resin or cement grout	SN-bolts; hollow bars	Self-drilling and installed in pre-drilled boreholes
Duplex coatings	Hot-dip galvanizing plus painting or powder coating	SN-bolts; water expandable friction bolts	In pre-drilled boreholes
Double corrosion protection (DCP)	Factory-made grouted corrugated sheathing	Rebar bolts	In pre-drilled boreholes
Hybrids of above-mentioned methods	See above	N/A	Defined by the method used

Table 17: Overview of corrosion protection methods.

No corrosion Protection, Blank and Sacrificial Corrosion Protection, Blank

- Common methods in tunneling.
- The material (steel) grade has an influence on the resistance to corrosion.

Sacrificial corrosion Protection, Galvanized

- Corrosion sets in only after the zinc layer is consumed, this delay leads to an increase in service life.
- For bolts and accessories (nuts, couplings, plates), hot-dip galvanizing is the most effective and recommended method. Reference standard: ISO 1461 (average zinc layer thickness for bolts: > 85 [μm]).
- Electrolytic galvanizing or sherardizing: thin layer, limited protection. May be used for accessories only.

Encapsulation by bonding agent, protective layer

- Not recommended as a stand-alone corrosion protection method. The lack of guarantee of full encapsulation, development of cracks over time, and the absence of proper quality control measures do limit the effectiveness of this method.
- The bonding agent must be able to withstand the given corrosion potential.

Note: Both acidic and highly alkaline environments can destroy standard cement-based as well as resin based grout covers.

- Common types: cement stone or resin (bulk or cartridge for both) coverage.

Duplex coatings, protective layer

- Painting or powder coating of a previously hot-dip galvanized element.
- Water expandable friction bolts: the coating must be able to resist the expansion process.
- Self-drilling installation processes can damage this type of protective layer.

Double Corrosion Protection, protective layer (DCP)

- Factory-made grouted corrugated sheathing; cased drilling, installation, and post-injection of the annulus between borehole wall and load-bearing element.

10.3. DURABILITY OF GFRP

GFRP bolts are susceptible to environmental influences such as ultraviolet light, higher temperatures and alkaline or acidic ground water. Strength and stiffness may increase, decrease, or remain the same, depending on the material and exposure conditions. A designer should always consult with the GFRP manufacturer to obtain durability factors, which are related to the raw material used for the matrix:

- A polyester matrix may be used for temporary applications only
- A vinyl ester or epoxy matrix must be used for permanent applications
- A vinyl ester or epoxy matrix is more durable in alkaline environment than a polyester matrix

GFRP bolts show a very low electrical conductivity, featuring protection against electrical stray currents. Stray current corrosion is different from natural corrosion as it is caused by an externally induced electrical current, which could originate from electric railways.

Note: Although GFRP bolts can be made UV resistant, this is typically not done in tunnelling.

Bolts are vital elements in underground construction which, if failing prematurely, put people's lives as well as equipment and potentially the entire structure at risk. Hence it is considered non-negotiable, that quality is of major concern and importance. Therefore, it is necessary to monitor and document all relevant characteristics of each element from purchasing over manufacturing to the installation to prove its final quality. The Quality Management (QM) process ensures that only proper products as per the specifications in the tender documents are installed. Certificates must be made available to prove bolt quality.

It is required that all parameters specified in the tender document are monitored and documented through the entire process of production and installation of the products. The following chapters describe test methods to ensure that these parameters are met and maintained.

Note: Suitability testing is not part of this chapter since it is part of the design process or the design verification process. It can be either based on actual (in-situ) testing or relevant experience.

11.1. PRODUCT TESTING

The verification of characteristics and performance of bolt systems and system components are evaluated and assessed by testing under laboratory conditions. Single components and the interaction of components must be tested.

Note: Testing in general must be performed on finished products as close as possible to the installed state. Testing on primary material or unfinished products delivers misleading results.

Tendon

A recommended standard **tensile test** of steel material is described in ISO 6892. This described procedures can be used to verify the required bolt properties (yield load, modulus of elasticity, elongation) of steel tendons.

Note: Clamping can be accomplished by a certain number of nuts, clamping jaws or a combination of clamping jaws plus plugs (in case of hollow bars).

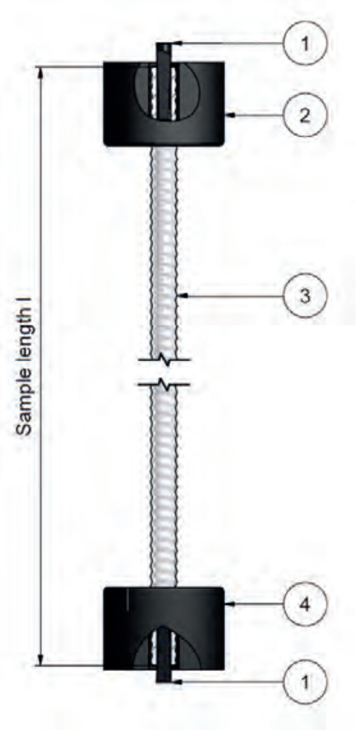


Figure 15. Example of a tensile test assembly for tendons. (1 plugs, 2 clamping top, 3 tendon, 4 clamping bottom).

This testing procedure gives results for the following bolt properties; **yield (proof) load** [kN] ($F_{p0,1}$, $F_{p0,2}$), **modulus of elasticity** [N/mm²], **elongation** at ultimate load [%] (A_{gt}). The characteristic value for these parameters should be defined as 5% fractile value so 95% of test values must be equal or higher than the given value.

Note: For a valid tensile test result the sample must not fail close (2.5 times tendon diameter) to a clamping device.

Note: The modulus of elasticity is nearly constant for common steel products used in tunneling.

Note: Reliable parameters of tendons (slotted tube) of self-drilling friction bolts or friction stabilizer bolts can also be tested with this testing procedure while tendons of water expandable friction bolts should be tested after expansion (activation) to nominal borehole diameter due to the influence of this cold-forming process on the material properties.

The **bond strength** [N/mm²] of a tendon can be determined by a **pull-out test.** A pre-defined length (5 times tendon diameter) of a tendon is covered with a typical bonding agent forming a specimen for the pull-out test. Per EN 10080 the pull-out force at slip values 0.01 mm, 0.1 mm and 1.0 mm is recorded. The mean value and the geometrical parameters are taken for calculation of the bond strength. To determine the characteristic value, a coefficient (0.7) is applied to counter the absence of a statistical number of tests (Figure 19).

Note: Tests for bond strength are not part of the quality assurance but the results are part of tender document specifications.

Note: The rib geometry of tendons regularly corresponds to the rib geometry of reinforcing steel of reinforced concrete construction. In squeezing ground conditions, the deformations occur immediately after installation during hardening of the cementitious bonding agent, so the bonding develops differently. For such situations, a relative rib area of 0.2-0.4 results in an optimized load transfer from the tendon to the grout. (Recommendation: fully mortared rock bolts (SN-bolts); Blümel, M., 1996.

The **cross section** [mm²] of steel tendons is determined by weighing the tendon and a back-calculation by using density of the material.

Note: The cross section is important for tendons subjected to shear or for sacrificial corrosion protection.

Shear tests on bolts are performed to evaluate the behavior of an installed bolt under shear at different load conditions. In DIN 21521-2 an exemplary test setting is recommended. In general, the opening of a shear plane as well as the orientation of a tendon must be considered due to their influence on the test results.

Note: As simplification for design the steel cross section can be taken to calculate the given load capacity. The given load condition is commonly a combination of tension and shear load that must be applied for the static calculations at the same time (equivalent stress condition).

Bolt Head and Coupling

The load capacity of a bolt head as well as a coupling is determined by a tensile test following ISO 6892 and ISO 15630-1 as described above. The test criteria is the ultimate load of the tendon.

Note: In squeezing ground conditions, bolts are usually loaded in the plastic range. Therefore, the test criteria for the bolt head should be changed to the nominal ultimate load of the tendon due to safety reasons during construction.

Mechanical Anchorage

The inner and outer bonding of an expansion shell can be tested in a model test, where a concrete model rock or a rock sample with a drill hole as described in the installation manual of the expansion shell type. The rock or concrete model rock must be chosen to be strong enough to transfer the applied forces during testing. After fixation of a mechanically bonded bolt sample the **anchorage capacity** [kN] can be determined by a pull-out test. The suitability of the anchorage and the specific expansion shell to be used is best determined by physical load testing.

Note: Only the inner capacity (bolt – expansion shell) is part of the quality assurance.

Note: The test is valid in case the failure can be observed in the mechanical anchorage element. If either the model rock or the tendon fails, the test is not valid.

GFRP Testing

The determination of the equivalent **cross section area** is vital and performed by a **volumetric measurement procedure** (CNR DT 203/2006 – Appendix B 6.1).

The ACI 440.3 R-12 - Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures should be use as standard reference for GFRP bolt (both bar and hollow bar constituted) testing. This standard is adapted for GFRP bolts.

Before performing a **tensile test**, the sample must be glued into a steel tube of sufficient length with resin to ensure that the bond strength exceed the tensile load of the specimen. To prevent failure of the hollow bar during tensile testing, the hollow bar in the clamping area must be filled with the same resin as used for bolt matrix prior to testing.

Note: The recommended minimum length in standards is typically shorter than the required one.

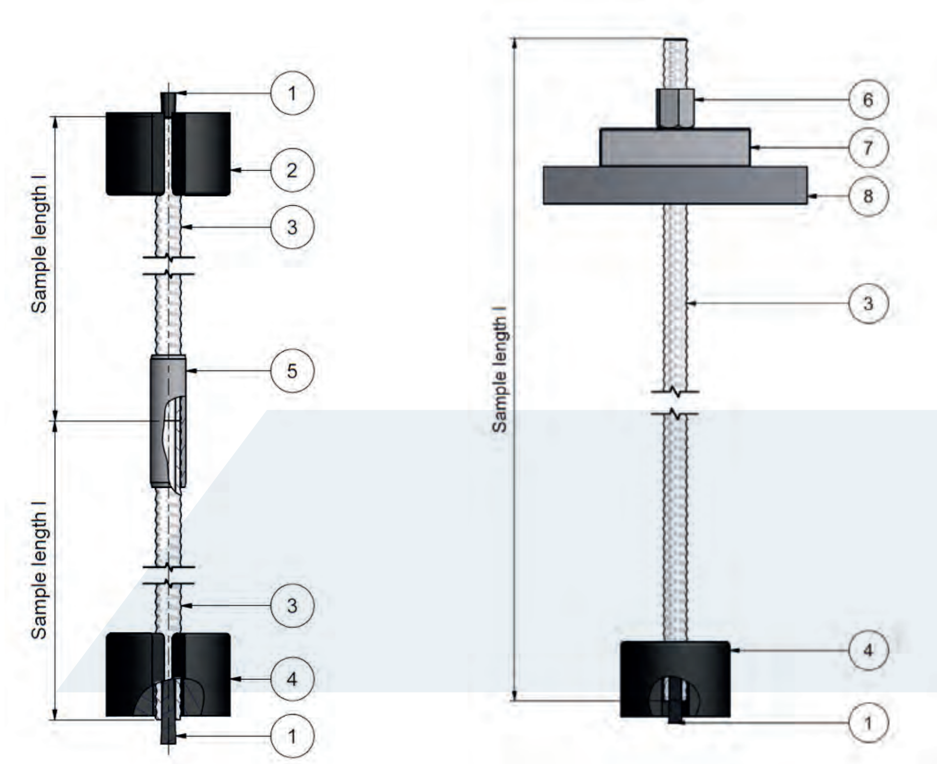


Figure 16. Exemplary functional test assembly for bolt heads and couplings. (1 plugs, 2 clamping top, 3 tendon, 4 clamping bottom, 5 coupling, 6 nut, 7 plate, 8 bearing plate).

Figure 17: GFRP Bolt – exemplary sample failure after tensile test.

When analyzing results of tensile tests, shear lag effects must be considered. The shear lag effect refers to the fact that innermost fibers (located near the bar center) are not subjected to as much stress as outermost fibers (Figure 18). The difference in stress values is greater for large diameter bars and it reduces the rated average strength. Based on the equivalent cross section the result of a tensile test is the **tensile strength** [N/mm²]. Features like couplings and bolt head can be tested similar as described in the section for testing steel products.

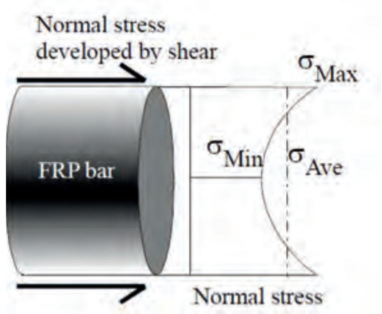


Figure 18. Stress distribution along the cross section due to shear lag effect.

GFRP pull-out tests are carried in laboratory to define the interface between the tendon and bonding agent. Using the same procedure as described to define the bonding strength for steel products the sample is embedded in a bonding agent. By using the result of the GFRP pull-out test including the sample size the **bond strength** [N/mm^2] can be calculated (ACI 440.3 R-12 - equation B.3.8.1).

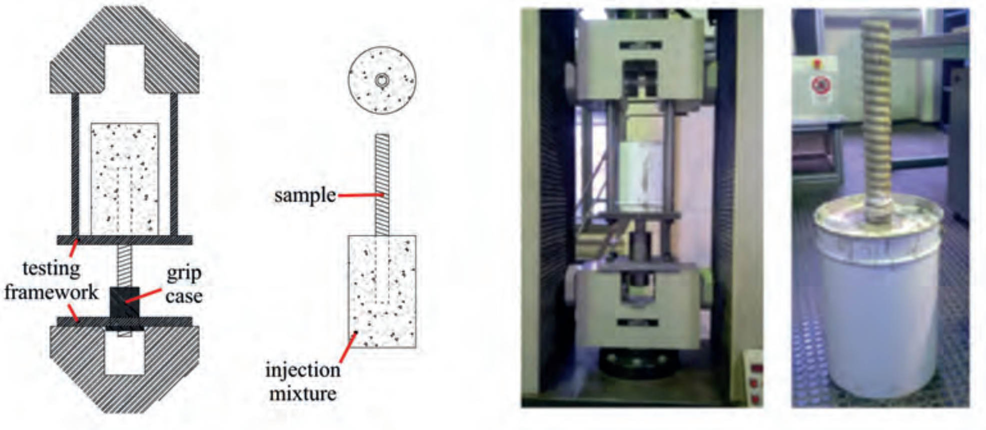


Figure 19. Scheme and pictures of a pull-out test assembly.

Dynamic testing

Dynamic testing of bolts is obtaining increased attention. These are mainly performed in the form of drop test of single impact uniaxial loads onto the bolt or other support elements. This method is obviously a very simplified simulation of ground conditions and seismic loading mechanisms taking place in-situ, but the tests do provide repeatable results for comparisons of different reinforcement elements.

11.2. ISO CERTIFICATION

A certification of the supplier according to ISO 9001 is considered as basis for the quality control of a bolt production.
Certified manufacturers and suppliers have the following advantages certified and approved by external, authorized bodies:

- All processes are defined
  - Manufacturing
  - Quality control (incoming inspection, production control and outgoing inspection)
  - Issue of certifications
  - Failure management (Defects are identified and corrective actions are set.)
- Internal and external monitoring to ensure the efficiency of all processes
- Products have a specification

Non-certified manufacturers and suppliers do not have standardized control and certification of their processes in place. Disadvantages may be:

- No traceability of processes
- No certified quality assurance
- No traceability of products

Consequently, there is a given uncertainty of non-correct certificates due to missing supervision and documentation

Note: Due to these differences, it is recommended to only allow certified manufacturers and suppliers to quote.

ISO certification: The ISO certificate provides proof that the supplier is certified and identifies which processes were subject to the ISO certification. Example: production, development and sales of bolts.

11.3. TEST REPORTS AND INSPECTION DOCUMENTS

Test reports and inspection documents assure quality and characteristics of system components or bolt systems. These documents may either refer to the suitability of components or bolt systems or to the compliance to the requirements of the production process and/ or product properties. Inspection documents shall verify the product specifications and that the products are in accordance with the specification stated in the order. The number and type of documents requested should be specified in the contract and order respectively. Different levels of inspection documents are available according to ISO 10474:2013 or EN 10204:2005:

- **2.1: Declaration of compliance with the order:**
  Manufacturer's declaration of compliance with the order without test results
- **2.2: Test report:**
  Manufacturer's declaration of compliance with the order with test results based on non-specific inspection
- **3.1: Inspection certificate 3.1:**
  Manufacturer's declaration of compliance with the order with test results based on specific inspection.

The document shall be validated by the manufacturer's authorized inspection representative, independent of the manufacturing department.

- **3.2: Inspection certificate 3.2**
  Manufacturer's declaration of compliance with the order with test results based on specific inspection.

The document shall be validated by both the manufacturer's authorized inspection representative and the purchaser's authorized representative or by an inspector designated by a third party.

Note: A supplier or re-seller cannot issue any documents based on ISO 10474:2013 or EN 10204:2005, only a manufacturer can.

Note: Special requirements for corrosion protection must be stated in the contract and adequate documentation as proof that these protection measures were applied.

Approvals

Construction products, such as support elements, must comply with national and local standards and regulations. A European methodology to proof the compliance with standards are technical assessments / approvals.

- **National Technical Approval (NTA):** confirms compliance with national regulations and standards valid in the country the approval was issued in.
- **European Technical Assessment (ETA):** Confirms compliance with applicable European standards.

Note: The supplier is responsible to meet the requirements for the system according to the technical approval.

Note: Technical approvals are not available for all support elements. Technical approvals are not available in all countries.

Other documentation:

- **Declaration of performance (DoP)** provides information on the performance of a product.
- The **CE marking** indicates that a construction product in its entirety is in conformity with its declared performance and that it has been assessed according to a harmonized European standard or an ETA has been issued for it.

Note: If any component or the primary material (a tube or a rebar for example) have a CE marking, this does not imply that the entire system features a CE marking. Example: CE marked tubes do not imply a CE marking of hollow bars.

Note: Some suppliers offer a CE certification referring to the Machinery Directive – 2006/42/EC or others. This type of CE certification cannot be applied for construction products.

- **Test reports:** As per individual agreement between customer and supplier.

11.4. QUALITY CONTROL DURING INSTALLATION

To ensure that the ground support systems work as designed it is important, as for every production process, to monitor and control key parameters affecting performance of a bolt in the installed state. In the following the key parameters are listed for individual types of bolts and information is provided on effects if these parameters do not meet values recommended by the suppliers.

The parameters listed below have an important influence on the quality and performance of installed bolts. In Table 18, an overview of these parameters is compiled, and it is marked, which of these parameters shall be monitored and logged, respectively. In any case, it is recommended that the results are evaluated.

		MECHANICALLY ANCHORED	BONDED BY BONDING AGENT			FRICTION BASED		COMBINED SYSTEMS; MECHANICALLY ANCHORED AND GROUTED	GFRP BAR	GFRP HOLLOW BAR
		EXPANSION SHELL TYPE	CEMENTICIOUS GROUTED (SN TYPE)	RESIN GROUTED (SN TYPE)	SELF-DRILLING HOLLOW BAR	WATER EXPANDABLE FRICTION BOLT	SELF-DRILLING FRICTION BOLT			
Regardless of bonding agent	Borehole diameter	M	M[1]	M[1]	M	M	M	M	M[1]	M[1]
	Torque (expansion/pre-tensioned)	M/L						M/L		
	Water pressure					L				
Resin	Type of resin			M	M			M	M	M
	Number of cartridges			M[1]					M[1]	
	Volume injected (bulk)			L	L			L	L	L
Mortar	Type of mortar		M		M			M	M	M
	Number of cartridges		M[1]						M[1]	
	Volume injected		L		L			L	L	L
	W/C ratio		L		L			L	L	L

Table 18. Overview of recommendations for monitoring.

L (Logging) ...Recording and documentation of every single bolt

M (Monitoring) … Regular checks of defined and relevant parameters to be reported
1 ... for use of cartridges only

Note: Deformable and/or energy absorbing: monitoring and/or logging based on recommendations of the manufacturer.

Note: The borehole diameter is an important parameter for most bolt types but commonly the (sacrificial) drill bit diameter is measured as an indication for the actual borehole diameter.

Mechanically anchored

To ensure that an expansion shell can transmit the design load into the ground the following parameters are relevant:
- Borehole diameter
- Torque applied to expand the shell and pre-tension the tendon respectively

Note: A hole exceeding the specified diameter or a torque lower than a value stated in the design or recommended by the supplier can reduce the capacity of the bolt significantly.

Friction bolts

New drill bits typically exceed their nominal diameter. In combination with the eccentricity of the drill string the borehole diameter may exceed the intended diameter. Friction bolts are very sensitive on the shape (diameter, roundness) of the borehole diameter.

For friction bolts the following parameter is relevant:
- Borehole diameter

Note: Boreholes exceeding the diameter specified by the supplier can significantly reduce the capacity of the bolt.

Water expandable friction bolts

New drill bits typically exceed their nominal diameter. In combination with the eccentricity of the drill string the borehole diameter may exceed the intended diameter.

For water expandable friction bolts the following parameters are relevant:
- Borehole diameter
- Expansion pressure

Note: Boreholes exceeding the diameter specified by the supplier and expansion pressures lower than those recommended by the supplier can significantly reduce the load capacity of the bolt.

Fully grouted bolts - resin

The following parameters are relevant when using cartridges:
- Borehole diameter
- Type of cartridges
- Curing time
- Number of cartridges inserted per hole
- Duration and speed of spinning of the bolt
- Ambient temperature

The following parameters are relevant when using bulk resin:
- Volume injected
- Injection pressure
- Type of resin
- Ambient temperature
- Presence of water

If the nut is tightened monitor the torque.

Note: The amount of resin inserted or injected is supposed to grout the bolt over its entire length to ensure proper bond and corrosion protection. If the amount of resin inserted or injected in the borehole is insufficient, either by the volume of the resin or due to a hole diameter exceeding the specification, the load capacity or durability might be affected.

Note: Improper spinning of the bolt in boreholes equipped with resin cartridges might lead to insufficient mixing and limited curing of the resin which will result in reduced load capacity of the resin and hence the bolt.

Fully Grouted bolts – cementitious

The following parameters are relevant for cartridges:
- Borehole diameter
- Number of cartridges inserted
- Type of cartridges inserted

The following parameters are relevant for bulk:
- Volume injected
- Pressure applied
- Water cement ratio
- Type of cement

If the nut is tightened monitor the torque.

Note: Same as for the resin a proper mixture and correct water/cement ration is fundamental to develop the required load capacity of the cement. The volume of cement inserted/injected into the borehole must ensure complete encapsulation of the bolt.

Testing of grout (cement based or resin based)

Grout shall be sampled and tested in accordance with the requirements set out in EN 196-1 to ensure compliance with the characteristic strengths and other properties specified in the design.

11.5. TESTING AFTER INSTALLATION

There are different options to test an installed bolt to prove its capacity in the given environment:

Destructive testing (sacrificial bolts only)

Bolts can be pull-tested until failure of the bolt or pull-out of the hole.

Verification testing

Non-destructive testing (production bolts).

Bolts should be pull tested to a defined proof load, according to local quality assurance requirements. Typically, the proof load is defined by the designer.
Proof loads must not exceed 90% of the specified nominal yield load (at 0.2% plastic deformation) and 80% of the nominal ultimate load.

If a production bolt (as opposed to a sacrificial bolt) is tested specific caution should be applied not to destroy the bond and any corrosion protection.

Note: For verification testing, it is recommended to test at least 3% of bolts installed. The suggestion is to carry out three for each kind of reinforcing system, carried out 24 hours after grouting.

Note: A GFRP bolt must be equipped with a steel bolt head for testing so each test bolt must be identified prior to installation.

Pull test procedure

It is important that during the pull test the load is applied in the bolt axis. Typically, the load is incrementally increased from a datum load to the proof load. The datum load is established to overcome the slack in the system and should not exceed 10% of the proof load.

Data obtained should be agreed beforehand with the designer and may include:
- Failure load
- Maximum load achieved
- Bolt head movement versus applied load
- Bolt head displacement versus time
- Loss of load at the bolt head over time
- Displacement of the bolt head under maintained load

Details for testing rock and soil nails are described in EN 1997, EN 14490, EN 1537 and EN ISO 22477. Local standards or specific requirements for the site or application as well as hazard classes need to be considered and define the number of tests to be done. All above mentioned methods can be applied for GFRP as well, considering the different material properties.

The need for long term monitoring needs to be assessed on the geotechnical category of the structure. Functionality of the drainage system, change of the ground water level, chemistry and hydrogeology, ground movements as well as degradation due to corrosion.

The most important job site controls are:
- The quality of grouting is tested to ensure that it complies with design specifications, with regard above all to how rapidly it sets.
- Checking the quantity of mixture grouted for each element inserted.
- Pull-out tests to check element-mortar-ground adherence and relative anchoring capacity.

Nowadays innovation and new solutions are always required in the tunneling industry to increase the level of safety and the production rate or to solve relevant unexpected problems and finally to decrease the construction cost by the application of a more effective solution.

The flow chart showed in the Figure 20 suggests a simple guidance about a way to follow for the development and the application of a new solution. The implementation of an innovative solution should follow the process described below.

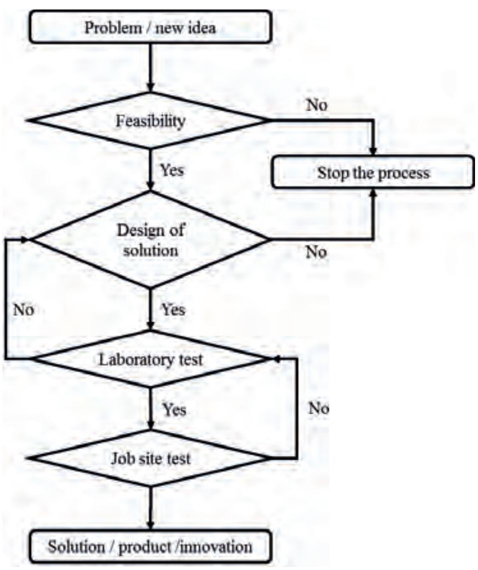


Figure 20. Innovation Flow Chart.

The suggested process shall be performed in compliance with the standard or following the Design-Assisted-by-Test procedure described in EN 1990, which is worldwide the only code describing such a process and can be taken as template.

During the last two decades, new materials and products have been developed. Methods of the Design-Assisted-by-Testing can be used as a suitable tool for determination of material properties and performance of structural members or components.

12.1. APPLICATION OF INNOVATIVE SOLUTIONS UNDER THE GUIDANCE OF EUROCODE

The Eurocode system permits a design based on a combination of tests and calculation for building and civil engineering works (EN 1990 - 5.2(1)). This Clause is an introduction to Annex D to EN 1990, which gives guidance on the planning and evaluation of tests to be carried out in connection with structural design, where the number of tests is sufficient for a meaningful statistical interpretation of their results.

Design-Assisted-by-testing is a procedure using physical testing (e.g. models, prototypes or in situ) for establishing design values. Such procedures can be used for those cases where the calculation rules or material properties given in the design Eurocodes are considered insufficient, or where a more economical design may result.

An essential requirement for using design assisted by testing is given in clause 5.2 (2)P. Tests should be set up and evaluated in such a way that the structure has the same level of reliability, with respect to all possible limit states and design situations, as would be achieved by design using the design Eurocodes. Hence, all uncertainties, such as those due to the conversion of experimental results and those arising from the statistical uncertainty associated with the design assisted by testing (e.g. the application of experimental results, and any statistical uncertainties due to the sample size) should be considered. Furthermore, the conditions during testing should so far as possible be representative of those which can be expected to arise in practice.

Moreover, partial factors comparable to those used in the design Eurocodes should be used (clause 5.2(3)): thus, EN 1990 clearly stipulates that design assisted by testing is not a possibility given to designers to reduce strongly partial factors.

Technical specifications include the required information for submitting a corresponding offer for the described task that the owner can choose among them. The style of tender documents differs from region to region, but all tender documents should describe the task as precisely as possible.

Among other essential information about the project, quantities and technical specifications for bolts are vital.

The goal for the definition of bolts in tender documents are distinct descriptions and definitions to determine a product and its way of installation for each tunnel section. After choosing the proper bolt system its minimum parameters for specification are noted in chapter 7. All necessary parts of a bolt system must be specified. In the same section, typical installation processes are described as well, which are very often part of a descriptive technical specification or stated on design drawings.

Note: A well-defined product only needs a brief technical specification. Too many parameters may be inconsistent with one another.

13.1. EXAMPLES

Discrete mechanically anchored: Expansion shell type

Solid bar mechanical steel bolt with expansion shell, installed into pre-drilled boreholes ø 45-55 [mm] and pre-tensioned.

Length: L = 3 [m]
Yield load: $F_{p0.2} \geq 240$ [kN]
Cross-section: ≥ 490 [mm²]
Elongation: $A_{gt} \geq 5\%$

Bolt head:
Domed steel nut
Flat steel plate 100x100x10 [mm], steel grade S235

Continuously bonded: Self-drilling hollow bar

Hollow bar steel bolts ø 32 [mm] with drill bit ø 51 [mm] and couplings, installed self-drilling (coupled), bolt head tensioned
Length: L = 6 [m]
Yield load: $F_{p0.2} \geq 330$ [kN]
Cross-section: ≥ 550 [mm²]
Elongation: $A_{gt} \geq 5\%$

Bolt head:
Hexagonal steel nut
Domed plate 200x200x12 [mm], steel grade S355

Bonding agent:
cement based, UCS (28 days) ≥ 25 [N/mm²]

Continuous frictionally engaged: Self-drilling friction bolt

Self-drilling friction bolt, un-tensioned

Length: L = 3 [m]
Yield load: $F_{p0.2} \geq 300$ [kN]
Cross-section: 600 [mm²]
Elongation: $A_5 \geq 5\%$

Bolt head:
Flat plate 150x150x12 [mm], steel grade S235.

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Blümel, M., 1996, Performance of Grouted Bolts in Squeezing Rock, Prediction and Performance in Rock Mechanics and Rock Engineering, Proceedings EUROCK ´96, Vol. 2 (1996), S. 885 – 891

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DIN EN ISO 14688-1:2013-12 Geotechnical investigation and testing - Identification and classification of soil - Part 1: Identification and description (ISO 14688-1:2002 + Amd 1:2013)

DIN EN ISO 14688-2:2011-06 Geotechnical investigation and testing - Identification and classification of soil - Part 2: Principles for a classification (ISO 14688-2:2004)

EN 447: Grout for prestressing tendons - Basic requirements

EN 1537: Execution of special geotechnical works - Ground anchors

EN 1990: Eurocode: Basis of structural design

EN 1997: Eurocode 7: Geotechnical design - Part 1: General rules

EN 10080: Steel for the reinforcement of concrete - Weldable reinforcing steel - General

EN 10204:2005-01 Metallic products - Types of inspection documents

EN 12501-1:2003 Protection of metallic materials against corrosion - Corrosion likelihood in soil - Part 1: General

EN 12501-2:2003 Protection of metallic materials against corrosion - Corrosion likelihood in soil - Part 2: Low alloyed and non alloyed ferrous materials

EN 14490: Execution of special geotechnical works - Soil nailing

EN ISO 6892-1: 2009 Metallic materials - Tensile testing - Part 1: Method of test at room temperature (ISO 6892-1:2009)

EN ISO 22477: Geotechnical investigation and testing - Testing of geotechnical structures - Part 1: Pile load test by static axially loaded compression (ISO/DIS 22477-1:2005)

ISO 1461:2009 Hot dip galvanized coatings on fabricated iron and steel articles - Specifications and test methods

ISO 9001:2015 Quality management systems — Requirements

ISO 10474:2013 Steel and steel products -- Inspection documents

Machinery Directive - 2006/42/EC, 17 May 2006, European Parliament and Council of European Community, Official Journal of the European Union, L 157/24-86, 9.6.2006

Recommendation – Fully mortared rock bolts (SN-Anchors) – Special Rib Geometry and requirements for the mortar; Schubert, W. (Ed.) Institute of Rock Mechanics and Tunnelling; Graz, Austria, 1997-07

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