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1. Introduction

Fastenings must be understood as a system consisting of the base material, the component to be fastened and the fastener itself. When selecting the material from which the fasteners are to be made, not only mechanical requirements must be met – the atmosphere to which the fasteners will be exposed also has to be taken into account. Only materials offering high resistance to corrosion can be considered for use where safety-relevant fastenings are to be installed in the aggressive environments found in locations such as road tunnels. Fasteners with high corrosion resistance are available today and can be adapted to suit the needs of the relevant application. When service life and safety aspects are taken into account, the higher cost of these highly corrosion-resistant materials makes good economic sense.

Since the 1980s, Hilti has conducted tests by subjecting fasteners to long-term exposure to the conditions prevalent in tunnels and already, at an early stage, published information about problems concerning the instability of many steel grades otherwise considered to be resistant to corrosion. Only connectors and fasteners made from steels containing at least 6% molybdenum, e.g. material number 1.4529, can be regarded as stable for use in road tunnels (private and heavy goods vehicle traffic, de-icing salt used winter), while all other ferrous alloys tested have been found to suffer pitting corrosion, at least in the tunnels under observation.

This means that the sudden, unexpected failure of individual fasteners due to stress corrosion cracking cannot be ruled out, especially fasteners made from the commonly used A4 stainless steel (CrNiMo steel).

This publication introduces the reader to a number of considerations that will help planning specialists to reach a qualified judgement regarding the situations in which this risk can be adequately compensated by other measures, and situations where only alloys that offer long-term stability may be used.

This brochure, following sound engineering principles, proposes a structured process for the selection of optimum materials grades for use in fastening systems, thus helping to counter the degree of uncertainty apparent in the field. This brochure has the objective of providing facts that actively assist engineers with the decisions they are required to make. It cannot, however, make the decisions for them.
2. General information about materials, applications and the use of products in corrosive environments

2.1 The reasons for carrying out field tests

A fastener’s main task is to provide a secure means of attaching a component to a base material, ensuring that the forces involved are taken up by the base material. This task must be fulfilled over a period of many years and decades, irrespective of external influences such as weathering, aging and/or corrosion.

Accordingly, the process of selecting fasteners and designing the configuration in which they are to be used must not only take mechanical parameters into account, it must, above all, give careful consideration to factors such as long-term behavior under fluctuating temperatures and resistance to corrosive atmospheres.

Especially in surroundings where highly corrosive media are present, fasteners are required to meet extremely demanding requirements. Failure caused above all by unpredictable corrosive processes may not only lead to considerable material damage to the structure or property, it may also present a risk of fatal injury. Tragic accidents and costly, time-consuming repairs or reconstruction have not only startled professionals in the construction business, they have also brought the problems of corrosion to the attention of the general public.

As a specialist in fastening technology for the construction industry, Hilti took up this challenge many years ago, carrying out comprehensive laboratory and field tests for the purpose of researching the effects of pollutants and aggressive substances on the corrosion resistance of fasteners. Long-term field tests are still continuing today in coastal and country atmospheres as well as in road and rail tunnels.

The objective of these tests is to identify, record and understand specific pollutants or aggressive environments and the effects they have on metals. Durable materials can be determined on the basis of these results, and corrosion-resistant fastening systems developed accordingly.

Standardized short-term tests such as the salt spray test¹, the alternating humidity test² or the Kesternich test³ are suitable, among other things, for monitoring the quality of the manufacturing process. Tests of basic principles, such as electrochemical tests carried out in the laboratory, can usually only be used to clarify general questions concerning corrosive mechanisms. Although such test are indispensible, they allow only very limited or conditional predictions to be made about the behavior of components in the environment encountered in practice. Field tests and weathering tests are thus still essential and indispensible and provide very good, reliable information about the behavior of the components concerned.

¹ ISO 9227
² EN ISO 6270-2
³ DIN 50018, EN ISO 6988
2.2 Corrosion and the risks it presents

Corrosion is the term applied to the destruction of a material (metal, wood, plastics, etc.) by a chemical or electrochemical reaction between a material and its environment, through which the function of the component manufactured from this material is impaired.

Corrosion is often a very complex process or series of processes. During these processes, some of the metal is dissolved or eaten away from the object concerned. As most corrosive processes are electrochemical, corrosion is possible only in the presence of an electrolyte (e.g. water). These processes, which often go unnoticed, are especially critical when the electrolytes contain aggressive substances such as chlorides, acids or a combination of these as found, for example, in the condensates on the walls of tunnels, particularly because damage to components here is often very local, in many cases not discernable by the naked eye and, accordingly, is all the more unpredictable. Typical forms of damage to be found in these locations are, for example, pitting corrosion and stress corrosion cracking, which are capable of causing a component to fail or no longer function as intended.

Steels resistant to stress corrosion cracking, as well as being of significance in the chemical and petrochemical industries, thus also have an important role to play in fastening applications in road tunnels and in the atmospheres found in the buildings housing indoor swimming pools. Alloys such as Cr steels, CrNi steels with inadequate corrosion resistance, and CrNiMo steels are still being used frequently, but erroneously, for applications in these types of atmospheres.

The Congress Hall (“Schwangere Auster”) in Berlin partially collapsed on May 21, 1980, due to stress corrosion cracking in the carbon steel cables in pre-stressed concrete sections. On May 9, 1985, the suspended ceiling over an indoor swimming pool in Uster, Switzerland, collapsed as a result of stress corrosion cracking in an incident that cost 9 lives. The ceiling was suspended from anchors made from austenitic CrNi stainless steel of the A2 class (AISI 304).

2.3 Stainless steels – their properties, how they function and how they corrode

“Stainless steel” is a generic term covering a multitude of alloys that differ according to their chemical composition and their resulting microstructure. In terms of their microstructure, we differentiate between ferritic, martensitic and austenitic steels as well as austenitic ferritic steels. Differences in microstructure have a great influence on corrosion resistance, mechanical-technological properties and on how a steel can be worked and machined.

Austenitic steels are particularly resistant to chemical attack. This is mainly due to their high chromium content of at least approx. 12%. They differ from each other first and foremost in terms of their nickel content and also in the amount of molybdenum they contain.

- Chromium is primarily responsible for the formation of a thin, dense passive layer.
- Where chloride ions are present, for example, this passivation can be destroyed locally and pitting may then occur.
- Re-passivation of initial pitting is the main factor that determines resistance to pitting corrosion

Fig. 1: Pitting corrosion on a fastener made from 1.4301 (A2) steel
Molybdenum cannot hinder initiation of pitting corrosion. A higher molybdenum content does, however, improve the steel’s re-passivation behavior.

Nitrogen (in a dissolved state) has a positive effect on resistance to pitting corrosion.

On the basis of a steel’s chemical composition, it is possible to express its resistance to chloride-induced pitting corrosion in the form of a number (rating). A stainless steel’s resistance to pitting corrosion is determined to a great extent by the chromium and molybdenum content of the alloy.

These two elements do not have the same effect but can, due to their “pitting resistance equivalent” and taking nitrogen into account, improve corrosion resistance in terms of resistance to chloride-induced pitting corrosion. The so-called pitting resistance equivalent (PRE) can be calculated using the classic formula which is in most widespread use:

\[
\text{PRE} = \%\text{Cr} + 3.3 \times \%\text{Mo} \\
\text{PRE} = \%\text{Cr} + 3.3 \times \%\text{Mo} + 30 \times \%\text{N}
\]

(for stainless steels with molybdenum content of < 3%)

The higher the pitting resistance equivalent, the higher the resistance to pitting corrosion. Alloys with a PRE of > 33, for example, are considered to be resistant to sea water. Austenitic CrNiMo steels with a PRE of > 46 remain stable in a road tunnel atmosphere and can thus be used for safety-relevant fastening applications. Hilti HCR (WN 1.4529) material is an example of an alloy that remains stable in road tunnel atmospheres.

Pitting corrosion, however, is a temperature-dependent process and, accordingly, a so-called critical pitting corrosion temperature (CPT) is frequently given in literature. An empirical equation has been developed for steels that have been subjected to a 3.5% salt solution:

\[
\text{Critical pitting corrosion temperature (CPT), } (^{\circ}\text{C}) = 10 + 7 \times (\%\text{Mo})
\]

The importance of the molybdenum content, in terms of its ability to increase the corrosion resistance of a steel subject to media containing chloride, and thus also in road tunnels, is emphasized by this. It is also confirmed in principle by the long-term road tunnel field tests carried out by Hilti. Accordingly, for use in a road tunnel atmosphere in which de-icing salt is present, an austenitic alloyed steel with a molybdenum content of at least 6%, or preferably 7%, is required in order to ensure absolute corrosion resistance. A higher molybdenum content not only increases resistance to pitting corrosion, it also indirectly reduces the risk of stress corrosion cracking.

### 2.3.1 Resistant materials

A suitable stainless steel for a certain application can be selected only when the characteristics of the various alloys are known. When the question of corrosion resistance is considered, special attention must be paid to the conditions under which the material is to be used. Its corrosion resistance, however, can be adversely affected by the design of the components manufactured from it and the influences of material processing (e.g. machining).

For assessment of the probability of corrosion of stainless steels in road tunnel atmospheres, in addition to state of the art information and choice of suitable materials, at-
tention should also be paid to construction supervisory authority approval Z.30.3-6 dated April 2009, which is applicable in Germany, and to any other existing national guidelines or regulations and the references and terms they contain.

Hilti has allowed the results of tests and experience gained to flow into the development of its fastening products. On the basis of experience gained under conditions very close to those met in practice, Hilti recommends products made from the austenitic 1.4529 material for applications in environments where exposure to chlorides is to be expected. Frequently used austenitic materials such as 1.4401, 1.4404, 1.4571 or, in particular, 1.4301, 1.4541 are, in many cases, definitely not fully corrosion-resistant and may be subject to stress corrosion cracking.

What is stress corrosion cracking?
Stress corrosion cracking is generally initiated by a pitting corrosion pore. The cracking results in very little deformation. Certain material groups such as copper-zinc alloys (brass), some wrought aluminium alloys, maraging steels (e.g. chromium steels and carbon steels) as well as many corrosion and acid-resistant steels can be considered to be susceptible to stress corrosion cracking. A difference is generally drawn between hydrogen-induced stress corrosion cracking and the anodic form, chloride-induced stress corrosion cracking, which can occur with austenitic stainless steels. In order for stress corrosion cracking to occur, three conditions must be fulfilled:

1. The material must be sensitive to stress corrosion cracking (influences: material composition, crystalline structure, heat treatment, surface finish, etc.);
2. Tensile stress must be present (inherent tension may be sufficient to cause it);
3. A specific corrosive agent or influence must be present (specific medium, chloride, temperature).

Where stress corrosion cracking occurs, depending on the type of steel and the corrosive agent involved, no visible products of corrosion, e.g. red rust, are generally formed. This makes this type of failure all the more dangerous. The main specific corrosive agent in the case of corrosion and acid-resistant austenitic steels is primarily chloride (from sea water and de-icing road salt, etc.). This corrosive agent has an effect even when present in very low concentrations, measured in some cases in parts per million, and also depends on the ambient temperature and the pH value. A combination of various chemical substances, mainly stemming from motor exhaust emissions but also from rubber abrasion and a variety of other types of dust which, in combination with chlorides, can have an extremely corrosive effect. The resulting precipitation and condensation due to temperature fluctuation (moisture film) can have very low pH values (sulfide, sulfate etc.) and a high salt content. These corrosive substances can become concentrated through alternating conditions where drying out is followed by further new condensation. The resulting electrolytes then form a very aggressive, corrosive medium. Crack initiation time and the speed of crack propagation depends on the material used, the level of tensile stress present, the concentration of the corrosive agent, ambient temperatures, and the degree to which the material has been strain hardened. Inherent tensile stress in the material can be sufficient to trigger the process. The time taken until a component cracks all the way through, and thus fails without warning, can be anything between several hours and many years and cannot be calculated. Failure of the component is sudden and without warning of any kind. Accordingly, as a rule, stable materials such as Hilti HCR should be used in these environments.
Can stress corrosion cracking be avoided?
In order to avoid stress corrosion cracking, at least one of the conditions mentioned above must be ruled out. Either the corrosive agent must be kept away from the object concerned, tensile stress must be avoided or a material not sensitive to stress corrosion cracking must be selected.

Keeping the corrosive agent away from the object concerned is, in most cases, virtually impossible. At the indoor swimming pool in Uster, where the tragic accident happened, it would have been hardly possible to avoid exposure to a low level of chloride in the atmosphere. Tensile stress also generally cannot be avoided. The only alternative, in most cases, is thus to choose a material that is not sensitive to stress corrosion cracking in the type of atmosphere concerned.

Corrosion resistance within a materials group (A4)
Within the A2 and A4 steel groups there are many types which, depending on the group, basically possess virtually the same corrosion resistance. However, there are differences between these steels with regard, for example, to their suitability for welding or polishing. Taking CrNiMo (A4) steel as an example, this is made clear below.

Chromium-nickel–molybdenum steels of the A4 group are generally characterized by a chromium content of 17%, a nickel content of 12% and a molybdenum content of 2%. The chromium content forms the basis for the steel’s resistance to corrosion. The molybdenum improves the steel’s re-passivation characteristics when exposed to corrosive attack.

The materials 1.4401 (X5 CrNiMo 17-12-2), 1.4404 (X2 CrNiMo 17-12-2) and 1.4571 (X6 CrNiMoTi 17-12-2), regarding their corrosion resistance, are members of the A4 and A5 steels groups. The differences between each of the materials are listed in the table below:

<table>
<thead>
<tr>
<th>Material</th>
<th>Chromium/nickel/molybdenum content</th>
<th>Carbon content [%]</th>
<th>Titanium content [%]</th>
<th>Special characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4401</td>
<td>16.5–18.5/10.0–13.0/2.0–2.5</td>
<td>≤ 0,07</td>
<td>–</td>
<td>Can be welded up to 6 mm without subsequent heat treatment, otherwise risk of intercrystalline corrosion</td>
</tr>
<tr>
<td>1.4404</td>
<td>16.5–18.5/10.0–13.0/2.0–2.5</td>
<td>≤ 0,030</td>
<td>–</td>
<td>Can be welded due to reduced carbon content</td>
</tr>
<tr>
<td>1.4571</td>
<td>16.5–18.5/10.5–13.5/2.0–2.5</td>
<td>≤ 0,08 5 x %</td>
<td>C ≤ 0,70</td>
<td>Can be welded due to titanium stabilization, cannot be polished due to hard titanium carbide</td>
</tr>
</tbody>
</table>

Use of 1.4571 material for welded parts has historical reasons. Up to the 1960s, stainless steels were stabilized with the addition of titanium, with a view to making them resistant to intercrystalline corrosion. Intercrystalline corrosion occurs when, during unfavorable or incorrect heat treatment (including welding), chromium carbide is formed, which has the effect of reducing the chromium content locally. Today, we are able to manufacture low-carbon steels. With these low-carbon steels (e.g. 1.4404), the formation of chromium carbide as a consequence of heat treatment, and thus intercrystalline corrosion, can be virtually ruled out.
The differences described above concerning the composition of the materials and their suitability for welding while retaining virtually the same degree of corrosion resistance, have the following consequences for fastening and connecting parts:

• Due to their virtually equal corrosion resistance, 1.4401, 1.4404 and 1.4571 materials can be used for connecting parts (taking for granted that CrNiMo steels are generally suitable for the application);
• Welding is not permissible on connecting parts. Accordingly, 1.4401 material may also be used to manufacture connecting parts.

**Bimetallic corrosion where different stainless steels are combined**
When stainless steels of different groups (e.g. A2 and A4) are used together, no bimetallic corrosion (contact corrosion) can occur as the corrosion (electrical) potential of the materials is almost equal. Care has to be taken only to ensure that the material with the lower resistance to corrosion still offers adequate corrosion resistance for the corresponding application.
3. Corrosivity in road tunnel atmospheres

From 15 years of field tests carried out in various road tunnels in Switzerland and France in cooperation with the Swiss Federal Institute of Technology (ETH) Zurich, Hilti has gained comprehensive knowledge of the relevant factors influencing corrosive mechanisms.

The most important influencing factors in road tunnel atmospheres are:

**Temperature / moisture**
- Air humidity and temperature fluctuations
- The maximum ambient temperature
- Seasonal fluctuations
- Rapid temperature changes / conditions favoring condensation
- etc.

**Dust and other deposits on components**
- The chemical composition of these deposits
- Salts (sulfates, chlorides, nitrates, etc.)
- Soot
- etc.

**Air pollution**
- Motor vehicles (especially sulfur dioxide, but also nitrogen oxides)
- Industrial emissions
- etc.

The chemical composition of the moisture film (condensate, seepage water) and its characteristics can be determined from these parameters:
- Chlorides (de-icing salt, coastal proximity, etc.)
- pH-value of the moisture film
- Speed of carbonation and salination of the concrete
- Other contaminants

As an example, fig. 2 shows the maximum detected depth of pitting on various austenitic stainless steels with a molybdenum content of < 5% after exposure for about 15 years in various road tunnels in Switzerland:

![Fig. 2: Maximum depth of pitting in CrNi, CrNiMo steels (molybdenum content ≤ 5%) with exposure of up to 15 years in various road tunnels](image)
CrNiMo steels with 45% molybdenum content (1.4439, 1.4539, 1.4565) also showed signs of pitting corrosion after a few months or years of exposure. Although the speed of corrosion of these materials was considerably slower than with the steels containing less or no molybdenum (1.4301, 1.4305, 1.4401, 1.4571, 1.4429), they did not indicate long-term corrosion resistance characteristics. Steel of the 1.4565 grade, for example, sometimes considered to be fully corrosion-resistant, showed signs of pitting corrosion after 15 years in the north section of the Gotthard Tunnel, whereas samples placed in the Seelisberg Tunnel and in the Gotthard middle section still showed no signs of corrosion after 15 years. Consideration must thus be given to the fact that the corrosive impact of the ambient conditions can vary considerably within the same tunnel. Strictly speaking, the specific results of tests are applicable only to a small area of each test location. The occurrence of corrosion at a certain location is, however, a strong indication that a certain steel will not remain absolutely stable in the long term.

As an example, fig. 3 shows the maximum detected depth of pitting on austenitic ferritic steel of the 1.4462 grade and on a few corrosion-resistant austenitic steels with a high molybdenum content as well as some nickel-based alloys:

![Fig. 3: Maximum depth of pitting on austenitic ferritic steels, steels with a high molybdenum content and the nickel-based alloys Hastelloy C4 and Inconel 625, exposed in various road tunnels for up to 15 years.](image)

The austenitic ferritic steel of the 1.4462 grade (3% molybdenum) showed signs of shallow pitting after long-term exposure in the Belchen, Gotthard North and Milchbuck tunnels. The duplex material (1.4507), with which exposure tests were carried out only in the Seelisberg Tunnel, showed signs of pitting corrosion after 15 years. The steels with a high molybdenum content (1.4529, Avesta 254 SMO, Avesta 654 SMO) showed no signs whatsoever of corrosive attack.

Figs. 2 and 3 show only a small extract from the results of the corrosion tests for each material.
4. Recommendations for fastening in road tunnels

4.1 The safety relevance of typical fastening situations in tunnels

According to the current level of knowledge, only very highly alloyed steels with a molybdenum content of over 6% remain stable in road tunnels.

As many of the fastenings in a tunnel tend to be of less significance or, respectively, safety is increased through the redundancy principle of multiple fastenings, the question of more economical alternatives is justified in such cases. A planner can thus, where necessary, achieve cost savings by making use of less highly alloyed steels after deciding on an acceptable level of risk and by taking into account the corrosive impact of the conditions prevailing in a certain tunnel.

When making these considerations, it must always be remembered that the possibility of failure of individual fasteners can never be completely ruled out with these types of materials.

The assessment and acceptance of the level of risk in individual cases is the responsibility of the applicable planning engineer or, respectively, the client. The following basic principles for assessment of the safety relevance of a particular fastening can serve as a guideline, but do not take responsibility from the shoulders of the planner.

4.1.1 Definition: Applications with high safety relevance

**Principle:** The possibility that failure of a fastener could lead directly or indirectly to failure of the complete structure, thus presenting a risk of fatal accident and/or financial loss or damage, can never be ruled out.6

Indirect failure would have to be expected when, for instance, after failure of a fastener, the load on neighboring fasteners becomes so high that static stability can no longer be guaranteed under all loading circumstances (this applies in particular to stress corrosion cracking of parts under high loads as well as loading in the event of fire, under forces of constraint and all loading situations under normal operating conditions).

**Typical cases:**
- Fastening a suspended ceiling under the roof of a tunnel
- Jet-type fans (unless adequately secured, e.g. by means of a safety chain)
- Overhead road signs and signal systems
- Fastening tunnel cladding sections such as fire protection slabs, noise control panels or decorative cladding (unless the static stability of the entire structure is ensured through adequate fastener redundancy).

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6 Also applies in cases where security cannot be verified.
4.1.2 Definition: Applications with moderate safety relevance

**Principle:** The possibility of failure of individual fasteners is actively taken into account during planning and does not lead to failure of the entire structure (redundancy). The designed static stability, with the usual safety factors for all expected loading situations, is maintained even after failure of a single component. Fasteners which have failed can be identified in routine checks and inspections and replaced during the course of regular maintenance.

In this case, in their planning and operating concepts, planners and operators make the assumption that the possibility of failure of individual fasteners under normal tunnel operation cannot be ruled out and that an event of this kind would not lead to closure of the tunnel or to replacement of all other fasteners.

**Typical cases:** (according to the principle mentioned above)
- Cable trays and pipe fastenings / supports
- Lighting units (especially when the connecting cable can effectively prevent it falling)
- Fastenings for items in emergency stopping places such as fire protection doors, switchgear cabinets and similar
- Fastenings beneath the roadway slab
- Installations behind cladding and panels, when failure does not lead to failure of the entire system
- Fastenings as described in 4.1.1 when the criteria from section 4.1.2 are taken into account in the overall static design and in the operating concept.

4.1.3 Definition: Applications with low safety relevance

**Principle:** Failure of several fasteners has no influence whatsoever on human safety and does not lead directly or indirectly to any significant material damage. Even failure that goes unnoticed does not result in significant consequential damage.

Fastenings of this type are used where components are positioned on floors, in cable trays or in inaccessible auxiliary installations and in situations where the fastener redundancy principle applies, i.e. where failure, even failure of several fasteners, cannot not lead to significant consequential damage.

4.2 Recommendations for the selection of materials for fastenings in road tunnels (anchors and other fastening parts)

4.2.1 Fastenings with high safety relevance

For fastenings with a high safety relevance and for maintenance-free fastenings such as those used for overhead installations (suspended ceilings, ventilation fans, cladding, etc.) which are inaccessible or accessible only with great difficulty, it is recommended that Hilti HCR quality materials are used without exception, even in atmospheres with a low chloride content. This applies not only to anchors but also to Hilti XBT fasteners for use with powder-actuated fastening tools.

In rare special cases, where the level of chlorides and other halogenides in the atmosphere is extremely low (for example, at a distance of more than 20 km from the
coast and where no de-icing salt is in use), materials with lower corrosion-resistance may also be suitable (e.g. 1.4401, 1.4404, 1.4571).

Carbonation of the concrete is also of special significance as the critical chloride content depends on the pH value. Accordingly, even when fastening solutions of this kind seem sensible and suitable, regular checks and inspections (at least every 2 years), including the subsequent removal of specimens and inspection of these by specialists for signs of corrosion, is essential and should be included in the operating concept. Only then can safety be ensured. In cases of uncertainty or where questions remain unanswered, Hilti can provide support by calling in technical specialists from central departments.

This means that only fasteners made from Hilti HCR steel can be considered for use in situations where safety relevance is high and where de-icing salt is used in the tunnel system and/or the tunnel lies within approx. 20 km of the coastline.

4.2.2 Fastenings with moderate safety relevance

As it is mandatory to take the possibility of failure of individual fasteners into account in applications with moderate safety relevance, in accordance with the principles described in 4.1.2 consideration may also be given to use of less highly alloyed steels for these applications.

• Although A4 steels offer far higher resistance to corrosion than A2 steels, they can be affected by pitting corrosion and may fail spontaneously due to stress corrosion cracking mainly as a result of their low molybdenum content (approx. 2%). It can certainly make good sense to use A4 steels for lightweight structures where proof can be given of redundant fasteners or where the fasteners are used close to the ground and outside the roadway area. Cast-in fasteners and fasteners used in fresh-air areas can also be made from A4 steel where the level of chlorides in the atmosphere is low (more than 20 km from the coast, no de-icing salt used) or where the fasteners are fully exposed to rainfall. Critical situations may occur, above all, where the chloride content is slightly higher (coastal regions, concrete containing chlorides) in conjunction with acidic condensates (SO2 content, etc.).

Hilti XCR and XBT steel fasteners are manufactured from a special steel that’s comparable to steels of the A4 group (approx. 2% molybdenum). Accordingly, in principle, the conditions that apply to the standard steels of the A4 group also apply to these fasteners. Due to their higher nitrogen content, these corrosion-resistant powder-actuated fasteners possess a slightly higher pitting resistance equivalent and are thus at least as corrosion-resistant and just as good in terms of their stress corrosion cracking behavior as the standard steels of the A4 group but can achieve far higher strength.

• Duplex steels can also be used for fasteners. The duplex steel WN 1.4462, in particular, has been tested by Hilti in long-term tests. In some road tunnels, this steel was found to be fully corrosion-resistant while in other tunnels it showed signs of local corrosive attack (see fig. 3). As carefully machined or processed duplex steels are generally less sensitive to stress corrosion cracking due to their lattice structure and ferritic content, their use in road tunnels can certainly be considered. Generally speaking, 1.4462 duplex steel can be rated above those of the A4 group, but its use has limitations, especially when it is to be used for fasteners such as anchors (see fig. 3).

7 Not to be confused with XBT HCR which, of course, is manufactured from Hilti HCR steel.
No experience has yet been gained with the less corrosion-resistant and less expen-
sive duplex steels, the so-called lean duplex steels. Super duplex steels could also
be suitable, at least theoretically, but also with these materials no relevant practical
experience in road tunnel atmospheres has yet been gained. From a cost point of
view, however, in most cases there is no advantage to be gained from use of these
materials.

• Hot-dip galvanized and duplex or multilayer-coated anchor systems made from car-
bon steel, so long as their tensile strength rating lies below 1000 MPa (risk of hydro-
gen embrittlement), may certainly also be given consideration for use in fastening
applications in road tunnel atmospheres where safety relevance is moderate. How-
ever, their higher rate of corrosion relative to their loadbearing cross section, com-
pared to corrosion-resistant austenitic steels, must also be taken into account. An-
chor systems of this kind must thus be subject to ongoing inspection with a view to
monitoring their rate of corrosion and to ensure that they are replaced in good time
if necessary (cost / benefit considerations). With these points in mind, systems of
this kind are rarely used in road tunnels today or, respectively, they are used only
where easy access allows easy replacement or where safety relevance is insignifi-
cant (see next section, 4.2.3).

• As a general rule, fasteners made from A2 steels are not suitable for use in road
tunnels. An exception to this is the so-called “lost forms” method of construction
used in the installation of fire protection slabs where A2 bolts are cast into the
concrete and thus protected from the effects of the road tunnel atmosphere. In
addition to this, a high degree of redundancy must also be ensured.

4.2.3 Fastenings with low safety relevance

Fastenings have low safety relevance in situations where failure – even multiple failure
– results in no direct or indirect damage whatsoever. Accordingly, virtually all material
grades can be used for this type of application. Planners must be aware of the con-
sequences of their choice of material and, where necessary, make allowance in the
operating concept for the tunnel system for the replacement of defective fasteners.

In this regard it must be pointed out that steels of the A2 group are, in principle, com-
pletely unsuitable for use in road tunnel atmospheres as they are subject to a very
high risk of stress corrosion cracking. Nevertheless, consideration could be given to
the use of this material in auxiliary installations for tunnels where, for instance, A2
steel screws may be adequate for lightweight electrical installations (low safety rele-
vance, high redundancy).
4.2.4 Decision tree for possible material selection

The decision tree shown in fig. 4 summarizes sections 4.2.1 to 4.2.3 in graphical form.

4.3 Recommendations for the selection of materials for connecting and supporting parts and structures in tunnels

A large number of connecting or supporting structures are required in a road tunnel. Examples of these are the channel systems used to support wall cladding, cable trays and pipes. In principle, with regard to safety relevance, these structures must be treated in the same way as fasteners.

Due to their generally lower strength requirements, however, and the generally less critical stress situation, these connecting and supporting parts can, under certain circumstances, be made from materials of a lower grade even where they have the same safety relevance as the anchors used to secure them. This situation is encountered frequently in practice, due mainly to the considerably higher influence the price of the material has on the overall cost of the installation. Accordingly, planners are required to take a life cycle engineering approach to help them reach a wise decision regarding a suitable material and corrosion protection solution for the application.

This has to be checked and assessed individually. Should the planner decide on an alternative to HCR (1.4529), the operating concept for the tunnel must make allowance for regular checks and inspections and probably also for periodical replacement of the parts.

Fig. 4: Decision tree for material selection
5. General comments

5.1 Installation and working procedures

The generally applicable rules according to the state of the art must be observed when installing and working with the parts and fastening systems. As a basic rule, welding or heating fasteners such as anchors, bolts, screws and powder-actuated fasteners is not permissible. Incorrect handling or working procedures can have a highly adverse effect on the corrosion resistance of parts.

5.2 Visual inspection of fasteners and connectors

When visual inspections are carried out during the course of routine checks and regular maintenance, corroded parts can be identified and replaced when necessary. For parts installed in tunnels, this usually means that the parts first have to be cleaned. Signs of corrosion on corrosion-resistant materials under exposure to aggressive tunnel atmospheres can take various forms:

- Light brown discoloration of the surfaces, pitting corrosion not visible without optical assistance;
- Obvious discoloration of the surface, pitting corrosion visible without optical assistance;
- Products of corrosion deposited on the surface and corrosion scars easily visible;
- Crevice corrosion at mechanical connections between parts

If corrosion has occurred on accessible, visible surfaces of fasteners or connectors (visible pitting corrosion, scarring from corrosive attack, etc.) it must also be expected that corrosion damage will have occurred in crevices or in the anchoring area. More extensive inspection and/or replacement of fastening parts is thus advised. Where discoloration is only slight, the fastening and connecting parts must be inspected very carefully during subsequent checks. It is recommended that sample specimens of such fasteners are taken for metallographic analysis. Additional analyses of the concrete (pH value, depth of carbonation, chloride content) can provide further information for estimation of the possible risk of corrosion. Active corrosion can be identified by taking spot measurements of electrical potential. It is recommended that the results are documented.

With screws, bolts and anchors it is not possible to come to any conclusion about corrosion in hidden areas solely on the basis of a visual inspection and the appearance of the visible parts. The part of the fastener in the concrete can be protected from harmful substances and from corrosion by the prevailing pH value and by the barrier effect of the concrete itself. Nevertheless, it may also be found that the concrete is carbonated and/or heavily contaminated with chloride in the area of the anchor. In such cases, corrosion must be expected, even on A4 materials.
5.3 Low temperatures

Low temperatures (< – 20 °C) can have a negative effect on the toughness of steel. Due to their lattice structure, austenitic materials are much less sensitive in this regard, right down to extremely low temperatures (approx. –60 °C). For applications in such environments, Hilti thus recommends use of austenitic materials of the applicable corrosion resistance class (depending on the corrosivity of the environment).

5.4 Technical developments, possible changes in the tunnel atmosphere

All recommendations given in this document are based on currently known facts and data. In the event of significant changes affecting the ambient conditions in a road tunnel during the course of time, the situation must be re-assessed either in general terms or for the specific tunnel. This applies, in particular, to changes concerning the majority vehicles using the tunnel, such as the type of fuel used or the means of propulsion.

Generally speaking, unforeseen incidents such as a vehicle impact, a fire, environmental catastrophe or accident involving chemicals could have a negative effect on the characteristics of the fasteners. In such cases, they must be examined by suitably experienced specialists and replaced over a wide area when necessary.

5.5 Implications for the road tunnel operating concept

Generally speaking, a difference must be drawn between signs of corrosion and actual damage through corrosion. The appearance of signs of corrosion does not inevitably lead to damage through corrosion. Changes can take place in the surface of the metal over a period of time due to deposits and the formation of a crust (salt deposits or other contaminants). Under certain circumstances this may result in formation of an acidic coating containing chloride, the effect of which is increased through alternating wet and dry phases. Depending on the thickness and type of deposits, as well as the period of time taken to form, regular cleaning (removal of deposits by washing) may considerably increase the life of the parts.

Apart from the implications for the road tunnel operating concept mentioned in section 4.1.2, it therefore makes good sense to ensure that effective cleaning of the fastenings and supporting/connecting parts is at least specified as a mandatory procedure.
6. Experience gained from 15 years of materials exposure tests in road tunnels

6.1 Comparison of several tunnels in Switzerland regarding corrosivity on the basis of exposure tests

Table 2 provides a summarized overview of the exposure tests carried out by the Hilti Corporation in road tunnels in recent years. It is designed to give engineers the opportunity to compare a planned tunnel with existing tunnels and to give them an impression of the corrosive impact of tunnel atmospheres and their effect on corrosion-resistant steels.

General data for the tunnel and the location where the exposure tests were carried out is shown in the top section of the table. The main factors (concerning electrolytes) that greatly affect corrosion are shown in the middle section. The severity of corrosive attack (area and depth of pitting) for selected materials of the classes CrNi, CrNiMo and high-molybdenum CrNiMo steels is shown in the lower section.

It must be stressed that the values shown apply only to the location where exposure occurred and not to the tunnel in its entirety. Changes in the amount of traffic using the tunnel over the period of exposure have a decisive effect on corrosion behavior. Nevertheless, trends towards changes resulting from increased traffic or a decrease in corrosion through low-emission motor technologies could not be determined.
<table>
<thead>
<tr>
<th>Length</th>
<th>Gotthard</th>
<th>Gubrist</th>
<th>Milchbuck</th>
<th>Belchen</th>
<th>San Bernardino</th>
<th>Seelisberg</th>
<th>Mont Blanc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test location, distance from entrance [m]</td>
<td>16900</td>
<td>3250</td>
<td>1900</td>
<td>3180</td>
<td>6600</td>
<td>9250</td>
<td>11600</td>
</tr>
<tr>
<td>(north entrance)</td>
<td>100</td>
<td>8700</td>
<td>600</td>
<td>100</td>
<td>900</td>
<td>680</td>
<td>1750</td>
</tr>
<tr>
<td>(west entrance)</td>
<td>8700</td>
<td>600</td>
<td>100</td>
<td>900</td>
<td>680</td>
<td>1750</td>
<td>1150</td>
</tr>
<tr>
<td>Period of exposure</td>
<td>2000</td>
<td>5000</td>
<td>1000</td>
<td>1500</td>
<td>3000</td>
<td>4500</td>
<td>6000</td>
</tr>
<tr>
<td>07/90 – 09/05</td>
<td>11/91 – 09/05</td>
<td>04/91 – 04/95</td>
<td>06/91 – 06/03</td>
<td>02/91 – 09/05</td>
<td>10/90 – 02/95</td>
<td>07/90 – 09/05</td>
<td>10/87 – 10/96</td>
</tr>
<tr>
<td>Effective duration of exposure [a]</td>
<td>15</td>
<td>14</td>
<td>12</td>
<td>14,5</td>
<td>4</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>No. of vehicles /a, 1995</td>
<td>6'114'502</td>
<td>11'450'051</td>
<td>–</td>
<td>14'721'154*</td>
<td>2'029'480</td>
<td>3'897'961*</td>
<td>1'938'904</td>
</tr>
<tr>
<td>Percentage of trucks, 1995</td>
<td>16,3</td>
<td>5,0</td>
<td>12,7</td>
<td>9,7</td>
<td>11,7</td>
<td>41,3</td>
<td></td>
</tr>
<tr>
<td>No. of vehicles /a, 2005</td>
<td>5'865'185</td>
<td>3'30'805</td>
<td>16'891'920</td>
<td>16'634'145*</td>
<td>2'242'195</td>
<td>7'389'425*</td>
<td>1'743'821</td>
</tr>
<tr>
<td>Percentage of trucks, 2005</td>
<td>k. A.</td>
<td>15,4</td>
<td>4,2</td>
<td>23,9</td>
<td>14,5</td>
<td>21,7</td>
<td>34,5</td>
</tr>
<tr>
<td>Average temp. over the year [°C]</td>
<td>14,4</td>
<td>14,3</td>
<td>17,7</td>
<td>8,3</td>
<td>12,1</td>
<td>18,5</td>
<td></td>
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<tr>
<td>Time with condensation on tunnel wall [%]</td>
<td>42</td>
<td>–</td>
<td>38</td>
<td>–</td>
<td>59</td>
<td>25</td>
<td>33</td>
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<tr>
<td>Chloride, Cl⁻ in dust [mg/l]</td>
<td>3252</td>
<td>2080</td>
<td>1921</td>
<td>187,5</td>
<td>1685</td>
<td>5987</td>
<td>–</td>
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<tr>
<td>Nitrate, NO₃ in dust [mg/l]</td>
<td>4,3</td>
<td>32</td>
<td>4,8</td>
<td>43</td>
<td>43</td>
<td>8,8</td>
<td>–</td>
</tr>
<tr>
<td>Sulfate, SO₄ in dust [mg/l]</td>
<td>118</td>
<td>371</td>
<td>162</td>
<td>274</td>
<td>274</td>
<td>307</td>
<td>–</td>
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<tr>
<td>Max. sulfur dioxide, SO₂ [ppm]</td>
<td>45</td>
<td>–</td>
<td>16</td>
<td>–</td>
<td>12</td>
<td>14</td>
<td>15</td>
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</table>

1.4529 (HCR)

<table>
<thead>
<tr>
<th>Pitting corrosion area as a percentage of entire area [%] after x months</th>
<th>0 (181 months)</th>
<th>0 (48 months)</th>
<th>0 (144 months)</th>
<th>0 (174 months)</th>
<th>0 (48 months)</th>
<th>0 (180 months)</th>
<th>0 (96 months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lochtiefe [µm], nach x Monaten</td>
<td>0 (181 months)</td>
<td>0 (48 months)</td>
<td>0 (144 months)</td>
<td>0 (174 months)</td>
<td>0 (48 months)</td>
<td>0 (180 months)</td>
<td>0 (96 months)</td>
</tr>
</tbody>
</table>

1.4571 (A5/AISI316Ti)

<table>
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<tr>
<th>Pitting corrosion area as a percentage of entire area [%] after x months</th>
<th>30 (24 months)</th>
<th>25 (24 months)</th>
<th>&lt;1 (24 months)</th>
<th>8 (24 months)</th>
<th>&lt;1 (48 months)</th>
<th>1 (24 months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of pitting [µm], after x months</td>
<td>5 (181 months)</td>
<td>&lt;1 (168 months)</td>
<td>&lt;1 (144 months)</td>
<td>6 (174 months)</td>
<td>18 (180 months)</td>
<td></td>
</tr>
<tr>
<td>----------------------------------</td>
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</table>

1.4401 (A4/AISI316)

<table>
<thead>
<tr>
<th>Pitting corrosion area as a percentage of entire area [%] after x months</th>
<th>12 (24 months)</th>
<th>2 (24 months)</th>
<th>&lt;1 (48 months)</th>
<th>15 (24 months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of pitting [µm], after x months</td>
<td>70 (24 months)</td>
<td>190 (24 months)</td>
<td>&lt;1 (48 months)</td>
<td>720 (24 months)</td>
</tr>
</tbody>
</table>

* two parallel tunnels
Disclaimer

All results, considerations and recommendations given in this brochure are based on the tests, principles and formulas described in this brochure and on the safety requirements in accordance with the technical instructions issued by Hilti. They apply only to applications comparable to the test constellations described in the annex. This applies, in particular, to the exposure tests carried out in various road tunnels. Extrapolation of the results to other environments is not permissible.

As all tunnels are different in terms of the conditions that prevail within, and the requirements to be met by a fastening solution vary significantly according to the actual design of the structure, geometry of the parts and the safety relevance of the fastening, the considerations and recommendations and, in particular, the limiting values given for individual applications, must be seen only as an approximate guide. Significant scatter of values may also occur within the bandwidth of environmental parameters applicable within a single tunnel. Assessment of the applicable tunnel, particularly in terms of the prevailing environmental parameters, is the responsibility of the planning specialist or, respectively, the client.

As the corrosion processes described here are long term, in the event of a decision to use a material that is not stable (the only material that can currently be described as stable is 1.4529 (HCR)) it is expressly recommended that specimens are taken from the tunnel periodically for subsequent specialist analysis and that this process is included in the operating concept for the tunnel and is carried out on a regular basis.

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Hilti accepts no liability whatsoever for damage or injury stemming from estimation of the safety relevance of a fastening and the resulting selection of a material. Likewise, Hilti accepts no liability for damage or injury stemming from assessment of the environmental conditions prevailing in a tunnel. Such assessments are exclusively the responsibility of the planning specialist or, respectively, the client. The considerations given here serve only to point out a few of the relevant aspects regarding fastening technology. It must be stated clearly that special attention must be given not only to the selection of a suitable material for a fastening, other relevant points such as legal and operational aspects must also be taken into account.