Part 5:

Direct fastening principles and technique
1. Introduction

1.1 Definitions and general terminology

Hilti direct fastening technology is a technique in which specially hardened nails or studs are driven into steel, concrete or masonry by a piston-type tool. Materials suitable for fastening by this method are steel, wood, insulation and some kinds of plastic. Fastener driving power is generated by a power load (a cartridge containing combustible propellant powder, also known as a “booster”), combustible gas or compressed air. During the driving process, base material is displaced and not removed. In Hilti terminology, DX stands for “powder-actuated” and GX for “gas-actuated” systems.

1.2 Reasons for using powder- or gas-actuated fastening

The illustrations below show some of the main reasons why many contractors take advantage of the benefits of powder or gas-actuated fastening.

- Speed is important.
- An easy-to-use, uncomplicated fastening system is required.
- A weather-independent fastening system is required.
- Electric power is not available or electric cables would hinder the work.
A complete fastening system with assured strength is required. Drilling is not viable because of noise. Drilling would be too difficult.

Drilling would cause too much dust.
### 1.3 Direct fastening applications

Typical applications for powder- or gas-actuated fastening are shown in the illustrations below:

- Fastening thin metal sheets: roof decking, wall liners and floor decking
- Fastening thicker steel members: e.g. metal brackets, clips
- Fastening soft materials such as wooden battens or insulation to steel, concrete or masonry
- Threaded studs for suspended ceilings, installing building services, bar gratings or chequer plate floors
- Connections for composite structures: fastening nailed composite shear connectors

**Illustrations:**
- Roof decking
- Wall liners
- Floor decking
- Metal brackets, clips and tracks
- Fixtures for mechanical and electrical installations
- Hangers with threaded connectors
- Wooden battens fastened to steel or concrete
- Grating fastenings
- Shear connectors
Hilti direct fastening systems are specially designed for each application and trade. Key applications and the corresponding fastening systems are shown below.

<table>
<thead>
<tr>
<th>Roof and floor decking in steel &amp; metal construction</th>
<th>X-ENP-19 L15</th>
<th>DX 76 PTR</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Roof and floor decking in steel &amp; metal construction" /></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gratings in the petrochemical and other industries</th>
<th>X-BT + X-FCM R</th>
<th>DX 351 BTG</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Gratings in the petrochemical and other industries" /></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interior partition walls (drywall) in interior finishing</th>
<th>X-GN</th>
<th>GX 120</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Interior partition walls (drywall) in interior finishing" /></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Concrete forms in building construction

<table>
<thead>
<tr>
<th>X-FS</th>
<th>DX 460</th>
</tr>
</thead>
</table>

Conduit clips and ties in mechanical and electrical installations

<table>
<thead>
<tr>
<th>X-EKS, X-ECT</th>
<th>GX 120-ME</th>
</tr>
</thead>
</table>
2. The direct fastening system

The fastener, tool and driving energy form a **fastening system** with its own specific characteristics. Examples of Hilti direct fastening system components are shown below.

<table>
<thead>
<tr>
<th>Fasteners</th>
<th>Fastening tools</th>
<th>Driving energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Image of powder-actuated tool]</td>
<td>[Image of powder-actuated tool]</td>
<td>[Image of powder cartridges]</td>
</tr>
<tr>
<td>[Image of gas-actuated tool]</td>
<td>[Image of gas-actuated tool]</td>
<td>[Image of gas cartridge]</td>
</tr>
</tbody>
</table>

**Powder-actuated tool**

**Gas-actuated tool**
2.1 Fasteners

Fasteners can be classified in three general types: nails, threaded studs and composite fasteners.

<table>
<thead>
<tr>
<th>Nails</th>
<th>Threaded studs</th>
<th>Composite fasteners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siding and decking nails</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General purpose nails</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blunt-ended fastener (requires pre-drilling)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>for steel</td>
<td>Knurling</td>
<td></td>
</tr>
<tr>
<td>for concrete</td>
<td>for concrete</td>
<td></td>
</tr>
</tbody>
</table>

Multi-part fasteners

The nails used (also known as drive pins) are of a special type equipped with washers to meet the needs of the application and to provide guidance when driven. Threaded studs are essentially nails with a threaded upper section instead of a head. Composite fasteners are an assembly consisting of a nail with an application-specific fastening component such as a clip, plate or disk made of metal or plastic.

Siding and decking nails can be recognized by their washers which are specially designed to hold down the metal sheets and to absorb excess driving energy. Fasteners designed for driving into steel usually have knurled shanks which increase their pull-out resistance. Fasteners for use on concrete have longer shanks than those for use on steel. Threaded studs may have either a metric (M6, M8 or M10) or Whitworth (1/4", 5/16" or 3/8") thread.

Nails and threaded studs are commonly zinc-plated for resistance to corrosion during transport, storage and construction. As this degree of protection is inadequate for long-term resistance to corrosion, use of these zinc-plated fasteners is limited to applications where they are not exposed to the weather or a corrosive atmosphere during their service life. The zinc layer on
fasteners driven into steel is, in fact, a disadvantage in that it reduces pull-out resistance. For this reason, the thickness of zinc on the fastener must be optimized to ensure good corrosion protection as well as high holding power. During production, tight control of the galvanizing process is necessary to prevent excess zinc thickness and thereby poor fastening performance. Fasteners must be 2 to 3 times harder than the material into which they are driven. The tensile strength of structural steel is commonly between 400 and 600 MPa. Fasteners for use on steel thus require a strength of approximately 2000 MPa. As Rockwell hardness is much easier to measure than strength, but good correlation exists between hardness and strength, this characteristic is used as a parameter in the specification and manufacturing of the fasteners. In the table below, HRC hardness is given for a range of tensile strengths (DIN 50150).

<table>
<thead>
<tr>
<th>Tensile strength (MPa)</th>
<th>770</th>
<th>865</th>
<th>965</th>
<th>1810</th>
<th>1920</th>
<th>1995</th>
<th>2070</th>
<th>2180</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRC</td>
<td>20.5</td>
<td>25.5</td>
<td>30</td>
<td>52.5</td>
<td>54</td>
<td>55</td>
<td>56.5</td>
<td>58</td>
</tr>
</tbody>
</table>

### 2.2 Manufacturing process

#### Standard hardened steel fasteners

Almost all powder and gas-actuated fasteners used throughout the world are manufactured from carbon steel wire which is subsequently thermally hardened to provide the strength needed for driving into steel and concrete. In nail manufacturing, shank diameter is determined by the wire diameter used. Threaded studs are made from wire corresponding to the required thread diameter. The manufacturing process, which is summarized in the diagram below, consists of cutting the wire to length, shaping the head, knurling, forging or thermo pulling the point, hardening, galvanizing and assembling with washers.

The process of hardening the steel to more than HRC 50 combined with the zinc plating presents a risk of hydrogen embrittlement.

This risk is mitigated by heat-treating the galvanized product at the optimum temperature for the correct time. Galvanized and heat-treated fasteners are subjected to impact bending tests to check the effectiveness of the process. Depending on their intended application, some fasteners are additionally sampled and tested under tension and shear.
Stainless steel fasteners

Hilti introduced the first powder-actuated stainless steel fastener in 1994. These fasteners, which are not thermally hardened, are manufactured from special stainless steel wire with an ultimate tensile strength of 1850 MPa. One effect of using steel of such high strength as a raw material is that the forming and forging processes present greater technical difficulties. These fasteners, on the other hand, suffer no risk of hydrogen embrittlement and their strength decreases only very slightly when subjected to high temperatures such as in a fire.

2.3 Fastener raw material

Hilti standard zinc plated fasteners are made from carbon steel wire with an ultimate tensile strength of 590 to 760 MPa.

Hilti X-CR / X-CRM / X-BT stainless steel fasteners are made from high-strength nitrogen alloyed stainless steel wire (Hilti designation CR500). Nickel and chromium are the components of stainless steel that make it resistant to corrosion. CR500 steel is compared to commonly used stainless steels like AISI 304 and 316 (European A2 and A4) in the graph at the right. Note that CR500 steel contains considerably more nickel and chromium than both 304 and 316.

Another comparison of interest is the difference in ultimate tensile strength, as shown in the graph at the right.
2.4 Powder- and gas-actuated tools

Definitions
In the ANSI A10.3-2006 standard, two basic types of tool are referred to: **direct-acting** and **indirect-acting**. The two types are defined by the manner in which the energy is transferred from the hot expanding gases to the fastener.

**Direct-acting tool:**
The expanding gases act directly on the fastener and accelerate it to a velocity of 400 to 500 m/s (1300 to 1600 fps). This velocity places the tool in the high-velocity class, thereby subjecting it to more stringent rules for usage.

**Indirect-acting tool:**
The expanding gases act on a captive piston that drives the fastener, which in Hilti indirect-acting tools reaches a velocity of less than 100 m/s (328 fps). Because of the lower velocity, the possibility and extent of injury due to incorrect operation is very much reduced. Rules for usage are less stringent than for high-velocity tools.

ANSI A10.3-2006 classifies powder-actuated tools according to velocity. With increasing velocity, rules for usage become more stringent, for example with regard to equipping the tools with shields. The lowest velocity tool capable of performing the application should be used.

<table>
<thead>
<tr>
<th>Class of powder-actuated tool</th>
<th>Average test velocity in m/s [fps]</th>
<th>Maximum single test velocity in m/s [fps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-velocity</td>
<td>100 [328]</td>
<td>108 [354]</td>
</tr>
<tr>
<td>Medium-velocity</td>
<td>150 [492]</td>
<td>160 [525]</td>
</tr>
<tr>
<td>High-velocity</td>
<td>&gt;150 [492]</td>
<td>&gt;160 [525]</td>
</tr>
</tbody>
</table>
**Hilti tools**

All Hilti tools supplied for construction applications are low-velocity, indirect-acting tools. Indirect-acting tools operate according to one of three different principles – co-acting, impact or contact operation – which each affect the operating characteristics and the application limit of the system. It should be noted that 100% co-acting operation can be achieved by pushing the fastener all the way back against the piston with a ramrod or, if the tool is so designed, with a built-in ramrod mechanism. Tools with nail magazines do not achieve 100% co-action because of the need for clearance between the piston end and the collated nail strip. Some single-shot tools allow the operator to make an impact-type tool work as a co-acting tool by using a ramrod.

<table>
<thead>
<tr>
<th>Operating principle</th>
<th>Characteristics</th>
<th>Operating principle</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-acting operation</td>
<td>• $X &gt; 0$ ; $Y = 0$</td>
<td>Impact operation</td>
<td>• $X = 0$ ; $Y &gt; 0$</td>
</tr>
<tr>
<td></td>
<td>• Highest application limit</td>
<td></td>
<td>• Lower application limit</td>
</tr>
<tr>
<td></td>
<td>• Lowest recoil</td>
<td></td>
<td>• Higher recoil</td>
</tr>
<tr>
<td>Contact operation</td>
<td>• $X = 0$ ; $Y = 0$</td>
<td></td>
<td>• Lowest application limit</td>
</tr>
<tr>
<td></td>
<td>• Lowest application limit</td>
<td></td>
<td>• Highest recoil</td>
</tr>
</tbody>
</table>
2.5 Cartridges (power loads, boosters)

Cartridges for indirect-acting tools are available in various standard sizes and each size is available in up to 6 power levels. In the United States, the powder in a cartridge, the sensitivity of the primer, and the cartridge dimensions are governed by technical data published by the Powder-Actuated Tool Manufacturers Institute, Inc. (PATMI). PATMI defines the power level by the velocity measured in a standard test in which a standardized 350 grain [22.7gram] cylindrical slug is fired from a standardized apparatus. The identification and limitations of use are addressed in ANSI A10.3-2006.

**PATMI colour codes, power levels and definition of cartridges**

<table>
<thead>
<tr>
<th>Size</th>
<th>Colour code</th>
<th>Power level</th>
<th>Velocity of 350 grain slug</th>
<th>Calculated energy (joules)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ft./sec.</td>
<td>[m/sec.]</td>
<td>minimum average maximum</td>
</tr>
<tr>
<td>6.8 / 11</td>
<td>Gray 1</td>
<td>370 ± 45</td>
<td>[113 ± 13.7]</td>
<td>111 144 182</td>
</tr>
<tr>
<td></td>
<td>Green 3</td>
<td>480 ± 45</td>
<td>[146 ± 13.7]</td>
<td>200 243 291</td>
</tr>
<tr>
<td></td>
<td>Yellow 4</td>
<td>560 ± 45</td>
<td>[171 ± 13.7]</td>
<td>280 331 386</td>
</tr>
<tr>
<td></td>
<td>Red 5</td>
<td>610 ± 45</td>
<td>[186 ± 13.7]</td>
<td>337 392 452</td>
</tr>
<tr>
<td></td>
<td>Purple / black 6</td>
<td>660 ± 45</td>
<td>[201 ± 13.7]</td>
<td>399 459 524</td>
</tr>
<tr>
<td>6.8 / 18</td>
<td>Green 3</td>
<td>550 ± 45</td>
<td>[168 ± 13.7]</td>
<td>269 319 373</td>
</tr>
<tr>
<td>[Cal. 27 long]</td>
<td>Yellow 4</td>
<td>630 ± 45</td>
<td>[192 ± 13.7]</td>
<td>361 419 480</td>
</tr>
<tr>
<td></td>
<td>Blue 4.5</td>
<td>725 ± 45</td>
<td>[221 ± 13.7]</td>
<td>488 554 625</td>
</tr>
<tr>
<td></td>
<td>Red 5</td>
<td>770 ± 45</td>
<td>[235 ± 13.7]</td>
<td>554 625 700</td>
</tr>
<tr>
<td></td>
<td>Purple / black 6</td>
<td>870 ± 45</td>
<td>[265 ± 13.7]</td>
<td>718 798 883</td>
</tr>
</tbody>
</table>

The German DIN 7260 standard specifies cartridge dimensions, colour codes and power levels, which are defined in terms of energy delivered when a cartridge is fired in a standardized apparatus. DIN 7260 specifies a 3.66 gram slug with a somewhat more complex geometry than that of the PATMI slug.
### DIN 7260 colour codes, power levels and definition of cartridges

<table>
<thead>
<tr>
<th>Size</th>
<th>Colour code</th>
<th>Power level</th>
<th>Specified energy (joules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8 / 11</td>
<td>White</td>
<td>weakest</td>
<td>120 ± 50</td>
</tr>
<tr>
<td></td>
<td>Green</td>
<td>weak</td>
<td>200 ± 50</td>
</tr>
<tr>
<td></td>
<td>Yellow</td>
<td>medium</td>
<td>300 ± 50</td>
</tr>
<tr>
<td></td>
<td>Blue</td>
<td>heavy</td>
<td>400 ± 50</td>
</tr>
<tr>
<td></td>
<td>Red</td>
<td>very heavy</td>
<td>450 ± 50</td>
</tr>
<tr>
<td></td>
<td>Black</td>
<td>heaviest</td>
<td>600 ± 50</td>
</tr>
<tr>
<td>6.8 / 18</td>
<td>Green</td>
<td>weak</td>
<td>200 ± 50</td>
</tr>
<tr>
<td></td>
<td>Yellow</td>
<td>medium</td>
<td>400 ± 50</td>
</tr>
<tr>
<td></td>
<td>Blue</td>
<td>heavy</td>
<td>500 ± 50</td>
</tr>
<tr>
<td></td>
<td>Red</td>
<td>very heavy</td>
<td>600 ± 100</td>
</tr>
<tr>
<td></td>
<td>Black</td>
<td>heaviest</td>
<td>800 ± 100</td>
</tr>
</tbody>
</table>

In order to achieve interchangeability of the tools and cartridges from various manufacturers, PATMI provides guidelines on cartridge dimensions. Manufacturers optimize the cartridge characteristics for their tools in order to achieve functional reliability and long life.

**Interchanging of components** is mentioned in 7.10 of ANSI A10.3-2006: “Only those types of fasteners and power loads recommended by the tool manufacturer for a particular tool, or those providing the same level of safety and performance, shall be used.”

It is the responsibility of the user of powder-actuated products to comply with this requirement.
3. Health and safety

The safety of powder-actuated fastening systems can be examined in terms of three general safety characteristics:

- **Operator safety** refers to safeguarding the operator and bystanders.
- **Fastening safety** is a measure of the adequacy of the in-place fastenings.
- **Functional safety** refers to the operability of the tool, especially the operator safety devices, under construction site conditions.

3.1 Operator safety

Hilti powder-actuated systems incorporate five main design features for maximum operator safety – the DX piston principle, drop-firing safety mechanism, contact pressure safety mechanism, trigger safety mechanism and the unintentional firing safety mechanism.

**Hilti DX/GX piston principle**

One of the main concerns about the use of explosive powder-filled cartridges to drive fasteners is what happens if the base material is missed by the fastener. The piston principle ensures that the energy from the propellant in the cartridge is transferred to a piston, the accelerated mass of which then drives the fastener. Because the piston is captive within the tool, roughly 95% of the driving energy is absorbed by the tool in the event of the fastener missing the base material. Thus, the velocity of a fastener that misses the base material is far lower than the velocities associated with fasteners from high-velocity tools (tools that do not operate with the piston principle).
Drop-firing safety
The drop firing safety mechanism prevents the tool from firing if dropped unintentionally. This mechanism is so designed that the tool, cocked or uncocked, will not fire when dropped at any angle onto a hard surface.

Trigger safety
This mechanism ensures that pulling the trigger alone cannot cause the cartridge to fire. The trigger in a Hilti DX- or GX-tool is uncoupled from the firing pin mechanism until the tool is fully compressed against the work surface.
**Contact pressure safety**
A Hilti tool is made ready for firing by compressing it against the work surface. This requires a force of at least 50 N [11.2 pounds]. Tools with large baseplates that can be easily gripped with the hand, for example the DX 76 and the DX 460 SM, GX 120, have an additional surface contact pin that must also be pushed back to allow firing. This is designed to prevent the tool firing when its nosepiece is not in contact with the work surface.

**Unintentional firing safety**
Hilti DX tools cannot be fired by pulling the trigger and then compressing the tool against the work surface (also known as “bump firing”). These tools can be fired only when they are (1) compressed against the work surface and (2) the trigger is then pulled.

**Cartridge (power load or booster)**
The propellant powder in the cartridge can only burn if the primer burns first. Burning of the primer is initiated by an impact applied with the correct velocity at the correct location of the cartridge. The propellant and primer are protected from external influences by the metal casing of the cartridge.

**Magazine strip**
Collated cartridges in strips of 10 (or 40) offer greater safety because the plastic strip helps protect the cartridge cases from impacts and ensures separation between the cartridges.

**Packaging**
The packaging must contain provisions with respect to tool compatibility.
Promotion of operator safety
Safety of the operator and bystanders is promoted by use of the appropriate safety equipment and by following the instructions in the operator’s manual. By supplying the powder-actuated tool in a lifetime kit box with space for eye protectors, operator’s manual, etc., retention and use of the safety equipment is much improved.

Tool compatibility information and installation guidelines printed on the cartridge and fastener packaging supplement the operator’s manual.

Hilti organizes operator training courses in which general safety measures for powder-actuated tools are covered as well as measures specific to each model of tool used. In some countries, certificates or operator IDs are issued upon completion of training courses to encourage attention to safety by operators and to allow safety officials to enforce training requirement regulations.
3.2 Fastening safety
Fastening safety depends on a correct prediction of the loads and the conditions to which the fastening is subjected and a correct prediction of fastening performance. The necessary conditions for predictable fastening performance are:
1. The fastening system must have been engineered and tested for the application.
2. The quality of the fastening system components used must correspond to the quality of those originally tested.
3. The fastenings must be made as foreseen in the engineering of the system or in the same way as when the system was tested.

Engineering and testing
Sources of information about the engineering and testing of a fastening system are the manufacturer’s technical literature, test reports, official approvals and publications in technical journals. If an “or equal” clause is used in the specification, then approval of any alternate fastening system should be made contingent on provision of documentation showing that the proposed fastening system has been engineered and tested for the given application.

Production quality
The need for the materials used on the job-site to correspond to the design of the product and to be of the same quality as those tested is clear. This requires the manufacturer to have a production quality control system, which is necessary for ISO 9001 certification.
Quality of installation

The use of fastening systems for which the manufacturer provides application guidelines and a technical advisory service helps ensure that fasteners will be installed correctly. The concept of controlling the quality of the work must include some feature that can be measured and that feature must indicate the performance of the fastenings.

The primary means of checking the quality of a powder-actuated fastening is by checking the stand-off over the surface of the fastened material. For fasteners that do not allow an accurate visual check of the stand-off, the use of a stand-off template is recommended. In some cases tensile testing of fasteners on jobsites is necessary. Threaded studs and some decking fasteners with suitable head design can be tensile-tested in their final position on a jobsite. Other fasteners like simple flat-headed nails have to be driven through a pull-over test specimen and then tested.
3.3 Functional safety

Construction professionals demand fastening systems that are dependable under the toughest jobsite conditions. The goal of functional reliability has to be integrated into the development, manufacture, sales and service of a fastening system. The development of a new fastening system must consider the operating conditions and the degree of reliability required. During development, system components and prototypes are tested to determine if they will function reliably. Pilot production lots are tested by contractors on their jobsites to ensure that the design can be produced in a quality that will function. Quality control is integrated in the manufacturing process to ensure that all components are manufactured according to specifications. Salespersons are trained so that they can advise their customers as to the proper system to use for the application. Tool repair and maintenance training help keep the fastening systems functioning.
3.4 DX Cartridge safety

Important information about cartridges for powder actuated fastening tools

Only use Hilti cartridges or cartridges of equivalent quality.
The use of cartridges of inferior quality in Hilti tools may lead to build-up of unburned powder, which may explode and cause severe injuries to operators and bystanders.
At a minimum, cartridges must:
1. be confirmed by their supplier to meet the "Combustion residue test" according to EU standard EN 16264,

or
2. bear:
   • The CE conformity mark
   • The proof mark of fire-arm test house
   • The tool designation
   • The identification number of the EU notified body
   • The number of the type test

For example:

3.5 DX Tools safety

Approvals for powder actuated fastening tool:
Hilti Powder Actuated Fastening tools are designed and tested according to “Directive 2006/42/EC” and are CIP approved.

Identifications on the Hilti DX tools:
4. Corrosion

For decades, Hilti is concerned about corrosion of fastening systems and has gained a lot of experience in this area based on laboratory- and field tests. Extensive testing and research are conducted in test facilities of Hilti Corporate Research department, located around the world in different climate zones. Hilti strives to provide the best possible support to customers for selecting the right product for safe and reliable fastening solutions. This chapter gives an overview of corrosion protection solutions for Hilti Direct Fastening elements. More details on corrosion are described in the Hilti corrosion brochure „Corrosion aspects of fastening systems 2010“.

4.1 Corrosion protection of direct fastening systems

The use of the corrosion protection system is dependent on different influencing parameters. Following table shows typical environmental and application conditions affecting the corrosion process.

<table>
<thead>
<tr>
<th>Humidity</th>
<th>Humidity accelerates corrosion.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Higher temperatures promote corrosion.</td>
</tr>
<tr>
<td>Salts</td>
<td>Salt accelerates corrosion.</td>
</tr>
<tr>
<td>Industrial pollution</td>
<td>SO2 accelerates corrosion.</td>
</tr>
<tr>
<td>Galvanic corrosion</td>
<td>Occurs when fastener is less noble than fixed parts.</td>
</tr>
<tr>
<td>Special applications</td>
<td>Include other influencing factors, i.e. indoor swimming pools, road tunnels, chemical industry.</td>
</tr>
</tbody>
</table>

Galvanic zinc coating

A typical corrosion behavior of galvanized zinc coated fasteners is characterized by a rather homogeneous surface reduction. It begins with zinc corrosion (white rust) till the zinc is completely removed. Corrosion of the carbon steel material will then take place (red rust).

Hydrogen embrittlement

A specific corrosion phenomenon of zinc plated DX fastening elements is hydrogen embrittlement, which will transpire if three different conditions are present simultaneously:
- High strength steel (> 1000 MPa)
- Presence of hydrogen
- Tensile stresses

Corrosion occurs when zinc plated, high-strength fastening element is used in wet atmosphere. During this corrosion process, hydrogen is formed and diffuses into the material. This leads to a decrease in ductility of the material, leading to sudden fastener failure even under very low static load.

Hilti's power actuated fasteners are thoroughly tested and controlled to prevent primary hydrogen embrittlement during the production process. To avoid secondary hydrogen embrittlement during the service life of a fastener when installed, the application conditions given for each nail in this document and other Hilti Literature must be followed.
4. Corrosion

For decades, Hilti is concerned about corrosion of fastening systems and has gained a lot of experience in this area based on laboratory- and field tests. Extensive testing and research are conducted in test facilities of Hilti Corporate Research department, located around the world in different climate zones. Hilti strives to provide the best possible support to customers for selecting the right product for safe and reliable fastening solutions.

This chapter gives an overview of corrosion protection solutions for Hilti Direct Fastening elements. More details on corrosion are described in the Hilti corrosion brochure „Corrosion aspects of fastening systems 2010“.

4.1 Corrosion protection of direct fastening systems

The use of the corrosion protection system is dependent on different influencing parameters. Following table shows typical environmental and application conditions affecting the corrosion process.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humidity</td>
<td>Increased humidity accelerates corrosion.</td>
</tr>
<tr>
<td>Temperature</td>
<td>Higher temperatures promote corrosion.</td>
</tr>
<tr>
<td>Salts</td>
<td>Increased salinity accelerates corrosion.</td>
</tr>
<tr>
<td>Industrial pollution</td>
<td>SO2 accelerates corrosion.</td>
</tr>
<tr>
<td>Galvanic corrosion</td>
<td>Occurs when fastener is less noble than fixed parts.</td>
</tr>
<tr>
<td>Special applications</td>
<td>Include other influencing factors, i.e. indoor swimming pools, road tunnels, chemical industry.</td>
</tr>
</tbody>
</table>

Galvanic zinc coating

A typical corrosion behavior of galvanized zinc coated fasteners is characterized by a rather homogeneous surface reduction. It begins with zinc corrosion (white rust) till the zinc is completely removed. Corrosion of the carbon steel material will then take place (red rust).

Zinc corrosion (white rust)  
Start of carbon steel corrosion (red rust)

The amount of material loss due to corrosion can be approximated in laboratory scale experiments. The so-called corrosion rate is generally listed as mm/year or g/m² h (laboratory values).

Hydrogen embrittlement

A specific corrosion phenomenon of zinc plated DX fastening elements is hydrogen embrittlement, which will transpire if three different conditions are present simultaneously:

- High strength steel (> 1000 MPa)
- Presence of hydrogen
- Tensile stresses

Corrosion occurs when zinc plated, high-strength fastening element is used in wet atmosphere. During this corrosion process, hydrogen is formed and diffuses into the material. This leads to a decrease in ductility of the material, leading to sudden fastener failure even under very low static load.

Hilti’s power actuated fasteners are thoroughly tested and controlled to prevent primary hydrogen embrittlement during the production process. To avoid secondary hydrogen embrittlement during the service life of a fastener when installed, the application conditions given for each nail in this document and other Hilti Literature must be followed.
Duplex coating

Duplex coating is a two layer coating consisting of a sealer layer with a zinc layer below. The sealer prevents the zinc from corrosion, so the duplex coating has got a higher corrosion protection than standard zinc plating.

Stainless steel

There is a wide range of different types of stainless steel, and they each have different corrosion resistance properties. A stainless steel material used in a wrong environment can lead to pitting corrosion and, subsequently, sudden fastener failure. In such a situation, prediction of fastener lifetime is not possible.

Hilti power actuated fasteners are made of CR500 and 1.4462 material, similar to A4 (AISI grade 316) and, for higher corrosion requirements, HCR (1.4529) material. The HCR (High Corrosion Resistance) material can be used in swimming pools and in road tunnels, where A4 material is not sufficient.

Stainless steel with pitting corrosion, e.g. A4 material used in a road tunnel

Suitable stainless steel used, e.g. HCR material used in a road tunnel

4.2 Fastener selection

Following table gives a general guideline of commonly-accepted applications in typical atmospheric environments. Suitability of fastening systems for a specific application can be significantly affected by localized conditions, including but not limited to:

- Elevated temperatures and humidity
- High levels of airborne pollutants
- Direct contact with corrosive products, commonly found in chemically-treated wood, waste water or salt water, concrete additives, cleaning agents, etc.
- Non-atmospheric corrosion like e.g. direct contact to soil, stagnant water
- Cyclic wetting
- Electrical current
- Contact with dissimilar metals
- Physical damage or wear

<table>
<thead>
<tr>
<th>Environmental conditions</th>
<th>Carbon steel</th>
<th>Stainless steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon steel</td>
<td>Duplex coating</td>
<td>CR500 or HCR</td>
</tr>
<tr>
<td>Galv. zinc coating</td>
<td>1.4462</td>
<td>1.4529</td>
</tr>
</tbody>
</table>

Special applications

- Road tunnels, indoor swimming pools, special applications in chemical industry

Suitable stainless steel used, e.g. HCR material used in a road tunnel

Consult experts for exceptions
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<table>
<thead>
<tr>
<th>Carbon steel</th>
<th>Stainless steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fastener</td>
<td></td>
</tr>
<tr>
<td>Galv. zinc</td>
<td>Duplex coating</td>
</tr>
<tr>
<td>coating</td>
<td>CR500 or</td>
</tr>
<tr>
<td></td>
<td>1.4462</td>
</tr>
<tr>
<td></td>
<td>HCR</td>
</tr>
<tr>
<td>Examples</td>
<td></td>
</tr>
<tr>
<td>X-ENP, X-UF</td>
<td>X-FCM-M</td>
</tr>
<tr>
<td>X-BT, X-CR</td>
<td>X-GR</td>
</tr>
<tr>
<td>On demand</td>
<td></td>
</tr>
</tbody>
</table>

**Environmental conditions**

**Fastened part**

- **Dry indoor**
  - steel (zinc coated, painted), aluminum, stainless steel, wood: ✔ ✔ ✔ ✔

- **Indoor with temporary condensation**
  - steel (zinc coated, painted), aluminum, stainless steel, wood: Consult experts for exceptions ✔ ✔ ✔ ✔

- **Outdoor, non-safety relevant or short-term (< 6 Month during construction)**
  - steel (zinc coated, painted), aluminum, wood: ✔ ✔ ✔ ✔

- **Outdoor, rural or urban environment with low pollution**
  - steel (zinc coated, painted), aluminum, stainless steel: Consult experts for exceptions ✔ ✔ ✔ ✔

- **Outdoor, rural or urban environment with moderate concentration of pollutants and/or salt from sea water**
  - steel (zinc coated, painted), aluminum, stainless steel: Consult experts for exceptions ✔ ✔ ✔ ✔

- **Coastal areas**
  - steel (zinc coated, painted), aluminum, stainless steel: X X ✔ ✔

- **Outdoor, areas with heavy industrial pollution**
  - steel (zinc coated, painted), aluminum, stainless steel: X X ✔ ✔

- **Close distance to streets**
  - steel (zinc coated, painted), aluminum, stainless steel: X X ✔ ✔

- **Special applications**
  - steel (zinc coated, painted), aluminum, stainless steel: X X Consult experts for exceptions ✔
Remarks:

- The ultimate decision on the required corrosion protection must be made by the customer. Hilti accepts no responsibility regarding the suitability of a product for a specific application, even if informed of the applications conditions.
- This table is based on an average service life for typical applications.
- For metallic coating e.g. zinc layer systems the end of life time is the point where red rust is visible over a large percentage of the product and widespread structural deterioration can occur – the initial onset of rust will occur much sooner.
- National or international codes, standards or regulations, customer and/or industry specific guidelines must be independently evaluated.
- These guidelines apply to atmospheric corrosion only. Other types of corrosion, such as crevice corrosion or stress corrosion cracking must be independently evaluated.

A typical service life of Hilti GX-WF nails in wood - wood connections is shown below:

<table>
<thead>
<tr>
<th>Service Classes in accordance with EN 1995 (Eurocode 5):</th>
<th>Service Class 1</th>
<th>Service Class 1,2</th>
<th>Service Class 1,2,3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Corrosion Protection for Hilti GX-WF wood nails (d ≤ 4mm):</td>
<td>No Corrosion Protection</td>
<td>Zinc coated HDG</td>
<td>A2</td>
</tr>
<tr>
<td>Dry indoor</td>
<td>20 to 50 years</td>
<td>up to 50 years</td>
<td>up to 100 years</td>
</tr>
<tr>
<td>Indoor environments with temporary condensation</td>
<td>✗</td>
<td>10 to 50 years</td>
<td>60 to 100 years</td>
</tr>
<tr>
<td>Outdoor with low pollution</td>
<td>✗</td>
<td>5 to 20 years</td>
<td>40 to 100 years</td>
</tr>
<tr>
<td>Outdoor with moderate concentration of pollutants</td>
<td>✗</td>
<td>2 to 10 years</td>
<td>20 to 40 years</td>
</tr>
<tr>
<td>Coastal areas</td>
<td>✗</td>
<td>up to 5 years</td>
<td>10 to 30 years</td>
</tr>
<tr>
<td>Outdoor, areas with heavy industrial pollution</td>
<td>✗</td>
<td>up to 5 years</td>
<td>10 to 30 years</td>
</tr>
<tr>
<td>Close distance to streets</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
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<td>Special applications</td>
<td>Consult experts for exceptions</td>
<td></td>
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<td>up to 100 years</td>
</tr>
<tr>
<td>Indoor environments with temporary condensation</td>
<td>X</td>
<td>10 to 50 years</td>
<td>60 to 100 years</td>
</tr>
<tr>
<td>Outdoor with low pollution</td>
<td>X</td>
<td>5 to 30 years</td>
<td>40 to 100 years</td>
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<tr>
<td>Outdoor with moderate concentration of pollutants</td>
<td>X</td>
<td>2 to 10 years</td>
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<td>X</td>
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<tr>
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<td>Special applications</td>
<td>Consult experts for exceptions</td>
<td></td>
</tr>
</tbody>
</table>

- Suitable
- Not suitable

**Remarks:**
- The use of certain wood species including, but not limited to, Oak, Douglas-fir or Western Red Cedar, require the use of stainless steel nails, independent of Service Class and environmental conditions.
- The use of certain wood treatments including, but not limited to, fire retardants or preservatives can change the chemical composition of the wood and may require the use of stainless steel nails, independent of Service Class and environmental conditions.
- The evaluation of corrosive environmental conditions depends on many factors and lies within the responsibility of the customer. The planned service life of the buildings or structures can be considered according to local or national building regulations and Eurocode (EN 1990).
- The table does not contain recommendations and Hilti does not assume liability for fastener selection based on its content.
- For the typical service life, it is assumed that the nails are selected, designed, installed and otherwise treated in accordance with Hilti’s published literature.
- Local building regulations and trade rules may differ from the table above. The local jurisdiction always needs to be followed.
- Wood to steel connections may require a minimum corrosion protection, independent of the environmental conditions.
5. Steel base material

5.1 Anchoring mechanisms

The following four mechanisms cause a DX- / GX-fastener to hold when driven into steel:
- clamping
- keying
- fusing (welding)
- soldering

These mechanisms have been identified and studied by analyzing pull-out test data and by microscopic examination of fastening cross-sections.

Clamping

As a fastener is driven, the steel is displaced radially and towards both the entry and opposite surfaces. This results in residual pressure on the surface of the nail, which leads to friction or clamping. Clamping is the primary anchoring mechanism of through-penetrating fasteners. This is indicated by the fact that when through-penetrating fasteners are extracted, the pull-out force decreases only slowly over several millimeters of displacement.

Keying

The keying mechanism is possible when the fastener is knurled, that is, it has fine grooves along the shank in which zinc and particles of base steel accumulate during the driving process. Microscopic examination of cross sections has shown that the grooves are not completely filled. Keying is an especially important anchoring mechanism for fasteners that do not penetrate right through the base material.
**Fusing (welding)**
Complete fusing of the fastener with the base steel is indicated by portions of base material clinging to the extracted fastener as well as by the decarbonized zone. Fusing or welding is observed mostly at the point of a fastener where the temperature during driving can be expected to be the highest. For fasteners that do not through-penetrate, this is an important anchoring mechanism. It can be relied upon only if the fastener point is manufactured without cracks and with an appropriate geometry. The thermo pulling process is ideal for achieving an optimized geometry. Control of all steps in the production process is necessary to avoid cracks in the point.

**Soldering**
In the zone further from the point, there is a prominent zinc layer separating the fastener from the base steel. This zinc, soldered to the base steel, also makes a contribution to the pull-out resistance of the fastener.

**Blunt-tipped fastener X-BT**
The X-BT fastener with a shank diameter of 4.5 mm is driven in a pre-drilled 4.0 mm diameter hole. This leads to displacement of the base material. Part of the base steel is punched down into the pre-drilled hole, generating high temperatures and causing friction welding. Due to elasticity of the base steel, additional clamping effects are also superposed. Displaced base material can be clearly seen in the photograph. Base material adhering to the fastener shank indicates a welding effect.
5.2 Factors influencing pull-out resistance

Powder-actuated fastening systems must be designed and manufactured to ensure that pull-out resistance will be adequate for the applications intended. Through understanding of the anchoring mechanisms, experience and testing, factors that influence pull-out strength have been identified. Some of these factors are:

- Depth of penetration in the base material
- Surface characteristics of the fastener
- Coatings on the steel base material
- Driving velocity
- Diameter of the fastener shank

Knowledge of the influencing factors is vital to the design of fastening systems and is useful for operators in understanding the various application guidelines and restrictions that apply to a fastening system. Some of the influencing factors are discussed in the following section.

Depth of penetration in the base material

The depth of penetration of fasteners in steel is taken as the distance that the point travels below the surface of the base steel, independent of the steel thickness. In other words the depth of penetration $h_{ET}$ can be greater than, equal to or less than the steel thickness. Resistance to pull-out increases with increasing depth of penetration. This is also true for through-penetrating fasteners where $h_{ET}$ is greater than the steel thickness. The design of a powder-actuated fastener has to take into account the depth penetration necessary to achieve the pull-out resistance required for the application. Application guidelines published for any fastener include the required nail head stand off $h_{NVS}$, which corresponds to the penetration depth.
Guide values for the depth of penetration of specific fastener types are as follows:

Galvanized fastener with knurled shank: \( h_{ET} = 12 \text{ to } 18 \text{ mm} \) (shank diameter 4.5 mm)
\( h_{ET} = 10 \text{ to } 14 \text{ mm} \) (shank diameter 3.7 mm)

Galvanized fastener with knurled tip: \( h_{ET} = 9 \text{ to } 13 \text{ mm} \) (shank diameter 4.5 mm)

Galvanized fastener with smooth shank: \( h_{ET} = 15 \text{ to } 25 \text{ mm} \)

Stainless steel fastener with smooth shank: \( h_{ET} = 9 \text{ to } 14 \text{ mm} \)

Blunt-ended fasteners: \( h_{ET} = 4 \text{ to } 5 \text{ mm} \)

The effect of penetration depth on pull-out strength can be demonstrated in experiments in which the driving energy is varied so as to produce varying penetration. The results of a test of this kind are summarized below. The application recommendations for fasteners are based on tests like these and they clearly show the importance of carrying out the fastening work in accordance with the recommendations of the manufacturer.

Steel: \( t_U = 20 \text{ mm (0.787")} \)
\( f_u = 630 \text{ N/mm}^2 \) (91.000 psi)

Tool: DX 76 / DX 76PTR and DX 860-ENP

Fastener: X-ENP-19 L15
Knurling on the fastener shank

Fasteners for use in steel base material usually have knurling on the shank so as to improve the resistance to pull-out. The effect of the knurling was shown in a test with fasteners that had knurled and unknurled shanks, but were otherwise the same.

The benefit of knurling is clearly seen from the test results. With virtually the same penetration (actually 106%), the smooth-shank fastener had only 68% of the pull-out strength of the knurled-shank type. Even with the penetration increased to 137%, the pull-out strength was still only 81% of that of the knurled-shank fastener. In this test, the steel thickness of 10 mm (0.394") allowed through penetration of the steel. If the steel is too thick for through penetration, the beneficial effect of knurling becomes even more pronounced.

Zinc coating on the fastener shank

Zinc on a fastener shank appears to act as a lubricant that reduces its resistance to penetration into steel. Reduced pull-out strength results because the lower resistance means less heat is generated, thus reducing the welding effect between the shank and the base steel. This was shown in an experiment with fasteners that were identical except for the thickness of zinc coating.

<table>
<thead>
<tr>
<th>Zinc thickness in mm</th>
<th>Average penetration $h_{ET}$ [mm / [in.]]</th>
<th>%</th>
<th>Average ultimate pull-out load $N_{u,m}$ [kN / [kip]]</th>
<th>%</th>
<th>Variation CV %</th>
</tr>
</thead>
<tbody>
<tr>
<td>ca. 10</td>
<td>12.12 [0.477]</td>
<td>100</td>
<td>8.53 / [1.918]</td>
<td>67</td>
<td>25.6</td>
</tr>
<tr>
<td>2–5</td>
<td>11.86 [0.470]</td>
<td>98</td>
<td>12.82 / [2.882]</td>
<td>100</td>
<td>9.3</td>
</tr>
</tbody>
</table>

Although driving the fastener through sheet metal, as is the case when fastening siding and decking, reduces the negative effect of zinc coating on pull-out strength, the reason for tightly controlling the galvanization process is clear.
Surface of the steel base material
Corrosion protection of structural steel is often achieved by hot-dip galvanizing. Tests have shown that if the fastener penetrates right through the steel, the galvanizing has no significant effect on pull-out strength. In the case of fasteners that do not through-penetrate, pull-out strength is reduced by about 25%. The summary of results from one test is shown below to illustrate these effects.

Average ultimate pull-out loads

Several important observations can be made based on these results:

- Pull-out loads in 6 mm (¼") steel base material are much less affected by the surface condition of the steel than they are in 20 mm (¾") steel. The reason is that the main anchoring mechanism of through-penetration fastenings is clamping, which is not affected by the surface condition of the steel.

- Hot-dip galvanizing appears to reduce the pull-out strength of non-through-penetrating fastenings by nearly 30%. Note, however, that even with hot-dip galvanizing, the pull-out strength was still 12.5 kN (2.8 kips).

- The negative effect of hot-dip galvanizing is explained by the tendency of zinc on the fastener to act as a lubricant that reduces heat generation during driving. This in turn reduces the tendency of the fastener point to fuse to the base steel. Zinc from the coating on the base steel apparently becomes attached to the fastener as it enters the base steel.

For applications where tensile strength of the fastening is critical and the steel has a heavy coating, the fastening system can be qualified by carrying out pull-out tests on site. If pull-out strength is not adequate, depth of penetration can be increased to improve the situation.
**Tensile stress in the steel**

The integrity of a powder-actuated fastening is dependent on a relatively smooth pin remaining anchored in structural steel. A large amount of test data, technical assessments, approvals and practical experience with powder-actuated fastenings is available to support use of powder-actuated fastening. Performance of fasteners anchored in the steel under tension was investigated by driving fasteners into unstressed steel plates and extracting them with the plates stressed in tension. The steel plates measured $6 \times 80 \times 455 \text{ mm} [0.236" \times 3.15" \times 17.9"]$ and possessed two different yield stresses - 328.6 MPa [47.7 ksi] and 411.7 MPa [59.7 ksi].

By expressing the steel stress in terms of % of actual yield, it was possible to combine the data for both steel grades and obtain a reasonable curve fit.

Of significance to the designer is the expected decrease in pull-out strength of the fastener at a typical maximum allowable design stress of 60 to 70 % of yield. At this stress, the pull-out strength reduction is less than 15%. The absolute value in the experiment was still greater than 2 tons.
Compressive stress in the steel
Compressive stress in the base steel has no influence on the pull-out strength of the fastener. This was demonstrated by placing fasteners in unstressed 15 mm [0.59"] thick steel plates having a yield strength of 259.3 MPa [37.6 ksi] and extracting them while the plates were compressed in a testing machine.

The minimal variation in pull-out load is simply random variation experienced in testing.

5.3 Suitability of the steel for fastening
There are three main factors determining the suitability of a construction grade steel member for DX fastening:
• Steel thickness
• Ultimate tensile strength
• Flexibility of the base steel member
5.4 Application limit diagrams

The application limit of a fastening system is a term applied to a combination of the maximum thickness $t_{II}$ and ultimate tensile strength $f_u$ of steel in which fastenings can be made. There are two general types of application limit diagrams:

- Short fasteners (e.g. siding and decking nails and threaded studs)
- Long fasteners (e.g. nails used to fasten wood to steel)

The application limit line for a short fastener is a plot of steel thickness versus ultimate tensile strength. In situations represented by steel thickness / ultimate tensile strength combinations above and to the right of the line, some of the fasteners may shear off during driving. The failure surface will be roughly at a 45° angle to the shank length.

The application limit lines for long nails used to fasten wood to steel are plots of nail shank length $L_s$ versus steel thickness $t_{II}$. Each line is valid only for one ultimate tensile strength of steel $f_u$. Attempts at working to the right of the limit line result in buckled nail shanks.
### 5.5 Thin steel base material

In the context of powder-actuated fastening, steel is considered thin when flange deformation during driving dominates fastener design. When the steel flange is thinner than about 6 mm [0.25"], flange deformation makes use of fasteners with a 4.5 mm [0.177"] shank diameter more difficult and switching to a 3.7 mm [0.145"] shank fastener leads to better results. Use of fasteners with tapered shanks and energy-absorbing washers improves performance and reliability.

A fastener can penetrate into steel only when the steel (flange) develops a resistance greater than the force required for penetration. This implies the use of energy in excess of that required for penetrating into the steel. In fact, if the driving energy remains constant, fasteners placed closest to the web will be driven deepest. All siding and decking fasteners should have a mechanism to clamp the sheets down tightly over the entire range of allowable standoffs. This is especially critical for fasteners used for fastening to thin steel.

Obviously, under shear loading, failure of the base material is more likely with thin steel than with thick steel. When approving fastening systems for a project, it is important to consider whether the system has actually been tested with thin base steel or not.

Hilti’s general recommendation for thin base steel fasteners is to place the fastenings within $b_x = 8 \times t_{ll}$ of the web.
5.6 Types of load and modes of failure

5.6.1 Shear loads
The shear loads acting on siding and decking fasteners come from:
- Diaphragm action of the fastened sheets
- Forces of constraint (for example due to temperature changes)
- Self-weight of siding material

Testing
Shear testing of siding and decking fastenings is done using specimens made up of a strip of sheet metal fastened to a steel plate. Suitable, non-slip fixtures have to be used at either end. In some cases specimens are bent up at the sides to hinder eccentricity.

Failure of the fastened material
The load-deformation curves of shear tests with powder-actuated fasteners show a nearly ideal behavior. After an initial elastic phase during which the clamping force of the washers against the sheet metal is overcome, the sheet metal reaches its yield stress in an area where the fastener bears against it. Then the fastener shank cuts through the sheet metal until the end of the sheet is reached. The large area under the load-deformation curve represents energy absorbed, and this is what makes the fastening method ideal for diaphragms.
Failure of the base steel
If the thickness of the fastened sheet metal is large compared to the base steel thickness, bearing failure of the base material is a possible mode of failure.

Pull-out from the base steel
The unavoidable eccentricity in the shear test specimen leads to a tensile load component on the fastener. Thick fastened material and thin base material is also involved in this mode of failure. This failure mode is generally not governing for base material thickness of $t_H > 6$ mm.

Fracture of the fastener
About 20 kN (4.5 kips) of force is required to shear the Ø 4.5 mm (0.177") shank of an X-ENP-19 L15 fastener. With about 2.5 mm (12 gauge) thick steel sheet as fastened material, a force of this magnitude could be possible. The force needed to break a Ø 3.7 mm (0.145") shank of an X-EDNK22 THQ12 fastener is about 13 kN (2.9 kips). This force can be generated with 1.5 mm (16 gauge) sheet steel. In practice, this failure mode is likely only where expansion joints are not provided to relieve forces of constraint from temperature differences.

5.6.2 Tensile loads
The most common source of tensile loading on siding and decking fasteners comes from wind suction acting on the roof or wall cladding. In diaphragms, fasteners can be subject to tensile loads in situations where the combination of geometry and thickness of decking fastened leads to prying. In designs with very stiff decking and wide beams or unbalanced spans, prying can also be caused by concentrated loads.
**Testing**

Tensile testing of siding and decking fastenings is carried out using specimens made up of a trapezoidal-shaped piece of sheet metal fastened to a steel plate. Suitable, vice-like fixtures are used to grip the specimen. This is often referred to as a pull-over test because the common failure mode is the sheet pulling over the washers or the head of the fastener. If the sheet thickness fastened is increased so that pull-over does not govern, pull-out will be the failure mode.

Some fasteners like the Hilti X-ENP have a head that can be gripped and pulled out by a suitable fixture. With these fasteners, a pull-out test can still be done even if pull-over is the original mode of failure. This fastener type has the further advantage of allowing in-place fasteners on a jobsite to be tested.

**Sheet pull-over**

In this failure mode, the sheet tears and is lifted up over the fastener head and washers. Depending on the sheet thickness and tensile strength, the washers may be bent up.

**Washer pull-over**

Another possible failure mode is that of the washers being pulled up over the head of the nail. Obviously, this happens when the sheet is somewhat stronger and/or thicker than when sheet pull-over occurs. This failure mode is also heavily dependent on fastener design.
Pull-out from the base steel

As sheet thickness and number of layers is increased, this failure mode becomes more likely. For a properly driven X-ENP-19 L15 pull-out from the base steel is not a likely mode of failure. The head and washer design of the HSN24 or X-EDNK22 THQ12 fasteners can allow this failure mode, especially with multiple layers of sheets.

Fracture of the fastener

A force of more than 30 kN [6.7 kips] is required to break the Ø 4.5 mm [0.177"] shank of an X-ENP-19 L15 fastener and, even if sheet or washer pull-over does not govern, pull-out strengths of this magnitude are not very common. This mode of failure will therefore hardly ever occur with these heavy-duty fasteners. The Ø 3.7 mm [0.145"] shank of an X-HSN 24 or X-EDNK22 THQ12 fastener may break at about 20 kN [4.5 kips] tension. Since these smaller fasteners will pull out at a force of 8 to 15 kN [1.8–3.3 kips], fractures due to tensile loads are rare. If fractured fasteners of this type are found on a jobsite, the most likely cause is that the application limit has been exceeded (the base steel is too hard and/or too thick for the pin).

Cyclic loading

Siding and decking nails used in wall and roof construction are subject to cyclic loading from wind suction. Cyclic load testing is carried out to determine characteristic resistance and allowable (recommended) loads. The approval requirements of the European Technical Approval ETA prepared by DIBt (Deutsches Institut für Bautechnik) govern the design-relevant number of load repetitions (5,000) and the necessary safety factors. Notes in this regard are found on the corresponding product data sheets.

If the fastener will be subjected to a large number of load repetitions and fatigue, we recommend carrying out a design check according to the requirements of Eurocode 3 (or similar code). Eurocode 3 gives the characteristic fatigue resistance and safety concept for steel
construction. To carry out the check according to Eurocode 3 it is necessary to have a statistical analysis of test data obtained under the application conditions. Except for siding and decking fasteners, the applicable product data sheets limit the validity of recommended loads to predominantly static loading. If a design analysis has to be carried out for true fatigue loading, test data can be obtained from Hilti. Examples of such data are shown below.

**X-EM8-15-14**
*(standard zinc-plated fastener)*
The X-EM8-15-14 has a shank diameter of 4.5 mm and a hardness of HRC 55.5 $(f_u = 2,000 \text{ MPa})$. The $\Delta F$-$N$ diagram shows the load range $\Delta F$ for a lower load of 0.05 kN. The individual test results are displayed as points and the curves show average and characteristic (95% survival probability) values. The failure mode was shank fracture or fracture in the M8 threading. The recommended load for predominantly static loading is 2.4 kN. Comparing this value to the $\Delta F$-$N$ diagram will lead to the conclusion that X-EM8-15-14 fastenings designed for 2.4 kN static loading will survive a large number of load repetitions. The fastenings can be said to be robust, even when the actual loading turns out to be in part cyclic.
X-CRM8-15-12 (stainless steel fastener)
The X-CRM8-15-12 has a shank diameter of 4.0 mm and a minimum ultimate tensile strength of 1,850 MPa. The \(\Delta F\)-N diagram shows the load range \(\Delta F\) for a lower load of 0.05 kN. The individual test results are displayed as points. The failure mode was shank fracture or fracture just below the head of the stud.
The recommended load for predominantly static loading is 1.8 kN. Comparing this value to the \(\Delta F\)-N diagram will lead to the conclusion that X-CRM8-15-12 fastenings designed for 1.8 kN static loading will survive a large number of load repetitions. The fastenings can be said to be robust, even when the actual loading turns out to be in part cyclic.

Mode of failure under cyclic loading
A major finding of cyclic loading tests is that the strength of a DX fastening subject to cyclic loading is not limited by failure of the anchorage. It is only when the number of cycles is very low – i.e. predominantly static loading – that nail pull-out is observed. The two schematic diagrams below show the relationship between failure mode and number of cycles. All tests show that the anchorage of DX fasteners in steel and in concrete is extremely robust with regard to resisting cyclic loading. Fasteners subject to a large number of load repetitions fracture in the shank, head or threading. A condition for obtaining this behaviour is that the fasteners are correctly driven. Fasteners that are not driven deeply enough exhibit low pull-out strength and in a cyclic loading test may not necessarily fail by fracture.
In older product information and data sheets, this basic suitability of DX fasteners for cyclic loading was emphasized by defining the recommended loads as cyclic recommended loads. At the time that this product information was assembled, a true safety concept for a strict check of DX fastenings subject to fatigue loading was not available. With Eurocode 3, this is today available. If a fatigue design analysis is carried out, it is important – as with static design – that adequate redundancy be provided.

**Failure of the sheet**
In cyclic load tests, failure of the steel sheet itself is common.
5.7 Effect of fasteners on structural steel

Driving powder- or gas-actuated fasteners into a steel member does not remove steel from the cross-section, but rather displaces steel within the cross-section. It is therefore not surprising that tests like those described in following sections show that both drilled holes and screws, either self-drilling or self-tapping, reduce the strength of a cross-section more than powder-actuated fasteners.

The results of the tests can also be used to show that it is conservative to consider a powder-actuated fastener as a hole. This allows the effect of fasteners in a steel member subject to static loading to be taken into consideration.

Fatigue seldom needs to be considered in building design because the load changes are usually minor in frequency and magnitude. Full design wind and earthquake loading is so infrequent that consideration of fatigue is not required. However, fatigue may have to be considered in the design of crane runways, machinery supports, etc. The S-N curves resulting from fatigue tests of steel specimens with fasteners installed are also presented.

5.7.1 Effect on the stress-strain behaviour of structural steel

The effect that powder-actuated fasteners (PAF’s) have on the stress-strain behaviour of structural steel was investigated in a systematic test programme using tensile test specimens containing PAF’s, self-drilling screws and drilled holes. A control test was carried out using specimens without any holes or fasteners.

Series A:
- ASTM 607, grade 50
- Cross-section 3.42 x 74 mm [0.135 x 2.913”]
- X-EDNK22 powder-actuated fasteners, shank diameter 3.7 mm [0.145”]
- Drilled holes, diameter 3.7 mm [0.145”]
- Self-drilling screws, shank diameter 5.5 mm [0.216”]

Series B:
- S235 and S355 steel
- Cross-section 6 x 45 mm [0.236 x 1.772”]
- Powder-actuated fasteners, shank diameter 4.5 mm [0.177”]
- Drilled holes, diameter 4.5 mm [0.177”]
The figures below show representative stress-strain curves for the tests (the plotted stress is based on the gross cross-section). Note that the line for the powder-actuated fasteners follows the control test line more closely than the lines for drilled holes or self-drilling screws.

The test results were evaluated in terms of utilization as a measure of ultimate strength. Utilization is the ultimate load of a sample expressed as a percent of the ultimate load of the control test.

Graphs of the utilization versus cross-section reductions show that:
- The utilization for PAFs is clearly better than that of drilled holes or self-drilling screws.
- The hole left by a removed PAF has the same effect as when the PAF is left in place.
- Increasing the number of PAFs across a section from one to two or more has a proportionally smaller effect on utilization than placement of the first fastener.
More detailed information on the test program and findings is published in the paper *Powder-activated fasteners in steel construction* (and the referenced literature), published in the STAHLBAU-Kalender 2011 (Publisher Ernst & Sohn, 2011, ISBN 978-3-433-02955-8). English Reprints of the paper can be distributed per request.

### 5.7.2 Effect on the fatigue strength of structural steel

During the late 1970s and early 1980s, a fatigue testing program consisting of 58 tests with over 1,100 specimens was carried out at the University of Darmstadt in Germany. The reason for the research at that time was to support the use of powder-activated fasteners for attaching noise-dampening cladding to railway bridges in Germany.

Parameters investigated in those tests are shown in following table:

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Steel thicknesses</th>
<th>Stress ratio R</th>
<th>Imperfections</th>
</tr>
</thead>
<tbody>
<tr>
<td>S 235 (St 37) / A36</td>
<td>6, 10, 15, 20, 26.5, 40, 50 mm</td>
<td>0.8, 0.5, 0.14, -1.0, -3.0</td>
<td>Fastener:</td>
</tr>
<tr>
<td>S 355 (St 52) / grade 50</td>
<td>[0.236, 0.394, 0.591, 1.043, 1.575, 1.969&quot;]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Loading conditions**

The terminology and notation is shown in the illustration below.
Fasteners tested

The primary fastener used in the tests was the Hilti ENP3-21 L15, the forerunner of the ENP2-21 L15. The difference is in the head shape, which has no effect on interaction with the base steel. Tests were also performed with the ENP2-21 L15, ENP3-21 D12 and the EM8-11-14 threaded stud, all of which have 4.5 mm diameter knurled shanks.

The results of the tests were evaluated by Niessner and Prof. T. Seeger from the University of Darmstadt in accordance with the provisions of Eurocode 3. An example plot of one test series is given at the right. The graph allows for a comparison with European fatigue categories 90 (m = 3) and 100 (m = 5) as well as American categories according to AWS-provisions.

Conclusions

- The effect of driving a Hilti powder-actuated fastener on the fatigue strength is well known and predictable.
- The constructional detail “Effect of powder-actuated fasteners on base material” (unalloyed carbon steel) was evaluated by Niessner and Seeger from the University of Darmstadt in compliance with Eurocode 3.
- The EC 3 detail category 90 with m = 3 or the detail category 100 with m = 5 is alternatively applicable.
- Wrong fastener installations as popped out or inclined fasteners are covered. Piston marks in the base material due to wrong use of the tool without a fastener or notches due to fasteners failed during the installation have to be removed by appropriate measures.
More detailed information on the evaluation of the test data and the test program is published in the paper “Fatigue strength of structural steel with powder-actuated fasteners according to Eurocode 3” by Niessner M. and Seeger T. (Stahlbau 68, 1999, issue 11, pp. 941-948).

English reprints of this paper can be distributed per request.
6. Concrete base material

6.1 Anchoring mechanisms
The following three mechanisms cause a DX-/GX-fastener to hold in concrete:
- Bonding / sintering
- Keying
- Clamping
These mechanisms have been identified and studied by analyzing pull-out test data and by microscopic examination of pulled-out fasteners and the concrete to fastener interface.

Bonding / sintering
When driving a fastener into concrete, the concrete is compacted. The intense heat generated during driving causes concrete to be *sintered* onto the fastener. The strength of this sintered bond is actually greater than that of the *clamping* effect due to reactive forces of the concrete on the fastener.
The existence of the sintered bond is demonstrated by examining pulled-out fasteners. The fastener surface, especially in the region of the point, is rough due to sintered-on concrete, which can only be removed by using a grinding tool.
When performing pull-out tests, the most common failure mode is breakage of the sintered bond between the concrete and the fastener, especially at and near the point.

Keying
The sintered material forms ridges on the fastener surface. These ridges result in a micro-interlocking of the fastener and the concrete.
This anchoring mechanism is studied by examining pulled-out fasteners under a microscope. As in the case of sintering, keying is primarily active in the region of the fastener point.
**Clamping**
The compressibility of concrete limits the buildup of compressive stress around the driven fastener. This in turn limits the effectiveness of clamping as an anchoring mechanism.

**Concrete failure**
Concrete cone failure is occasionally observed when using a testing device with widely spaced supports. The fact that the concrete failed indicates that the fastener bond to the concrete was stronger than the concrete.

The tendency of stressed concrete to relax further reduces the compressive stress and hence the clamping effect. For these reasons, clamping of the fastener shank contributes only insignificantly to the total pull-out strength.
6.2 Factors influencing resistance to pull-out

Factors that can affect the pull-out strength of fastenings to concrete include:
- Depth of penetration into the concrete
- Concrete parameter (compressive strength, grain structure, direction of concrete placement)
- Distance to concrete edge and fastener spacing

**Depth of penetration \( h_{ET} \)**

Fasteners that are driven deeper typically have a higher resistance to pull-out. This relation is best shown by placing groups of fasteners with different driving energy and comparing the results for each group with the others. The result of such a test is shown in the graph at the right. Note that fastener driving failures were not considered in calculation of the average ultimate load, \( N_{u,m} \).

The value of increasing the depth of penetration in order to increase pull-out strength is limited by the increasing fastener driving failure rate. Provided that the penetration depth is the same, fastenings in concrete with a higher compressive strength hold better than fastenings in lower strength concrete. The ability to exploit this characteristic is also limited by increased fastener driving failure rate with higher strength concrete. As could be expected, the depth of penetration at which the failure rate is at a minimum decreases with increasing concrete strength.

Pull-out strength and fastener driving failure rate both increase with increasing penetration depth. The optimum depth of penetration is taken as the depth at which the yield in terms of pull-out strength begins to decrease. This is within a range of 18–32 mm depending on the grade and age of the concrete as well as the strength of the fastener.

\[
\text{yield} = N_{u,m} \cdot \left( \frac{100 - p}{100} \right)
\]
Concrete parameters
The concrete parameters (such as the type and size of concrete aggregates, type of cement and the location on top or bottom surface of a concrete floor) do affect the fastener driving failure rate, sometimes significantly.

Fastener driving failures are caused by the fastener hitting a hard aggregate, such as granite, located close to the concrete surface. A hard aggregate can deflect the fastener and in a severe case, the fastener may bend excessively, leading to concrete fracture in a cone shape and no hold being obtained by the fastener.

In case of slight fastener bending, concrete spalling may occur at the surface. However, because pull-out strength is obtained mostly in the area of the fastener point, concrete spalling does not affect the permissible load of the DX-/GX-fastening.

Softer aggregates such as limestone, sandstone or marble may be completely penetrated when hit by the fastener.

Overhead fastening is usually associated with a higher rate of fastener driving failure than floor fastening. This is due to the distribution of the aggregates within the concrete. Large aggregates tend to accumulate at the bottom of a floor slab. At the top, there is a greater concentration of small aggregates and fines.
There are several possible ways of reducing the failure rate when powder-actuated fasteners are used for fastening to concrete. There are two basic ideas: one is to reduce concrete tensile stresses near the surface and the other is to delay the effect of these stresses.

**Pre-drilling the concrete (DX-Kwik)**
By pre-drilling a very small hole (5mm diameter, 18 or 23 mm deep), the stresses are relocated to greater depth in the concrete. Fasteners placed with DX-Kwik are surrounded by a stress “bulb” located deep in the concrete. With this method, virtually no fastener driving failures occur.

**Spall stop fastener guide**
A spall stop is a heavy steel fastener guide. Its weight and inertia counteract the stresses at the surface for a very short time. This allows redistribution of the stresses to other parts of the concrete.

Changing from a long to a short fastener reduces the magnitude of the stresses and thus the rate of fastener driving failure.
**Edge distance and fastener spacing**

If fasteners are placed too close to the concrete edge, pull-out load capacity will be reduced. Minimum edge distances are therefore published with a view to reducing the effect edges have on pull-out strength. The corresponding data has been obtained from tests and analysis and is given in part 2 of this manual.

Additional provision is made for fastener spacing when positioned in pairs or where fasteners are placed in rows along a concrete edge. These edge distances and spacing also have the purpose of helping to prevent concrete spalling and/or cracking due to fastening. However, spalling has generally only an insignificant influence on pull-out strength.

**6.3 Effect of time on pull-out resistance**

The effect of age on pull-out strength has been investigated in comprehensive tests. The main concern is, in fact, the effect of concrete relaxation in the area around the driven fastener.

This graph provides an overview of tests performed with DX-Kwik fasteners. Since standard DX fastenings have the same anchoring mechanism, this statement is also valid for standard DX fastenings. The test results indicate very strongly that relaxation of the concrete has no detrimental effect on the pull-out resistance of DX fastenings. The test data also shows that sintering and keying are the dominant anchorage mechanisms because they do not rely on friction between the fastener and the concrete.
6.4 Effect on concrete components

Fastenings in the compression zone of the structure have no effect on concrete compressive resistance as long as detailed provisions on edge distance and spacing are complied with.

Fastenings in the tensile zone are subject to the following provisions:

a. Installations on plain load-bearing components such as concrete walls or ceilings are generally possible without restrictions as the load-bearing behaviour of these components is only negligibly affected by the fasteners. The predominant condition is static loading. This statement is based on experimental investigations carried out at the Technical University of Braunschweig, Germany.

b. Fastenings in reinforced concrete beams: it has to be ensured that the main reinforcement steel will not be hit or penetrated by the DX fasteners. This measure of precaution is mainly founded on the reduction of the ultimate strain of the steel reinforcement. Exceptions are possible when the structural engineer responsible for design is consulted.

c. Fastenings in pre-stressed concrete members: it has to be ensured that the pre-stressing steel reinforcement or cables will not be hit or penetrated by the DX fasteners.

If the concrete is too thin, concrete will spall off on the rear surface. The minimum thickness of concrete depends on the shank diameter of the fastener used.

<table>
<thead>
<tr>
<th>Fastener shank diameter $d_{nom}$ (mm)</th>
<th>Minimum concrete thickness $h_{min}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>60</td>
</tr>
<tr>
<td>3.5 / 3.7</td>
<td>80</td>
</tr>
<tr>
<td>4.5</td>
<td>100</td>
</tr>
<tr>
<td>5.2</td>
<td>100</td>
</tr>
</tbody>
</table>
7. Masonry base material

7.1 General suitability

Direct fastening technology can also be used on masonry. The joints between bricks or blocks and the covering plaster layer on virtually all types of masonry (exception for lightweight aerated concrete blocks) provide an excellent substrate for light-duty and secondary fastenings.

Suitability table: DX fastening on masonry

<table>
<thead>
<tr>
<th>Masonry material</th>
<th>Unplastered masonry (joint width ≥ 10 mm)</th>
<th>Fastenings in masonry blocks or bricks</th>
<th>Plastered masonry (thickness ≥ 20 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clay brick</td>
<td></td>
<td>Clay brick</td>
</tr>
<tr>
<td></td>
<td>solid</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>vertical perforated</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>horizontally perforated</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Clay clinker</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>solid</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>vertical perforated</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Sand-lime block</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>solid</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>perforated</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>hollow</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Aerated concrete</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Lightweight concrete</td>
<td></td>
<td>Lightweight concrete</td>
</tr>
<tr>
<td></td>
<td>solid</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>hollow</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Hollow concrete</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Slag aggregate</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>solid</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>perforated</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>hollow</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

++ suitable + limited suitability – not fully investigated — not suitable

*) Joints must be completely filled with mortar

The above table is based on laboratory and field experience. Because of the wide variety of types and forms of masonry in use worldwide, users are advised to carry out tests on site or on masonry of the type and form on which the fastenings are to be made.
8. Temperature effects on the fastening

8.1 Effect of low temperatures on fasteners

Steel tends to become more brittle with decreasing temperature. Increased development of natural resources in Arctic regions has led to the introduction of steels that are less susceptible to brittle failure at subzero temperatures. Most siding and decking fasteners are used to fasten the liner sheets of an insulated structure and are not exposed to extremely low temperatures during service. Examples of situations where the fastenings are exposed to extremely low temperatures during their service life are:

- Fastenings securing cladding in single-skin construction
- Construction sites left unfinished over a winter
- Liner sheets in a cold-storage warehouse

Low temperature embrittlement

The susceptibility of fasteners to become brittle at low temperatures can be shown by conducting impact bending tests over a chosen temperature range. The ability of Hilti drive pins to remain ductile over a temperature range from +20°C to −60°C is shown clearly by the fact that the impact energy required remains nearly constant throughout this temperature range.

### Impact bending test - DSH57 (4.5 mm diameter, HRC 58 ± 1)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Impact energy (foot-pounds)</th>
<th>Impact energy (Joules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>°F</td>
<td>°C</td>
<td>minimum</td>
</tr>
<tr>
<td>68</td>
<td>20</td>
<td>35.1</td>
</tr>
<tr>
<td>32</td>
<td>0</td>
<td>35.8</td>
</tr>
<tr>
<td>−4</td>
<td>−20</td>
<td>31.4</td>
</tr>
<tr>
<td>−40</td>
<td>−40</td>
<td>34.4</td>
</tr>
<tr>
<td>−76</td>
<td>−60</td>
<td>35.6</td>
</tr>
</tbody>
</table>

### Impact bending test - X-CR (4.0 mm diameter)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Impact energy (foot-pounds)</th>
<th>Impact energy (Joules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>°F</td>
<td>°C</td>
<td>minimum</td>
</tr>
<tr>
<td>68</td>
<td>20</td>
<td>14.8</td>
</tr>
<tr>
<td>32</td>
<td>0</td>
<td>17.7</td>
</tr>
<tr>
<td>−4</td>
<td>−20</td>
<td>14.8</td>
</tr>
<tr>
<td>−40</td>
<td>−40</td>
<td>16.2</td>
</tr>
<tr>
<td>−76</td>
<td>−60</td>
<td>14.2</td>
</tr>
</tbody>
</table>
Impact bending test - X-CR (3.7 mm diameter)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Impact energy (foot-pounds)</th>
<th>Impact energy (Joules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>°F</td>
<td>°C</td>
<td>minimum</td>
</tr>
<tr>
<td>68</td>
<td>20</td>
<td>11.5</td>
</tr>
<tr>
<td>32</td>
<td>0</td>
<td>12.9</td>
</tr>
<tr>
<td>4</td>
<td>-20</td>
<td>13.1</td>
</tr>
<tr>
<td>-40</td>
<td>-40</td>
<td>14.2</td>
</tr>
<tr>
<td>-76</td>
<td>-60</td>
<td>12.3</td>
</tr>
</tbody>
</table>

Tests conducted according to DIN EN 10045 parts 1–4
Distance between supports = 22 mm
The symbol “>” indicates no breakage of the specimens. In the other cases, about 50% of the specimens suffered breakage.

8.2 Effect of low temperatures on fastenings to steel

Effect of low temperatures on pull-out strength

Tests show that very low temperatures tend to increase pull-out strength with both standard zinc-plated fasteners and with the stainless steel. The results of two tests are summarized below. The fasteners were driven at room temperature and tested at −40°C to −70°C. A control sample was tested at 20°C. Explanations for the greater strength at low temperatures include increase in the strength of the zinc that is displaced into the knurling as well as increased strength of the fusing at the point of the fastener.

Base steel: S355K2G3
h = 25 mm
f_y = 402 MPa
f_u = 538 MPa

Fastened material: sheet steel, 2 x 1 mm
Tool: DX 750
Fastener: ENPH2-21 L15

Impact bending test - X-CR (3.7 mm diameter)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Impact energy (foot-pounds)</th>
<th>Impact energy (Joules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>°F</td>
<td>°C</td>
<td>minimum</td>
</tr>
<tr>
<td>68</td>
<td>20</td>
<td>11.5</td>
</tr>
<tr>
<td>32</td>
<td>0</td>
<td>12.9</td>
</tr>
<tr>
<td>4</td>
<td>-20</td>
<td>13.1</td>
</tr>
<tr>
<td>-40</td>
<td>-40</td>
<td>14.2</td>
</tr>
<tr>
<td>-76</td>
<td>-60</td>
<td>12.3</td>
</tr>
</tbody>
</table>

Tests conducted according to DIN EN 10045 parts 1–4
Distance between supports = 22 mm
The symbol “>” indicates no breakage of the specimens. In the other cases, about 50% of the specimens suffered breakage.
Two facts stand out from this testing:

- **Pull-out strength increased as temperature decreased**
- **Pull-out from the base steel was the only mode of failure observed. There were no fractures!**
8.3 Fire rating of fastenings to steel

Standard zinc-plated, thermally hardened steel fasteners

When subjected to high temperatures as in a fire, both powder-actuated fasteners and structural steel lose strength. Data for standard zinc-plated, thermally hardened fasteners and structural steel are plotted in the graph below.

Up to about 300°C [572°F], the strength loss for DX fasteners is roughly proportional to the yield strength loss of structural steel. At 600°C [1112°F], DX fasteners have about 12% of their 20°C [68°F] strength left and structural steel about 26%. Since DX fasteners obtain their high strength through a thermal hardening process, the loss in strength at elevated temperatures is proportionally greater than for structural steel. The relevance of different strength losses has to be evaluated in the context of the proportion of the material strengths that are actually exploited in a design. In a design calculation, it is conceivable that some steel will actually reach yield stress. The material strengths of an X-ENP-19 L15 fastener is 30 kN [6.74 kips] in tension and 18.6 kN [4.18 kips] in shear respectively. The recommended working load in tension and shear for an X-ENP-19 L15 16 gauge (1.5 mm) fastening is 4.7 kN [1.057 kips] in tension and 4.6 kN [1.034 kips] in shear, respectively. Thus, the exploitation of the X-ENP-19 L15 strength at about 600°C is only 16 to 25% compared to about 74% for structural steel.

In a fire, powder-actuated fastenings will not be the governing factor. If the fire protection requirements permit the use of structural steel, then powder-actuated fastening can also be used without negative impact on fire protection.
**CR500 stainless steel fasteners**

Hilti X-CR/X-CRM fasteners are much more resistant to loss of strength at high temperatures than standard fasteners. The effect of temperature on ultimate shear stress of X-CR/X-CRM/X-BT fasteners was determined in single lap joint shear tests by the Swiss Federal Laboratory for Materials Testing and Research (EMPA). The results are plotted in the diagram below. This test was done by shearing 4.5 mm diameter fasteners that were inserted in steel plates with 4.6 mm diameter drilled holes.

In Japan, similar tests were carried out by JTICM (Japan). These tests were done by driving a 4.5 mm diameter X-CR nail through a 6 mm steel plate into a second 6 mm thick steel plate and shearing the two plates. From the graph it is apparent that the results are nearly the same.

At 600°C, the CR500 material has 64% of its 20°C shear strength left. By comparison, standard fasteners have only 12% and structural steel only about 26%. The excellent fire resistance of the CR500 material alone justifies its use for some applications.
8.4 Fire rating of fastenings to concrete

Concrete is weakened and damaged by fire but not as quickly as steel. In ISO-standard fire tests conducted with DX-Kwik fastenings at the Braunschweig Technical University in Germany the only failure mode was fracture of the nails.

The actual test data are shown in the table below:

<table>
<thead>
<tr>
<th>Tested in crack width</th>
<th>Tensile load, F (N)</th>
<th>Fire resistance/ time to failure (minutes)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>250</td>
<td>103</td>
<td>Nail fracture</td>
</tr>
<tr>
<td>0.2</td>
<td>250</td>
<td>107</td>
<td>Nail fracture</td>
</tr>
<tr>
<td>0.2</td>
<td>350</td>
<td>73</td>
<td>Nail fracture</td>
</tr>
<tr>
<td>0.2</td>
<td>350</td>
<td>91</td>
<td>Nail fracture</td>
</tr>
<tr>
<td>0.2</td>
<td>500</td>
<td>56</td>
<td>Washer pullover</td>
</tr>
<tr>
<td>0.2</td>
<td>500</td>
<td>92</td>
<td>Nail fracture</td>
</tr>
<tr>
<td>0.2</td>
<td>500</td>
<td>93</td>
<td>Nail fracture</td>
</tr>
</tbody>
</table>

The characteristic failure stress curve from the previous graph can be used to calculate the failure load for various shank diameters with exposure to fire of different lengths of time. The calculated failure loads for 3.7, 4.0 and 4.5 mm shank diameter fasteners after 60, 90 and 120 minutes exposure to fire are shown in the table below.
### Failure loads for various shank diameters and fire exposure times

<table>
<thead>
<tr>
<th>Shank diameter (mm)</th>
<th>Fire exposure time and failure stress</th>
<th>60 minutes</th>
<th>90 minutes</th>
<th>120 minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>32.1 MPa</td>
<td>22.3 MPa</td>
<td>19.1 MPa</td>
</tr>
<tr>
<td>3.7</td>
<td></td>
<td>340 N</td>
<td>240 N</td>
<td>200 N</td>
</tr>
<tr>
<td>4.0</td>
<td></td>
<td>400 N</td>
<td>280 N</td>
<td>240 N</td>
</tr>
<tr>
<td>4.5</td>
<td></td>
<td>510 N</td>
<td>350 N</td>
<td>300 N</td>
</tr>
</tbody>
</table>

This table can be used to determine recommended loads for the ISO fire resistance required.
9. Design concepts

The recommended working loads $N_{\text{rec}}$ and $V_{\text{rec}}$ are suitable for use in typical working load designs. If a partial factor of safety design method is to be used, the $N_{\text{rec}}$ and $V_{\text{rec}}$ values are conservative when used as $N_{\text{Rd}}$ and $V_{\text{Rd}}$. Alternatively, the design resistance may be calculated from the recommended loads by multiplying by the factor 1.4, which considers the uncertainties from the load on the fasteners. Exact values for $N_{\text{Rd}}$ and $V_{\text{Rd}}$ can be determined by using the safety factors where given and or reviewing test data. Based on cyclic tests it can be stated that DX fastenings can be said to be robust, even when the actual loading turns out to be in part cyclic. Design loads (characteristic strength, design resistance and working loads) for the X-HVB shear connector are listed and specified per design guideline.

The designer may encounter two main fastening design concepts:

**Working load concept**

$$N_S \leq N_{\text{rec}} = \frac{N_{\text{Rk}}}{\gamma_{\text{GLOB}}}$$

where $\gamma_{\text{GLOB}}$ is an overall factor of safety including allowance for:

- errors in estimation of load
- deviations in material and workmanship

and $N_S$ is in general a characteristic acting load.

$N_S = N_{\text{Sk}}$

**Partial factors of safety**

$$N_{\text{Sk}} \times \gamma_F = N_{\text{Sd}} = \frac{N_{\text{Rk}}}{\gamma_M} = N_{\text{Rd}}$$

where:

- $\gamma_F$ is a partial factor of safety to allow for errors in estimation on the acting load and
- $\gamma_M$ is a partial factor of safety to allow for deviations in material and workmanship.
The characteristic strength is defined as 5% fractile:

\[ N_{Rk} = N_{u,m} - k \times s \]

The \( k \) factor is a function of the sample size and the accuracy required. The characteristic strength of fastenings to concrete is determined based on a 90% probability while fastenings to steel are based on a 75% probability.

Structural analysis of the fastened part (e.g. roof deck panel or pipe hung from a number of fastenings) leads to calculation of the load acting on a single fastening, which is then compared to the recommended load (or design value of the resistance) for the fastener. In spite of this single-point design concept, it is necessary to ensure adequate redundancy so that failure of a single fastening will not lead to collapse of the entire system. The old saying “one bolt is no bolt” can also be applied to DX fastening.

For standard DX fastenings on concrete, a **probability-based design** concept based on multiple fastening is applied in order to allow for fastener driving failures and the large scatter in holding power observed. This concept applies to tensile as well as shear loading and is described in following chapter.
10. Determination of technical data for fastening design

The determination of technical data is based on the following tests:

- Application limits
- Tensile tests to determine pull-out and pull-over strength
- Shear tests to determine bearing capacity of the attached material and the base material.

These tests are described in more detail in the sections “Steel and other metal base material” and “Concrete base material”.

10.1 Fastenings to steel

Failure loads in tension and in shear are normally distributed and the variation coefficient is <20%. The test data for each test condition are evaluated for the average and characteristic values. The characteristic value is based on the 5% fractile for a 75% probability.

The application range of the fastener is determined by application limit test where fasteners are set on steel plates of thickness ranging from the minimum recommended thickness \(t_{ll,\text{min}}\) to full steel (\(\geq 20\ \text{mm}\)) and varied plate strength.

The application limit is reached when 1 shear off failure with 30 fasteners tested occurs, or if a detrimental effect on the load values (resistance) occurs, or if a detrimental effect on the load values (resistance) occurs.

Due to the small scatter in failure loads fastenings in steel can thus be designed as single points, although good engineering practice should be kept in mind. System redundancy must be always ensured.
10.2 Profile sheet fastenings

In addition to general fastenings to steel, specific data applies to profile sheet fastenings:

**Cyclic loading**

Profile sheet fastenings are subjected to repeated loading to simulate wind effects. Cyclic pull-through tests are additional optional tests where the failure load at 5,000 cycles is determined.

The design value of the pull-through resistance for repeated wind loads is the design value of the static pull-through resistance multiplied by a reduction factor of $\alpha_{\text{cycl}}$.

- If cyclic tests are carried out:
  $$\alpha_{\text{cycl}} = 1.5 \left( \frac{N_{Rk,\text{cycl}}}{N_{Rk,\text{sta}}} \right) \leq 1$$
  (The factor 1.5 takes the different safety levels for fatigue and predominately static design into account)

- If no cyclic tests are carried out:
  $$\alpha_{\text{cycl}} = 0.5$$

**Sheet bearing capacity**

Profile sheet fastenings may be subjected to shear stresses from building movements or thermal dilatation of the sheets. Tests are undertaken to prove the suitability of the fastenings to support the deformations imposed.

For this, shear tests are carried out using a substrate of the minimum and maximum thickness and 2 layers of profile sheet of the thickness specified.

The fastening is considered suitable if an elongation of 2 mm is achieved without the sheet coming loose or showing an excessive reduction in pull-out load capacity. In this case, no consideration of forces of constraint is required since sufficient ductility is provided by the fastening due to hole elongation.

**Standardization**

The pull-over strength of profiled sheet fastenings is given with reference to core sheet thickness. Ultimate load data is standardized to the minimum sheet thickness and strength as specified by the relevant sheet standard. The correction applied is as follows:

$$F_{u}' = F_u \times \frac{t_{\text{min}}}{t_{\text{act}}} \times \frac{f_{u,\text{min}}}{f_{u,\text{act}}}$$
10.3 Fastenings to concrete (standard DX / GX)

The failure loads in tension and shear show a large scatter with a variation coefficient of up to 60%. For specific applications, fastener driving failures may be detected and the fasteners replaced (e.g. threaded studs). For others, however, detection may not be possible (e.g. when fastening wooden battens) and this must be taken into consideration.

The design resistance is therefore determined for:

- failure loads without considering fastener driving failures
- failure loads considering a 20% rate of fastener driving failure

Evaluation of technical data and design according to the single point design approach based on fractiles and a safety factor is not feasible for such systems. The characteristic value would become zero at a variation coefficient of about 50%.

The evaluation of the data and the determination of the design resistance is therefore based on a multiple fastening, i.e. a redundant design, in which the failure probability not of a single, but of a number of fasteners supporting a structure is calculated. By this system, load may be transferred between the fasteners, if slip or failure or more of one of the fasteners occurs.

Test data

The test data for the fastener is consolidated to form a master pullout load distribution.

Static system

Two static systems are examined

- A suspended beam allowing unrestrained flexure of the beam
- A beam directly attached to the surface, which shows restrained flexure
Calculation method
The calculation method used is the Monte Carlo method, by which holding values taken stochastically from the master distribution are attributed to the individual fasteners of the system and the system is checked to determine whether the imposed line load can be supported. By performing a large number of such simulations, statistical information on the failure probability of a system under a given line load is obtained.

Design parameters
The design is based on the following parameters:
• Failure probability: 1 × 10^{-6}
• Number of fasteners: 5
• Line load uniformly distributed
• Failure criterion: 2 edge or 3 central fastenings

The result is expressed in recommended load per fastening.
Effect on a fastening design

The overall condition for a fastening design in practice is that redundancy of the complete system has to be ensured. The effect of the Monte Carlo approach on a design is illustrated with two examples below.

Example:

Fastening of a plumbing with five ceiling hangers.

1. Due to the stiffness (EI) of the plumbing a redistribution of the dead load (g) to the remaining hangers is given in case of two neighbouring hangers failing.
   ➢ Fixing of each hanger with one nail is sufficient.

2. The plumbing is not stiff enough to redistribute the dead load to the neighbouring hangers in case of one fastener failing.
   ➢ Each hanger has to be fastened with five nails.

10.4 DX fastenings to concrete (DX-Kwik)

Failure loads in tension and shear are log-normally distributed and the variation coefficient is <20%. The test data is evaluated to yield the 5% fractile based on a 90% probability. The recommended working loads are obtained by applying a global safety factor of 3 for tension and shear.

The determination of technical data for cracked concrete (tensile zone) is based on tensile tests. Shear tests in cracked and uncracked concrete give similar results and are therefore not performed.

Failure loads in cracked concrete show a higher variation coefficient. Test data is also evaluated to yield the 5% fractile. The recommended load for the tensile zone is taken as the smaller of the following values:

- \( N_{rec} = \frac{N_{Rk}}{\gamma_{GLOB}} \)  \( \gamma_{GLOB} = 3.0 \) for 0.2 mm crack width
- \( N_{rec} = \frac{N_{Rk}}{\gamma_{GLOB}} \)  \( \gamma_{GLOB} = 1.5 \) for 0.4 mm crack width.
The application range of the fastener is determined by application limit test where fastenings are made on concrete of varying strength and age according to the application conditions specified (pre-drilling and setting). The attachment height is kept at the lower end of the range specified. The application limit is reached, if the failure rate exceeds 3% or the pull-out values strongly deviate from a lognormal distribution. The sample size is 30 per condition.

**10.5 Fastener design in the USA and Canada**

Testing of powder-acted fasteners is carried out according to the ICC-ES AC 70 acceptance criteria and ASTM E 1190 standard test method. The test procedure covers tensile and shear testing in steel, concrete and masonry. The determination of the allowable (recommended) load is shown below. The recommended working load is derived from the test data by taking the average failure load or the calculated characteristic load divided by a global safety factor.

Three different options have to be distinguished:

<table>
<thead>
<tr>
<th>COV ≥ 15%</th>
<th>COV &lt; 15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>based on characteristic load</td>
<td>based on lowest ultimate load</td>
</tr>
<tr>
<td>N = 30 tests</td>
<td>N = 10 tests</td>
</tr>
<tr>
<td>( F_{\text{rec}} = \frac{F_{u,m} - 2s}{\nu} = \frac{F_{u,m}}{\nu} )</td>
<td>( F_{\text{rec}} = \frac{\text{min} F_u}{\nu} )</td>
</tr>
<tr>
<td>( F_{\text{rec}} = \frac{1 - 2\text{COV}}{\nu} )</td>
<td>( F_{\text{rec}} = \frac{F_{u,m}}{\nu} )</td>
</tr>
</tbody>
</table>

with a safety factor of \( \nu = 3.5 \) with a safety factor of \( \nu = 5 \)

where:
- \( F_{\text{rec}} \) = allowable (recommended) load
- COV = \( s/F_{u,m} \) = coefficient of variation in a test series
- \( s \) = standard deviation in a test series
- \( F_{u,m} \) = average ultimate load in test series