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Powder-actuated fasteners and fastening screws in steel construction

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A Wiley Brand

Commentary On

"Powder-Actuated Fasteners and Fastening Screws in Steel Construction"
by Hermann Beck, Michael Siemers, Martin Reuter and Erwin Schöffendt

Steel Construction Calendar 2019 – Stahlbaukalender 2019

To Whom It May Concern,

The attached technical article is provided to the North American engineering community in order to further develop the technical understanding of powder-actuated fasteners and screw fasteners in steel construction. Since there are slight differences in some aspects of this technical discussion with respect to North American and European country engineering and construction practices, Hilti, Inc., issues the following clarifications.

Section 2.1
Safety aspects of both high- and low-velocity powder-actuated tools are addressed in the ANSI A10.3 standard. High-velocity tools may still be used in North America under very limited conditions, but they have been almost completely replaced by low-velocity powder-actuated tools. Hilti offers low-velocity powder-actuated tools with improved safety measures for the user. The relative safety precautions and features of high- and low- velocity powder-actuated tools should be understood before specifying or using these fastening systems. In addition, OSHA requires every user be trained on each powder-actuated tool they use.

Section 2.2.5
The Hilti X-CP72 P8S23 sill plate fastener is mechanically plated to a zinc thickness ≥ 86 µm. This fastener was developed to meet various code requirements regarding the corrosion resistance of fasteners for pressure treated wood sill plates including SBX/DOT, zinc borate ACQ, CA-B, CBA-A and ACZA to concrete base material. The X-CP72 P8S23 meets the zinc coating thickness requirements of ASTM A153, but it is not hot dip galvanized. Please refer to the Hilti North American Product Technical Guide Volume 1: Direct Fastening 2021, Section 3.2.10.

Section 2.4.1
Any discussion of fastener stand-off needs to consider the clamping effect between the attached sheet and base steel. Tight contact and positive clamping action between the fastened part and the base steel is essential to an accurate fastener stand-off measurement. Please refer to the Hilti North American Product Technical Guide Volume 1: Direct Fastening 2021, Sections 3.5.1.2.4 and 3.5.1.3.3, for a discussion on proper fastener installation and the power adjustment guide for steel decking applications.

Section 2.8
Please refer to the Hilti Corrosion Handbook, dated 06/2021, for a discussion on the difference between hydrogen embrittlement and hydrogen assisted stress corrosion cracking (HASSC). The Hilti X-CR and X-R fasteners, which can be found in Sections 2 3.2.5 and 3.2.7 of the Hilti North American Product Technical Guide Volume 1: Direct Fastening 2021, are not susceptible to HASCC. However, most types of stainless steel and virtually all hardened steel zinc plated fasteners are susceptible to this brittle failure mechanism.

Section 3.1.2.9
Screws should only be used in non-corrosive applications, regardless of their coating, unless they are specifically listed as being suitable for outdoor or exposed conditions. More detailed corrosion resistance guidelines for Hilti screw fasteners are provided in the Hilti Corrosion Handbook, dated 06/2021.

Section 3.1.3

More detailed guidance on Hilti screw fastener installation instructions is provided in the Hilti North American Product Technical Guide Volume 1: Direct Fastening 2011, Section 3.6.1. Screw fasteners should be installed with screwdrivers equipped with a torque clutch or depth gauge at the appropriate rpm's. Caution should be taken with the use of rotary impact wrenches for installation of self-drilling screws in thin metal, as this can lead to over-driving and thread stripping.

Section 4.1.3

As of the printing of this article, certain seismic fastening applications are now recognized by the International Code Council – Evaluation Services (ICC-ES) for the use of powder-actuated fasteners. Revisions to the ASCE 7 reference standard and by incorporation, the IBC 2012, 2015 and 2018, allow for the use of powder-actuated fasteners to resist seismic forces under certain conditions. Subsequent revisions to the ICC-ES Acceptance Criteria for Fasteners Power-Driven into Concrete, Steel and Masonry Elements, AC70, and powder-actuated fastener Evaluation Service Reports are complete, consistent with ASCE 7-16 Section 13.4.5 and the IBC 2018. Interested readers should refer to the Evaluation Service Reports or contact Hilti for guidance.

Screw fasteners for cold-formed steel connections subjected to seismic forces are addressed through the American Iron and Steel Institute (AISI) S100 North American Specification for the Design of Cold-Formed Steel Structural Members. AISI S100 is referenced in the IBC 2018, and does not prohibit the use of screw fasteners for resisting seismic forces. Interested readers should refer to AISI S100, Evaluation Service Reports, or contact Hilti for guidance.

Please direct powder-actuated and screw fastening technical inquiries to your local Hilti Field Engineer or Technical Support at 1-877-749-6337.

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Notes by the publisher Ernst & Sohn:
Updated annually, the "Stahlbau-Kalender" has been accompanying key developments in steel construction and related areas in Germany since 1999. The calendar is both a compendium for planning and construction using steel as well as a guide to its correct calculation and design. Timeliness, quality and the practical content of the contributions emphasize the significance of the "Stahlbau-Kalender" as a reliable source of information and aid, such that it has become an essential handbook for engineers and architects who manage steel construction projects of all sizes.
The editor, Professor Ulrike Kuhlmann, is head of the Institute for Design and Construction at the University of Stuttgart, and her choice of authors is determined by a continuous search for real-life examples. The contributors thus work within the industry, in engineering offices or at the interface of research and practice in academia and are renowned experts in their respective fields.

Content

1 Introduction

Powder-actuated fasteners and screw fasteners are used for decades in steel construction for the connection of thin gauge sheet metal in single or multi-story buildings [1]. The classical applications are fastenings of load-bearing sheeting of roof structures, liner trays for walls or sheeting of composite decks to steel members. Figure 1 shows typical examples of fastening applications in light-gauge steel construction:

- Fastening thin-gauge trapezoidal metal sheets or liner trays to hot-rolled beams or thin C- or Z-profiles,
- Joints between cold-formed thin-gauge profiles.

Powder-actuated fasteners and fastening screws are high-strength fasteners made of carbon or stainless steel. For the fastening of load-bearing metal sheet or liner trays only powder-actuated fasteners made of carbon steel are available to date. Powder-actuated fasteners have a wide scope of application for fastening of components to steel, concrete and masonry [4–9]. The materials most fastened are steel, wood, insulation and, in some cases, also plastic.

Powder-actuated fasteners are driven into the supporting material directly in a single operation. The powder-actuated fastening tool specified for each particular type of fastener must be used for the driving operation. Fastening screws are distinguished between self-drilling and self-tapping screws. Self-drilling screws are equipped with a drill point, so no separate predrilling is necessary. The screw drills the hole and forms a thread simultaneously in a single operation. Self-drilling screws are also used for the connection of thin-gauge metal sheets with each other. Self-tapping screws are screwed into a predrilled hole. In that process the screw forms a thread in the base material.

The decision to use powder-actuated fasteners or metal construction screws depends, from a technological point of view, on the thickness of the supporting base material. In order to ensure a reproducible driving process for powder-actuated fasteners, the material into which the fasteners are driven must meet minimum thickness requirements. Depending on the fastening system used, this minimum thickness is between 3 and 8 mm. Accordingly, the powder-actuated fasteners currently available on the market are unsuitable for the purpose of fastening profile metal sheets at overlap joints (sheet to sheet) or for fastening Z-brackets to profile metal sheets. Self-drilling screws are used predominantly in the field of construction where sheets of this thickness are involved.

The main cost-efficiency advantage of powder-actuated fasteners lies in the high productivity that can be achieved with systems of this kind. When compared with fastening screws, this advantage becomes even greater as the thickness and strength of the base material increases, especially where the powder-actuated fastening system is capable of covering the entire strength

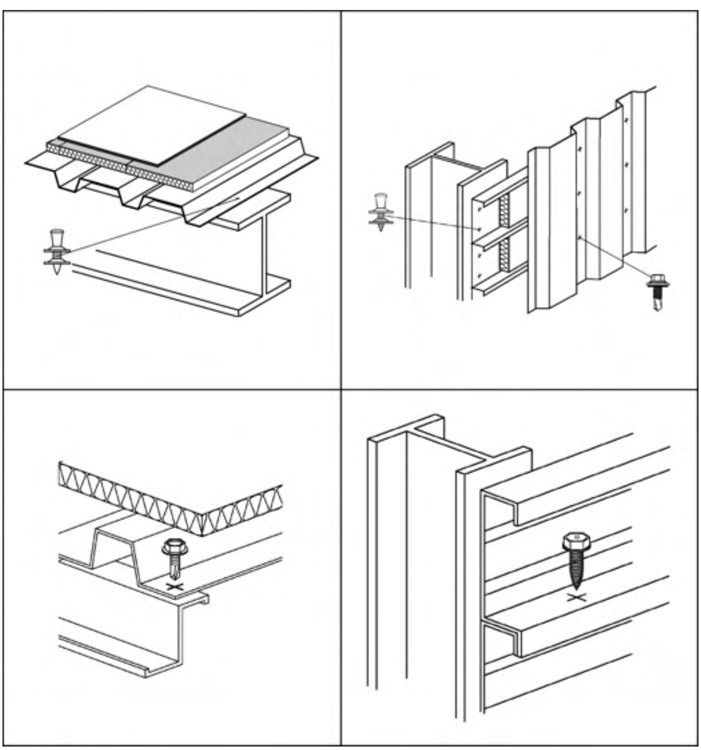
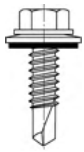
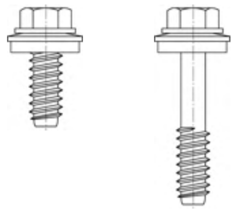
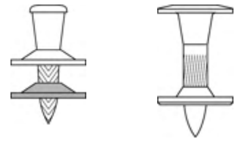
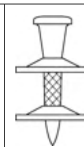


Figure 1. Use of powder-actuated fasteners and fastening screws in light-gauge steel construction

Table 1. Fasteners for metal sheets and liner trays

	Self-drilling screw	Self-tapping screw	Powder-actuated fastener	
				
Component I – thickness [mm]	$0.4 \leq t_I \leq 2.0$	$0.5 \leq t_I \leq 2.0$	$0.63 \leq t_I \leq 2.5$	$0.63 \leq t_I \leq 1.5$
Component II – thickness [mm]	$0.4 \leq t_{II} \leq 15.0$	$t_{II} \geq 1.25$ [1)]	$t_{II} \geq 6.0$	$3.0 \leq t_{II} \leq 6.0$

t_I … Thickness of each individual sheet
[1)] $t_{II} \geq 0.5$ mm for self-tapping screws with point

tolerance range of S355 material. In the 3 to 8 mm thickness range the productivity advantage of powder-actuated fastening is less pronounced as the driving time for fastening screws in this material thickness range is only about one second per millimeter of material thickness. The values given in Table 1 provide a guide concerning the base material thickness range that can be covered (component II) as well as the thicknesses of the metal sheets to be fastened (component I) for fasteners covered by European Technical Assessments (ETA).

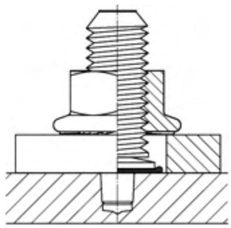
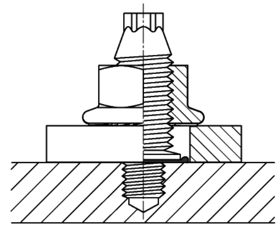
This publication is based on the previous articles "Powder-actuated fasteners in steel construction" [2] from the "Stahlbau-Kalender 2005" and "Powder-actuated fasteners and fastening screws in steel construction" [3] from the "Stahlbau-Kalender 2011", respectively. It is an update and extension of these articles especially on the following topics:

– CE-marking of powder-actuated fastening tools and cartridges: The integration of powder-actuated fastening tools within the Machinery Directive [10] and cartridges into the Pyrotechnic Directive [11] was completed. Type approvals of fastening tools, testing of cartridges itselves and cartridges in combination with fastening tools are executed in compliance with European Standards serving as basis for CE-marking of both tools and cartridges.
– Transfer of European Technical Approvals into European Technical Assessments in compliance with the implementation of the Construction Product Regulation (CPR) [12] per July 1, 2013: After a five years transition period all European Technical Approvals expired latest per June 30, 2018 and had to be replaced by new European Technical Assessments. Therefore, all relevant test and acceptance criteria – basically CUAPs (see [3]) – had to be transferred into European Assessment Documents (EADs). Additionally, new assessment documents were issued (e. g. for nailed shear connectors) or are in preparation (e. g. for threaded studs), respectively.
– Introduction of new technologic developments: These concern threaded studs and their use on thin coated base material. The tension and shear resistance of blunt-tip threaded studs driven into a predrilled hole was further optimized. Furthermore, also screw-in threaded studs are available on the market. Table 2 gives an overview about recent developments of blunt-tip threaded studs as well as guide values of their performances and application ranges.
– Challenges for fastening technology: The increased use of high-strength construction steel (up to S700MC) – the application of these steels will be directly covered in the upcoming new generation of the Eurocodes – leads to highest requirements both on direct fastening with powder-actuated fasteners as well as fastening screws. As well relevant is the increased use of thicker reactive fire protective coating and its effect on selection, performance and approval of the respective fastening solution.

The concept of this publication remains unchanged with the version of the article from 2011 [3]. The technologies of powder-actuated fasteners and fastening screws will be introduced separately in Section 2 and Section 3. The following sections on fastener design, applications, national approvals and European Assessments will be discussed jointly for powder-actuated fasteners and fastening screws. Sections 7 to 10 introduce the new European Assessment Document for the fasteners and their relevant uses.

Nevertheless, the relevance and influence the individual parameters have on loading capacity can be interpreted from performance data provided in ETAs – especially for powder-actuated fasteners – only to a certain extent. A motivating reason for writing this article remains as before to illustrate, by means of example, the influence

Table 2. Recent developments of blunt-tip and screw-in threaded studs

	Blunt-tip threaded studs	Screw-in threaded studs
		
	Increase of the loading capacity of the anchorage through optimization of the shank geometry embedded in the base material.	Alternative battery powered fastening method based on the technology of self-tapping screws.
Base material	Construction steel S235 to S960	Construction steel S235 to S355 Aluminium
Material of threaded studs	Stainless steel	Stainless steel Carbon steel
Minimum thickness of coated base material (without need of rework of the corrosion protection)	8 mm	6 mm
Tension resistance N_{Rk} (Construction steel S235, 8 mm thick)	≤ 10.0 kN	≤ 6.0 kN

of individual parameters on loading capacity and thereby provide a better understanding of the possible applications of powder-actuated fastening as well as its application limits.
The applicable technical data is generally determined from tests. The fundamental technical relations are thus explained in this paper on the basis of examples and test results. Figures given apply only to the fastening system tested and to the specific application conditions. A quantified generalization of the information given here to cover powder-actuated fasteners and fastening screws from other manufacturers or, respectively, fasteners of a different type from the same manufacturer, is possible only after consultation with the applicable manufacturer.

2 Powder-actuated fastening technology

2.1 Fastening systems

2.1.1 Components and driving energy

The powder-actuated fastening technique involves using a fastening tool to drive a high-strength steel fastener (nail or threaded stud) directly into the base material. Penetration of the fastener causes plastic displacement of the base material (Figure 2).

A portable, hand-held, powder-actuated fastening tool is used to drive the fasteners. For applications in steel construction the driving energy is usually provided by firing a cartridge containing a combustible propellant in powder form. Other possible energy sources for direct fastening tools are compressed air, combustion of gas and electrical energy from batteries.
The fastener, the fastening tool and the driving energy together make up the fastening system, Figure 3. The quality of the fastening obtained depends not only on

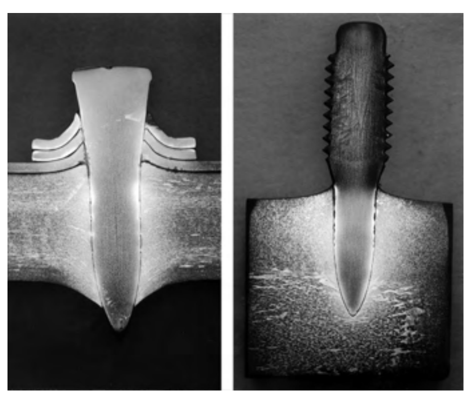


Figure 2. Ground cross-sections of fasteners after driving

Figure 3. Components of direct fastening systems

Table 3. Scope of application of fastening systems

Fastening system	Driving energy	Scope of application	Example of powder-actuated fastening tools
powder-actuated with large caliber 6.8/18 or 6.3/16, Blue to Black	300 – 600 J	sheet metal to steel, shear connector, threaded studs	Hilti DX 76, DX 860 Würth BGF MF-14, BGF MF-14S Spit P560, P525L
powder-actuated with small caliber 6.8/11 or 6.3/10, Green to Black	70 – 400 J	threaded studs, base profiles of glass facades (only DX 450), wood to steel	Hilti DX 5, DX 450, DX 351 Würth DIVA® 1, BST 2 Spit P370, P390
powder-actuated with small caliber 6.8/11, Brown	80 – 100 J	blunt-tip threaded studs	Hilti DX 351
gas-actuated	80 – 120 J	light fastenings: cable fixings, dry-wall tracks etc.	Hilti GX 3 Würth DIGA® CS-2 POWER Spit PULSA 800P+, 800E Dewalt TRAK-IT® C5
battery-actuated	80 – 100 J	light fastenings: cable fixings, dry-wall tracks etc.	Hilti BX 3 Dewalt DCN 890

the fastener but also on the fastening tool, as the tool has a decisive influence on the quality and reproducibility of the driving operation.

The energy accelerates a piston within the tool, which itself transfers the energy on the fastener and further drives the fastener directly into the base material. The driving velocity is the key physical parameter that determines whether it is possible to drive a fastener into a hard substrate such as steel. Even a technically "perfect" fastener could never be pressed statically into solid steel or driven by hand into a hard base material with a few hammer blows.

Battery-actuated fastening tools operate without any combustion and the piston is mechanically driven. The electrical energy of the battery is utilized in the tool to tighten springs or rotate flywheels which in turn transfer mechanical energy on the piston.

With a view to limiting the recoil of the tool, the maximum driving energy used with portable, powder-actuated fastening tools is restricted to approx. 600 J. With this available energy, the fastening tools in use in the construction industry are capable of driving fasteners of up to approx. 5 mm shank diameter into steel base material. Although driving fasteners of greater diameter would be technically possible, the tools required could no longer be held by hand. In the construction industry fastening tools with a piston per DIN EN 15895 [13] are used exclusively. The piston functions as an intermediate element between the fastener and the propellant cartridge, with the effect of reducing the velocity at which the fastener is driven.

Propellant cartridges are available in compliance with DIN EN 16264 [14] in various calibers and lengths. Common calibers are 6.3/10, 6.3/16, 6.8/11 and 6.8/18. Cartridge energy levels are indicated by a cartridge color and an energy scale according to [14] as follows:

White/Brown	- extra low	- energy scale 2
Green	- low	- energy scale 3
Yellow	- low/medium	- energy scale 4
Blue	- medium	- energy scale 5
Red	- medium high	- energy scale 6
Black	- extra high	- energy scale 7

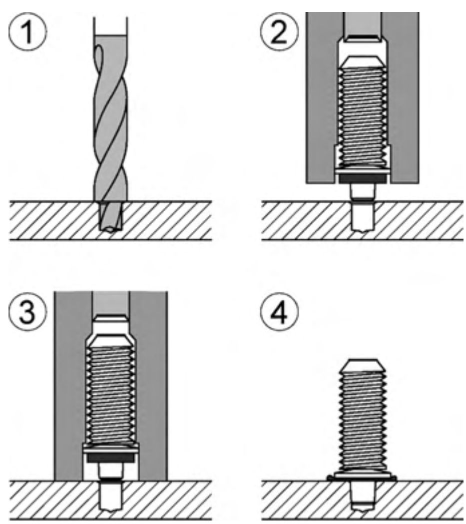
The different energy scales of the powder cartridge cover an energy range of approximately 70 to 600 J. For comparison: The maximum driving energy provided by gas- or battery-actuated fastening tools is in the range of 80 to 120 J. Compressed-air tools – not relevant in the German market – may reach about 250 J. Table 3 provides guide values of the driving energy range of the different fastening systems as well as indication to their typical use of application.

In addition to the "conventional" direct fastening technology, fastening systems involving blunt-tip powder-actuated fasteners with predrilling of the base material were developed. Predrilling requires an additional work step but it extends the application range of direct fastening:

- Fastening to thin (≥ 8 mm) and coated base material without through penetration of the base material
- Use extension to high strength construction steel up to S960.

Figure 4 shows the working steps in case of fastening systems with predrilling. Common predrilling diameters are in the range from 4.0 to 4.7 mm. The blunt-tip fasteners are driven into the base material at the predrilling location. The shank diameter of the stud exceeds the diameter of the predrilled hole in order to allow the stud to be anchored in the steel base material. Special stepped drill bits are to be used in order to reach the correct drilling depth. For fast drilling of the holes suitable drills with high rotational speed (≥ 3500 rpm) should be used. Consequently drills and the respective stepped drill bits form components of the direct fastening system.

The terminology of direct fastening has not been standardized. In English, the fasteners are known as "power-actuated fasteners" to include all different energy sources. In particular in case of cartridges as energy source the terms "powder-actuated fasteners" or "cartridge-fired pins" are used. In German, the word *"Setzbolzen"* has become established as the generic term for all types of power-actuated fasteners. These terms refer to the nails equipped with steel washers for fastening profile metal sheets and the nails for general (non-removable) fastening applications as well as the threaded studs used to create removable fastenings (Figure 7).



Step 1: Predrilling with specified stepped drill bit

Step 2: Positioning of the stud centered to the predrilled hole. The front part of the stud protrudes – held by means of a spring – from the tool to allow the positioning of the stud above the predrilled hole

Step 3: Compress and subsequently trigger the tool

Step 4: Blunt-tip stud driven into the base material

Figure 4. Working steps for direct fastening blunt-tip stud with predrilling

2.1.2 Historical development

2.1.2.1 From high-velocity tools to low-velocity piston tools

The history of direct fastening using powder-actuated tools goes back to the beginning of the 20th century. The Englishman *Robert Temple* invented an *explosively actuated penetrating means* in 1915. This high-velocity fastening tool was developed by *Temple* for use by the navy in special underwater applications [15]. The technique could be used, for example, to make temporary repairs to the hulls of ships by "nailing" metal sheets over the leaking or damaged area.

The first high-velocity fastening tools for use in applications in the construction industry appeared on the market in the USA in the 1940s. As the name implies, high-velocity fastening tools are characterized by the velocity of the fastener (up to 600 m/s) as it leaves the muzzle of the tool. This high velocity is the result of the energy released on ignition of the propellant acting directly on the fastener (Figure 5). The fastener then leaves the tool with high kinetic energy, similar to that of a bullet fired from a gun. This presents a hazard not only to the operator of the tool but also to any bystanders in the vicinity. Penetration of the fastener in the material is uncontrolled. The fastener may, in fact, be driven right through (so-called through-shot) [16] if the supporting material behind the part to be fastened is not as expected, i. e. too light and flimsy or if no supporting material is present at that point. The motivating factor behind further development of these tools was the improvement of working safety. The goal was to develop fastening tools capable of providing high fastener driving energy but, at the same time, with a low muzzle velocity.

Placement of a piston between the fastener and the cartridge was found to be the solution. This captive piston, accelerated by the energy released as the cartridge is fired, then drives the fastener into the supporting material. Although the entire energy released by combustion of the propellant is available to the driving operation, the free-flight energy transferred to the fastener is greatly reduced – according to the piston/fastener mass ratio. The first piston-principle tools became available in 1958 [17]. These tools quickly became established and high-velocity tools for use in the construction industry disappeared from the European and American market by the end of the 1960s.

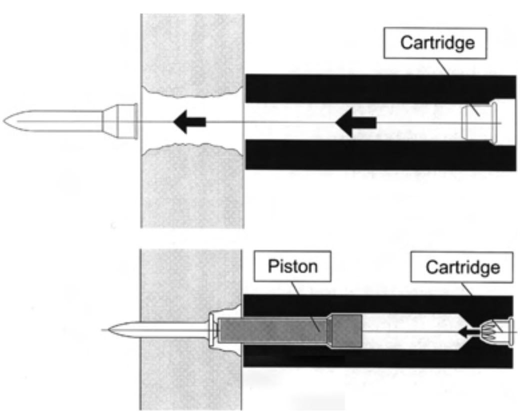


Figure 5. High-velocity tool principle versus low-velocity piston principle

2.1.2.2 Optimizations

Further development of piston-type tools then concentrated on increased productivity in practical use. Today, in addition to tools for driving single fasteners, there are also semi-automatic and fully-automatic tools on the market. Fully-automatic tools make use of fasteners and cartridges in magazine strips and the tool's piston is returned automatically to the starting position after each fastener is driven. Semi-automatic tools require a manual cycling action to return the piston to its outset position. Semi-automatic and fully-automatic tools can generally also be converted for use as single-fastener tools simply by replacing the fastener magazine with a single-fastener baseplate. Each fastener must then be inserted in the tool manually. The propellant cartridges are collated either in plastic magazine strips or in metal discs.

Gas-actuated as well as battery-actuated tools are fully-automatic fastening tools capable of high productivity. Gas-actuated tools use a combustible gas propellant contained in a replaceable canister (the so-called "gas can"). Depending on the specific tool used, the capacity of the gas can is sufficient up to approximately 1200 fastenings and the accumulator capacity of battery-actuated fastening systems reaches approximately up to 800 fastenings.

Fully-automatic stand-up powder-actuated fastening tools allow ergonomically optimized fastening of profiled steel sheeting in roof construction in upright standing operator position. These tools offer highest possible fastening productivity of several thousand fastenings per day.

2.1.3 CE marking of powder-actuated fastening tools

Powder-actuated fastening tools were integrated in the new edition of the Machinery Directive [10] for the first time in 2006. The Machinery Directive defines in general the essential requirements to be met by machinery. The detailed safety requirements for powder-actuated fastening tools, the necessary tests and how they are to be evaluated are laid out since 2011 in the European harmonized standard DIN EN 15895 [13]. This standard covers exclusively powder-actuated fastening tools equipped with a piston and with a maximum fastener exit speed (muzzle velocity) of 100 m/s. DIN EN 15895 [13] adopted the stringent safety and test requirements

given in the C. I. P. (Commission International Permanente) resolutions [19]. In the members states of the C. I. P. (e. g. Germany, France and Austria) these C. I. P. resolutions were the legal basis for the obligatory type approvals of the powder-actuated fastening tools.
Since 2011, powder-actuated fastening tools may only be put on the European and German market with CE marking. The assessment of their conformity is carried out in accordance with [10] on the basis of EC type testing [18] which has to be carried out by an accredited, independent testing agency. In Germany this agency is the *Physikalische Technische Bundesanstalt Braunschweig und Berlin (PTB).*
The following points, among others, are required to be verified as part of EC type testing:

- The robustness of the fastening tool in the event of unforeseen excess pressure within the tool.
- The contact pressure required to trigger the tool. This must be at least 1.5 times the weight of the tool and at least 50 N.
- Safety measures to prevent the tool firing in the event of it falling from a height of between 1.5 and 3.0 m.

In order to ensure that the tools can be used outside Europe, powder-actuated fastening tools must, as before, be approved in accordance with the C. I. P. resolutions [19]. Therefore, the type identification plates on tools show – in addition to the CE marking according to [10] – also the required marking confirming compliance with the C. I. P. resolutions [19] (Figure 6).
Labor-law provisions for commercial use of powder-actuated fastening tools are covered in Germany by the safety standard DGUV No. 56 [20]. Compared with powder-actuated fastening tools, gas- or battery-actuated as well as pneumatically driven fastening tools were always covered by the Machinery Directive. Testing and safety requirements for gas-actuated and pneumatically driven tools are laid out in EN 792-13 [21] and for battery-actuated tools in IEC EN 62841-1 [22], respectively. The respective conformity assessment results into CE marking to be affixed on the tools.

PTB S 813	CE
Conformity with C.I.P. resolutions [19]	Conformity with the Machinery Directive [10]
PTB abbreviation indicating the testing agency S abbreviation standing for powder-actuated tool of the Class A 813 approval certificate number	

Remark: Powder-actuated fastening tools of Class A per C.I.P. [19] correspond with those tools covered by DIN EN 15895 [13].

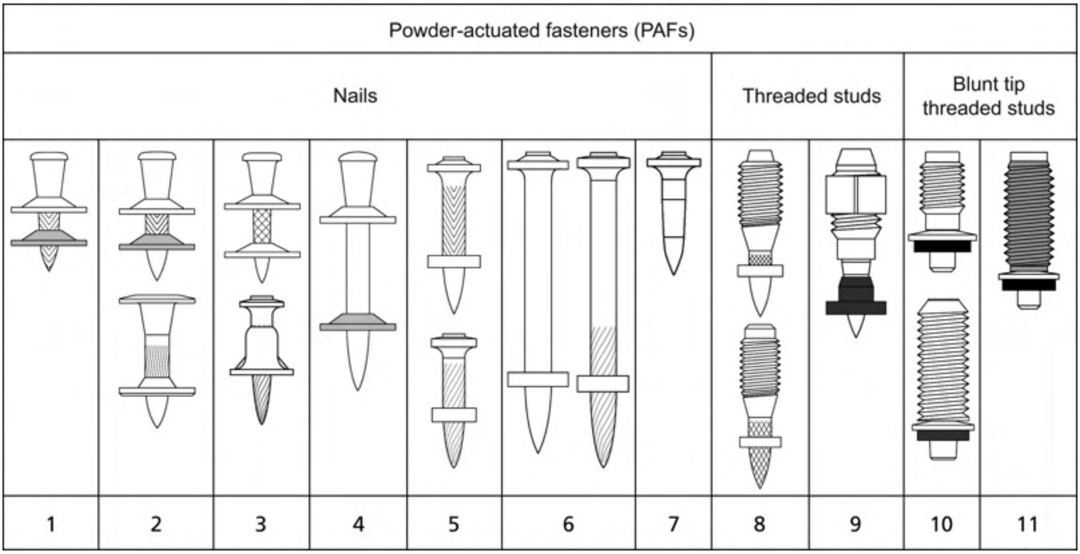
Figure 6. Conformity marking of powder-actuated tools

2.1.4 CE marking of cartridges

The European standardization activities with regard to CE marking of cartridges are also completed and all old German DIN-standards (DIN 7260-1, DIN 7260-2) have been withdrawn. The cartridges for powder-actuated fastening tools are covered since 2007 by the Pyrotechnics Directive (current version 2013/29/EU [11]). Safety requirements and the respective tests are defined since 2014 in the harmonized European standard DIN EN 16264 [14]. The respective technical basis as well as the acceptance criteria for cartridges were entirely adopted from the present C. I. P. resolution [19]. The system test of cartridges in combination with the powder-actuated fastening tool is specified in "section 5.6. Collation test" of DIN EN 16264 [14]. The new standard requires unchanged that collated cartridges are to be tested with each type of powder-actuated fastening tool for which the use of the respective cartridge is recommended. During this collation test, the influence of unforeseen excessively high pressure on the cartridge and the cartridge magazine strip is tested. DIN EN 16264 [14] explicitly allows that a system test executed in compliance with the C. I. P. resolutions [19] by a C. I. P. recognized body can be equivalently used as collation test (e. g. [23]). The suitable tools have to be listed on the packaging of the collated cartridges. The further information has to be provided on the packaging:

- CE marking, followed by the identification number of the notified body responsible for checking the conformity of the cartridge.
- Relevant category according to Pyrotechnics Directive [11]: Cartridges are allocated into category P1, which are articles, other than fireworks articles, which present a low hazard in use without the need of special operator qualification.
- Minimum age limit of 18 years.
- Caliber and power level given by color and number.
- Net explosive content NEC. That value is relevant for transportation and storage [149].

If the cartridge is in addition to the CE marking also approved according to the C. I. P. resolutions [19], the packaging must then also show the mark "CIP" in combination with the symbol of the legal authority responsible for the testing.



1 Nail with knurled tip (d = 4.5 mm) for fastening sheet metal to base material ≥ 6 mm
2 Nail with knurled shank (d = 4.5 mm) for fastening of sheet metal and shear connectors
3 Nail with conical shank (d = 3.7 mm) or knurled tip (d = 4.0 mm) for fastening sheet metal to thin base material ≤ 6 mm
4 Nail with smooth shank (d = 4.5 mm) for fastening sheet metal to concrete of the grades up to C50/60
5 Nail with knurled shank and tip for fastening thicker (predrilled) sheets
6 Nail with smooth shank and knurled tip, in lengths up to about 120 mm, for universal use on concrete and in light duty applications on steel
7 Nail with thin and short smooth shank for light duty, non-structural applications
8 Threaded stud with knurled shank and tip made from carbon steel – with plastic washer for guidance
9 Stainless (two-part = nail body + threaded sleeve) threaded stud – with guiding washer on the thread
10 Stainless, blunt-tip threaded stud with sealing washer for coated base material ≥ 8 mm (model made from two parts – cylindrical stem plus threaded sleeve – or one-piece model)
11 Stainless blunt-tip threaded stud with sealing washer and with molded threaded sleeve of glass-fibre reinforced plastic

Figure 7. Powder-actuated fasteners for applications on steel

2.2 Powder-actuated fasteners: Features and characteristics

Figure 7 provides an overview of the range of fasteners available, their main features and their areas of application.

2.2.1 Geometry and form

Powder-actuated fasteners of the types 1 to 9, as shown in Figure 7, consist of 3 sections: the point, the shank and the head. The head of the threaded stud takes the form of a taper at the end of the threaded section. When driven, the point of the fastener penetrates the supporting material, the shank transmits the driving forces and the head forms the interface with the driving piston in the fastening tool. In the completed connection, the shape of the head determines the pullover loading capacity of the component or material fastened. Shear and tensile forces are transmitted by the shank, whereby shear forces are transferred to the supporting material by way of bearing pressure. Tensile forces are resisted by the anchorage obtained in the contact area between the fastener and the base material. The length of the fastener is determined by the material and thickness of the component to be fastened and by load requirements. In the case of powder-actuated fasteners for profile metal sheets, the maximum thickness to be fastened occurs at combined side lap and end overlap locations (four layers of sheeting, fastening type d, Figure 71) and the minimum thickness to be fastened is a single layer of thin sheet metal (0.6 mm or 0.75 mm). In order to reliably obtain a cost-efficient loading capacity, the fastener must be long enough to achieve a certain type-specific minimum depth of penetration at the maximum fastening thickness. The fastener, however, should not be too long. Only a fastener with a comparatively short shank is capable of penetrating solid steel and thus providing the suitability desired in practice for a broad range of application conditions. The geometry of powder-actuated fasteners for profile

metal sheets is thus optimized for fastening thin, cold-rolled profile sheets: it is short and compact. Fasteners with a correspondingly longer shank are required for fastening thicker components.
Powder-actuated fasteners have a shank diameter of between 3.0 and 5.0 mm. Higher forces can be taken up by thick fasteners during driving. This allows the use of higher driving energy, resulting in an increase in the range of application conditions under which the fastener can be used. The fastener's diameter also has an influence on the minimum thickness of the material into which it can be driven, e. g. 6 mm thickness for fasteners with a diameter of 4.5 mm, which is the typical diameter for profile metal sheet fasteners used in European steel construction applications. Fasteners with a diameter of 3.7 mm or less, sometimes with a conical shank, are used on thinner supporting materials.
Threaded studs are available in different material, thread lengths and diameters. Common thread types are M6, M8 and M10. Blunt-tip threaded studs Type 10 and 11 per Figure 7 consist of a blunt tip and a threaded section with a chamfered end. The blunt tip is either cylindrical or slightly conical and also slightly chamfered at its front in order to ease centric positioning of the stud above the predrilled hole. Stainless studs with molded threads serve as alternate options for applications exposed in C3 category of corrosivity of the atmosphere. These categories are specified in DIN EN ISO 9223 [25].

2.2.2 Knurling

The fine pattern of grooves on the surface of the point or shank of a zinc-plated powder-actuated fastener is known as knurling. It forms a micro-keyed hold between the fastener and the supporting material, thus increasing the loading capacity of the anchorage obtained by the fastener and reducing pullout load value scatter. All powder-actuated profile metal sheet fasteners available on the market today are designed to be used on steel base material and thus feature knurling. Figure 8 shows examples of point knurled fasteners.
Use of smooth-shank, unknurled, galvanized carbon steel fasteners on construction steel is basically possible (see Section 5.7). Knurled fasteners, however, are clearly superior to those with smooth shanks, not only with regard to their loading capacity but also in terms of the

Figure 8. Examples of point knurled fasteners

range of application conditions under which they can be used. Stainless steel powder-actuated fasteners require no knurling due to their different contribution of anchoring mechanisms.

2.2.3 Washers and magazines

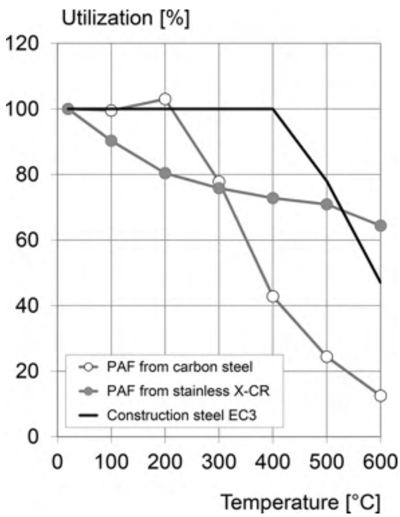
Washers help to guide and center the fasteners in the powder-actuated fastening tool. The steel washers fitted to profile metal sheet fasteners, in conjunction with the head, improve the metal sheet's ability to resist pullover failure and ensure that the sheet is pressed tightly against the supporting material when fastened. When the component to be fastened has a certain minimum thickness (approx. 2.5 to 3.0 mm), no steel washers are required to improve pullover failure resistance relative to the values achieved with a standard head (typically 8 or 10 mm diameter) as the anchorage obtained then determines the fastening's tensile loading capacity. Plastic washers generally break and disintegrate when the fastener is driven.

2.2.4 Fastener materials and mechanical properties

To allow a fastener to be driven into steel, its hardness and strength must be approximately 4 to 5 times that of the base material. Depending on the material from which they are made, powder-actuated fasteners have a hardness of between 49 and 58 HRc. The corresponding guide values for the strength and fracture forces of fasteners with a shank diameter of 4.5 mm are given in Table 4 [24, 26, 27]. The wire material used in the manufacturing of galvanized powder-actuated fasteners is generally a heat-treatable type with a carbon content of approx. 0.65% and a tensile strength of about

Table 4. Mechanical properties at room temperature

			Powder-actuated fastener strength		
Material	Hardness (HRc)	Ultimate strength [N/mm^2]	Diameter [mm]	Tensile strength [kN]	Shear strength [kN]
Heat-treatable carbon steel	58	≈ 2200	4.5	≈ 35	≈ 21.5
Heat-treatable carbon steel	54	≈ 2000	4.5	≈ 32	≈ 20.0
Corrosion resistant austenitic CrNnMo steel [28]	57	≈ 2200	3.7	≈ 23	≈ 15.0



Note: The line representing construction steel shows the influence of temperature on the yield point in accordance with [29].

Figure 9. Influence of temperature on the strength of powder-actuated fasteners.

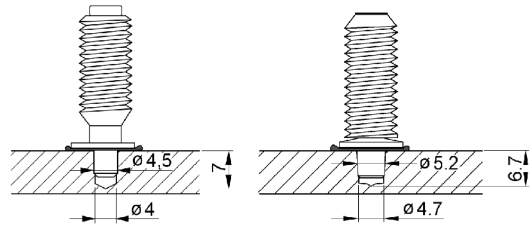


Figure 10. Blunt-tip powder-actuated fastener
a) cylindrical shank with d = 4.5 mm
b) conical shank with mean nominal diameter d = 5.2 mm

600 N/mm². The required hardness of powder-actuated fasteners made from carbon steel is achieved through heat treatment. The heat treatment process must be applied carefully in order to avoid a brittle structure (e. g. formation of martensite) in the finished fastener. The required ductility of the fastener can thus be ensured, which is of great relevance not only during the driving operation but, of course, also for the fastening application itself (e. g. powder actuated fasteners used to attach shear connectors in composite beams).

The raw material for stainless powder-actuated fasteners is drawn stainless wire. Material selection is determined by the durability requirements in use as well as by the high mechanical strength requirements to allow driving fasteners into the base material. The maximum strength of stainless powder-actuated fasteners amounts to approximately 2200 N/mm².

Figure 9 shows the influence of temperature on the strength of powder-actuated fasteners made from carbon steel or, respectively, austenitic stainless steel. The influence of temperature on stainless steel is low. The influence of temperature on the strength of powder-actuated fasteners made from carbon steel, on the other hand, is greater than its influence on standard construction steel due to the fact that carbon steel's high strength at room temperature is the result of a heat treatment process.

2.2.5 Corrosion protection

Powder-actuated fasteners made from carbon steel are generally coated with a thin layer of zinc (approx. 10 µm) as temporary protection from corrosion during storage, transport, installation and when exposed to weathering during the construction phase. This type of fasteners is intended for use in safety-relevant fastening applications where the finished fastening is not directly exposed to the weather or moist atmospheres [30, 31] (see Section 2.8). Hot-dip galvanizing is not possible due to the influence it has on the already hardened grain structure of the fastener. In addition, a thick zinc layer would have a negative effect on the anchorage obtained by the fastener in the supporting steel.

Stainless steel fasteners suitable for the corresponding ambient conditions should be used in situations where the fastenings are exposed to the weather or dampness. Stainless blunt-tip threaded studs made from duplex steel 1.4462 are also used under highly corrosive ambient conditions (e. g. in the petrochemical industry or on off-shore platforms).

Substructures in these facilities are, of course, coated or hot-dip galvanized in order to meet requirements for their own protection from corrosion. Blunt-tip threaded studs are suitable for fastenings to coated base materials without preparation and rework of the coating. The minimum base material thickness specified by the manufacturer (e. g. 8 mm) and the respective installation instructions are to be observed. Through penetration of the base material is avoided and the entrance location is sealed by means of a sealing washer with a diameter of approximately 12 mm (Figure 10). Screw-in threaded studs – introduced in Section 3.1.2.5 – also meet within their defined range of application these corrosion requirements. If stainless steel sharp-tip threaded studs are used on coated base material, the corrosion protection of the base material – especially on the back side of thin penetrated materials – will be damaged. The coating then has to be repaired or touched-up at the entrance point and the point of through penetration on the back side.

2.2.6 Manufacturing process

Powder-actuated fasteners are manufactured from a wire material in an industrial process. The manufacturing of a powder-actuated fastener can be broken down into 4 processes: shaping, formation of the grain structure within the material, galvanization and the fitting of the washers. The exact details of each step in the manufacturing process, the workshop drawings and specifications are not published by the fastener manufacturers. The workshop drawings and inspection plans for the manufacturer's own production control procedures for products requiring European Technical Assessment (ETA) or national approval are deposited with the DIBt (or with the corresponding European Technical Assessment Body) and the notified surveillance body. The manufacturers of products holding ETA are obliged to verify conformity of the products with the provisions of the corresponding ETA. Declaration of conformity is made by issuing a declaration of performance (DoP) and affixing the CE marking in compliance with the Constructive Product Regulation [12].

2.3 Interdependency: powder-actuated fastener – fastening tool – cartridge

As the fastener driving process has a decisive influence on the hold obtained by the fastener, the quality of a fastening made using a powder-actuated fastening tool depends on all components of the fastening system (Figure 3) – the fastener, the powder-actuated fastening tool and the driving energy. Fastener driving velocity, fastener guidance, transmission of energy from the piston to the fastener, dissipation of excess energy or variation of driving energy are a few of the factors that influence the hold obtained by the powder-actuated fastener.

In [32], for example, *Seeger* describes the influence of various powder-actuated fastening tools on the fastening quality obtained with threaded studs under otherwise unchanging conditions. With one of the tools, 82% of the threads were no longer free-running due to plastic deformation of the stud while, with another tool, all threads remained intact. In addition, a difference of up to 40% in pullout load values was determined.

Another example are the fastening systems with predrilling for thin base materials. Only the tools specified by the manufacturer are allowed to be used for driving the threaded studs. An important aspect is, for example, the holding and positioning of the stud in the fastener guide of the fastening tool. Furthermore, those specified systems may also use tools with piston brakes. These allow to meet the narrow tolerance range of the depth of penetration (see Section 2.5.3.1).

Accordingly, the entire powder-actuated fastening system must be verified as a whole as part of the procedure for European Technical Assessments (ETAs). The specified and verified system components – the powder-actuated fastener (single or in magazine strips), the fastening tool with or without fastener magazine, the driving piston and the propellant cartridge – must be stated in the ETA. For blunt-tip fastenings, the fastening system includes also the specified stepped drill bit.

2.4 Powder-actuated fastening terms and definitions

2.4.1 Depth of penetration and fastener stand-off

Figure 11 shows examples of powder-actuated fastenings. The part to be fastened is designated "component I" and the base material "component II".

The depth of penetration is defined as the distance between the surface of the base material and the point of the fastener after driving. This corresponds to the total distance traveled by the fastener in the base material. Depth of penetration greater than the thickness of the base material results when the fastener penetrates right through, to the extent that the point is visible on the reverse side of the supporting member. If the depth of penetration is 5 mm smaller than the base material thickness, any additional increase in the thickness of the material has no further effect on the fastener driving process or the anchorage of the fastener. The term "solid steel" is used to describe this situation. The depth of penetration of a powder-actuated fastener in solid steel thus corresponds to its depth of embedment.

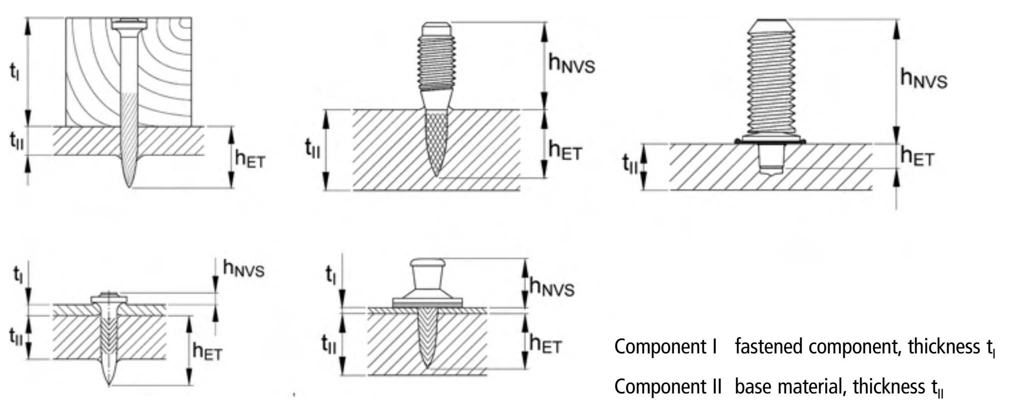


Figure 11. Components I and II, depth of penetration h_{ET} and fastener stand-off h_{NVS}

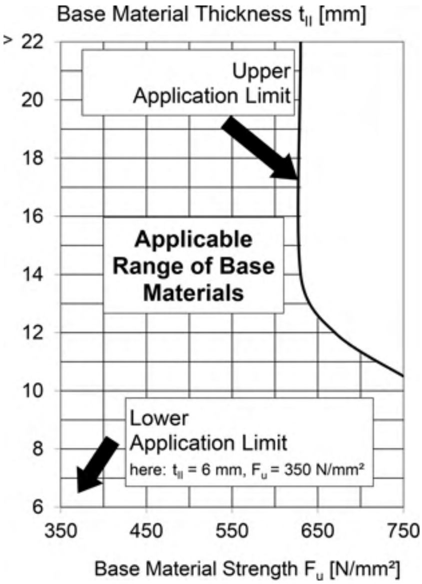


Figure 12. Application limit diagram

Fastener stand-off is the distance from the head of the driven fastener to the surface of the component fastened or, in the case of a threaded stud, to the surface of the base material. Fastener stand-off h_{NVS} is the reference dimension used to check the depth of penetration and thus the quality of the fastening (e. g. Figure 119).

2.4.2 Application range and application limits

The thickness and strength of components I and II determine the application range for a given fastening system. The base materials in which powder-actuated fasteners can be driven and obtain a reliable hold are defined in application limits charts. Figure 12 shows an example for a profile metal sheet fastener ([30] or, respectively, Figure 119). The possible combinations of base material thickness t_{II} and base material strength $F_{u,II}$ take the parameters for component I implicitly into account (strength and/or minimum and maximum fastenable thickness).

The lower application limit depends on the minimum thickness and minimum strength of the supporting material. This is determined by the loadbearing capacity of the hold obtained by the fastener in its longitudinal axis. The criteria for the upper application limit are fastener driving ability and also loadbearing capacity. In the event of exceeding the upper application limit, shear breakage of the fastener during driving occurs more frequently as the fastener is overstressed due to the higher driving resistance. When fastening soft wood components, buckling of the fastener or excessive deformation of the wood is the decisive cause of failure during the driving operation (see Figure 83).

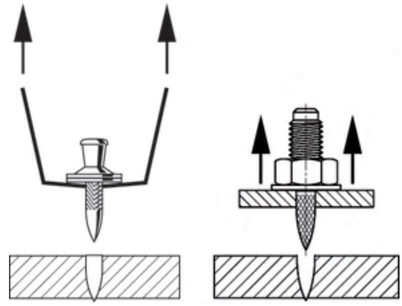


Figure 13. Anchorage failure

The criteria for determining the upper application limits are not explicitly defined in the applicable regulations. In the case of fastenings for profile metal sheets – as with the loading capacity – a characteristic upper application limit, considering the unavoidable variation of the system components, is specified by the manufacturer. Verification of the upper application limit must, of course, be provided within the scope of the assessment procedure (e. g. Table 23).

Depending on the application, the upper application limit may have to be more stringently defined in some cases. This may be necessary, for example, in situations where no further space is available for replacement of a sheared fastener or where a few individual cases of shear breakage may already lead to considerable wear or damage to the fastening tool.

Generally speaking, care must be taken as the influence of the base material on fastening quality is not continuous above or below the values representing the upper and lower application limits. Simple extrapolations, such as the reduction of recommended load values in proportion to the amount by which the minimum supporting material thickness ($t_{II,act}/t_{II,min}$) has been undercut, are incorrect as they do not represent the actual physical behavior.

2.5 Anchorage in unalloyed structural steel

The term "anchorage" refers to the hold obtained by the fastener in the base material. Failure of the anchorage results in the fastener being pulled out of the base material (Figure 13).

Metals with plastic deformation behavior, generally speaking, provide suitable anchorage for powder-actuated fasteners. The most important base material for fastenings made with powder-actuated fasteners is unalloyed structural steel as per EN 10025-2 [33]. Within the scope of the assessment procedures, the anchorage obtained by the powder-actuated fastener in construction steel must be systematically verified. Assessment of the loadbearing behavior of powder-actuated fasteners driven into construction steel is based on a comprehensive set of data determined experimentally.

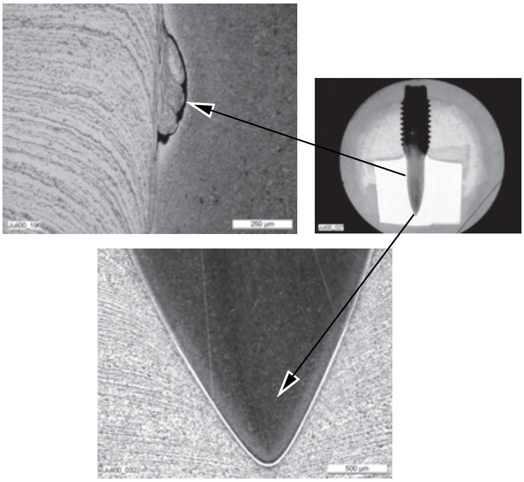
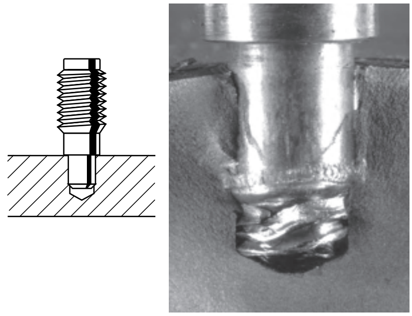


Figure 14. Micrographs of fastener anchorage



Remark: The photograph shows the fractured area of the base material after a fatigue test.

Figure 15. Cross section of a blunt-tip fastener

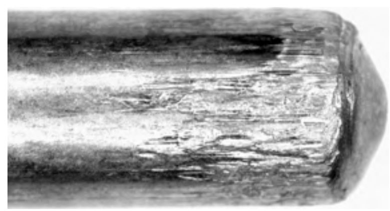


Figure 16. Base material adhering to a pulled-out fastener with cylindrical shank

2.5.1 Anchorage mechanisms

The anchorage obtained by a galvanized powder-actuated fastener in steel is determined by several mechanisms and principles: friction hold, keying hold, a welding effect and a soldering effect [9, 34]. The resilience of the displaced base material exerts a clamping pressure on the surface of the fastener. A tensile force applied externally to the fastener can thus be taken up by friction. Knurling on the shank of the fastener increases the coefficient of friction at the areas in contact and has the effect of creating a microkeyed hold in the base material as this material flows into the tiny depressions in the surface of the fastener during the highly dynamic driving process.

High temperatures are generated at the surface of the fastener during the driving process due to friction between the fastener and the base material. These high temperatures are responsible for the bonding component of the anchorage obtained: Bonding, on the one hand, takes the form of a soldering effect (melting of the zinc coating) and, on the other hand, partial welding of the fastener material to the base material. This welding effect takes place where the zinc layer is scraped away. This occurs, above all, at the point of the fastener. Metallographic analysis of the ground cross section of specimen fasteners (Figure 14) provides proof of this microkeyed hold and material bonding. The anchorage obtained by stainless steel fasteners takes the form of a welding effect and a friction hold.

General analytical computation models for determination of the loading capacity of the anchorage are not published or, respectively, are not part of the applicable regulations (e. g. EN 1993-1-3 [35]). Verification of the loading capacity of the anchorage thus has to be provided by tests. The relative shares of each of the mechanisms in the loading capacity of the anchorage are not constant and depend on the fastening system used, the thickness of the base material and the tensile strength of base material. An experimental analysis of the distribution of the loading capacity along the depth of penetration of the fastener is provided by [36].

The base material is not only laterally displaced when a blunt-tip fastener is driven. The edges around the end of the fastener also shave metal cuttings off the wall of the predrilled hole (Figure 15). This action generates high temperatures which, in conjunction with the high contact pressure, lead to partial friction welding of the stainless steel pin to the supporting material. Figure 16 shows the base material that remains welded to the shank of a fastener after it has been pulled out. At the same time, the resilience of the supporting material also exerts a clamping force on the fastener.

2.5.2 Load-displacement characteristics

The anchorage displays very rigid, not ductile load displacement characteristics when a tensile force is applied centrally to a fastener set in solid steel. Once the maximum load has been exceeded, the tensile load drops immediately. Accordingly, a load-displacement curve for the anchorage is not recorded when tensile loading tests are carried out. More ductile characteristics are displayed by fasteners driven very deeply in steel plates, resulting in complete penetration of the plate. An example of a curve of this kind is given in Figure 17 [37].

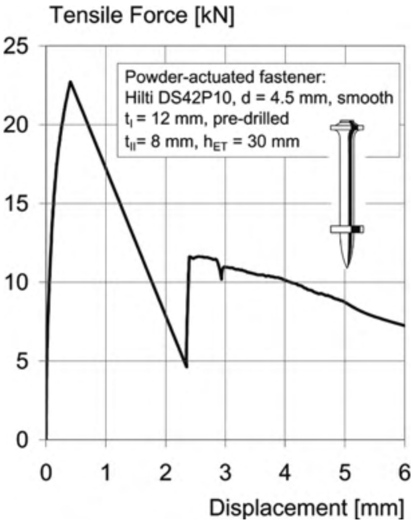
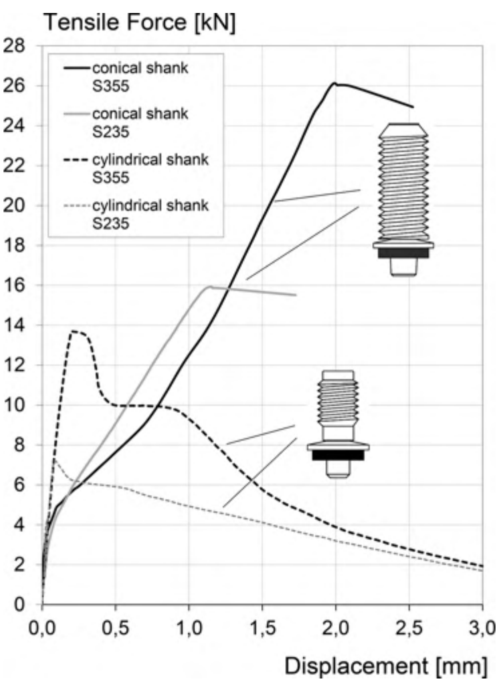


Figure 17. Load-displacement curve for fastener with great driving depth and complete penetration of the base steel



Blunt-tip threaded studs: Hilti X-BT with cylindrical shank (d = 4.5 mm), X-BT-GR and X-BT-MR with conical shank (d = 5.2 mm), Figure 10.

Figure 18. Load-displacement curves for blunt-tip fasteners in solid steel

Nevertheless, even in this case, the tensile load drops rapidly to a lower frictional load value (clamping force component) when the maximum load is exceeded.

Blunt-tip threaded studs also achieve comparatively ductile load-displacement characteristics when set in solid steel. Figure 18 shows examples of load-displacement curves for S 235 and S 355 steels for two different types of shank (Figure 10).

After reaching loading capacity, which is determined by failure of the welded zones, the blunt-tip stud types with cylindrical shank still take up forces approximately equal to the recommended working loads (1.8 to 2.3 kN) with a displacement of 2 to 3 mm. Loading capacity in this area is the result of the clamping hold and, to a certain extent, to the keying hold provided by the material bonded to the point of the fastener shank (Figure 16).

The types with conical shank are less stiff but reach about double as high pullout resistance. For those studs the forces are transferred more uniformly within the contact area of the shank along its depth of penetration. When reaching the ultimate force, a higher share of that contact area fails exceeding the local shear resistance of the base material. Consequently, those studs show less post peak deformation. The maximum service loads of these studs amount to approximately 3.6 to 4.6 kN with respective small deformations in the range of 0.1 to 0.2 mm.

2.5.3 Parameters influencing anchorage

2.5.3.1 Depth of penetration

Depth of penetration is the key parameter influencing the quality of the fastening. Figure 19 shows a good example of how it influences the pullout loads achieved by threaded studs [38]. Each dot represents the result of an individual test. As the thickness of the base material was 20 mm, the point of the threaded stud was fully embedded in the base material in all of the tests. The pullout load values for fasteners set in solid steel rise as depth of penetration increases. Loading capacity is low (with high coefficient of variation of the values obtained) when the depth of penetration is less than 12 mm. At this depth, only part of the smooth point and none of the knurled cylindrical shank of the fastener is embedded in the supporting material. Powder-actuated fasteners must therefore be driven to a type-specific minimum depth of penetration in the base material by applying the correct driving energy, which is ensured by use of the appropriate cartridge power level and the power setting of the fastening tool.

The fastener penetration depth range h_{ET} to be observed is influenced by the fastener shank diameter, the knurling, the shape of the shank and point, the means of corrosion protection and the material from which the fastener is made. Guide values for the depth of penetration of specific fastener types are as follows:

- Galvanized fasteners with knurled shank (4.5 mm): h_{ET} = 12 to 18 mm

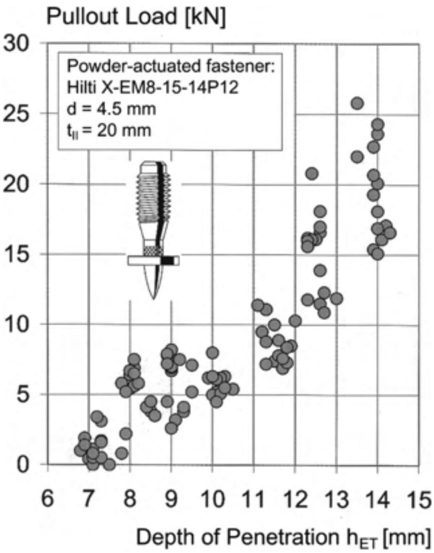


Figure 19. Influence of depth of penetration in solid steel

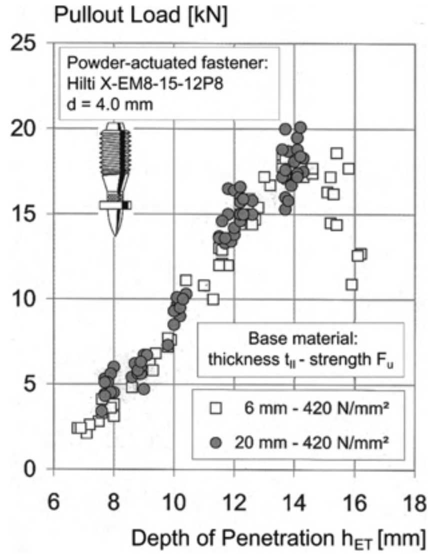


Figure 20. Influence of depth of penetration in base materials with a thickness of 6 mm or 20 mm

- Galvanized fasteners with knurled tip (4.5 mm): h_{ET} = 9 to 13 mm
- Galvanized fasteners with knurled shank (3.7 mm): h_{ET} = 10 to 14 mm
- Galvanized fasteners with smooth shank: h_{ET} = 15 to 25 mm
- Stainless steel fasteners with smooth shank: h_{ET} = 9 to 14 mm
- Blunt-tip fasteners: h_{ET} = 4 to 5 mm

The correct depth of penetration h_{ET} is checked by measuring fastener stand-off h_{NVS} (Figure 11). The fastener stand-off range to be observed and the maximum permissible thickness of the component to be fastened are defined in the ETA or, respectively, in the technical documentation provided by the manufacturer. Observance of these conditions ensures that fasteners are driven to the correct depth.

Figure 20 shows two further test series carried out with threaded studs, the depth of penetration of which was greatly varied. For the first series of tests (t_{II} = 20 mm), the threaded studs remained fully embedded in the base material in every case. For the second series of tests (t_{II} = 6 mm), the base material was always penetrated right through. All other test parameters remained constant. In analogy with Figure 19, the decisive influence of depth of penetration on fastener anchorage, irrespective of the thickness of the base material, was confirmed. Base materials with a thickness of 20 mm tend to achieve a higher loading capacity. Compared to the influence of the depth of penetration, the effect of various supporting material thicknesses is only minor.

The test series carried out on 6 mm thick construction steel also demonstrated the effect of driving with excess energy. Not only the point and the shank of the fastener were then driven into the base material, but also a part of the tapered transition between the shank and the threaded section of the stud. This caused the surface of the base material to be forced aside around the fastener, thus effectively reducing the area of contact between the fastener and the base material. This explains the drop in loading capacity for depths of penetration greater than 15 mm. Accordingly, the technical documentation provided by the manufacturer or, respectively, the fastener approval documentation, specifies not only the maximum but also the minimum fastener stand-off value to be observed.

Figure 20 also shows that this drop in loading capacity occurs only with the 6 mm thick base material. The explanation for this is that the maximum energy available from the fastening tool is not sufficient to drive the fastener to excessive depth in case of thick base material. As a general rule it can be presumed that the fastener driving process is insensitive to the use of excess energy when the base material has a thickness of about 8 to 10 mm or more.

Fastening systems which allow very accurate adjustment of the driving energy are required when fastening to base materials with a thickness of 6 mm or less, as the sensitivity of the anchorage to excess energy increases correspondingly. In extreme cases, this may cause the fastener to gain no hold at all. The fastener may be driven to its intended depth of penetration but, if fastener driving energy is set incorrectly, the excess energy still stored in the piston may be sufficient to knock the fastener out of its anchorage as the piston completes the driving operation.

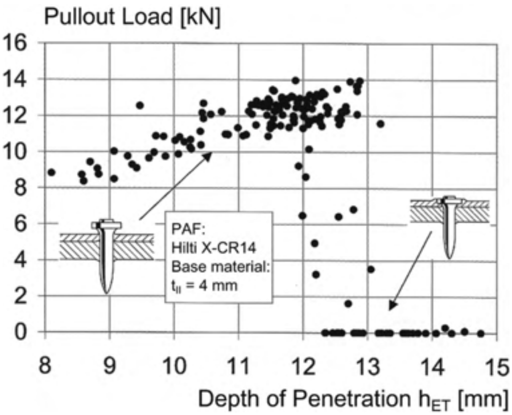


Figure 21. The effect of excess driving energy when fastening to thin materials

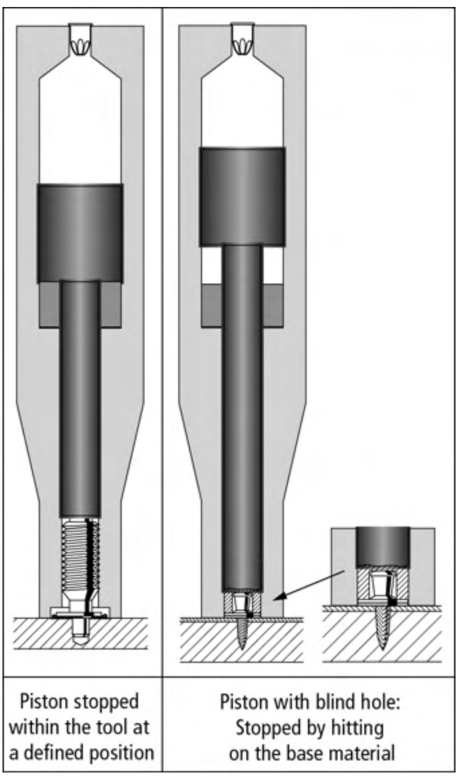


Figure 22. Piston brake concepts

Figure 21 shows the effect of excess driving energy on fastenings made in base materials with a thickness of t_{II} = 4 mm. The tests were carried out with a broad range of excess energy values for the purpose of illustrating this effect.

The negative effect of excess energy on fastener anchorage can be avoided when this point has been taking into account by the design of the fastening tool. The tool must ensure that excess energy from the piston is not transferred to the base material through subsequent contact with the head of the fastener and thus damaging the fastener anchorage. This concept is referred to as the "piston brake". This stops the piston within a set distance after the fastener has been driven to the required depth. When a fastening tool equipped with a piston brake is used, the fastener can always be driven with slight excess energy. This has the following advantages: Fastener driving performance is increased and reproducibility improved as allowance is made for the unavoidable variation in driving energy released by the cartridge. The piston brake can be an integral feature of the tool, i. e. the piston is designed to come into contact with a predefined stop piece. The piston can also be stopped by allowing it to strike the supporting material. This type of piston brake can be implemented in tools that feature a blind hole in the piston face.
For fastening on thin materials ($3 \le t_{II} < 6$ mm) only integrated piston brakes are suitable. Fasteners can then be driven with excess energy. If fastening tools without integrated piston brake are to be used for this material thickness range, the fastener stand-off value range h_{NVS} should be set so that: a) negative energy effects can be ruled out and b) fastening quality can be checked reliably (Figure 21).

2.5.3.2 Base material thickness

Figure 23 shows the results of tests evaluated according to the thickness of the base steel [38]. Each dot represents the characteristic pullout load values from a series of 90 individual tests.
So long as the fastener penetrates right through the supporting material, loading capacity also increases slightly as base material thickness is increased. The increase, however, is much lower than the increase in the area of contact between the fastener and the base material. The optimum is achieved with base materials of a thickness in which the point of the fastener only just penetrates right through [39]. On the whole, however, the influence of the thickness of the base material is comparatively slight. The loading capacity achieved by thin (6 mm) material, for example, is almost at the level of solid steel. Figure 23 again confirms that depth of penetration is the parameter with the greatest influence on fastener anchorage.
With materials less than 6 mm thick, however, the influence of the base material thickness is considerable. Loading capacity is then determined by the absolute area of contact between the fastener and the base material (Figure 24). A minimum depth of penetration must also be observed for this thickness range. When depth of penetration is several times the supporting material thickness, the depth of penetration threshold value above which anchorage loading capacity becomes

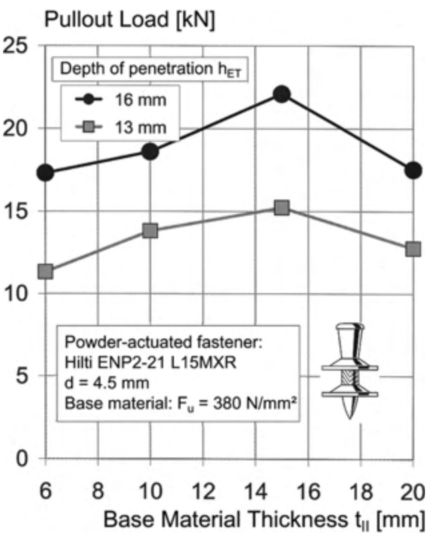


Figure 23. The influence of base material thickness for $t_{II} \geq 6$ mm

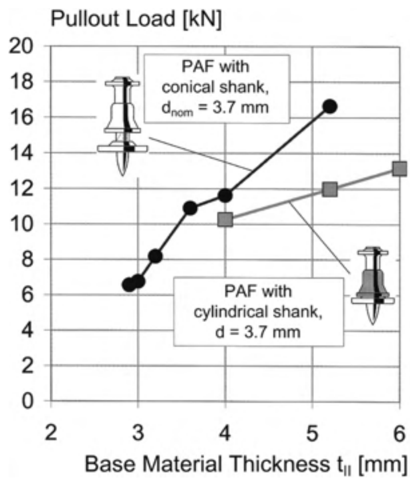


Figure 24. The influence of base material thickness for $t_{II} < 6$ mm

independent of depth of penetration, is exceeded (Figure 25) – subject consideration of excess energy effect in accordance with Figure 21.

2.5.3.3 Base material strength

The loading capacity of the anchorage generally increases as the strength of the base material is increased [38] (Figure 26). The degree to which this parameter has an effect, however, also depends on the type of fastener used, the depth of penetration and the thickness of the supporting material.

As a part of the European assessment procedures, verification of the pullout loading capacity at the lower end of the application limit scale must be provided (low-strength steel of various thicknesses). Exceeding the upper application limit may result not only in shear breakage of fasteners as they are driven, but also in reduction of the loading capacity of the anchorage obtained. The fasteners no longer penetrate the material centrically but bend as they are driven. If the minimum depth of penetration is not reached due to insufficient driving energy, it is possible that no hold is obtained even in solid steel. Resilience in the fastener's longitudinal axis then prevents penetration and no hold is obtained (Figure 27) [40]. As part of the European assess-

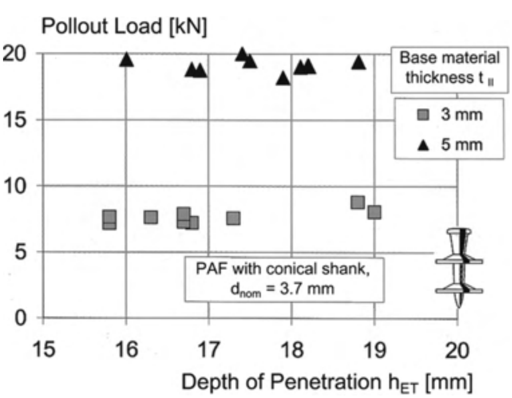


Figure 25. The influence of depth of penetration for $t_{II} < 6$ mm

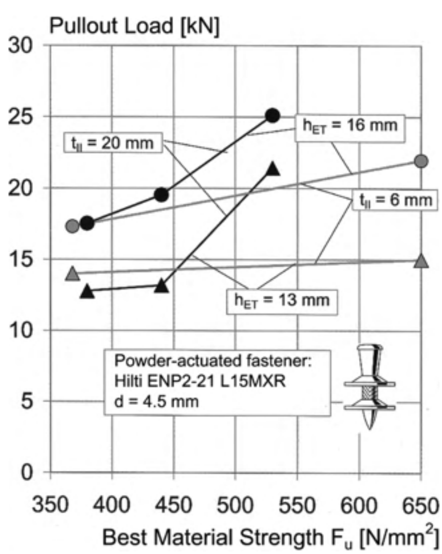


Figure 26. The influence of base material strength

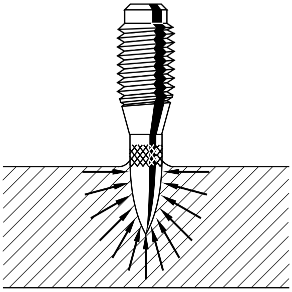


Figure 27. Elastic reaction (resilience) when depth of penetration is inadequate

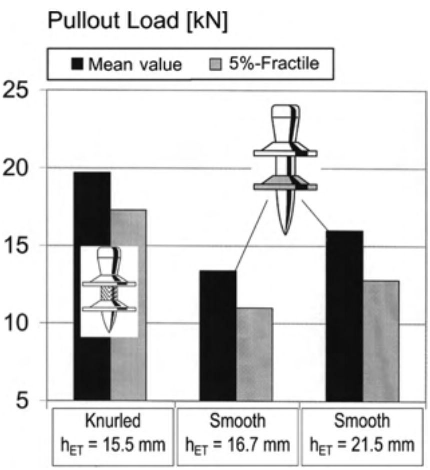


Figure 28. The influence of knurling on the fastener

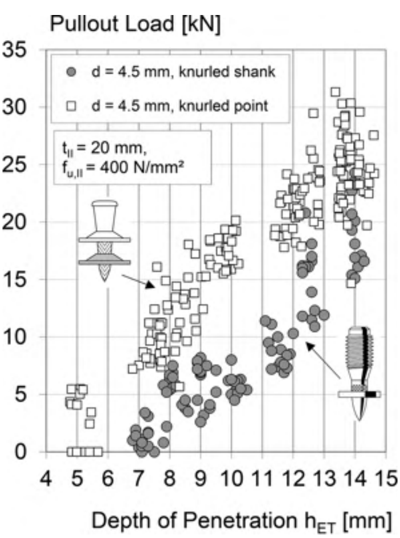


Figure 29. Influence of tip knurling on the required fastener driving depth

ment procedure, verification of loading capacity thus also has to be provided for fastenings made at the upper end of the application limit scale.

With blunt-tip powder-actuated fasteners, the strength of the base material is the most important influencing parameter as correct depth of penetration is ensured by a fastening system with an integrated piston brake. The curves in Figure 18 show how loading capacity increases as base material strength increases. This is due, on the one hand, to the welding effect's greater influence on the hold obtained and, on the other, to the supporting material's greater shear resistance. This, in the end, determines the loading capacity in the area of the welded zone (Figure 16). For example, more than half of the blunt-tip fasteners driven into high-strength S 960 steel achieve an ultimate load of about 30 kN in tests with mode of failure being breakage of the fastener shank. Blunt-tip threaded fasteners are also often used on coated base materials with a coating thickness of up to 500 μm. For systems with piston brake the effective depth of penetration is thus reduced approximately by the amount of the coating thickness. This leads to a reduction of the pullout resistance, see Section 5.8.1.

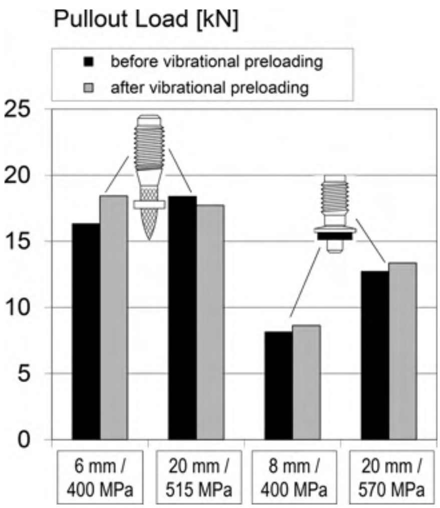
2.5.3.4 Knurling

The effect of knurling on the fastener (see Section 2.2.2) is shown as an example in Figure 28, with data from pullout tests using fasteners with knurled and smooth shanks in which all other test parameters remained the same. Both types of fastener tested were driven into the same steel using the same fastening tool. The loading capacity of the longer, smooth-shank fasteners is significantly lower than that of the knurled fasteners in all cases. Even an increase in the depth of penetration cannot compensate for the lack of knurling.

The knurling on the shank of the fastener, however, is effective only when the fastener is driven to sufficient depth. The key advantage of fasteners with knurled tips (see Figure 7, type 1, 5 and 8) is that part of the knurling is in contact with the base material, and is thus effective, even at a low depth of embedment. The minimum depth of penetration and the necessary driving energy is thus lower for fasteners with knurled tips. Figure 29 shows this effect on the basis of test results obtained with fasteners with a knurled tip. For the purpose of providing an immediate comparison, results obtained with fasteners with a knurled shank are also given (see Figure 19).

2.5.4 Robustness of the anchorage

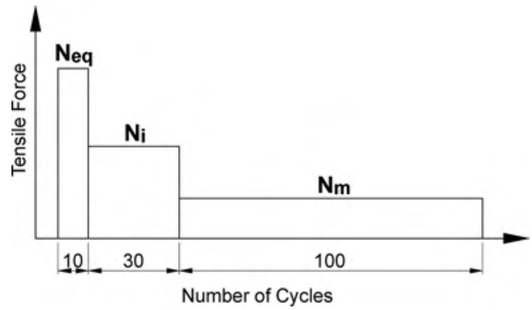
The question of anchorage robustness refers, on the one hand, to the effect of repetitive tensile loading on the fastener. Does repetitive loading cause fatigue of the anchorage or, in other words, cause the fastener to work loose? If so, how significant is this effect? On the other hand, there is also the question of whether the loads on the base material, and its stress-strain state in the area



Carbon steel fastener with knurled tip: Hilti X-EM8H

Blunt-tip stainless steel fastener: Hilti X-BT

Figure 30. The influence of vibrational preloading



According to [41]: $N_m \approx 1.25$ times the service load,
$N_{eq} \approx 2.5$ times the service load

Figure 31. Preloading pattern for simulated seismic tension tests of powder-actuated fasteners

around the fastener penetration, have an influence on anchorage of the fastener. In answering these questions, a difference must be drawn between purely static loading and vibrational stressing of the base material.

When assessing these aspects, it is always presumed that the fasteners are driven according to the manufacturer instructions within their specified depth of penetration.

2.5.4.1 Vibrational loading of powder-actuated fasteners

In the vibrational loading tests both nails and threaded studs are used and subjected to vibrational loading. In the case of the threaded studs, the tensile force is applied directly to the fastener by way of the threaded section, whereas with the nails, the tensile force is transferred to the fastener, for example, by a strip of sheet metal. High vibrational prestressing, i. e. at more than twice the recommended working load, has no effect on the loading capacity of the anchorage obtained by the fastener.

Figure 30 shows, as an example, the characteristic loading capacities achieved in the corresponding series of tests carried out with two types of threaded studs on base materials of various thicknesses and strength grades. The loading level of the dynamic preloading was 50% of the characteristic pullout resistance determined in reference tests carried out before the dynamic loading tests. The number of vibrational cycles applied was 10´000. The scatter of the results lies within the usual range of pullout tests performed without preloading. The same behavior was observed in the tests on thin, low-strength materials as well as on thick, high-strength materials.

Tests of this kind can be used to determine the suitability of the powder-actuated fasteners for situations where they will be subjected to dynamic loading such as encountered during earthquakes (see Section 4.1.3). Figure 31 shows the preloading pattern for the validation of seismic loading according to the US acceptance criteria for power-actuated fasteners (ICC-ES AC70, Acceptance Criteria 70 [41]). Applying this protocol, a seismic loading beyond admissible service loads is simulated. After the preloading the residual static resistance is determined in the test.

Provided the residual static resistance amounts to at least 80% of the strength from respective control tests, the static values are allowed to be used unchanged for seismic loading. Currently explicit rules for the validation of seismic actions are not yet given in the European Assessment Documents. Nevertheless, a first assessment on the seismic suitability of powder-actuated fasteners can be made in keeping with the validation concept provided in AC70 [41]. A similar assessment concept is already covered by European assessment procedures for anchors under seismic action (Category C1 per ETAG 1, Annex E [42]).

Dynamic testing using strips of sheet metal forms part of the assessment procedure for powder-actuated fasteners for sheet metal attachment. These tests serve to determine the sheet metal's own resistance to vibrational loads. The tests are designed so that fractures due to vibrational stress occur within the range of approx. 2´000 to 20´000 cycles (see Section 7.3.2).

The test results available ([3, 43] and others]) show that the anchorage is not the decisive factor in the fatigue fractures at the joint. The sheet metal failed due to being pulled over the fastener. In the tests with threaded studs, the stud itself failed due to fatigue fracture of the material – in general slightly below the surface of the base material – from which the fastener is made. Figures 32 and 33 show the results (individual values, linear regression and characteristic Wöhler curve) of pulsat-

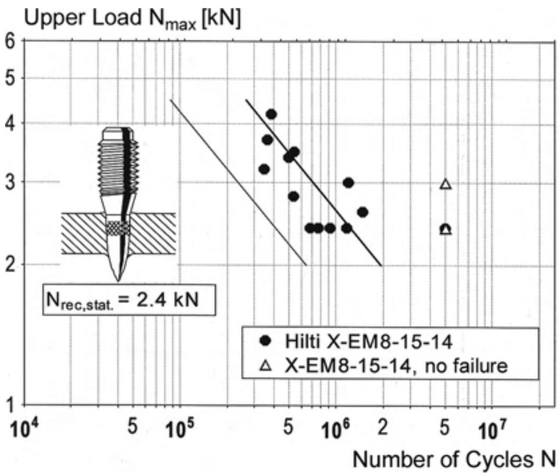
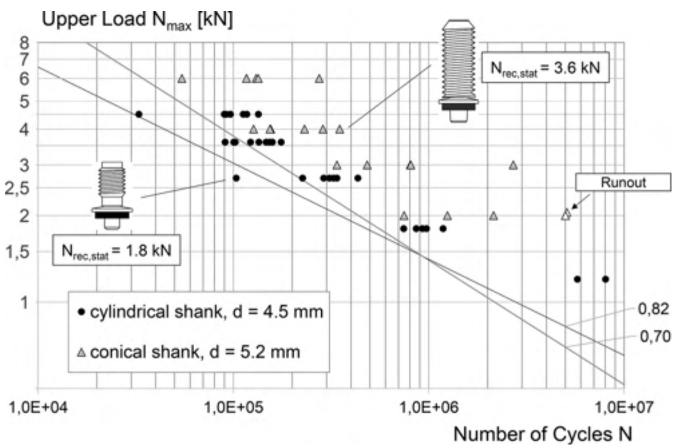


Figure 32. Pulsating tensile tests with galvanized carbon steel threaded stud



Blunt-tip threaded stud Hilti X-BT (d = 4.5 mm), X-BT-GR and X-BT-MR (d = 5.2 mm), Figure 10.

The drawn lines show the 5%-fractile of the Wöhler curve of the respective test series with values given at 5 million load cycles

Figure 33. Pulsating tensile tests with stainless steel blunt-tip threaded studs made from material 1.4462

ing tensile loading tests ($R = N_{min}/N_{max} \approx 0$) in which the tensile load is centrically applied to threaded studs. The conclusion drawn from these tests is that the anchorage's fatigue strength cannot be determined by tensile loading tests of this kind as the threaded stud or the component fastened fails first. Nevertheless, these tests clearly verify the robustness of the types of fastener tested with regard to the dynamic loading component always present in static loads. The manufacturer's recommended loads N_{rec} for each type of threaded stud are given in the illustrations for the purpose of comparison [9].

The tests also show that a generally applicable value cannot be given for the fatigue strength of powder-actuated fasteners. The fatigue strength is product specific and depends on the material, the geometry of the notches and grooves in the fastener, how these are formed (transitions, thread formation, knurling) and the manufacturing process (e. g. thread forming). Please refer to Section 4.1.2. for verification of fastener fatigue strength.

2.5.4.2 The influence of static stress in the base material

Tests to determine the influence of static tensile or compressive stress in the base material on fastener pullout loading capacity are described in [44]. In these tests, the base material is subjected to constant tensile or compressive stress in a test rig while fastener pullout loads are determined (Figure 34).

Figure 35 shows fastener pullout loading capacity relative to tension or compression on the base material. For the purpose of the tests, the stresses applied to the base material are given as ratio to the actual yield point of the base material.

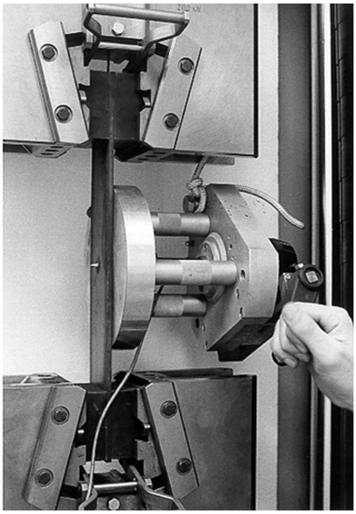


Figure 34. Test setup for pullout tests from base material subjected to stress

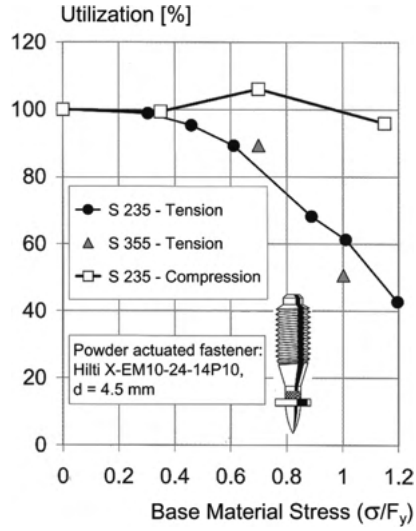


Figure 35. The influence of stress in the base material on loading capacity of the anchorage

Compressive stress in the base material has neither a negative nor positive (load-increasing) effect on the pullout resistance of the fastener. Only under high tensile stress, causing the base material to yield over its entire cross section, do fastener pullout loads drop significantly. Nevertheless, the anchorage still behaves very robustly, as fastener pullout loads of 40 to 50% of the values obtained in unstressed base material were achieved up to shortly before reaching the ultimate tensile strength. At the maximum recommended working stress ($\approx 0.7 \cdot F_y$), the influence on pullout loading capacity is about 15%. This effect is covered adequately by the applicable safety factors [44].

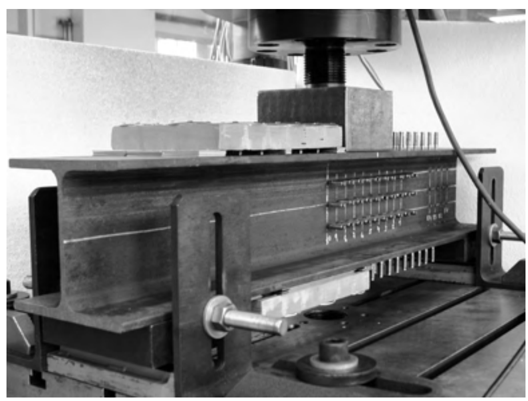


Figure 36. Test setup for application of dynamic stress to the base material

2.5.4.3 The influence of vibration of the base material

An experimental investigation on the influence of pulsating loads or vibration of the base material on fastener anchorage is documented in [45]. The purpose of the study was to prove, by way of tests, that the fasteners examined could not be "shaken out" of their anchorage through movement of the base material. When contemplating a model, with the point of the fastener likened to a wedge, it may be considered feasible that pulsating compressive forces in the base material could cause the fastener to be squeezed out of its anchorage. Stainless steel and carbon steel fasteners were tested in [45]. These fasteners were driven into two different test beams, an HE-A 140 steel profile (Figure 36) and a 50 mm thick solid steel plate. Each of these test beams were set up as a single span on rollers and dynamically loaded in their center by a servo-controlled hydraulic cylinder. The fasteners were positioned in the tension and compression zones as well as in the web of the steel profile. The loading protocol selected (Figure 37) was oriented toward the fatigue strength of steel with powder-actuated fasteners (see Section 2.7.2). This represented the upper limit for the number of cycles and the allocated stress ranges. For stress ranges below fatigue strength it was also possible to create high-frequency vibration (50 Hz).

Figures 38 and 39 show examples of the results from [45]. They compare the pullout loads after subjection to vibration with reference values from tests carried out with the same base material before subjection to vibration. Oscillation and vibration of the base material was found to have no damaging effect on the anchorage of the fasteners tested.

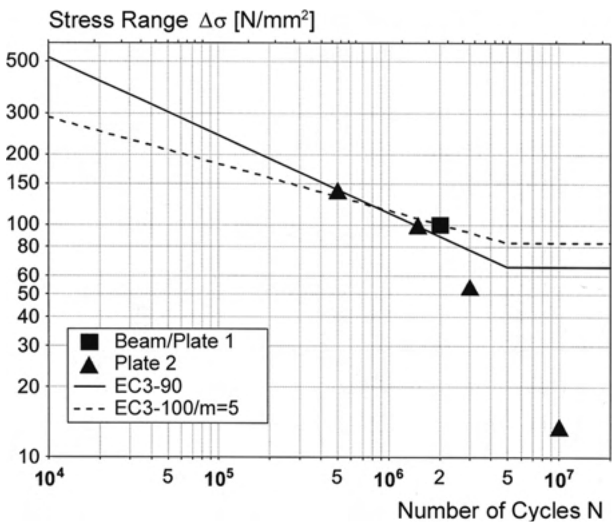


Figure 37. Stress ranges corresponding to the loading protocol

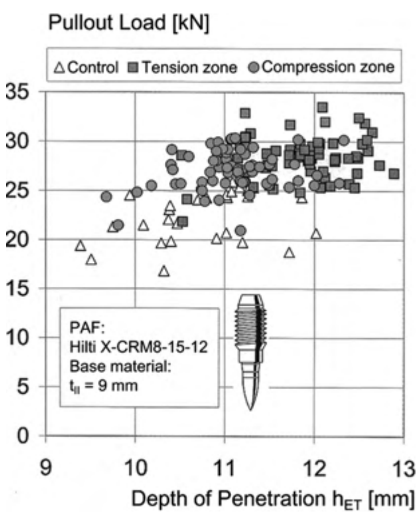


Figure 38. Influence of vibration of the base material on stainless steel threaded studs

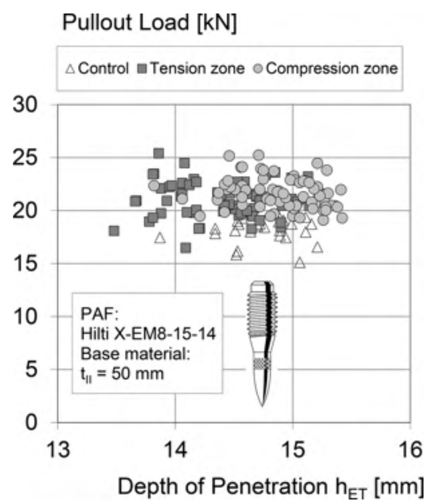


Figure 39. Influence of vibration of the base material on carbon steel threaded studs

2.5.4.4 Influence of ground fastener points

Powder-actuated fasteners must be driven to a depth within the specified range if they are to achieve proper anchorage. In the case of fasteners with 4.5 mm shank diameter driven into materials between 6 (min t_{II}) and approx. 15 mm thick, this results in the fastener penetrating right through the base material. The projecting points could spoil the appearance of the object or, in situations where persons could come into contact with the surface in question, the points could present a risk of injury. If a flat surface is required for reasons of appearance, the points and the bulge on the back side of the material of the base structure have to be ground flush with an angle grinder.

The sharpness of the points can be reduced by grinding them off lightly. This has no effect on pullout loading capacity as long as the surface bulge at the rear is not ground away.

However, if the tip of the fastener and the bulge are ground off flush with the surrounding surface, the pullout resistance of the fastener will be reduced. This reduction in loading capacity depends on the thickness and strength of the base material. An experimental investigation of powder-actuated fasteners for sheet metal fastening [46] resulted to the reduction of pullout resistance according to Table 5.

Grinding off the points does not cause uncontrolled damage to the fastener anchorage. However, the influ-

Table 5. Influence of ground fastener points [46]

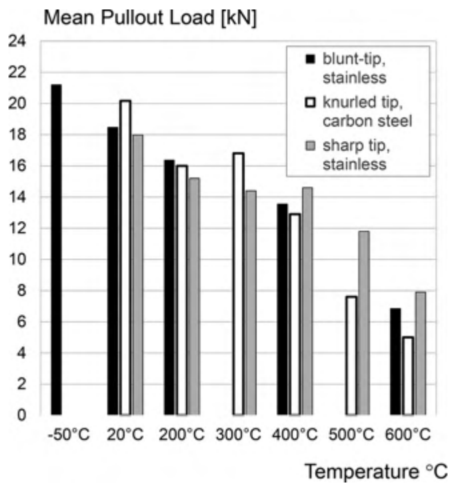
	Pullout load N_{Rk} [kN]	
Base material: thickness t_{II} / ultimate strength f_u	Control	Back side ground flush
6 mm, 390 N/mm²	15.85	9.86
6 mm, 630 N/mm²	25.90	18.48
8 mm, 390 N/mm²	13.16	10.98
8 mm, 630 N/mm²	23.32	22.77
10 mm, 390 N/mm²	14.17	13.77
10 mm, 630 N/mm²	23.24	22.03

PAF: Hilti ENP2-21L15, h_{ET} = 16.5 to 17.0 mm
Component I: t_I = 1.0 mm

ence on allowable loads shall be taken into account by applying load reductions for the applicable fastener type.

2.5.4.5 The influence of temperature

Figure 40 shows the influence of temperature on the loading capacity of powder-actuated threaded studs. The test samples were heated in an oven while the temperature of the base material close to the fastening was continuously measured by means of a thermal sensor. When reaching the target temperature of the base material, the tension resistance of the threaded stud was determined. Independent on type and material of the threaded stud pullout failure of the stud was controlling in all tests.
The increase of the temperature of the base steel member leads to a reduction of the mean pullout resistance. Up the 400 °C the decrease is relatively low, beyond 400 °C a steeper decline of the resistance is observed similar with the strength of the construction steel itself. Stainless steel threaded studs with and without tip behave pretty similar and very good natured. At 600 °C they reach about 40% of the pullout resistance in the reference cold state. For these studs the scatter of the pullout values remains also low at the high temperatures (coefficient of variation < 10%). For the carbon steel studs the relative reduction in the temperature range between 400 und 600 °C is more pronounced. However, at a member temperature of 600 °C, these studs still reach 25% of the pullout resistance at room temperature. That higher effect of the temperature on the anchorage of threaded studs made from carbon steel is explained by the higher temperature effect on the stud material itself (Figure 9).
The resistance of the anchorage at elevated temperatures due to a fire will not control design in most cases. Such a verification might be required, for example, in situations where stainless steel threaded studs are used to fasten substructures for fire protection cladding to steel beams or on tunnel walls.



Tested threaded studs:
Blunt-tip, stainless: Hilti X-BT-MR M10/15 SN 8
Sharp-tip, stainless: Hilti X-ST-GR M8/10 P8
Point knurled, carbon steel: Hilti X-EM8H-15-12-P8

Figure 40. The influence of temperature on the anchorage

Fastener anchorage is very robust at low temperatures. The stainless steel material's higher coefficient of thermal expansion has no negative effect on the pullout resistance. Figure 40 shows exemplarily pullout resistances at -50 °C of blunt-tip threaded studs made of stainless steel material 1.4462.

2.6 Fastener anchorage in alloyed steels, cast iron and non-ferrous metals

Powder-actuated fasteners can be driven into metals that have adequately plastic deformation properties. The loading capacity of the anchorage obtained and the characteristics of the anchorage mechanisms are, however, specific to the material and differ from those of unalloyed structural steel. Therefore, the behavior of powder-actuated fasteners on unalloyed structural steel cannot be transferred to other materials. This also applies to the application limits which are defined in terms of base material thickness and strength.
The most important metals used in construction in addition to unalloyed structural steel are:
– Stainless steels
– Aluminum
– Cast iron with spheroidal graphite
The general suitability of powder-actuated fasteners for driving into stainless steel or aluminum has been verified [47–49]. Figure 41 shows, for example, the pullout load capacity of stainless steel nails in aluminum 6061. However, generally applicable load values or, respectively, application limits are not published by the manufacturers. The values for the actual application to be

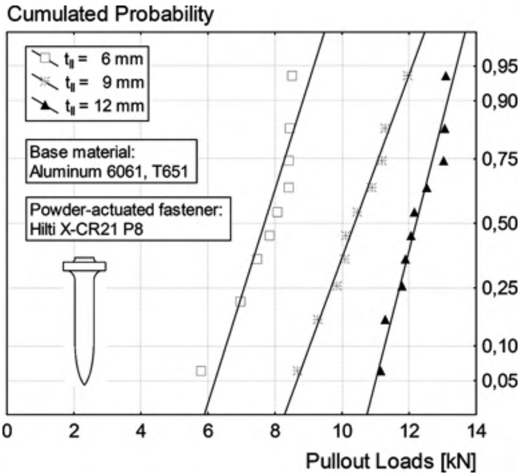


Figure 41. Example of the loading capacity of stainless steel powder-actuated fasteners in aluminum

carried out must be determined and verified in each individual case for the base material specified.

Regarding the suitability of the fastening system, attention must be paid to the following points:

For durability reasons it is necessary to use stainless steel powder-actuated fasteners when the base material is stainless steel or aluminum. The stainless steel used for substructures often has a high strength, so in many cases it is not possible to drive powder-actuated fasteners into this material. If the fasteners can be driven properly, however, then the bond between the stainless steel fastener and the stainless steel base material is capable of taking up high loads. The critical factor with stainless steel base materials is the low application limit

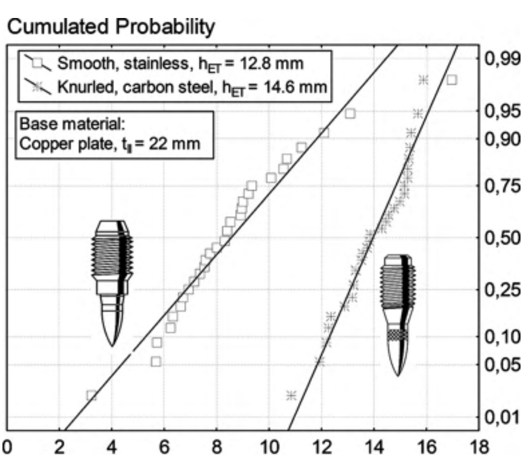


Figure 42. Loading capacity of threaded studs set in a copper plate

(t_{II} = 4 to 6 mm) that may be reached already with comparatively thin base materials. Blunt-tip stainless steel fasteners, however, can be driven into stainless steels without any problem. Nevertheless, as stainless steel is more difficult to machine, predrilling takes longer and results in higher drill bit wear. This aspect must be taken into account when assessing the productivity of the system.

Exactly the opposite is the case when the base material is aluminum. The critical factor here is the low rigidity or, respectively, lack of thickness of the base material. Powder-actuated fasteners cannot be driven reliably into extruded profiles with a thickness of 3 or 4 mm unless a special fastening tool is used. This is because the fastener is driven too deeply into the material even when the tool is set to the lowest possible driving power. On thicker aluminum of suitable strength, the resistance of the material is sufficient to allow fastenings of reproducible quality to be made. Figure 41 provides an appropriate example for a 6061 aluminum alloy with a strength of approx. 330 N/mm^2 (state T651). The fastener penetrates right through aluminum base material sheet of all thicknesses t_{II} = 6, 9 and 12 mm, and the positive influence that greater thickness has on the anchorage obtained is directly proportional to the thickness. The resulting pullout loading capacity, however, lies clearly below that of similar fastenings in unalloyed structural steel as no “adhesive” bond was formed between the fastener and the aluminum. This reduced loading capacity is of little relevance in the case of nailed connections (Figure 7, types 1 to 7) as the holding values achieved are high enough for most applications and the loading capacity of the joint often depends on the strength of the material or component fastened. With threaded studs, on the other hand, a load is already placed on the anchorage when the nut or screw-on component is tightened. The influence of the reduced pullout loading capacity is then relevant and must be taken into account when the tightening torque to be used for the installation is specified (see Section 5.8.2).

A further example of the loading capacity of powder-actuated fasteners driven into a non-ferrous metal is given in Figure 42. This shows the results of pullout tests with stainless steel fasteners and carbon steel fasteners with knurled shank on a copper plate with a thickness of 22 mm (for a special application in industrial plant manufacturing). It can be seen that the knurling is especially effective in soft metals. In applications where, however, a very noble base material such as copper is involved, as in this particular case, the use of galvanized carbon steel fasteners is not permissible for reasons of lack of durability (contact corrosion).

Cast iron with spheroidal graphite is a material frequently used for components such as in the construction of wind power plants. Powder-actuated fastening is a technology that may be suitable for fastening control boxes or cabling inside these facilities. Powder-actuated fasteners also obtain a good hold in this material, but the loading capacity obtained is lower than in unalloyed structural steel of similar strength. The suitability of the fastening system proposed to be used should be verified by carrying out appropriate tests taking the specific job site condition into account [66].

2.7 Influence on the base material structural steel

2.7.1 Influence on net section efficiency

The influence of powder-actuated fasteners on the static stress-strain characteristics of construction steel has been systematically analyzed in [50]. Tensile tests were conducted using steel coupons into which various types of powder-actuated fasteners were driven at various spacings. Table 6 provides an overview of the test parameters. Tensile tests conducted using specimens containing self-drilling screws or drilled holes provide a direct comparison with other mechanical fastening methods.

Figures 43 and 44 show examples of stress-strain curves for construction steel of high and low tensile strength. The influence of the fastener types tested is very good-natured. The presence of the fasteners in the steel does not change the fundamental loadbearing characteristics of the construction steel in terms of its elasticity and plasticity. The fastener driving operation does not cause embrittlement of the base material, i. e. the gross sectional area of all test specimens yielded plastically before subsequent strain hardening. Strains at maximum load were between 10 and 20%.

The most important evaluation parameter in the tests was the loading capacity of the net cross-sectional area. This was compared with the theoretical loading capacity (Figure 45). The theoretical model is based on the presumption that the influence of the cross-sectional reduction on loading capacity is linear.

Theoretical utilization = $(A_{Net} / A_{Gross}) \cdot 100$

Experimental utilization = $(N_u / A_{Gross} \cdot F_u) \cdot 100$

With the following:

A_{Gross} Gross cross-sectional area calculated from the measured dimensions of the cross section

A_{Net} Net cross-sectional area considering the presence of powder-actuated fasteners, self-drilling screws or drilled holes

N_u Ultimate tension load determined from tests

F_u Tensile strength of the (unweakened) steel tested

Figure 45 shows that the experimental utilization of the test specimens is higher with powder-actuated fasteners than with drilled holes or self-drilling screws of the same area in every series of tests carried out. It exceeds clearly the theoretical estimate. Even with a large reduction (25 to 30%) of the cross-sectional area, the loading capacity of the test specimens still reaches 90 to 95% of the value for the unweakened gross cross-sectional area.

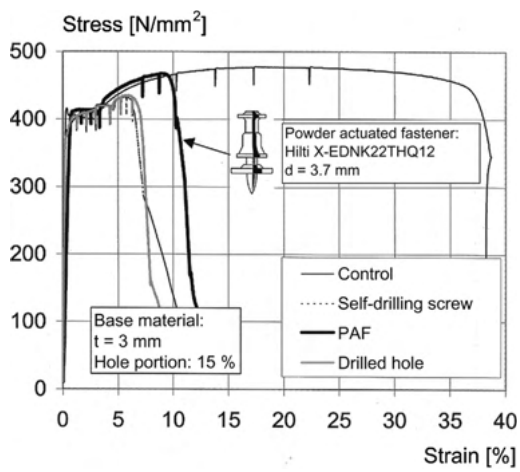


Figure 43. Stress-strain characteristics of higher strength steel with powder-actuating fasteners

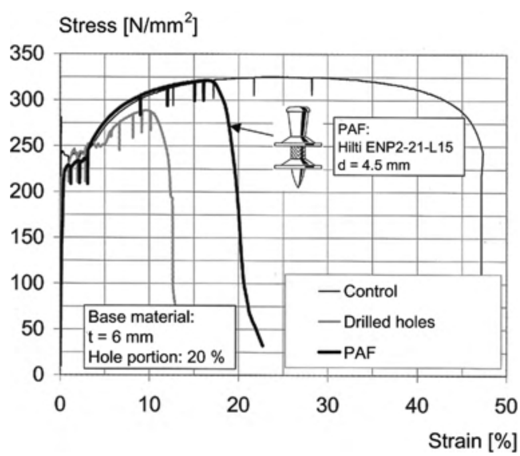


Figure 44. Stress-strain characteristics of lower strength steel with powder-actuating fasteners

Table 6. Test parameters: Influence of powder-actuated fasteners on the net section efficiency of structural steel [50]

Types	Base steel	Cross-sections of coupons
– Powder-actuated fasteners [1)] · zinc plated (knurled) or stainless · powder-driven or air-driven – Self-drilling screws – Drilled holes	S 235 [2)] S 355 [2)] Grade 50 [3)]	6.0 x 45 mm 3.5 x 74 mm

[1)] Hilti ENP2-21L15, X-EM10, X-EDNK22 THQ12, X-CRM8
[2)] according to DIN EN 10025-2 [33]
[3)] according to ASTM 607

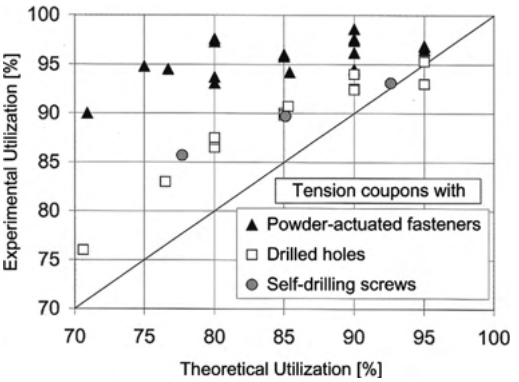
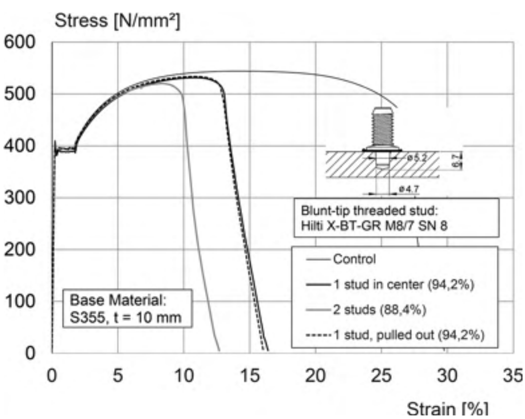


Figure 45. Theoretical and experimental utilization of structural steel with powder-actuated fasteners



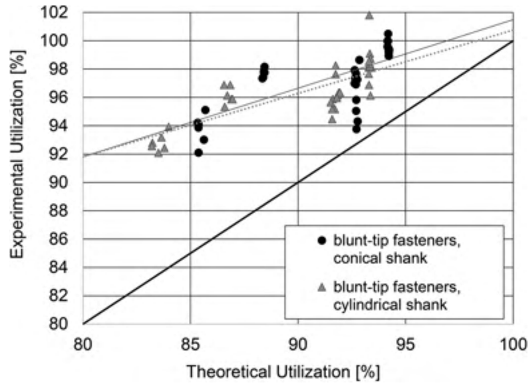
Dimension in the parallel length of test sample: 10 x 54 mm.

The percent values indicate the ratio between the net area and the gross area. The net area considers the shank of the blunt-tip fastener and the remaining area of the drilled hole below the front of the shank.

In case of 2 studs within the cross-section: edge distance in each case = 17 mm, stud spacing = 20 mm

Figure 46. Stress-strain characteristics of structural steel with blunt-tip fasteners

Figure 46 shows examples of stress-strain characteristics of 10 mm thick construction steel S355 into which blunt-tip powder-actuated fasteners with predrilling were driven. The general behavior is similar with the behavior of construction steel with powder-actuated fasteners without predrilling. The net section utilizations tend to be slightly lower for steel with blunt-tip fasteners with predrilling compared with steel samples with directly driven fasteners. Figure 47 shows the utilization of construction steel with blunt-tip powder-actuated fasteners and allows a respective comparison with Figure 45.



Blunt-tip fasteners: Hilti X-BT with cylindrical shank (d = 4.5 mm), X-BT-GR with conical shank (d = 5.2 mm), Figure 10.

Figure 47. Theoretical and experimental utilization of structural steel with blunt-tip fasteners

Table 7. Maximum permissible ratio A_{gross}/A_{net} up to which the deduction for holes in the components under tensile stress can be neglected.

Steel grade [1]	Maximum permissible ratio A_{gross}/A_{net} DIN EN 1993-1-1:2010 [52]	ANSI/AISC 360-16 Specification for Structural Steel Building [54]
S235	1.10	–
S275	1.12	–
S355	1.00	–
ASTM A36 [2]	–	1.35
ASTM A572 Grade 50 [3]	–	1.08

[1] S235, S275, S355 according to DIN EN 10025-2 [33]
[2] ASTM A36 with $f_y = 248$ N/mm² and $f_u = 551$ N/mm²
[3] ASTM A572 Grade 50 with $f_y = 345$ N/mm² and $f_u = 448$ N/mm²

On the basis of these results, the definitions for the weakening effect of holes on steel sections under tensile stress can be applied conservatively. The old and withdrawn DIN standard 18800-1:1990 [51] still provided explicit limits of ratios A_{gross}/A_{net} (1.2 for S235 and 1.1 for S355) up to which the deduction for holes could be neglected. This limiting ratio can be calculated from the current basic standard DIN EN 1993-1-1 [52] by equalization of the plastic tension resistance of the gross area (formula 6.6 of [52]) with the net section fracture resistance (formula 6.7 of [52]), Table 7. For comparison, the corresponding ratios for typical American construction steel in accordance with [54] are also given.
These maximum permissible values per DIN EN 1993-1-1 [52] are lower compared with DIN 18800-1 [51], as

on the one hand, a partial factor γ_{M0} of 1.00 was specified in the German NAD [53] and, on the other, the minimum strength for S355 was reduced to 490 N/mm^2.

Considering the presence of a powder-actuated fastener conservatively as drilled hole and considering the typical application cases in practice, the weakening effect of holes made by powder-actuated fasteners is in general clearly below the maximum permissible values for S235 and S275 according to DIN EN 1993-1-1 [52]. Explicit verification of the loading capacity of the net section is thus not required. In exceptional cases where the number of fasteners concentrated within the area is above these limits, verification calculations for the component under tensile stress can be carried out in accordance with [52] (see formula (6.7) of [52]).

When conservatively applying the design rules for drilled holes as well for powder-actuated fastener, the presence of a powder-actuated fastener must, strictly speaking, be taken into consideration in verification calculations where components made from S355 are under high tensile stress. However, the influence of powder-actuated fasteners on the tensile strength of construction steel is – based on the empirical test results – much more favorable than that of drilled holes. Furthermore, the reduction of the net area with the factor 0.9 according to formula (6.7) per DIN EN 1993-1-1 [52] is not required for powder-actuated fasteners as well as for blunt-tip fasteners. Figure 45 and 47 clearly indicate that the assumed theoretical utilization represents a conservative design model without applying any additional reduction factor. The explanation for this is that the base material is not removed in case of directly driven powder-actuated fastener, but simply displaced in the area around where the fastener is driven. Furthermore, favorable compressive residual stresses occur within the material both in case of directly driven powder-actuated as well as blunt-tip fasteners. Figure 49 shows based on numerical simulations the residual circumferential compressive stress state in the base material after driving a powder-actuated fastener. The maximum permissible ratio A_{gross}/A_{net} for tension members with powder-actuated as well as blunt-tip fasteners can be increased approximately by 10%, as the reduction of the net area with the factor 0.9 is not required for tension members with these fasteners.

Recent investigations [55] in context with the upcoming new generation of the Eurocodes – addressing also the use of high strength construction steel up to S960 [56] – have shown that the use of the reduction factor 0.9 is only required in case of holes with notches (e.g. for punched holes). No reduction is necessary for drilled holes with a comparably smooth surface of the hole. The corresponding adoption of the design provisions for the next Eurocode generation is still in discussion. In analogy with these results, powder-actuated sharp-tip and blunt-tip fasteners can be conservatively considered like smooth drill holes. For the verification of the net section resistance the application of the reduction factor is not required. With a view to introducing clear, unequivocal rulings on these points in building regulations, it is recommended that the corresponding design rules for components under tensile stress are defined in ETAs for fasteners.

In addition to the tensile tests of steel coupons described in [50], *Engelhardt* and *Beck* also carried out tests using open web steel joists. For these full scale tests, profile metal sheet was fastened to the top chords of the joists and powder-actuated fasteners were also driven into the bottom chord. The open web steel joists were then loaded uniformly and bent until failure. The joists tested were typical of those in use in the American market, their chords taking the form of a thin, double-angle with a thickness of ≥ 3 mm. The results of the tests showed that the powder-actuated fastening method, compared with other methods of fastening, has no negative influence on loading capacity. Please refer to [44] and [57] for details.

2.7.2 Influence on fatigue strength

2.7.2.1 Sharp-tip powder-actuated fasteners

The influence of powder-actuated fasteners on fatigue strength of the base material was investigated in the 1970s in connection with research projects carried out by the *Studiengesellschaft für Anwendungstechnik von Eisen und Stahl e.V* (a German group carrying out research on engineering applications for iron and steel). These investigations were initiated by the intended use of a sandwich-type structure designed to reduce noise on steel bridges carrying rail traffic [53]. Fastening solutions with powder-actuated fasteners were part of that study and were investigated by *Seeger* and *Hanel* [58].

Further systematic analysis to determine the fatigue strength of a base material containing powder-actuated fasteners was conducted in the early 1980s by *Melber* [59]. An overview of the test parameters for more than 1´000 fatigue tests is provided in Table 8. Figure 48

Table 8. Test parameters: Fatigue tests of structural steel containing powder-actuated fasteners [59]

Steel grade	Plate thickness [mm]	Stress ratio R	Imperfections	Powder-actuated fasteners (PAFs)
St 37 St 52	6, 10, 15, 20, 26.5, 40, 50	– 3, – 1, 0.14, 0.5, 0.8	PAF pulled out, PAF driven inclined, PAF driven inclined and pulled out	d = 4.5 mm, zinc plated and knurled [1)]

[1)] Hilti ENP3-21-L15, ENP3-21D12, ENP2-21L15, EM8

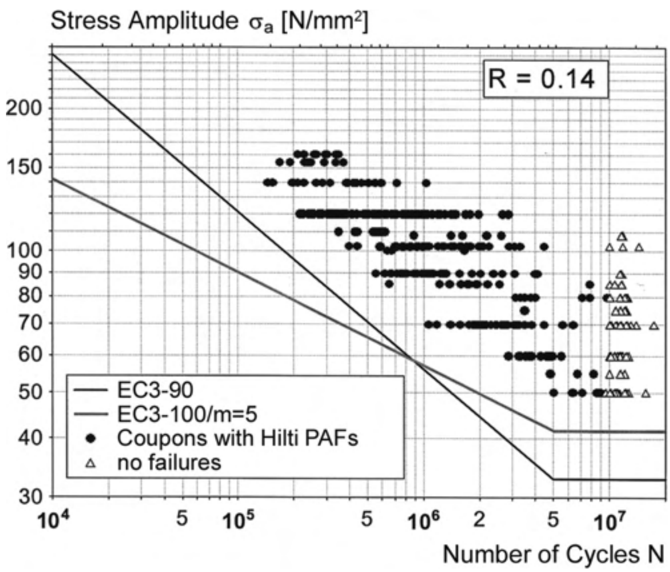


Figure 48. Fatigue strength test results of base steel containing powder-actuated fasteners for R = 0.14 [60]

shows examples of the test results for the strain ratio R = 0.14 in a Wöhler diagram.

The behavior of the constructional detail "base steel with powder-actuated fasteners" was found to be surprisingly good-natured. Driving fasteners into the base material generally has no decisive influence on the fatigue verification of welded steel structures [60, 61]. Only in special cases, e. g. when compared to the flush grinding of welded butt joints, do powder-actuated fasteners lead to a lower fatigue strength than the corresponding welded constructional detail.

The qualitative explanation for this behavior is given in [58]: On the one hand, strain-hardening of the plastically deformed base material occurs locally in the vicinity of the powder-actuated fastener while, on the other hand, residual compressive stresses in the base material acting toward the circumference of the fastener are superimposed upon the tension applied by external forces, thus reducing fatigue-relevant peak tension. An analytical estimate of residual internal stresses is given in [34], and the result of a numerical simulation of the driving process is shown in Figure 49 [62].

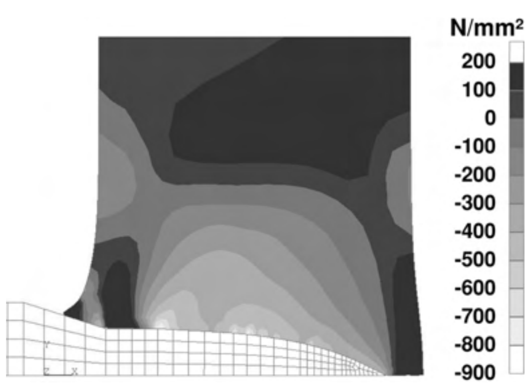


Figure 49. Residual compressive stresses acting toward the circumference in the vicinity of the fastener

The results of tests [59] were evaluated by *Niessner* und *Seeger* [60, 61] in accordance with Eurocode 3, EN 1993-1-9 in 1998. This evaluation resulted in the allocation of the constructional detail "base steel with powder-actuated fasteners" into the fatigue classification table of the Eurocode, see Table 9.

2.7.2.2 Blunt-tip and screw-in threaded fasteners

If blunt-tip powder-actuated or screw-in threaded studs are intended to be used on steel construction subjected to fatigue loading, a separate fatigue classification is required for the base material based on experimental investigations. Though the embedment process of blunt-tip threaded fasteners with predrilling is similar to directly driven powder-actuated fasteners, an adoption of the classification given in Table 9 to blunt-tip fasteners is not permissible, since the residual stress states in the base material differ significantly as a result of the predrilling. For screw-in threaded fasteners shown in Table 2, which will be introduced in detail in Section 3.1.2.5, the anchorage in the base material is achieved via thread forming. Therefore, also for these fasteners separate fatigue tests are required for the assessment of the fatigue classification of the base material. Table 10 provides an overview on the test parameters to be considered in the fatigue test programs. Figure 50 provides a summary of results of fatigue test shown in a Wöhler diagram.

Table 9. Fatigue classification of the constructional detail "base steel with powder-actuated fasteners" in keeping with Eurocode 3 (table taken from [60])

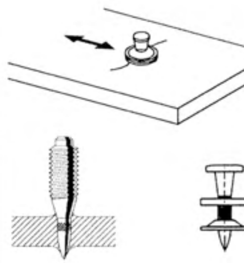
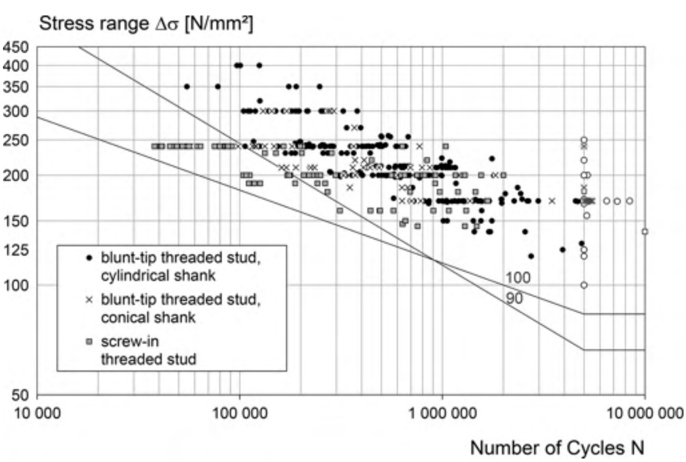
Non-welded details			
Detail category	Constructional detail	Description	Requirements
90 m = 3 - - - - - - - 100 m = 5		The effect of powder actuated fasteners on base material. Powder actuated fasteners with diameters from 3.7 to 4.5 mm installed with powder actuated piston tools in base material with thickness ≥ 6 mm. Loadings on the fastener itself, according to manufacturer specifications, have no effect on the base material and need not to be considered.	The detail category 90 with m = 3 or the detail category 100 with m = 5 is alternatively applicable (recommendation: 90, m = 3 for $N < 10^6$; 100, m = 5 for $N > 10^6$). The appropriate depth of penetration of the powder actuated fasteners is given according to the application rules of the manufacturer. Wrong fastener installations as popped out or inclined installed 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. A minimum distance of 15 mm between the axis of the powder actuated fastener and the edge of a neighbouring notch is required.

Table 10. Test parameters: Fatigue tests of structural steel containing blunt-tip and screw-in threaded fasteners, respectively

Steel grade	Plate thickness [mm]	Stress ratio R	Imperfections	Threaded fasteners
S235, S355, S460, S690, S960 [1)]	3, 4, 6, 8, 20, 40 [2)]	– 1, 0.1, 0.3, 0.5	drill hole only, threaded fastener pulled out	Blunt-tip fasteners with d = 4.5 and 5.2 mm made from stainless material. Screw-in fasteners with d = 5.8 mm made from stainless or carbon steel.

[1)] S355, S460, S690 and S960 only for blunt-tip threaded fasteners Hilti X-BT
[2)] 3, 4 and 6 mm only for screw-in threaded fasteners Hilti S-BT

Based on a statistical evaluation of the test results in compliance with DIN EN 1993-1-9 [63], the fatigue detail category 100 with m = 5 is recommended for the fatigue design of the base material [64, 65]. It covers both cases "Base material with blunt-tip powder-actuated fasteners" as well as "Base material with screw-in fasteners". The slope of the Wöhler curve is smaller compared with typical welding details. Therefore, the



Tested threaded fasteners:

Blunt-tip studs, cylindrical shank: Hilti X-BT M8-15-6 SN12-R

Blunt-tip studs, conical shank: Hilti X-BT-GR M8/7 SN 8

Screw-in studs: Hilti S-BT-MR M8/7 SN 6, S-BT-MF M8/7 AN 6

Shown for comparison: Fatigue detail categories 100 (m=5) and 90 (m=3) according to [63]

All values with number of load cycles ≥ 5 million are runouts (circle for X-BT, square for S-BT and X for X-BT-GR)

Figure 50. Fatigue test results of base steel containing blunt-tip and screw-in threaded fasteners

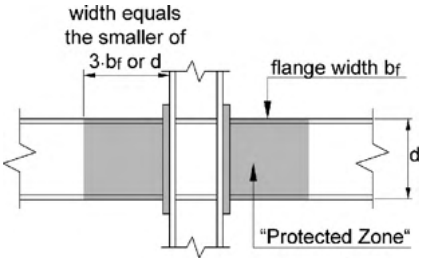
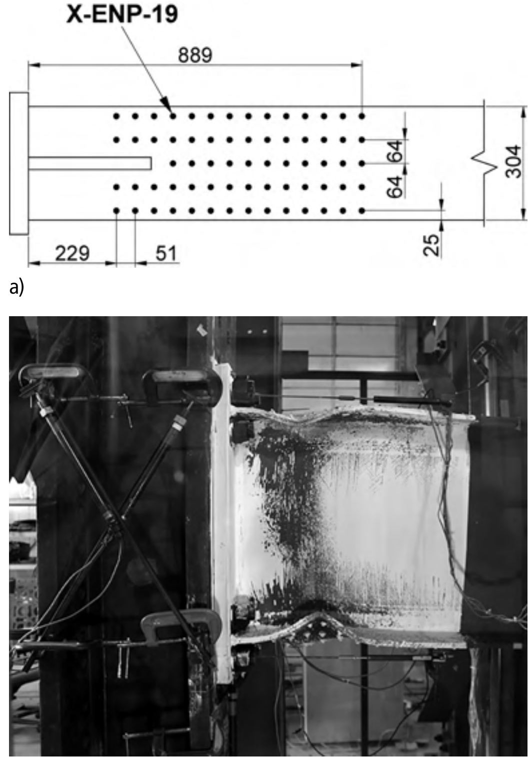


Figure 51. Definition of „Protected Zone" for dissipative beam joint according to [69]



a)

b)

Figure 52. Dense fastening pattern of powder-actuated fasteners and beam deformations after cyclic bending test;
a) Dense fastening pattern of powder-actuated fasteners on top and bottom flange (Test 12 of [70], US-section W36x150),
b) Test #6 of [70], US-section W24x62

category 100 with m=5 is recommended also for tension stresses. For wind towers, off-shore structures or in crane construction the rules of private certification bodies – e. g. DNVGL – often have to be observed. The fatigue tests results build also the basis for the fatigue classification in compliance with the fatigue design provisions of these private classification societies (in detail see [66, 67]).

2.7.3 Effect on cyclic resistance

The effect on the inelastic cyclic resistance of structural steel is relevant for dissipative steel structures under seismic loading. DIN EN 1998-1 [68] defines the dissipative zones of dissipative structures in which the ability to dissipate energy in case of seismic loading concentrates. American steel construction standards [69] specify these dissipative zones as so called "Protected Zones" in which special care related with the production and assembly are to be observed. Restrictions related with fastenings to steel are stated in the standard. Figure 51 shows an example of the definition of "Protected Zones" in case of the rigid joint of a frame, where the connection area of the horizontal beam is designed as dissipative element for plastic seismic design.
Composite decking is supposed to be fixed to the beams also within the area of the "Protected Zone" by means of powder-actuated fasteners. *Eatherton et.al.* investigated the effect of powder-actuated fasteners on the cyclic deformation behavior by means of full scale tests [70]. As in case of static net section efficiency a good natured effect of the fasteners on the inelastic cyclic beam resistance was determined. The test results of beams with powder-actuated fasteners meet the requirements of SMRF ("Special Moment Resistance Frame") related with the plastic deformation ability as well as the capacity of energy dissipation. Figure 52 shows an example of a dense fastening pattern of powder-actuated fasteners on the flanges of the test beam. The dense fastening pattern does not reflect practical cases, however, an extreme limiting case was selected related with the test purpose. Figure 52 further shows a photo of the plastic deformation of the beam joint after the cyclic test. Within the range of acceptance criteria for SMRF there was no difference of the inelastic cyclic behavior of samples with powder-actuated fasteners installed compared with unaffected control specimen.
Based on the research of *Eatheron et.al.* the US steel construction standard ANSI/AISC 341 was modified in the recent issue from 2016 [69]. Fastening of metal sheet using powder-actuated fasteners with a maximum diameter of 4.5 mm was explicitly allowed also in the "Protected Zones" of beams.

2.8 Corrosion

Ambient conditions have a significant influence and must be taken into account when selecting the type of powder-actuated fastener to be used. The applications discussed in this paper are generally safety-relevant, permanent fastenings. For such applications, corrosion of the types described here is of great significance and, accordingly, the resulting rules applicable to the application must be observed. Powder-actuated fasteners are also used for a great number of low duty – temporary or permanent – applications without safety relevance. Examples of these are the fastening of metal track for the installation of drywall partitions or the temporary fastening of wood battens etc. during construction work. For these non-structural applications zinc plated fasteners are in principle applicable, assuming the potential for corrosion-related failure of the fastener has been considered and found acceptable.

The type of corrosion relevant to high-strength carbon steel or stainless steel powder-actuated fasteners is stress corrosion cracking, which is accelerated or even initiated by tensile stress. Stress corrosion cracking causes fractures, in which very little deformation takes place, originating from a point at which corrosion has occurred. This is known as a brittle fracture when the overall tensile stress remains within the elastic range of the stress-strain characteristics of the material. The loss of material through surface corrosion is not a decisive cause of failure of powder-actuated fasteners made from carbon-steel.

In the case of cathodic stress corrosion cracking, embrittlement is initiated by the diffusion of hydrogen in the metallic lattice. With anodic stress corrosion cracking, embrittlement is the result of local dissolution of the metal material. Cathodic stress corrosion cracking is thus also known as hydrogen embrittlement. High-strength carbon steels, above all, are at risk. Methods of corrosion protection and the areas of application of high-strength powder-actuated fasteners must therefore be chosen so that hydrogen embrittlement can be reliably avoided. In literature on the subject, a difference is drawn between primary and secondary hydrogen embrittlement.

Primary hydrogen embrittlement refers to the inclusion of hydrogen in the metal's grain structure during the production process, for example during pickling or electrochemical galvanizing. With electrochemically galvanized fasteners, primary hydrogen embrittlement can be counteracted by suitable heat treatment processes (e. g. tempering at approx. 200 °C). This reduces the concentration of dissolved hydrogen to an uncritical level. The monitoring of these processes in the manufacturing of powder-actuated fasteners forms a significant part of the control procedures carried out in the manufacturing plant. This can be done, for example, by conducting bending tests with samples of the fasteners produced. The fasteners must achieve a minimum ductility (capacity for plastic deformation) [71]. Secondary hydrogen embrittlement can occur with carbon steel high strength fasteners when the material from which they are made has suffered local corrosion, resulting in the diffusion of hydrogen in the material.

A thin layer of zinc applied by electrochemical galvanization ensures protection from corrosion during transport and installation (construction site), where exposure to the weather, of course, cannot always be completely avoided. This type of coating, however, does not provide adequate protection from corrosion for fasteners constantly exposed to the weather. Due to the possibility of secondary hydrogen embrittlement, the use of carbon steel fasteners for permanent fastenings in safety-relevant applications is thus permissible only in dry, indoor areas [30, 31] or where a durable and reliable means of protection from moisture can be ensured. For information on the subject of the seal in the area immediately between a sheet metal fastened and the base material, please refer to [72].

Anodic stress corrosion cracking is typical of high-alloy stainless steels. Depending on the electrolytes involved and the type and level of mechanical stress, a crack in the steel originating from a local break in the passive layer can begin to grow. Progressive dissolution of the metal occurs in the crack and at the point of the crack. Conditions of this kind which are critical for austenitic steels of the corrosion resistance class CRC II or CRC III can be found, for example, in acidic atmospheres containing chloride (e. g. in indoor swimming pools or in road tunnels). In those atmospheres stainless steel from the corrosion resistance class CRC V is to be used for load bearing fastenings and members according to DIN EN 1993-1-4 [73].

With regard to contact corrosion where an electrolyte is present (moisture from the weather or from condensation), care must generally be taken to ensure use of the right combination of materials (please refer to [74], for example). The ratio of surface areas of the materials in contact is also of decisive importance. Materials with small surface area are subject to a high level of corrosion when in electrochemical contact with a larger area of a more noble metal. Powder-actuated fasteners which are to be used in a moist environment and exposed to the weather should therefore, at least, be made from the same material or, preferably, from a more noble material than the material of the component to be fastened.

Due to the great difference in surface areas in contact, the effect on static loading capacity of the accelerated corrosion of a less noble base material through contact with a fastener made from a more noble material is generally very low. Similar conclusions apply for hot-dipped galvanized grating which are fixed by means of stainless grating fastener attached to powder-actuated or screw-in threaded fasteners.

3 Fastening screw technology

3.1 Basic principles

3.1.1 Methods and terminology

In the field of lightweight steel construction, fastening screws are used to fasten profile metal sheets, liner trays and sandwich panels to the supporting substructures and to fasten sheet metal to sheet metal, e. g. at overlap joints. In the field of ventilated façade construction, fastening screws are used for the fixing of the brackets to base steel members, for connection of the supporting system components with each other and finally for the fastening of the external cladding to the supporting profiles. The requirements to be met by these screws vary considerably and depend on the application for which they are used. In applications where profile metal sheets are fastened and for all connections within ventilated façades the screws are subjected to wind loads and must be designed accordingly. Screws at longitudinal and transverse overlap joints, however, only have a non-structural purpose, provided the sheets are not part of a steel deck diaphragm, which secures the lateral stability of a building.

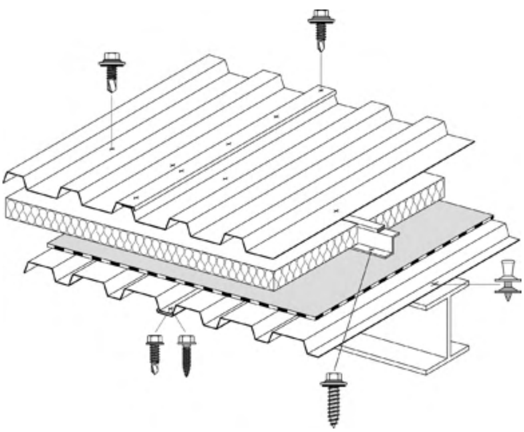


Figure 53. Typical composition of a lightweight metal structure

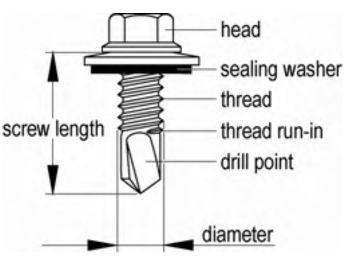


Figure 54. Fastening screw designations

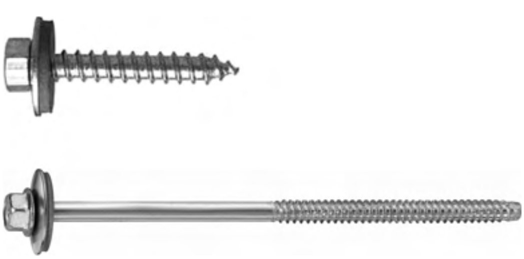


Figure 55. Self-tapping screws with a point or blunt tip

Figure 56. Self-drilling screws

The various types of screws can be differentiated according to how they are used and for which purpose they are used. Self-tapping screws, for example, are driven in a predrilled hole. In doing so, the screw forms a thread in the base material. Screws that incorporate a drill point are known as self-drilling screws. No predrilling is required with these screws as drilling and driving take place in one operation.
Regarding the application for which they are used, sandwich panel screws and screws for fastening roofing membranes must also be mentioned at this point. These also take the form of self-tapping or self-drilling screws, which are optimized for this particular application.

3.1.2 Fastening screws: features and characteristics

For the purpose of identifying the terms used, the most common screw designations are shown in Figure 54.

3.1.2.1 Self-tapping screws

Self-tapping screws are either made with a point or have a blunt tip (Figure 55, Table 11). Screws with a point and coarse thread are used mainly for fastening to timber structures. They can also be used on steel base materials with a thickness t_{II} of up to about 4.0 mm, but self-drilling screws are increasingly taking over in this application. Self-tapping screws with a blunt tip are used on thicker steel.
The predrilled hole diameter required depends on the thickness of the base material and are specified in national technical approvals or in the European Technical Assessments.

3.1.2.2 Self-drilling screws

Self-drilling screws are self-tapping screws with a drill point. Manufacturers offer screws with drill points of various lengths in order to provide fastening solutions that cover the greatest possible range of steel base material thicknesses.
Screws with a reduced diameter drill point are used to join sheet metal (e. g. at overlaps) and to fasten profile metal sheets to timber. Some of these self-drilling screws also feature a so-called undercut. This undercut is a threadless area of the shank beneath the head that allows the screws to be deliberately overtightened in order to avoid pushing the sheets apart when the screw is driven. Screws with undercut are further used for fixed bearing as well as skids (loose bearing) within the supporting structure of ventilated facades. They provide safe functionality of the skid as the connected components are not pressed too tight against each other.

Table 11. Areas of application for self-tapping screws

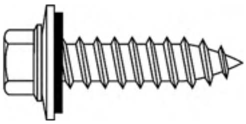
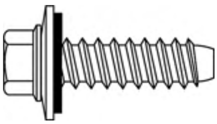
Screw	Base material thickness t_{II}	Example of application
 with point	0.63 – 4.0 mm (steel) ≥ 26 mm (screw driving depth in timber)	Overlap joints and profile metal sheets and sandwich panels on timber
 with blunt tip	≥ 1.25 mm	Profile metal sheets or sandwich panels on steel beams

Table 12. Areas of application for self-drilling screws

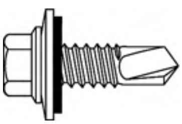
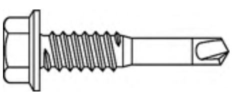
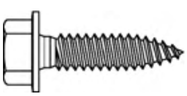
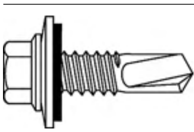
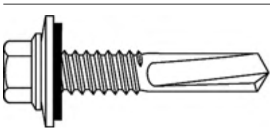
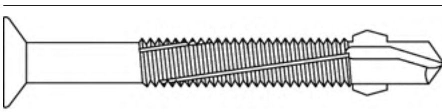
Screw type	Total sheet metal thickness Σt_i	Examples of applications
 (1) With short drill point	2 x 0.63 mm – 3.0 mm	Overlap joints and profile metal sheets on C- and Z-profiles
 (2) With reduced diameter drill point	2 x 0.40 mm – 2 x 1.50 mm	Overlap joints
 (3) Without drill point and undercut	2 x 0.40 mm – 2 x 1.25 mm	Overlap joints
 (4) With medium drill point	1.5 – 6.0 mm	Profile metal sheets on C- and Z-profiles
 (5) With long drill point	4.0 – 14.0 mm	Profile metal sheets on steel beams
 (6) Wing screw	2.0 – 5.0 mm	Wood on steel

Figure 57. Self-drilling screw without drill point

Figure 58. Screw for fastening sandwich panels

Figure 59. Roofing membrane fastener: screw and load distribution plate

So-called wing screws are used to fasten wood components to steel substructures. The point of these self-drilling screws incorporates additional "wings" that serve to ensure that the hole drilled through the wood is of greater diameter than the hole drilled in the steel support. This is necessary in order to ensure that the metal chips created by drilling into the steel are transported out through the hole in the wood and that the wood material fastened is not pushed away from the steel substructure. The wings break off when they come into contact with the steel substructure and the screw then continues to drill into the steel.
Self-drilling screws without drill point penetrate the steel base material without drilling (type 3 shown in Table 12). This drilling method is called flowdrilling. In this process, the fastening and substrate material is softened, plasticized and displaced as a result of the friction heat. Thereby the screw achieves an optimum keyed hold and thus develops the ability to take up higher loads (Figure 116). A further advantage of this type of screw is that the driving process causes no metal chips to be formed. This avoids the need for subsequent cleaning or finishing, as there are no metal chips to be removed. The screw's sharp point also ensures that it can be started and driven reliably, without wandering out of position, even when started at a slight angle.

3.1.2.3 Sandwich panel screws

Sandwich panel screws are optimized for fastening sandwich panels to steel or timber substructures. These screws, either self-tapping or self-drilling, feature in general an additional supporting thread that grips the outer skin of the sandwich panel and ensures that the sealing washer is pressed against it with adequate pressure while avoiding damage or local deformation of the sheet metal. For this purpose, the secondary thread has a larger diameter than the lower thread that is driven into the supporting structure. Sandwich panel screws without a secondary thread are also available on the market.

3.1.2.4 Screws for fastening roofing membranes

Roofing membrane fasteners (screw with load distribution plate, see Figure 59) are used to mechanically fasten sealing systems with integrated thermal insulation to underlying liner trays made from profile metal sheet. The waterproof roofing membrane systems are made from plastic, bitumen or synthetic rubber materials [76]. These materials are fastened from the exterior using screws that are driven through the insulation and into the underlying sheet metal. A load distribution plate under the head of the screw holds the membrane in place. Due to the ever-higher requirements to be met by the thermal insulation and associated efforts to reduce or avoid thermal bridging effects, the metal load distribution plates are increasingly being replaced by plastic plates with sleeves. The keyed hold obtained with the inner layer of sheet metal is provided by the screw thread.
The basic design of this screw with load distribution plate corresponds to that of the sandwich panel screw with supporting thread. The thread below the head serves to support the load distribution plate, which reduces the risk of damage to the roof through walking on it (so-called "tread proof" screws).

3.1.2.5 Screw-in threaded studs

Screw-in threaded studs are mechanical fasteners manufactured from coated or zinc plated carbon steel or from stainless steel material. The fasteners feature a connection thread in the upper area, e. g. M6, M8, M10 for attachment of the fixtures and a screw-in thread with a diameter of approximately 5.5 mm for screwing the stud into the base material. Similar to self-tapping screws, the base material is to be predrilled at the fastener location. A specific stepped drill is used for drilling so that the required drilling depth and diameter can be precisely observed. At the end of the drilling process, the stepped drill removes the coating around the drill hole in a ring shape. This is the visible sign for the installer that the drilling process is finished. When using an cordless drill driver suitable for drilling in construction steel the drilling of the borehole will take around 8 seconds. The threaded stud is equipped with a sealing washer with a diameter of 10 or 12 mm at the transition between the connecting thread and the screw-in thread. The sealing washer prevents the penetration of moisture and corrosive media into the borehole and also covers the circular area where the corrosion protection was removed by the drilling process. Therefore, the borehole itself and the area around the borehole are durably protected against corrosion.
For base material thickness ≥ 6 mm, a blind hole is drilled into the base material by the stepped drill. The base material coating on the back side of the steel won´t be damaged in that case. No rework of the coating is

then required. Base materials with thickness < 6 mm are drilled through when drilling the borehole or the back side coating is damaged by the drilling process. In that case the back side coating needs be professionally reworked if required.
In order to achieve the required screw-in depth as well as proper compression of the sealing washer, the threaded stud needs be installed with a suitable setting tool (depth gauge) and a suitable cordless drill driver. The required screw-in depth is inspected via the fastener stand-off using stand-off gauges. If necessary, the depth gauge needs to be adjusted in order to achieve the required screw-in depth. For drilling the borehole and for the installation of the screw-in stud the tools and devices recommended by the manufacturer are to be used. Calibrated torque wrenches for tightening the nuts or grating fasteners are to be used and the defined installation torque must be observed. Figure 60 shows the features of a screw-in threaded stud.

3.1.2.6 Screw head shapes and drive types

The material to be fastened is pressed against the supporting structure by the head of the screw. The hexagonal head is the head shape in most widespread use for fastening screws. This head shape allows transmission of high torque without applying high contact pressure. The round head is another head shape that is used on corrugated sheets due to the smaller sealing washer diameter and on exterior facades for reasons of appearance. The drive type used with this head shape is the so-called TORX™.
Screws with a countersunk head or pan head are equipped with a Philips cross recess (PH2) or the so-called Pozidrive cross recess. These screws are used mainly in the carpentry and drywall trades. Screws with a cross recess drive are suitable for use in metal construction where thin steel substructures are used and only a low torque is required to drive the screw.
Other head shapes and drive types for special applications such as mounting solar panels or screws with torque control are described in [75].

3.1.2.7 Sealing washers

Screws for fastening the outer skin of buildings are equipped with sealing washers in order to ensure that no leakage occurs at the fastening point. The sealing washers consist of a metal washer with a vulcanized layer of EPDM synthetic rubber. The metal washer allows the seal to be pressed against the outer sheet metal skin with the necessary pressure. The screws, however, must be driven with care. Inadequate tightening as well as excessive compression of the sealing washer can lead to a poor seal and leakage. In order to help avoid incorrect screw driving, use of a depth gauge is recommended. The depth gauge required depends on the type of screw to be used.
Possible errors or faults while installing the screw can also be avoided by certain features of the design of the

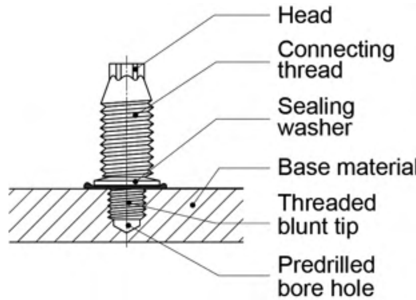


Figure 60. Assembled screw-in threaded stud

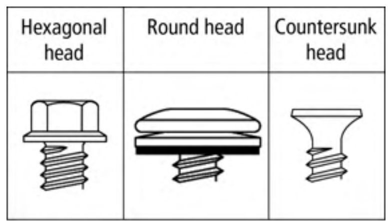


Figure 61. Screw heads

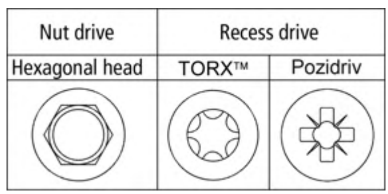


Figure 62. Drive types

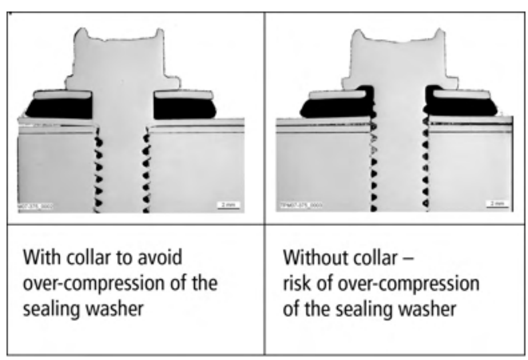


Figure 63. Screws with sealing washer, with and without collar

screw itself. For instance, there are screws available on the market with an additional collar under the head that avoids over-compression of the sealing washer when the collar comes into contact with the metal sheet.

3.1.2.8 Materials and their mechanical characteristics

Fastening screws are in generally manufactured from carbon steel standardized in accordance with DIN EN 10084 [77] (so-called carbon steel screws, typically with a carbon content of about 0.2%), or from stainless steel in accordance with DIN EN 10088-1 [78]. In order to allow the screws to cut a thread in the steel base material, they must be made from a material that is substantially harder than that of the base material. Carbon steel screws are thus case-hardened. After the hardening process they have a mean tensile strength of about 1´000 – 1´200 N/mm^2 and a shear strength of 600 – 700 N/mm^2. Stainless steel screws have a mean tensile strength of about 800 – 900 N/mm^2 and a shear strength of 400 – 500 N/mm^2.

3.1.2.9 Corrosion protection

Carbon steel screws, like powder-actuated fasteners, should be viewed in the same way as high-strength building components (f_u > 1´000 N/mm^2). The same technical relationships, as described in Section 2.8., thus apply.
Carbon steel screws are usually galvanized with a thin, approx. 8 µm zinc layer designed to protect the screws from corrosion during storage, transport, installation and outdoor conditions on construction sites. They are intended for use at safety-relevant joints and connections that are not directly exposed to the weather or damp atmospheres.
Carbon steel screws for metal construction may also feature a higher-grade corrosion protection. Duplex coatings consist of a of zinc coating and one or more additional organic coatings and can thus resist up to 15 cycles in the Kesternich test without corrosion. From a technical point of view, carbon steel screws with duplex coatings are suitable for applications in category of corrosivity C2 according to EN ISO 9223:2012 [25] (e. g. for unheated rooms where condensation might occur or outdoor atmospheres with low amount of pollutants). However, the use of carbon steel screws in categories of corrosivity ≥ C2 is currently – independent of the type of corrosion protection system – not covered within the ETAs. The ETA requires in that case the use of screws made of stainless steel. These screws are typically manufactured from stainless steel of the corrosion resistance class CRC II [73]. For increased corrosion requirements also screws made from stainless steel of the corrosion resistance class CRC III [73] are available on the market.

3.1.2.10 The manufacturing process

The screw manufacturing process is described below, taking coated carbon steel and stainless steel self-drilling screws as examples.
Carbon steel screws go through the five stages shown in Figure 64. First of all, the raw material is supplied in the form of coiled wire, which is then straightened and cut to the appropriate length (1). In a second stage the head and drive recess are formed in an upsetting process, e. g. Philips cross recess or hexagon head (2). The blank is then cleaned and the tip formed in a pinching operation (3). The thread is formed during the fourth stage of the process, the thread-rolling operation (4). The first roller presses and rolls the screw blank against the second roller, thus forming the thread. At this stage of the process, the burrs created during the tip-forming operation are also removed. In the subsequent heat treatment process the screw is case-hardened in order to give it the necessary strength, hardness and toughness. Finally, at the fifth stage, the screw is coated (e. g. galvanized) and equipped with a sealing washer for outdoor use (5).
During the manufacturing process for stainless steel screws, after the head has been formed (2), the drill point and thread run-in are welded on in an inductive welding operation. All further steps in the production process are carried out as shown in Figure 64. During the heat treatment process, only the tip and the thread run-in are hardened.

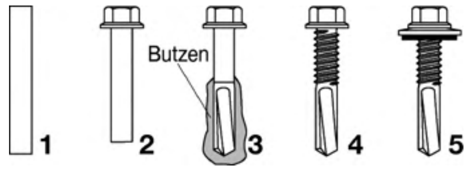
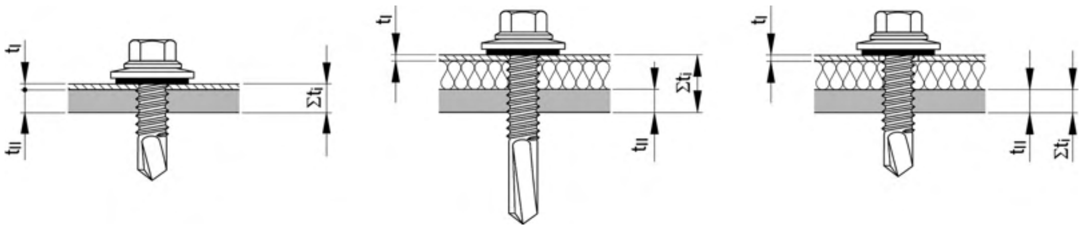


Figure 64. The manufacturing process for screws made from carbon steel

3.1.3 Interdependency: Screws – screwdrivers

The quality of a screw fastening and the drivability of a screw depends not only on the screw but also on the operator and, not least, on the screwdriver and screw driving bit or socket used. Important parameters in the operation are the pressure applied by the operator, the speed and torque of the screwdriver and the fit of the head of the screw in the socket or bit on the power tool. Great efforts are being made by manufacturers to develop screwdrivers that, due to being optimized for the application, make the driving operation easier and ensure that a high quality fastening is obtained. Some examples of these tools are: cordless screwdrivers with a high battery capacity and high torque, additional devices that allow the operator to drive collated screws on large roof areas while maintaining a comfortable upright stance, and adapters that serve as a screw guide and depth gauge when driving long sandwich panel screws. When the screwdriver, bit or socket, the accessories and the screws are optimally matched, the operator's influence on the correct screw driving process can be reduced significantly (e. g. with a view to achieving the best possible seal).



without intermediate layer | with intermediate layer | with intermediate layer, component I predrilled

Figure 65. Drilling capacity $\sum t_i$

3.2 Definitions used in describing screw fastening

3.2.1 Area of application and application limits

A screw's application limits are mainly defined by its screw-cutting ability, i. e. its so-called screw-cutting torque, and its drilling capacity. No further rise in loading capacity is to be expected when the screw's length of thread engagement is greater than 6 mm as, beyond this point, the screw itself is the decisive factor in failure of the screw fastening. This is why the corresponding approvals stipulate that, in base materials with a thickness of up to 6 mm, the full length of the screw's cylindrical threaded section must be screwed in and, in thicker base materials, at least 6 mm of the screws cylindrical threaded section must be screwed in.

The length of the screw's shank, i. e. the length of the section between the thread run-in and the head, is of significance in determining a screw's area of application. The maximum possible total thickness of the "stack" to be connected, consisting of the base material, the sheet metal to be fastened and any thermal insulation present, is determined by the length of the screw shank. The carbon steel threaded section welded on to stainless steel screws in order to improve their thread forming abilities should not be taken into account in this calculation. The information provided by the manufacturer concerning this point should be observed.

Over and above this, self-drilling screws must possess the necessary drilling capacity $\sum t_i$ in order to be able to drill all the way through the total stack to be connected. A drilling capacity of up to 14 mm in steel of the S 355 grade is now considered to be state of the art. This demands a drill point that is capable of drilling through the steel, but its length must ensure that the drilling operation is completed before the thread begins to grip. The definition of drilling capacity is shown in Figure 65.

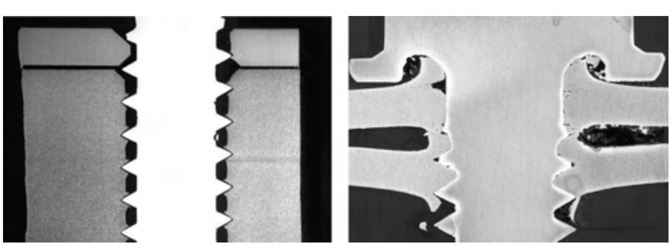
The minimum sheet metal thickness for use of screws is 0.4 mm, which results in a minimum fastening stack of 2 x 0.4 mm. The metal sheets must offer adequate rigidity in order to allow the screws to be driven properly and so that the load can be taken up reliably.

3.3 Anchorage

3.3.1 Anchorage mechanisms

Screws are anchored in the base material by way of a keyed hold, i. e. fastening screws form a thread in the base material. Figure 66 shows ground cross-sections of a self-tapping screw in thick steel and a blunt-ended self-drilling screw at a joint between two thin metal sheets. The thread of the screw displaces steel around the hole. The bulges can be seen in the photo on the left. The photo on the right shows a joint between two thin metal sheets made with self-drilling screws that have no drill point. These screws simply displace the metal. The result is a joint capable of taking up higher shear loads than a joint made with conventional self-drilling screws.

The anchorage obtained by powder-actuated fasteners is based on various mechanisms with varying degrees of effectiveness depending on the base material. In contrast to the keyed hold formed by a screw thread, these mechanisms cannot be represented by a model. Experimental assessments are to be carried out in order to investigate the robustness of the anchorage obtained by



a) b)

Figure 66. Anchorage in thick steel and joining thin metal sheets

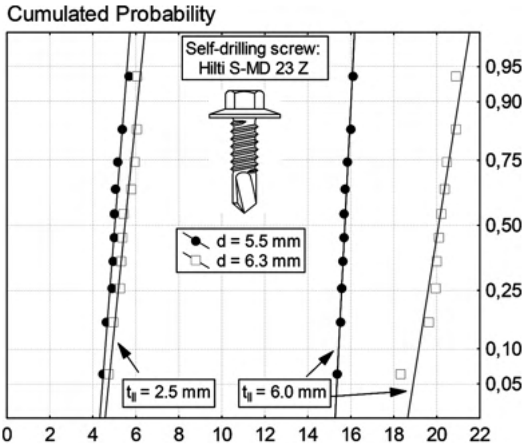


Figure 67. The influence of screw diameter and base material thickness on the anchorage

powder-actuated fasteners and to verify resistance to influences on the fasteners themselves as well as external influences resulting from the stresses placed on the base material (see Section 2.5.4). The robustness of the anchorage obtained by fastening screws and its resistance to these influences can, in principal, be taken for granted due to the keyed hold and verification by way of tests is generally not necessary.

3.3.2 The parameters influencing the anchorage

3.3.2.1 Thickness of the base material

Not every screw can be used for every sheet metal thickness. Screws used to join thin metal sheets must be designed differently from those used to join thicker materials.

It is recommended that screws with a reduced diameter drill point are used to join thin metal sheets. These screws drill a smaller hole in the part to be fastened and in the base material, which allows the screw to take up a higher load. The screws gain a more positive hold in the sheet metal. An even further improved hold can be obtained when screws without a drill point are used. Failure of a screw fastening under tensile loading at a joint between thin metal sheets in the 0.4 mm to 2.0 mm thickness range is generally due to the screw being pulled out of the base material.

With thicker base materials (2.0 – 3.0 mm and thicker) and in case of thin fixed sheets, failure of the fastening is more frequently due to the fastened sheet being pulled over the head of the screw. When the thickness of the base material is about 6.0 mm or greater, breakage of the screw is generally the failure mode responsible for failure of the anchorage. Any further increase in the thickness of the base material, and thus improved anchorage, therefore, does not result in increased in loading capacity.

3.3.2.2 The strength of the base material

In order to be able to form a thread in the steel base material, the strength (i.e. hardness) of the screw's thread flanks must be higher than that of the base material. Pullout failure is therefore due to failure of the thread formed in the base material. Because of this, there is a direct relationship between the strength of the base material and screw loading capacity. The loading capacity of screws in steel of the S355 grade is approx. 8 – 10% higher than that of steel of the S235 grade.

3.4 Influence on the base material structural steel

3.4.1 Influence on net section efficiency

When installing a self-drilling screw, a hole is drilled by the drill point in the base material. For self-tapping screws and screw-in threaded studs, predrilling the base material is also required before the fastener installation. All types of screws and screw-in threaded studs lead to a reduction of the gross area of the base material due to the drilling process. The effect of powder-actuated fasteners, drilled holes and self-drilling screws on the static stress-strain behavior of structural steel was systematically investigated in [50] (see Section 2.7.1.). Figures 43 to 45 in Section 2.7.1. show the effect of drilled holes and self-drilling screws on the static stress-strain behavior of structural steel. The presence of the holes and self-drilling screws leads to a reduction of the tensile strength of the section depending on the cross-sectional reduction. However, there is no change in the fundamental performance of structural steel in terms of elastic as well as plastic behavior. All samples develop a plastic yielding plateau of the gross area with subsequent strain hardening. Strains at ultimate are in the range between 5% and 10%. The effect on the base material due to predrilling for screw-in threaded studs is comparable to the effect observed due to self-tapping screws, because the diameters of the predrilled holes are in a similar range.

Cross-sectional reductions due to drilled holes or due to the use of self-drilling screws in components subject to tensile stress can be neglected if the maximum permissible ratios A_{gross}/A_{net} for S235 and S355 according to Table 7 are not exceeded. For the steel grades S235 and S275 the cross-sectional reduction due to self-drilling screws or screw-in threaded studs is in most standard applications clearly below that permissible ratio A_{gross}/A_{net}. An explicit verification of the load-bearing capacity of the net cross-sectional area is therefore not required. In exceptional cases, where the limit values are exceeded due to the concentration of fasteners, the verification for components subjected to tensile loads can be carried out according to formula (6.7) of DIN EN 1993-1-1 [52]. According to DIN EN 1993-1-1 fracture of the net section is in general controlling design for S355. Also in that case, the rules for net section design

can be conservatively applied for drilled holes for self-drilling screws or screw-in threaded studs.
Drill holes applied in the compression zone of sections can be neglected as long as they are "filled" with connection members. This requirement is considered to be fulfilled when using self-drilling screws, self-tapping screws and screw-in threaded studs.

3.4.2 Influence on fatigue strength

The effect of screw-in threaded studs on the fatigue strength of construction steel is described in Section 2.7.2.2 together with the discussion of the influence of blunt-tip powder-actuated fasteners.

4 Design

The semi-probabilistic design concept applying characteristic values and corresponding partial factors – using the general design equation (1) – is used in all European Technical Assessments (ETAs) as well as all national approvals for fastener design.

$$E_d \leq R_d \tag{1}$$

with
E_d design value of actions
R_d design value of resistance

In the past, the allowable working design concept was used in the national approvals. It was based on global safety factors. That concept is currently still used by the manufacturers in their technical documentation in case no ETA or other national approval exists. This applies especially for powder-actuated fasteners for light duty fastening applications (e. g. fixing of cable conduits). The manufacturers then publish recommended service loads [9, 66]. Verification then takes place at working load level:

$$S_k \leq R_{rec} \tag{2}$$

with
S_k characteristic action (e. g. weight attached to a hanger)
R_{rec} recommended service (working) load

For respective verification at design load level, the partial factor for the action γ_F must be taken into account in the calculation. The following formula then provides verification at design load level S_d:

$$\gamma_F \cdot S_k = S_d \leq \gamma_F \cdot R_{rec} \tag{3}$$

4.1 Loading capacity

4.1.1 Predominantly static loading

The characteristic values of the resistance and the respective partial factors are given in the European Technical Assessment (ETA). For certain types of failure, e. g. hole elongation in the fixed sheets, the characteristic loading capacity can be calculated in accordance with DIN EN 1993-1-3 [35]. Other resistances like pull-out capacity of powder-actuated fasteners or the fracture strength of fastening screws are product specific and require experimental testing for reliable assessment. The required tests are defined in the relevant assessment criteria (see Section 7 to 10). Their evaluation results to the characteristic resistances and the allocated partial factors.
Wind loading on fasteners used in roofs and façades is in general considered as quasi-static and predominantly static loading. Potential dynamic effects on fastening design are considered by DIN EN 1993-1-3 [35] and the respective ETAs (see Section 7.3.2).
Steel deck diaphragm design is covered by DIN EN 1993-1-3 [35]. Powder-actuated fasteners as well as self-tapping screws are allowed to be used to fasten profile metal sheets being part of a diaphragm. The fastenings must be designed so that the sheet metal to be fastened is the decisive factor in the event of failure. Loadbearing capacity is to be limited by the loading capacity of the fasteners in terms of their resistance to hole-elongation failure along the side lap connection of the steel panels, for which typically self-drilling screws are used. Regarding details concerning calculations for the design verification of steel deck diaphragms, DIN EN 1993-1-3 [35] makes references to ECCS publication no. 88 [79]. The German National Annex DIN EN 1993-1-3/NA:2017 [80] lists as NCI (Non-contradictory Complementary Information) further sources related with provisions for the design of steel deck diaphragms. These refer to the method by *Schardt & Strehl* [81, 82] and the respective adoption in DIN 18807-3 [83]. Furthermore, it is referred to a publication by *Kathage et.al.* [84] in which a modification of the method by *Schardt & Strehl* is proposed in compliance with European regulations. Therefore, the method by *Schardt & Strehl* can be further used in Germany as an alternative method to ECCS [79] for diaphragm design.

4.1.2 Fatigue loading

For fatigue strength design of powder-actuated fasteners and fastening screws, apart from pullover tests with dynamic loading (see Section 7.3.2), there are neither notch classifications in EN 1993-1-9 [63] nor general testing guidelines listed in the assessment criteria for ETAs. For specific applications it is recommended that verification of fatigue strength is calculated in keeping with the regulations of DIN EN 1993-1-9 [63] on the basis of test data. Eurocode 3 offers a complete verification concept. It regulates the statistical evaluation of fatigue strength tests and the partial factors for the applicable actions, taking damage tolerance into account.
In accordance with Section 2.5.4.1, the anchorage of powder-actuated fasteners is generally not the decisive factor in the fastening's resistance to fatigue. This is de-

termined by failure of the steel from which the powder-actuated fastener is made. Due to the multitude of types available, it is impossible to make a generally applicable statement about the resistance of powder-actuated fasteners or fastening screws to fatigue. Verification of resistance to fatigue must be provided for a certain product in each specific application. With threaded studs, the possible influence of geometric imperfections, e. g. the load not being taken up exactly centrically in the actual components concerned or a non-uniform force distribution within a group of studs must be taken into account. Those effects need to be considered either experimentally or by means of numerical simulation of the structural detail. The demand to resist fatigue loading is very rare both for powder-actuated fasteners as well as fastening screws. The main purpose of dynamic testing of powder-actuated fasteners is to examine the fundamental robustness of the fastener anchorage in steel base material and to confirm the resistance to the variable portions of imposed loads in quasi-static design. Furthermore, the motivation of these tests is to show that the characteristic number of load cycles at service load level of the fastener clearly exceeds the threshold value of 10´000 below which the actions may be considered as not fatigue relevant.

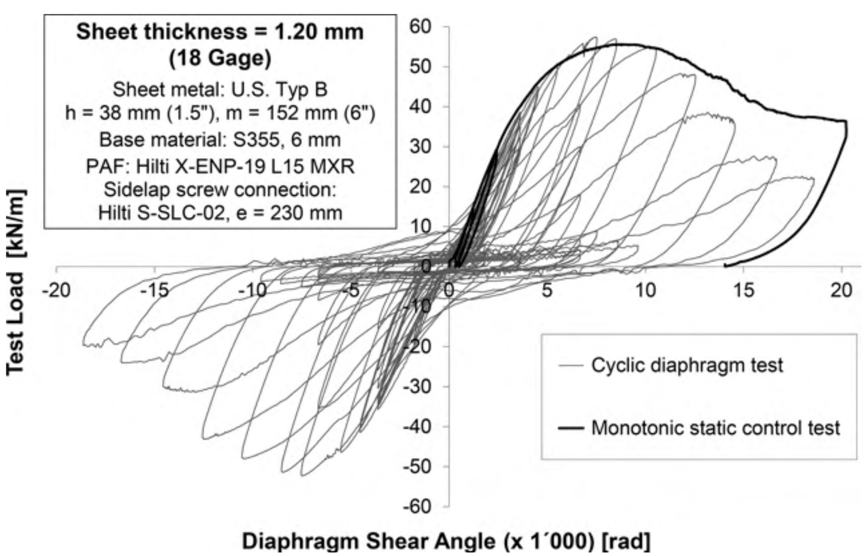
4.1.3 Seismic loading

The current European Assessment Documents (EAD) for powder-actuated fasteners and fastening screws (Table 16) do not cover dynamic loading subsequent to earthquakes. A first assessment of the suitability of fasteners can be made when following the provisions from the USA, see Section 2.5.4.1. The results are then characteristic resistances which may be applied for a quasi-static seismic design in case of tension and shear loading (e. g. [85]).

In the USA, powder-actuated fasteners and fastening screws have been used for decades as mechanical fasteners of steel deck diaphragms of non-dissipative structures [86]. For verification of the seismic loading, a substitute static load is then used. The good suitability of powder-actuated fasteners and fastening screws, especially compared to arc-spot-welds, has been investigated and verified experimentally [87–90]. Failure of the sheet metal is generally ductile and the anchorage obtained by the powder-actuated fasteners displays robust behavior under dynamic loading (see Section 2.5.4.1).

Figure 68 shows an example of a plastic, cyclic load-displacement behavior of a steel deck diaphragm using a 1.2 mm thick sheet. The total deformation capacity results from the deformations of the metal sheet itself, the inclination of the fastening screws along the sidelap of the sheets and from hole elongation at the deck to frame connections of the powder-actuated fasteners (Figure 69).

Figure 68 further shows a comparison with the monotonic load-displacement curve for a test with the same test parameters. Even where considerable plastic deformation takes place, the load peaks for each cycle are within the range of those on the monotonic reference



Width of profiled steel sheeting: 0.91 m, spacing of ribs m = 0.152 m
Powder-actuated frame fastener pattern: 36/9, that means that each rib is fixed by one pin with an additional fastener at the laps of fastening type b and d.

Figure 68. Cyclic load-displacement behavior of steel deck diaphragms under seismic loading [90]

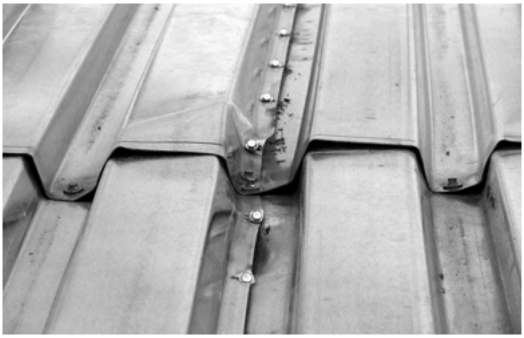


Figure 69. Sheet deformation and screw inclinations during diaphragm tests at the location of deck end laps (fastening type c and d) [90]

curve. This good-natured behavior can thus also be taken advantage of in dissipative structures by making use of the capacity method [91]. The Canadian standard already defines a behavior factor for steel deck diaphragms, the respective realization of such provisions within the US steel standards is currently in preparation. [92] provides a short survey of that topic as well as further literature references on that subject.

It is essential that simultaneously with the definition of the behavior factor for structures in which steel deck diaphragms form part of the horizontal load resisting system, the corresponding assessment criteria for all fasteners must be defined in order to ensure ductile behavior of the steel deck diaphragm in the entire range of application. Especially the maximum thickness of the steel deck must be limited depending on the type of fastener used. To achieve and maintain ductile diaphragm behavior, the following aspects are to be considered:

– Sufficient resistance of the anchorage of powder-actuated fasteners at the end overlap of the panels (fastening type c and d) in order to prevent sudden load drops in case failure at the end lap occurs.
– Sufficient shear resistance of the fastening screws at the sheet sidelap connections in order or prevent sudden opening of the sidelap connections due to screw fracture.
– Reliable design of the transfer to the support forces of the horizontal diaphragm into the vertical bracings or shear walls.

It is not possible to generalize suitability for powder-actuated fasteners or fastening screws. Suitability needs to be assessed by means of product specific assessment to consider the specific features and performance of each fastener.

This brief excursion to the USA points out the generally good suitability of powder-actuated fasteners and fastening screws even for situations where they are subjected to dynamic, seismic loading. In Germany, at present, seismic verification would require a project specific approval for the selected fastening solution.

Bracing trusses or frames made of steel are used for seismic strengthening of concrete structures. Powder-actuated fasteners can also be used for the fastening of thin web sheets (1 to 4 mm) acting as supplemental stiffening component of braced frames. Regarding experimental research of that application it is referred to the investigations of *Gündel* [93].

4.1.4 Verification of resistance to fire

For connections with powder-actuated fasteners or fastening screws to steel there is generally no need for the fastening to be given a fire rating. No fire rating is required where a fastening is made to an unprotected, unrated steel substructure. If, however, the steel structure is equipped with a means of passive fire protection such as a suspended ceiling, cladding or intumescent coating, these measures also effectively protect the fastenings in place in the steel. Where necessary, verification of the fastening's resistance to higher temperatures can be provided by calculation (see Section 2.5.4.5).

In situations where the powder-actuated fasteners provide a means of shear connection, verification of resistance to fire can also be calculated using a temperature-dependent shear-loading capacity reduction factor (e. g. nailing of webs in the folded structure in Figure 97 [94]). This verification procedure is also used with the X-HVB shear connector in composite construction. The corresponding temperature-dependent reduction factor $k_{\theta,X\text{-}HVB}$ specific to the powder-actuated fastener is given in the European Technical Assessment ETA-15/0876 of this shear connector [95]. It must be noted that the influence of temperature on the loading capacity of carbon steel powder-actuated fasteners is greater than on standard construction steel as the fasteners' high strength at room temperature is the result of a heat treatment process (see Figure 9).

4.2 Serviceability

Deformation after installation is limited mainly to deformation of the fastened components or, respectively, the base material. Deformation of the fasteners or their anchorage, as a rule, is extremely low and thus negligible. In accordance with the assessment criteria for profile metal sheet fastening, verification of fitness for use is implicitly covered by the corresponding evaluation of test results. Separate verification of fitness for use is then unnecessary (see Section 7.3.4).

With regards to the calculation of deformations of steel deck diaphragms it is referred to [79] and [84].

For general fastenings and connections, where necessary, displacement under the working load must be stated and, when relevant, compared to the maximum permissible displacement.

4.3 Durability

The environmental conditions to which powder-actuated fasteners and fastening screws may be exposed are regulated by the provisions made in European Technical Assessments (ETAs) and national approvals, respectively. Use of high-strength carbon steel powder-actuated fasteners for permanent, safety-relevant applications is restricted to dry interiors [30, 31]. Stainless steel fasteners are mandatory where the powder-actuated fastening technique is used for fastening of base profiles for glass facades in building construction [28].
The stainless steel fasteners available on the market are not suitable for use in safety-relevant, permanent fastenings in atmospheres containing chloride (e. g. indoor swimming pools and road tunnels). Use is possible only in individual cases (e. g. for a glass roof over a road) when verification of durability for the actual fastening situation is provided within the scope of an individual approval. This approval must reliably assess the risk of corrosion while taking air pollution, construction physics aspects and constructive conditions into account [73].
Both, national German approvals as well as European Technical Assessments (Table 19 to 22), require the use of stainless screws in case of exposure to categories of corrosivity ≥ C2 according to EN ISO 9223:2012 [25]. Such screws are typically manufactured from stainless steel grades allocated to corrosion resistance class CRC II (A2 – steels). In case of higher demands screws allocated to corrosion resistance class CRC III (A4 – steels) are also available on the market.

4.4 Verification of fastenings with components made from various materials

In addition to common steel to steel joints, powder-actuated fasteners and fastening screws are also used to join other materials. Applications of this kind include, among others:
- Fastening profile metal sheets to timber using fastening screws
- Fastening wood materials to steel using powder-actuated fasteners or fastening screws
- Fastening profile metal sheets to concrete using powder-actuated fasteners
- Joining aluminum sheets using self-drilling screws
- Fastening aluminum to steel using powder-actuated fasteners
- Fastening plastic roofing membranes using fastening screws

DIN EN 1995-1-1 [96] is to be applied for the purpose of the verification of connections incorporating timber and wood materials. Corresponding design resistances (Figure 121) required for application of these standards are given in the approvals.
The resistance values for other materials must be determined in accordance with the relevant European assessment documents (see Section 6.1). The load-bearing capacities and partial resistance factors are then given in the approvals themselves.

5 Applications in steel, façade and composite construction

5.1 General information

Figure 70 shows some of the following possible uses for powder-actuated fasteners and fastening screws in steel construction.
- Fastening thin cold-rolled profiles to hot-rolled profiles (roofs, facades, composite decks)
- Fastening thin, cold-formed profile sheets to thin C- and Z-profiles
- Joining thin, cold-formed profile sheets (or liner trays) to each other
- Fastening thicker steel components, for example: angle brackets, mounting brackets, stop pieces or checker plates
- Fastening wood and wood materials
- Fastening sandwich panels using fastening screws
- Structural connections of thick sheets or plates
- Light duty fastenings of cables or conduits (with gas- or battery-actuated fastening tools)
- Threaded stud connections e. g. for suspensions of water pipes or other building service components or the fastening of grating

Applications for fastenings with threaded studs are summarized in Figure 84.
As a basic rule, the redundancy principle must be applied to fastenings or connections made using powder-actuated fasteners and fastening screws. The constructional design needs to be such that failure of one screw or one powder-actuated fastener does not result into a collapse of the fixed member. Redundancy is established through group fastenings or – as in case of suspensions using single threaded studs – through the flexural stiffness and resistance of the suspended member (e. g. suspension of rigid pipes continuous over several supports). The saying “One bolt is no bolt” applies to fastening screws and, in the same sense, also to powder-actuated fasteners. All structural applications – such as the use of fastening screws or powder-actuated fasteners in steel deck diaphragms or the use of nailed shear connectors – are highly redundant.
Driving fasteners into steel and joining metal sheets or steel plates, however, is subject to certain limitations, not only in a physical sense but also with regard to the technical aspects of tool design. The decisive parameters for the cost-efficient use of the technique are the area of application that can be covered, the achievable loading capacities and productivity on the jobsite. In order to ensure that the fastening technologies can be used safely and without problems, the application limits for fastening screws as well as powder-actuated fasteners, as listed in the ETAs or national approvals, must be observed.

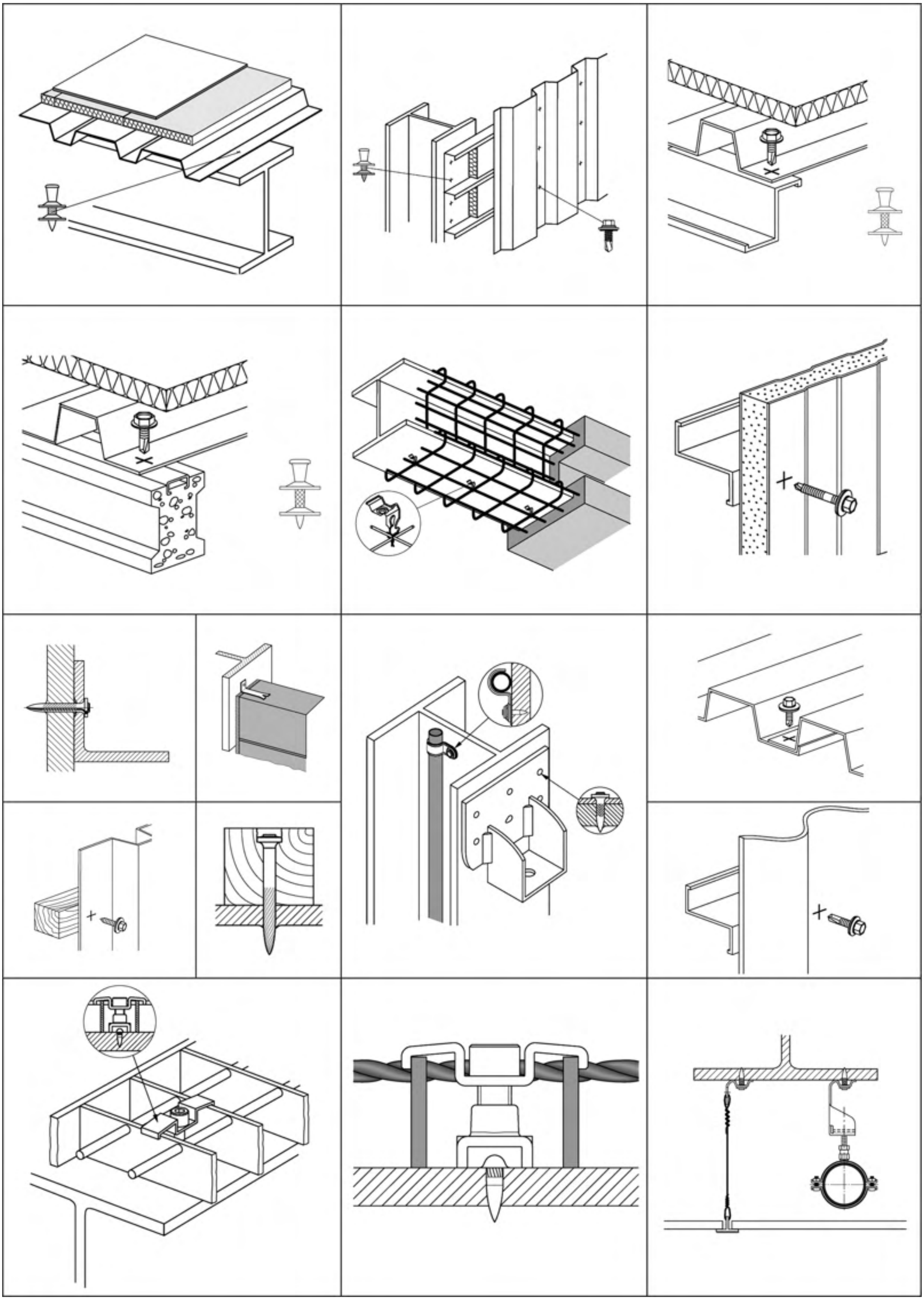


Figure 70. Uses for powder-actuated fasteners and fastening screws in steel construction

The applicable range of base materials can vary considerably, especially with powder-actuated fastening systems. It can range from complete coverage of S355 grade steel in all thicknesses to limited coverage of S235 in a restricted thickness range. Also the applicable thickness of the fixed components varies, e. g. the use of powder-actuated fasteners for a base material thickness of 3 mm is limited to maximum fixed sheet thickness of 2 x 1.0 mm [99]. Such limitations should be taken into account right at the planning stage. The varying application limits depend on the system due to the use of various powder-actuated fastening tools. In addition to this, stainless steel fasteners – with the exception of blunt-tip threaded studs – generally have a lower application limit than carbon steel fasteners.

The classic main application for powder-actuated fasteners and fastening screws is the joining and fastening of thin, cold-rolled metal profile sheets. The area of application that can be covered diminishes as the thickness of sheets to be fastened increases. Only in exceptional cases are powder-actuated fasteners used as means to connect comparatively thick steel plates (see Section 5.10). Compared with bolts or welding, the direct fastening method using powder-actuated fasteners reaches its application limits relatively quickly. Nevertheless, powder-actuated fasteners are far more suitable than fastening screws for use as a "genuine" steel construction fastening method, especially where subjected to shear loading only, as in this situation full use can be made of the much higher strength they offer.

Regarding execution of connections of cold-formed load-bearing members by means of powder-actuated fasteners or fastening screws, it is referred to the details given in the recently issued DIN EN 1090-4:2018-09 [97]. This standard replaces the national execution standard DIN 18807-3 [83]. DIN EN 1090-4 [97] requires the use of fasteners meeting European standards or respective European Technical Assessments (ETAs). In the general execution standard DIN EN 1090-2 [98] powder-actuated fasteners may be allocated to the group of special fasteners and are covered accordingly.

5.2 Fastening thin gauge cold-rolled profiles

Trapezoidal profile metal sheets may be fastened in single or multiple layers. In the applicable ETAs, the various types of fastening are designated as type a, b, c or d. Fastening type a stands for a single layer of sheet metal, type b indicates a side lap (2 layers), type c stands for an end overlap (2 layers) of sheet metal and type d describes a 4-layer overlap where side lap and end-overlap joints meet. Tensile forces acting on the fasteners are caused mainly by wind suction loads on the facade of the building. Shear loads result from the facade´s self-weight, temperature fluctuations or from diaphragm action. The selection between powder-actuated fasteners and fastening screws depends, from a technology point of view, on the thickness of the sheets and plates to be connected as well as on the environmental conditions.

Figure 71 provides an overview of the types of fastening and the corresponding loads for powder-actuated fasteners as well as metal construction screws. Liner trays are simply butted together (i. e. not overlapping)

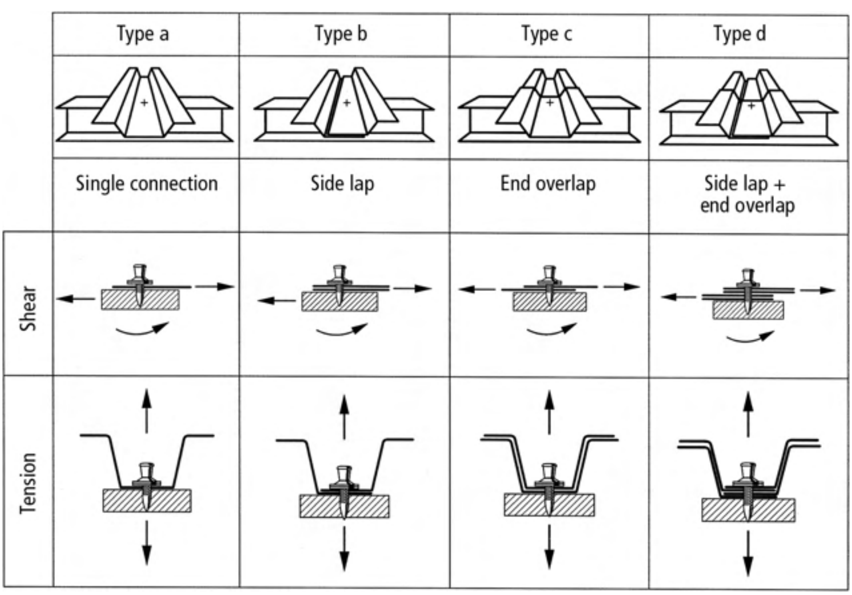


Figure 71. Types of fastening and loading

so only a single layer requires to be fastened. In accordance with [100], it is recommended that trapezoidal metal roof sheets with a thickness of greater than 1 mm are also butt jointed.
For details of structure, materials, design and assembly of the roof and wall surfaces, please refer to the comprehensive literature available ([79, 101-105] and others) as well as the information brochures published by the IFBS (*Industrieverband für Bausysteme im Stahlleichtbau*, www.ifbs.de) [100].
The bracing effect of profiled steel sheeting is also utilized for stabilization of beams against lateral buckling. The rotational spring stiffness of profiled steel sheeting fixed with powder-actuated fasteners was determined by *Lindner* by means of rotational stiffness tests [106]. Respective rotation coefficients C_{100} in combination with gravity loading are given for the powder-actuated fastener X-ENP-19 L15 – covered by the European Technical Assessment ETA-04/0101 [30] – according to Table NA.3 of DIN EN 1993-1-3/NA [80].

5.2.1 Base material thickness $t_{II} \geq 6$ mm

Approved powder-actuated fasteners (e. g. [30, 31]) are preferred for fastening the loadbearing profile steel sheeting of insulated, built-up roofs or, respectively, the inner liner trays on insulated walls. The advantages of powder-actuated fasteners over fastening screws are:
- higher loading capacity
- higher application limit
- better coverage of fastening types a, b, c and d
- high productivity even on thick S355 steel substructures

Trapezoidal profile metal sheets and liner trays can be fastened cost-efficiently and with high productivity using collated powder-actuated fasteners and fastening tools with nail magazine. Highest productivity is achieved with fully automatic "stand-up" fastening tools, which can be used on roofs. Approved fasteners which can cover the entire range of steel strength grades including, S235, S275 and S355, irrespective of the thickness of the material, are available on the market [30]. Higher strength fine grain steel grades ≥ S420 are currently not yet covered in any fastener ETA (see Section 7.5.1).

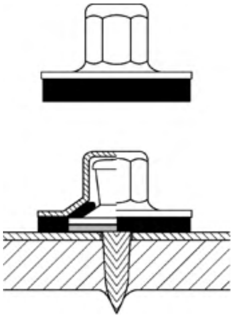


Figure 72. Powder-actuated fastener with sealing cap

With S355 steel, the maximum drilling capacity of a self-drilling screw is 14 mm [107]. At present, thicknesses greater than this cannot be covered (i. e. drilled through) by self-drilling screws. Although the application limit achieved by some self-tapping screws is also high enough to fully cover S355 steel [107, 108] productivity sinks due to the need to predrill the hole in a separate operation.
A comprehensive range of stainless steel fastening screws is available on the market. These can thus be used in situations where they are directly exposed to the weather or in corrosive atmospheres. There are no stainless steel powder-actuated fasteners available for fastening profile metal sheets that will be exposed to moist conditions, e. g. on uninsulated roofs. Use of powder-actuated fasteners made from carbon steel is restricted to dry indoor conditions, respectively, measures must be taken to permanently and reliably protect the fasteners from corrosion, e. g. application of sealing caps [72].
These sealing caps thus protect the fastener head from corrosion where they are exposed to the weather on uninsulated roofs. In this application particular attention must be paid to ensure that the profile metal sheets are pressed tightly against the supports. This can be achieved by selecting the right cartridge power level and by carrying out appropriate checks on the jobsite. This firm contact pressure (see Figure 2, left and [72]) prevents access of moisture to the fastener shank along the interface between the sheet fastened and the base material. With a view to achieving this, powder-actuated fastening tools of the type in which the piston is stopped only when it contacts the base material (see Figure 22, right) are to be preferred as these tools are better able to ensure that the sheet metal is pressed firmly against the base material.
If it cannot be ensured that the profile metal sheets are pressed snuggly and firmly against the supporting structure in this way then stainless steel self-tapping screws should be used on uninsulated sheet metal roofs.

5.2.2 Base material thickness $t_{II} < 6$ mm

Self-drilling screws and, in some cases, self-tapping screws, are generally currently used in this base material thickness range (Table 19 and 22). Since 2013 powder-actuated fasteners are also approved for the thickness range t_{II} between 3 and 6 mm (ETA-13/0172 [99]). For reliable use of powder-actuated fasteners on thin materials it is important that the fastening tool is equipped with a built-in piston brake (Figure 22, left) as the required fastener driving depth can then be ensured on a reproducible basis. The built-in piston brake avoids negative effects on the anchorage which are the result of excess energy transferred into the nail (see Section 2.5.3.1 and Figure 21).

Typical materials in the 3 to 6 mm thickness range are hollow profiles, steel profiles cast in concrete and heavy cold-formed C- and Z-profiles with formed edges for rigidity. The wall thickness of most C- and Z-profiles is considerably less than 3 mm (min $t_{II} = 1,5$ mm) and thus unsuitable for use with powder-actuated fasteners. Self-drilling screws are thus generally used for fastenings on these materials.

Self-drilling screws are generally used to fasten thin, cold-formed profile metal sheets together at overlap joints. Screws with a reduced drill point are also used for this application in order to increase the loading capacity. A type of screw that penetrates sheet metal without drilling has also been available for a few years. Similar to a drywall screw, the self-tapping thread on this type of screw runs all the way to the point and penetrates the sheet metal without creating metal cuttings (Figure 57). Screw fastenings of this kind, requiring no predrilling, achieve a greater shear loading capacity (Figure 116). The maximum drilling capacity possible with this type of screw is 2.5 mm with steel and 3.0 mm with aluminium and thus relatively low compared to that of self-drilling screws.

High shear loading capacity at overlap joints is particularly relevant for steel deck diaphragms. Apart from this, sidelap joints of metal panels should be designed and made in accordance with the relevant standards [97] and installation guidelines [100].

5.2.3 Timber and concrete supports

5.2.3.1 Fastening to timber

Self-tapping screws with a coarse thread (Table 11) are normally used to fasten profile metal sheets to timber. The loading capacity of the metal sheets is stated explicitly in the applicable national approvals and ETAs. With regard to the loading capacity of the connection obtained by the screws in the timber, the values given are those required in order to achieve calculable verification in accordance with DIN EN 1995-1-1 [96]. These are:

- characteristic plastic bending moment of the screw $M_{y,Rk}$
- characteristic pullout parameter $f_{ax,k}$
- effective screw-in depth l_{ef}

The pullout parameter $f_{ax,k}$ and the plastic bending moment $M_{y,Rk}$ should be determined by carrying out tests. Manufacturers don't offer powder-actuated fasteners for fastening thin profile metal sheets to timber as neither the high strength of these fasteners nor a special tool is required for this application. Thick sheet metal plates (up to about 8 mm) without predrilled holes, e. g. like seating plates, could be nailed onto timber in one operation [109], but there is currently no fully-developed product solution for this type of application available on the market.

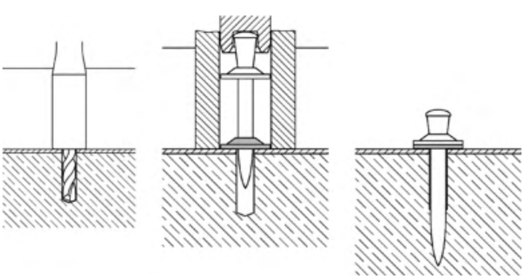


Figure 73. Procedure: Fastening profile metal sheets to concrete using powder-actuated fasteners

5.2.3.2 Fastening to concrete

Figure 70 shows how profile metal sheets can be fastened to steel sections with a thickness between 3 and 6 mm cast into concrete using either self-drilling screws or powder-actuated fasteners. Using powder-actuated fasteners to fasten the profile metal sheets directly to the concrete is the most cost-efficient solution in terms of total costs as the outlay for the cast-in steel sections and the work involved in installing these in the pre-cast components can then be saved. The direct fastening method also avoids problems encountered due to incorrectly or inaccurately positioned cast-in profiles. In order to ensure reliable fastener anchorage, it is necessary to drill a shallow hole in the concrete at the point where the fastener is subsequently driven. The procedure is illustrated in Figure 73.

It is important that this method of fastening is taken into consideration at the planning stage, before the precast concrete components are produced. With high-strength fasteners, this method is suitable for use on concrete grades up to C50/60.

Direct fastening using powder-actuated fasteners on concrete covers a considerably greater range of fastening types than fastening screws and powder-actuated fasteners on thin steel (for $t_{II} = 3$ mm), as the anchorage obtained in concrete is considerably more robust with regard to thermal constraints. The head pullover resistance of these fasteners is also higher than that of the corresponding fastening screws. This is what determines the loading capacity of the fastening in the compression zone of the concrete. In most applications (profile metal sheets on single-span beams or profile metal sheet liner trays on cantilever pre-cast columns with a fixed support) the fasteners are anchored in the compression zone of the concrete component. If the powder-actuated fasteners are positioned in the cracked tension zone of the concrete component, e. g. where beams are overhanging, the local influence of the cracked concrete on the pullout loading capacity of the powder-actuated fastener must be taken into account and the total loading capacities reduced accordingly [110]. In the cracked tension zone of the concrete, the pullout loading capacity of the fastener is the decisive factor.

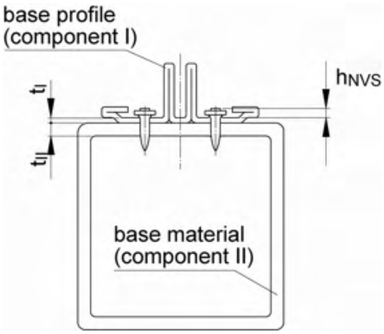
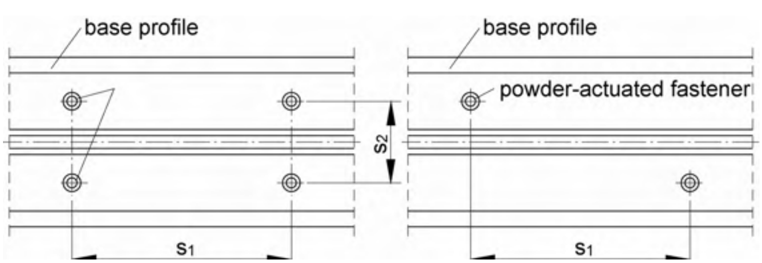


Figure 74. Example of application: Base profile with powder-actuated fastener

The assessment documents to achieve a European Technical Assessment are available (see Section 6.1), however, a powder-actuated fastening covered by an ETA is not yet available.

5.3 Fastening of base profiles of glass facades

This application involves fastening of the base profiles of glass facade to a steel substructure [111]. The wall thickness of commonly-used steel or aluminum profiles varies between 1.5 and 3.0 mm. Figure 74 shows an example of this application and the typical shape of the type of profile required for the construction of the facade. The panes of glass are secured by cover profiles fixed by screws in the screw-fastening channel of the base profile.
The powder-actuated fasteners are stressed in a transverse direction by the facade's self-weight – at the supports for the panes of glass – and in a longitudinal direction by the action of wind suction. Suitability for the application can thus be verified along the lines of the EAD for profile metal sheet fastenings [150]. The only basic difference to the tests of powder-actuated fasteners for profile metal sheets given in Table 23 is the combined shear and tensile loading tests for the forces of constraint as, in contrast to the profile metal sheet surfaces, there is no great temperature difference between the supporting structure and the base profile in the erection state. Verification is thus not necessary for steel base profiles but must be provided on the basis of test data for aluminum profiles in order to make allowance for variations in longitudinal expansion in the installed state. In accordance with the national technical approval Z-14.4-766 [28], in order to limit forces of constraint, the aluminum profiles may have a maximum length of 6 m and a maximum nail spacing distance of 250 mm must be observed. Verification of forces of constraint by calculation is then unnecessary.
The powder-actuated fasteners used for this application (stainless steel fasteners with a shank length of 14 mm) are long enough to allow steel base profiles with a thickness of up to 2.5 mm to be fastened without predrilling. The powder-actuated fasteners can be positioned symmetrically to the screw channel or alternately in the longitudinal direction (Figure 75). At the ends of the profile sections the fasteners must be placed symmetrically.
A basic prerequisite for the use of powder-actuated fasteners is the space available to allow access with the fastening tool in the narrow channel of the base profile. A minimum width of approx. 11 mm is required for powder-actuated fasteners with a head diameter of 8 mm. The height of the screw-fastening channel must also be taken into account with regard to access with the fastening tool. Also in this case, the quality of the fastening obtained is checked by way of the fastener stand-off h_{NVS} (Figure 74). A further prerequisite on which suitability of the powder-actuated fastening solution depends is that the heads of the fasteners – even in the upper h_{NVS} tolerance range – must not hinder installation of the glass panes.
In accordance with the national technical approval Z-14.4-766 [28], the minimum thickness of the base material is 4 mm in case of hollow sections. A maximum edge distance of c = 40 mm is to be observed. For greater edge distances the flexibility of the 4 mm thick hollow section would be too high in order to achieve consistent fastener installations. The approval [28] in-



$s_1 \leq 250$ mm with aluminum base profiles [28]

Figure 75. Position relative to the screw channel and spacing; a) symmetrically relative to the screw channel, b) alternately positioned

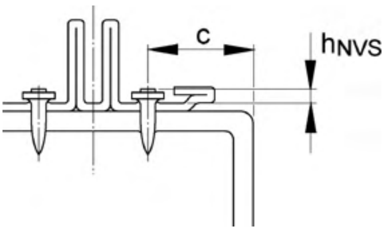


Figure 76. Edge distance for fastening base profiles to tubular sections

cludes explicitly suitable base profiles from various façade manufacturers (Gutmann, Jansen, Raico, Schüco and Stabalux).

In order to avoid damage of the anchorage by excess energy (see Section 2.5.3.1), fastener driving power must be set carefully in accordance with the manufacturer's instructions [28]. Fine adjustment of the driving power should be carried out by making several test fastenings. Reproducible fastenings can then be made within the required nail stand-off range without any problem, even on thin tubular profiles with a wall thickness of 4 mm using an approved fastening system [28].

Notes on installation:

On thin base materials the fastener driving power required depends not only on the thickness of the material but also on edge distance c. Lower power is required when fasteners are placed close to edges. Test fastenings should thus be made at the correct edge distance c. When the work is being carried out, attention must therefore be paid to variations in edge distance, e. g. when various tubular profiles are used on the same structure. For base material thickness between 4 and 8 mm, powder-actuated fasteners are correctly installed, within the required stand-off range, when they are *not* absolutely tight and flush against the part fastened (see Figure 76). A very slight gap should be visible between the collar at the head of the nail and the surface of the base profile. This allows nail stand-off to be checked visually very easily. For thicker base material $t_{II} \geq 8$ mm there is no detrimental effect of usual excess energy on fastener anchorage. Therefore, the powder-actuated fasteners are accepted to be driven tight and flush using cartridge and energy setting recommended in the approval [28].

Base profiles can also be fastened with fastening screws. Screws have the disadvantage of forming metal cuttings. With a view to avoid obstruction problems (clearance or space for the screw head), facade system manufacturers also offer special screws for this purpose (e. g. in accordance with [112] for fastening aluminum profiles to timber). MAG spot welding is also used to fasten base profiles to steel substructures (see [113]).

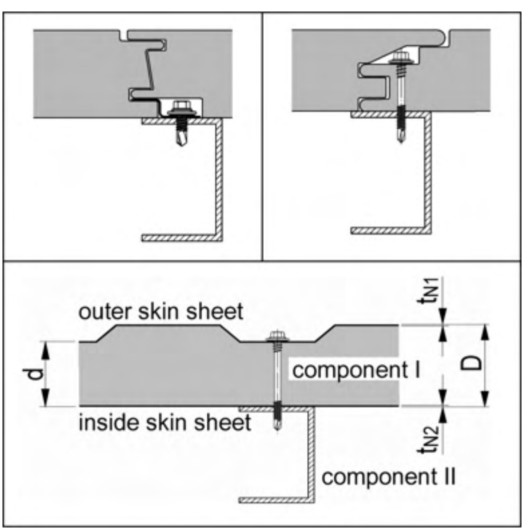


Figure 77. Methods that can, in principle, be used to fasten sandwich panels

5.4 Fastening sandwich panels

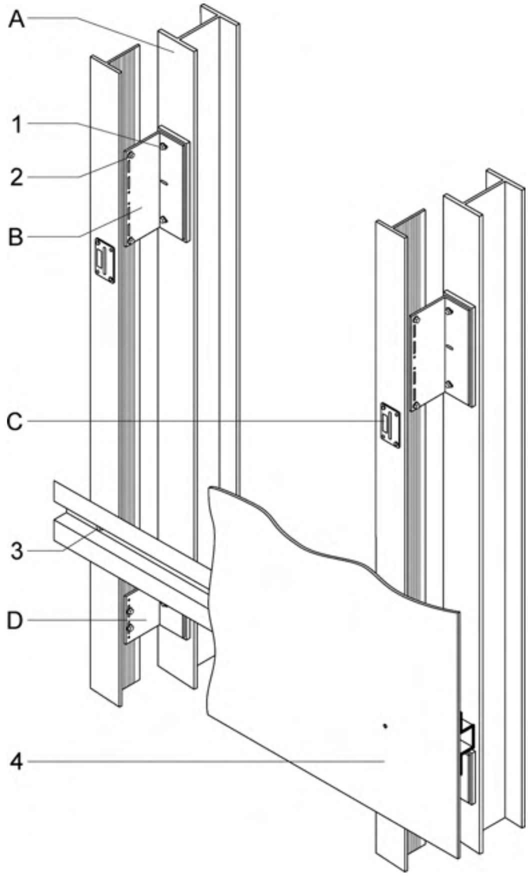
Sandwich panels are generally fastened with fastening screws (see Section 3.1.2.3). The panels are either drilled through by the screw from the outside or they are fastened at the long edge where the screws are hidden from view. Figure 77 shows the methods of fastening that are, in principle, possible. In view of the many different designs of hidden fastenings available, please refer, for example, to [114].

When clips are used to mount sandwich panels, the clips could, in principle, be fastened with powder-actuated fasteners. At present, however, there is no system available on the market that would be compatible with these fasteners. The technical problems to be overcome are the lack of access for powder-actuated fastening tools and the low fastener head stand-off permitted in view of the tongue-and-groove joints between the sandwich panels.

With regard to structure, materials, design and assembly of decking and siding, please refer to the literature in [104, 115], the additional literature listed in these documents and the information brochures published by the IFBS (*Industrieverband für Bausysteme im Stahlleichtbau*, www.ifbs.de, i. e. the German association for lightweight steel construction systems).

5.5 Ventilated façade construction

In this application, brackets made from aluminium, glass-fibre reinforces plastic or steel are fixed to the base material with suitable screws. Depending on the type of façade substructure, either horizontally or vertically running load bearing profiles made from aluminium or steel are connected with the brackets. The cladding is attached to the substructure of the façade.



A	Supporting structure	1	Anchorage of bracket to the supporting structure
B	Bracket (fixed point)	2	Fastening of the profile to the bracket
C	Mounting bracket	3	Fastening of the secondary profile to a profile
D	Bracket (skid)	4	Fastening of the cladding to the secondary profile

Figure 78. Ventilated facade: Fastening screws for the anchorage of brackets to the supporting structure and for connection of the facade components

Description and components

Ventilated facades represent a multi-layer exterior wall construction, which can be fastened to various base materials. The substructure consists of brackets, load-bearing profiles and fasteners. Brackets are typically made from aluminium or steel. The metal brackets might be thermally decoupled or equipped with a thermal isolation component attached to the foot of the bracket in order to reduce the effect of heat bridges. Thermally optimized brackets with parts made from glass-fibre reinforced plastic are also available on the market. The thickness of typical L-shape brackets is approximately 4 mm at the bracket foot and 2.5 mm in the area of the bracket web. Figure 78 shows the fundamental setup of the substructure of a ventilated façade.

Usability of the fasteners

The use of all types of fasteners is to be validated based on a national test certificate *(abP)*, e. g. P-BWU02-148007 [116], a national technical approval (abZ), e. g. Z-14.4-769 [117], a general construction technique permit (aBG) or a European Technical Assessment (ETA). In the absence of such documents design and execution has to be done in compliance with a project-specific approval (ZiE). National approvals and ETAs for fastening screws for the fastening of profile metal sheets are not suitable for the fastener design of ventilated facades as these documents only contain characteristic resistance values for non predrilled components. In most cases, the brackets and profiles for the substructure of ventilated facades contain predrilled holes or pre-punched slotted holes. The documents available for this application take into account the predrilled and pre-punched holes and the material strengths.

Anchorage of brackets to the supporting structure

The brackets are anchored to steel, aluminium, wood or wood-based supporting structures using suitable stainless steel self-drilling screws or self-tapping screws. The brackets are usually predrilled so that the self-drilling screws only have to drill through the supporting structure. For the definition of the clamping length, the thickness of the bracket foot and the thickness of thermal isolators need to be considered. Either stainless screws with or without sealing washer can be used. The sealing washer or a collar below the screw head increase the pull-through resistance of the screw. A sealing function is not required in that area. The fasteners are loaded by actions due to dead loads, wind, snow and ice-loads, thermal constraints and special loads (attachments). When designing the screws, it must be ensured that their characteristic resistance values consider a potentially existing isolator plate at the bracket foot. For the fastener design, the presence of any non-loadbearing layers, e. g. fire protection layers or claddings need to be considered as well. Furthermore, any additional tensile load due to the eccentric load application on the bracket shall be considered in the calculation of the screw loads.

Connections within the substructure

All components of the substructure are to be assembled free of constraints and taking into account the material specific change in length due to temperature and humidity. When selecting the fasteners, it must be ensured that the sliding points, intended to absorb the expansion in length, will work in practice. Rivets or self-drilling screws made of stainless steel are used in general. In case both parts to be connected are made from aluminium, screws completely made of stainless steel (monoblock screws) can be used. A hardened, drill point made of carbon steel is not required for drilling into aluminium profiles. For the constraint-free connection of the profiles to the bracket it is recommended to use specific screws, which ensure the function of the sliding point. These screws have a thread-free area directly below the screw head, which is adapted to the profile and wall bracket thickness. Such screws secure the functioning of the skid: on the one hand, the two components are so tightly connected to each other after assembly that they do not rattle when exposed to wind and, on the other hand, that no constraints occur when the length of the profile changes due to the effect of temperature.

Fastening of the cladding

When fastening the façade cladding, a general distinction is made between visible and concealed fastening. As in case of connections within the substructure of ventilated facades, stainless self-drilling or tapping screws are used for the attachment of the cladding. For visible fastening, screws with small and/or flat heads are preferred for architectural and aesthetic reasons. These can be colored like the cladding itself. In case of concealed fixings (mounting brackets, agraffes systems), the geometry of the used screw heads has the meet the geometric system conditions to allow easy assembly of the cladding. If perforated sheet is used as cladding, the geometry and pattern of the holes needs to meet the conditions given in national technical approvals (abZ), ETAs and test certificates (abP).

5.6 Powder-actuated fastening of thick, predrilled metal sheets

The term "thick sheet metal" refers to sheet metal with a thickness beyond about 3 mm in a single layer. With material of this thickness, it can no longer be ensured that the material to be fastened is pressed firmly against the base material unless a hole is drilled in advance. As the fastener is driven, material is displaced latterly but also toward the sheet metal. Bulges on the side from which the fastener is driven and on the reverse side are common. Due to the – in comparison with several thinner layers of the same total thickness – greater stiffness of the single layer of thick sheet metal to be fastened, it does not take on the shape of the bulge but lifts away from the base material slightly. This results in a gap between component I and the base material (Figure 79). The gap is all the more pronounced if the supporting material is solid steel as, in this case, material can only be displaced upwards.

The formation of a gap makes installation more difficult when, for example, further powder-actuated fasteners have to be driven through a component that is no

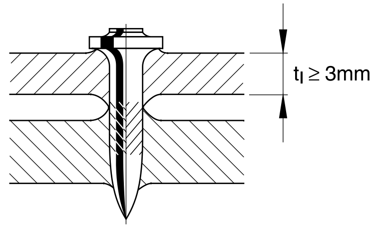


Figure 79. Formation of a gap between component I with $t_I \geq 3$ mm and component II

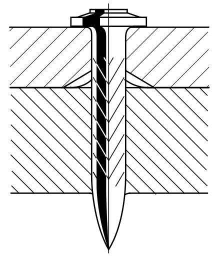


Figure 80. Fastening components with predrilled holes, countersunk on the reverse side

longer in contact with the base material. In addition to this, the gap between the parts results in unintentional bending stress on the shanks of the fasteners, above all when the fasteners are driven in a single row.

For this reason, it is recommended that holes are predrilled in thick sheet metal with a thickness of $t_I \geq 3$ mm. This then ensures that component I is always pressed firmly against the base material. The holes should be drilled slightly undersize (e. g. 4 mm hole for fasteners with a shank diameter of 4.5 mm) and countersunk slightly on the reverse side (Figure 80). If possible, this work should be carried out in a workshop. Predrilling also extends the application limits of the fastening system and reduces the fastener driving energy required.

Figure 81 shows a practical example. The nailed-on angle bracket is intended to prevent the steel beam from lateral buckling. For the angle bracket it is essential that the holes were predrilled to allow a tight fit of the bracket with the substrate. The required shear forces could then be taken up without superposition of a bending moment acting on the fastener shank.

Fastenings that connect plane components offer greater robustness to unintentional bending stress: for example, the fastenings around the edges of chequer plates. These fastenings, on the one hand, simply serve to hold the plates in position and, on the other, a gap of about 2 mm has very little influence on the shear loading capacity of the connection [37]. Chequer plates with a thickness of about 6 mm can, theoretically, be fastened without predrilling holes as long as components I and II are within application limits. Nevertheless, predrilling

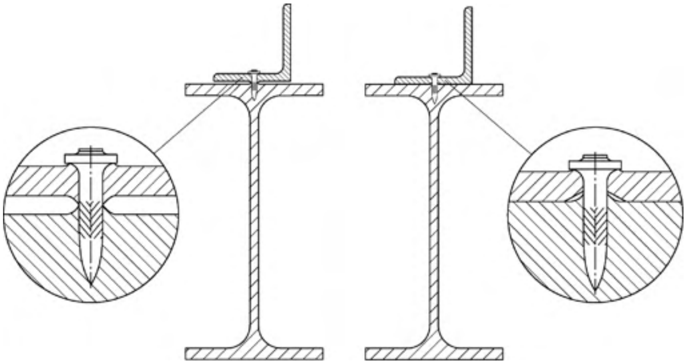


Figure 81. Angle bracket designed to prevent a steel beam from lateral buckling; left: unacceptable design

the holes will also prove to be the better solution in most cases. It allows rapid progress with the installation work (especially with imperfect, slightly bent plates) and lower fastener driving energy can be used, which means that the fastening tool is subjected to less wear.
Due to the slight undersize drill hole there is no initial lateral slip between the powder-actuated fasteners and the fixed component I (Figure 70). It can thus be ensured that all nails forming a group of fasteners play a part in the connection. For the purpose of verification, the elastic resistance of the total cross-section of the group of fasteners can be taken into account.
Self-drilling screws (if their drilling capacity is adequate) or self-tapping screws can also be used to fasten thicker metal sheets. The European Technical Assessments for metal construction screws (Table 19) cover the fastening of thin trapezoidal profile metal sheets and liner trays. The maximum thickness for component I is limited to 2 mm, and thicker sheets are not formally covered by the ETAs. As with powder-actuated fasteners, it is also possible to make group fastenings without slippage with self-drilling screws. When self-tapping screws are used, it is recommended that the part to be fastened is predrilled to ensure adequate clearance and that the minimum required screw driving depth of 6 mm in component II is observed.
If long components are to be fastened, either with powder-actuated fasteners or fastening screws, the possibility of constraining forces occurring due to temperature (i. e. expansion and contraction) must be taken into account. If not verified exactly, to be on the safe side, the maximum component dimensions may be limited in the approval [118].

5.7 Fastening of wood and wood materials

Square timber with a thickness of more than 40 mm is fastened to the trapezoidal profile metal sheet with fastening screws in situations where this timber is to act as a spacer between the inner and outer skins of a double-skin roof structure (Figure 82). In accordance with national technical approvals [119], the maximum thickness of the sheet metal base material is limited to 2.5 mm and the individual sheet thickness is limited to a maximum of 1.5 mm.
If the timber is to be fastened in a single operation with metal construction screws, self-drilling wing screws suitable for thick base materials (up to about 5 mm) should be used (Table 12) [120]. If, on the other hand, conventional metal construction screws are used, the timber must be predrilled to a diameter large enough to allow the metal cuttings from the screw driving operation to be pushed out through the hole.
Powder-actuated fasteners are used to fasten wood materials to steel for secondary purposes, e. g. finishing ceilings, planking on steel beams or in the construction of containers. Smooth-shank powder-actuated fasteners made from carbon steel are frequently used for fastening wood to concrete. A wide range of lengths are thus available on the market. Generally speaking, these nails can also be driven into steel. Nevertheless, if reliable anchorage is to be obtained, the nails must be driven significantly deeper ($h_{ET} \geq 18$ mm) than knurled powder-actuated fasteners. Despite being driven to

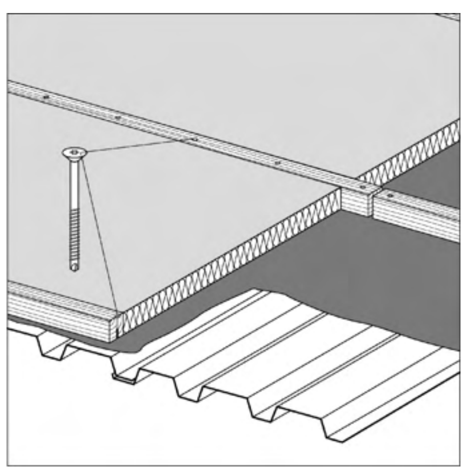


Figure 82. Fastening square timber to trapezoidal sheet liner trays

Table 13. Examples of the characteristic loading capacities of fastenings for wood on steel using powder-actuated fasteners.

Wood material thickness [mm]	N_{Rk} [kN]	V_{Rk} [kN]		
		OSB	Plywood ρ = 400 kg/m³	Plywood ρ = 600 kg/m³
12	0.40	1.0	0.9	1.4
22	0.56	1.5	1.4	1.8
37	0.56	2.1	1.8	2.2
52	0.56	2.2	1.9	2.2

greater depth, the loading capacity achieved by these nails is significantly lower than that of knurled fasteners. Considering the tensile loading capacity that fastenings are required to possess, the loading capacity of smooth-shanked nails is, however, generally adequate. Table 13 indicates the order of magnitude of the characteristic tensile and shear loading capacities that wood fasteners with a shank diameter of 4 mm and a head diameter of 8 mm [118] are required to provide in accordance with DIN EN 1995-1-1 [96].

Compared with the values given in Table 13, the characteristic tensile loading capacity of a screw fastening as per [119], at a value of $N_{Rk} = 1.25$ kN, is more than twice that of the corresponding powder-actuated nail fastening. The difference is due to the larger head shape of the metal construction screw (head diameter = 11 mm). The shear loading capacities of the powder-actuated fasteners and screw fastenings are, however, in the same order of magnitude.

The maximum base material thickness for galvanized powder-actuated fasteners is depending on the type between about 6 and 10 mm. Smooth-shanked powder-actuated fasteners, as a rule, must be driven to sufficient depth to ensure that their cylindrical shank is gripped by the base material. The point then clearly projects (≈ 10 mm) on the back side of the base material. The range of applications for which these nails can be used is limited by the tendency to buckle when driven as the thickness t_I of the part to be fastened increases (Figure 83).

With structurally relevant fastenings care must be taken to ensure that application limits are observed as fasteners that have buckled within the wood cannot be reliably identified as failures from the outside. Manufacturers offer long fasteners for this application in single or collated form. It must be noted, however, that the collated fasteners driven by magazine-type tools have a lower application limit than single fasteners [118]. This is due to technical system limitations.

Nails are now also increasingly used to fasten wood materials and gypsum board (drywall) with a thickness of at least 12 mm to thin steel supporting structures ($t_{II} \geq 1.5$ mm). These nails, which have a narrow shank diameter of 2.2 to 2.8 mm, are driven by gas-actuated or compressed-air tools and their use is regulated by national technical approvals [121]. In the USA, these nails and tools are already in widespread use for fastening wood cladding (planks, boards, etc.) to steel framing. Walls and ceilings nailed in this way act as diaphragms contributing to the lateral stability of residential and commercial buildings [122, 123].

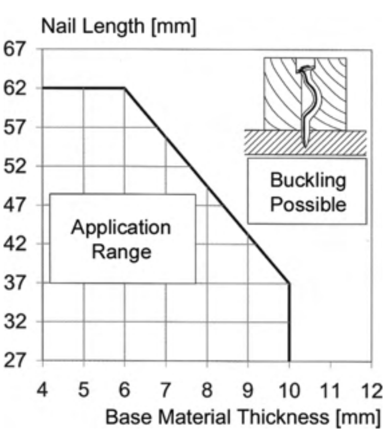


Figure 83. Application range for fastening wood

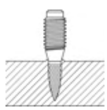
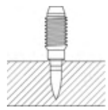
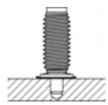
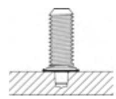
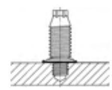
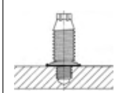
5.8 Detachable fastenings with threaded studs

5.8.1 Criteria for stud selection

The use of threaded studs enables detachable fastenings, e. g. fixing of brackets for cable trays in mechanical and electrical installations or the fastening of grating or checker plates both in combination with specific grating or checker plate holders. Further applications include connections of U-shape strut channels made from steel, hangers for tubes or sprinkler pipes or the variety of light duty fixings like connection of switch cabinets, signs or luminaires. The connection of the fixture is done conventionally by means of nuts and washers or by means of flange nuts only. Figure 84 shows a series of application examples.

The range and technology of threaded studs is shown in Table 14. The main criteria for stud selection are the environmental conditions, thickness and strength of the

Table 14. Types of threaded studs

	Sharp-tip threaded studs		Blunt-tip threaded studs			
Type						
Material	Carbon steel, electroplated	Stainless steel	Stainless steel with glass-fibre thread	Stainless steel	Carbon steel	Stainless steel
Environmental conditions[1]	C1	C3	C3	C3 to C5	C1 to C3	C3 to C5
Type of base material	S235 to S355[2]	S235 to S355[2]	S235 to S960[3]		S235 to S355, Aluminium[4]	S235 to S355, Aluminium[4]
Minimum base material thickness	4 to 6 mm[5]		8 mm[6]		6 mm[6]	6 mm[6]
Predrilling	No		Yes, required			
Method	Direct fastening				Screw-in threaded studs	

[1] Category of corrosivity of the atmosphere C1 to C5 according to DIN EN ISO 9223 [25].
[2] The upper application limit published by the manufacturer is to be observed.
[3] For the currently offered Hilti X-BT fastening system the full coverage up to S960 is given independent on the base material thickness.
[4] $R_m \geq 270$ N/mm^2
[5] The minimum base material thickness provided by the manufacturers for the respective fastening system is to be observed.
[6] For coated base material without damage of the corrosion protective system; thinner base materials are possible with through drilling as well as rework of the corrosion protection following manufacturers provisions [66, 67].

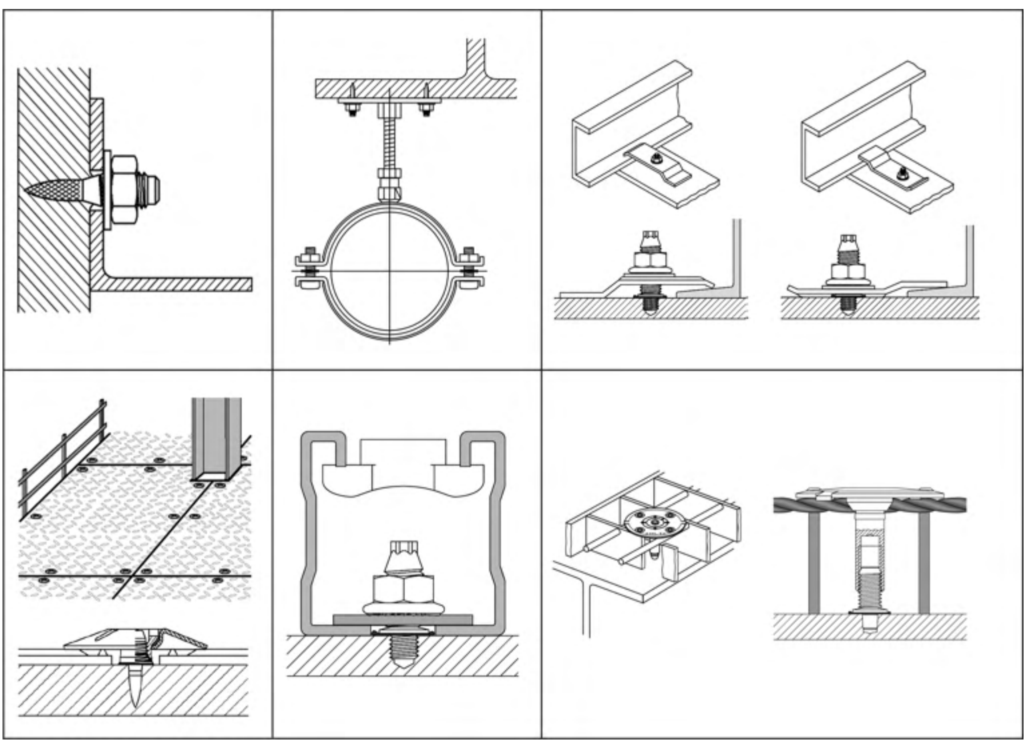


Figure 84. Examples of fastenings with threaded studs

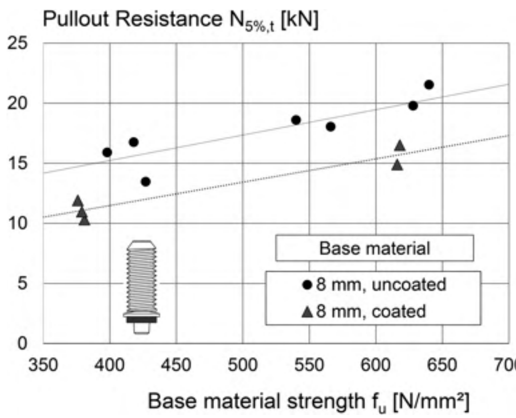
base material, the potential presence of base material coating and the required stud performance.

Electroplated threaded studs made of high strength carbon steel are only allowed to be used in dry indoor conditions (see Section 2.8). For safety relevant connections exposed to moisture or weathered environments, threaded studs made of stainless steel suitable for the respective category of corrosivity are to be used. However, the application limit of sharp-tip stainless studs for thicker base material $t_{II} \geq 12$ mm made of S355 is substantially lower compared with threaded studs made from carbon steel [9]. If blunt-tip studs involving predrilling are used, construction steel S355 is covered independent form its thickness. Specifically for power-actuated driven blunt-tip studs, the use for steel grades up to S960 is possible without limitations. Higher strength steel up to S700, which are intended to be added in the upcoming next generation of EN 1993-1-1 [124], are consequently also completely covered. Higher strength steels S690 to S960 are often used in crane construction. Fastening applications to cranes are e. g. fixing of sockets and clamps for hydraulic or electrical lines on these units. If the threaded studs are used in areas of the crane structure subjected to fatigue loading, the knowledge of the fatigue detail category "base material with threaded stud" is required for the respective product. For industrially manufactured units the optimization of the production process represents a further selection criterion for the fastening method – here compared with welded threaded studs. The threaded studs with sealing washer shown in Table 14 enable fast installation on coated base material in the workshop without the need of pre- and rework of the coating generally required when using welded studs. Provided the minimum base material thickness specified by the manufacturer according to Table 14 is observed, also the backside coating remains intact. Application on thinner base material is possible, however, the base material is drilled through when preparing the pilot hole for the threaded studs. In that case the back side coating is damaged by the drilling process and needs to be professionally reworked if necessary.

This benefit of blunt-tip threaded studs is of special relevance for mobile use – independent from electricity – for fastenings to existing units. Easy and robust execution of fixings to coated base material in weathered environment is a further relevant selection parameter. The geometric position of studs – used for fastenings like suspensions or cable tray attachments in open car parks and fixing of grating in plant construction – are often not planned in detail. Such connections can be carried out quickly on the jobsite with the mobile stud fastening system even in case of high corrosion requirements in case of offshore platforms or offshore wind parks. The base materials in these cases are in general pre-painted or hot-dipped galvanized.

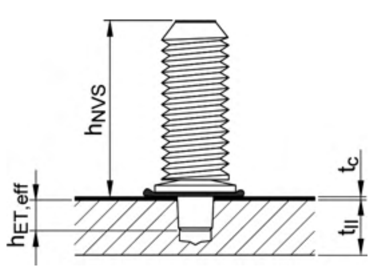
The geometry of the fastening systems to secure the position of gratings is designed that the grating may be laid down on its support before the threaded studs are installed. They are driven from above through the openings of the grating. For that purpose respectively long and narrow fastener guides are to be used which allow access of the fastening tools to the base material.

For many light duty applications, the tensile and shear load capacity is not a decisive selection criterion, provided, of course, that a certain minimum load capacity is reliably and reproducibly ensured. The resistance of the anchorage needs to be high enough to allow trouble-free assembly when applying the defined installation torque specified by the manufacturer. The load-bearing capacity becomes relevant in heavy duty applications, e. g. in case of long span suspensions of pipes in mechanical installations, in case of end plate fixation of brackets or in case of accidental uplift loads on grating fastenings which are located in the wave-zone area of offshore units. Directly driven blunt-tip threaded studs



Each dot corresponds with the 5%-fractile of a test series with 20 blunt-tip threaded studs Hilti X-BT-MR or X-BT-GR. The thickness of the coating in these tests amounted between 550 to 820 µm.

Figure 85. Effect of base material coating on the pullout resistance of blunt-tip threaded studs



h_{NVS} distance from the head of the threaded stud to coating of the base material

t_c thickness of the coating

$h_{ET,eff}$ effective depth of penetration in the steel base material

Figure 86. Effective depth of penetration in coated base material

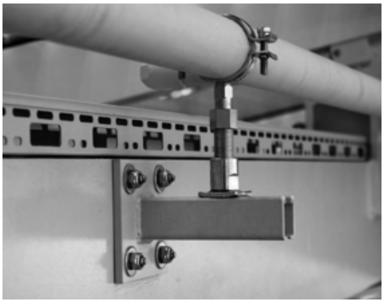


Figure 87. Fastening of brackets with blunt-tip threaded studs

offer the highest characteristic resistances in the range of N_{Rk} = 10 kN in low strength S235 steel in combination with an applied partial factor $\gamma_M = 2.0$. For these fasteners the maximum coating thickness has to be considered in the experimental investigations. Figure 85 shows an example of the effect of the coating thickness up to 500 µm on the anchorage of blunt-tip threaded studs. The effective depth of penetration in the base material will be reduced by the coating, see Figure 86. The proposal to apply a partial factor $\gamma_M = 2.0$ is based on the current draft of a European Assessment Document (EAD) for threaded studs which is not yet released officially. That EAD draft is based on the fundamental concept of EAD 330153-00-0602 [150] for sheet metal powder-actuated fasteners but provides complementary rules and details relevant for detachable fastenings by means of threaded studs.
Figure 87 shows the fastening of a bracket to coated base material supporting sprinkler pipes.
The shear resistance represents a further selection criterion for threaded studs. In case of group fastening with threaded studs the ductility of the shear load-displacement characteristics is of special importance, in detail see Section 5.8.3.

5.8.2 Failure modes and hints on installation

The failure modes of powder-actuated fasteners and fastening screws for fastening of profiled steel sheeting are summarized in Figure 105. Dependent on tension and shear loading it is distinguished between failure of the fixed member (component I) and failure of the base material. These failure modes are to be applied analogously for the assessment of threaded stud connections. In general threaded studs are used to attach thicker metal sheets or components with thickness ≥ 2 mm. Therefore, typically failure of the base material or the stud itself will control the connection resistance. If the shear load is introduced via a lever arm, the threaded stud is subject to bending. The potential failure modes in that case are failure of the anchorage, which leads to pullout of the stud from the base material, as well as plastic bending deformation and fracture of the stud itself, see Figure 88.
Although threaded studs are made from high-strength material, they cannot be pretensioned like high strength bolt joints. In general manufacturers specify stud specific installation torque which is typically in a range of 5 to 10 Nm (maximum 20 Nm). Nevertheless, also in case of 20 Nm no effective pre-stressing action develops. These torques are not sufficient to achieve tight clamping of thicker plates (approximately 5 to 10 mm) or to activate significant friction forces in the contact joint. As a comparison, the torque that can be applied to an 8.8 grade M10 bolt is $M_v \approx 50$ Nm and for an M8 bolt it is $M_v \approx 25$ Nm. The application of an uncontrolled torque beyond the recommended values may cause the threaded studs to be pulled out. Threaded studs which have been pulled out in this way are not suitable for a second use and must be replaced by driving or screwing a new stud.
Problems of this kind can be avoided in practice by:
– Training the workforce
– Driving or screwing the studs correctly to the specified depth. This ensures that the stud achieves the required pullout resistance.
– Use of a torque wrench to tighten the nuts in a controlled manner and thus avoid overtightening. Alternatively, power screwdrivers can be used to tighten the nuts in accordance with the manufacturer's specifications.

Due to the predrilling, blunt-tip threaded studs can be positioned very accurately also in hand-held operation.

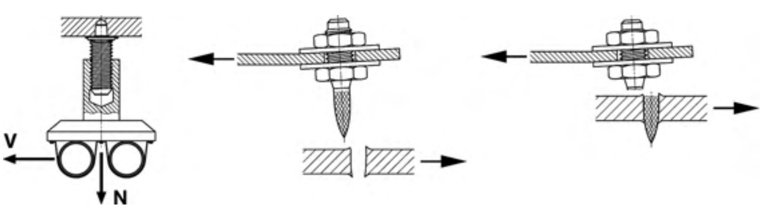


Figure 88. Loading and failure mode of threaded studs loaded with lever arm

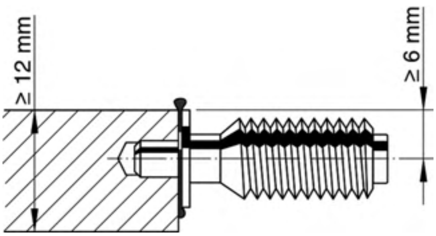
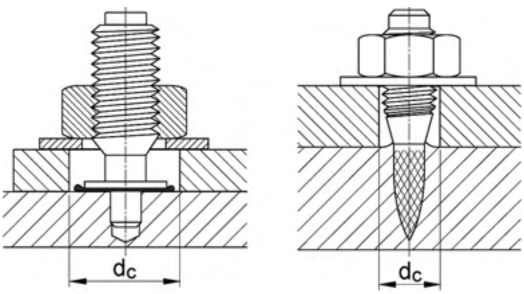


Figure 89. Installation of blunt-tip studs in the butt end of a beam flange



d_c hole diameter in fixed component

Figure 90. Plate connection with threaded stud, clearance

Very small edge distances ≥ 6 mm are possible. Fastenings can even be made in butt ends of beam flanges. When the stud is positioned centrally, the minimum flange thickness is then 12 mm (Figure 89).
For attachment of the fixture without constraints, threaded stud connections are designed with a certain clearance in the fixed material. The clearance allows adjustment of the position of the fixed member. In contrast, a nail connection is immediately immovable and cannot be detached non-destructively.

5.8.3 Group fastenings

The size of the clearance is relevant with respect to joint acting in shear of several threaded studs forming a fastener group. The random positioning of the contact points of the threaded studs with the plate has to be considered. Figure 91 shows the most unfavorable position of a row of 4 studs and group of 4 studs in a rectangular plate, respectively. In case of a rectangular plate and centric force introduction at least 2 studs act jointly from the beginning. In case of unfavorable position in a row, the shear force is initially distributed to only one threaded stud until the deformation of this stud corresponds to the clearance. Beyond that shear deformation all 4 studs will then jointly contribute to the shear load transfer.
Whether all 4 studs of a group can be fully used for load transfer depends on the size of clearance as well as the ductility and deformation capacity of the shear

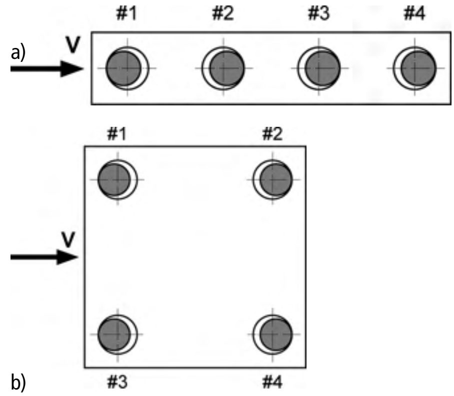
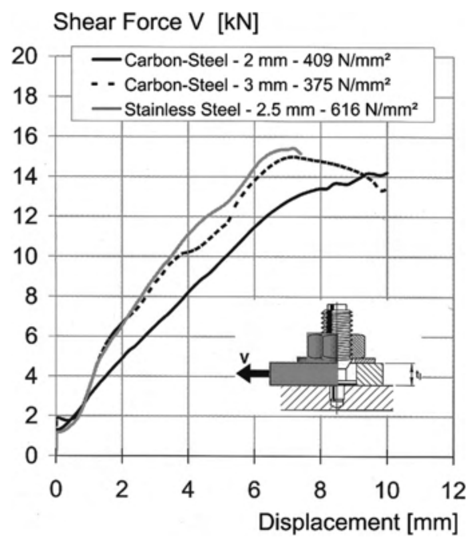


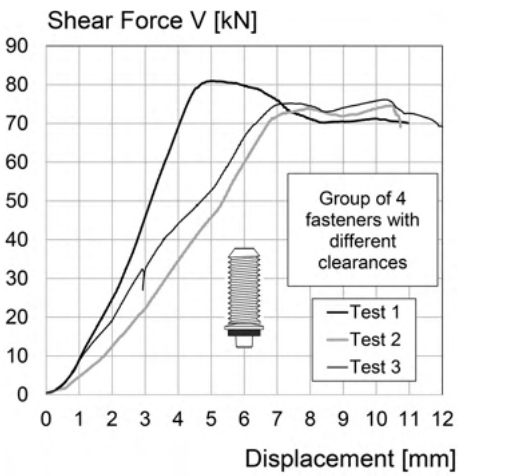
Figure 91. Unfavorable position of studs in groups with 4 fasteners; a) row of 4 studs, b) rectangular plate with 4 studs



a) Blunt-tip threaded stud Hilti X-BT with cylindrical shaft, d = 4.5 mm (Figure 10)

Figure 92. Shear loading capacity of blunt-tip studs with a load introduction via the sealing washer in dependence of thickness and strength of the fixed steel

force-displacement behavior of the single stud connection. The latter depends on the material of the threaded studs as well as the type of shear force introduction. In case of blunt-tip threaded studs with sealing washer, the shear force can be introduced into the stud via the metal part of the sealing washer, which leads to a ductile load-displacement behavior (Figure 92).
For each individual item, the manufacturer has to define the maximum number of threaded studs that can be fully used for load transfer for a defined maximum clearance. The respective European Assessment Document is also in preparation in that regards. The assess-



Tested threaded stud: Hilti X-BT-MR M10/15 SN 8 with conical shank, d = 5.2 mm (Figure 10), shear load introduction via the sealing washer.

Base material: 10 mm, S355; Component I: 10 mm S355

Group setup:
Row of 4 studs with numbering of studs per Figure 91.

Clearance:
Test 1: all studs are simultaneously in contact: clearance = 0

Test 2: stud 1: clearance = 0, stud 2, 3 and 4: clearance = 2.5 mm

Test 3: stud 1 and 2: clearance = 0, stud 3 and 4: clearance = 2.5 mm

Test 3 corresponds statically with the configuration of a centrically loaded rectangular plate, for which it is assumed that 2 studs act simultaneously from the beginning.

Figure 93. Shear resistance of a group of 4 studs depending on the threaded stud position in the hole (clearance = 2.5 mm)

ment is done for maximum service shear force of the group. Strength and deformation capacity of the stud initially loaded must be sufficiently high that a fracture of that stud is reliably avoided. Furthermore, a sudden "zip-failure" of the group must be excluded.
Figure 93 shows a comparison of shear tests of a group of 4 fasteners with different clearances of the individual threaded studs. The test equipment must be designed that the clearance can be adjusted individually for every stud of the group.
The conclusions from that example of group tests are as follows:

– Test 1: When all 4 studs act simultaneously from the beginning, the shear capacity of the group corresponds with the quadruple shear resistance of the single stud. The mean shear resistance of the single stud amounts in the specific case to approximately 19 kN (mean based on 10 single tests).
– Test 2 and 3: Although unfavorable clearance distributions were simulated in the test, the overall ductility of the connection is sufficiently high, that almost the full resistance of test 1 could be reached. No critical sudden zip-failure occurred. In the specific case (clearance = 2.5 mm) all 4 threaded studs of the group can be considered in shear design. The service shear force amounts to 5.6 kN per stud (considering the partial factors $\gamma_m = 2.0$ and $\gamma_F = 1.40$) corresponding with a total service shear force of 22.4 kN for the group of 4 studs.
– As expected, the deformation characteristic of test 2 and 3 is less stiff than in test 1. Also the deformation at maximum shear load is respectively higher. The displacement in the service state increases in the most unfavorable case of test 2 with somewhat more than 1 mm and in case of the rectangular plate with only approximately with 0.5 mm.

5.8.4 Applications for grounding, bonding and lightning protection

Stainless blunt-tip studs can also be used as electrical earthing and grounding points. This method has the advantage of requiring no special preparation or subsequent finishing of the coating on the base material at the point at which the fastener is driven. Figure 94 shows the grounding connection of a blunt-tip stud. The electrical connection is achieved via the threaded stud and its anchorage in the base material.
In compliance with IEC EN 60947-7-1439-1 and IEC EN 60647-7-2, a single blunt-tip stud has been verified as being suitable for a 10 mm^2 copper wire connection and two coupled studs for a 16 mm^2 copper wire connection [125]. Greater wire cross sections up to 120 mm^2 can be electrically connected when combining the stud with a special conductivity disc. In these cases, the current is conducted into the base material via the cable lug and the conductivity disc. The purpose of the threaded stud is then primarily to press the cable lug and the conductivity disc against the surface of the base material and to ensure that necessary contact over time.
For sealing gas pipelines pipe flange connections are prestressed by means of bolts resulting to high stress

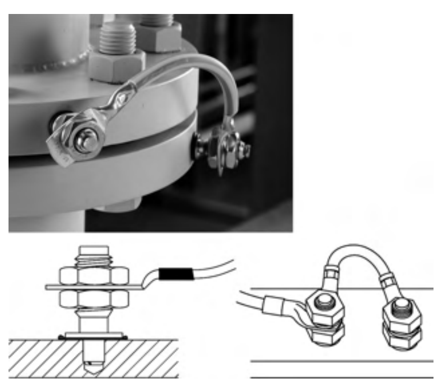


Figure 94. Grounding point provided by a blunt-tip threaded stud

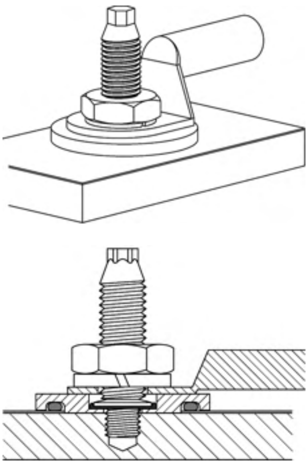


Figure 95. Grounding point with special conductivity disc

utilization in these thick pipe flanges. Due to the good-natured effect of powder-actuated fasteners on the steel base material (Section 2.7), it is in general acceptable to apply threaded studs on these highly stresses flanges. Furthermore, the threaded studs are usually installed in the flat flange face or at the low-stressed edge of the flanges, so that their influence on the integrity of the flange connection is negligible. Corresponding numerical investigations and verification on that topic are available in [126].

5.9 Fastening waterproofing membranes

Welded membranes are widely used to form a waterproof seal on flat roofs. The sealing system consists of a sealing membrane and, in most cases, also incorporates thermal insulation. Self-drilling screws with load-distribution plates have been developed for this application in lightweight metal construction. These screws are driven through the thermal insulation and into the load-carrying profile metal sheet and thus hold the membrane in place. Figure 96 shows the composition of a typical roof with the sealing membrane and the thermal insulation.

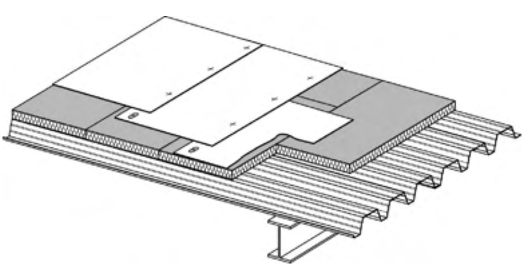


Figure 96. Roof composition with sealing membrane and integrated thermal insulation

Due to the high requirements to be fulfilled by the thermal insulation, the fasteners used must also be optimized in terms of their thermal conductivity properties. Screws that fully penetrate the insulation present a thermal bridge, the effects of which must be minimized.

5.10 Powder-actuated fasteners as a means of connecting steel plates

An exceptional example of how this fastening technique was used in a major project is the folded-sheet structure of the ship terminal at Yokohama. The substructure consists of triple-flange beams with a conical cross section (Figure 97). The connection of all web sheets to the flanges was not achieved conventionally by means of longitudinal fillet welds, but by nailing the sheets to the flanges at regular, short intervals. The primary motive for this unique use of the powder-actuated fastening technique was the architectural relationship with historical riveted structures. The entire steel structure remains visible. In order to achieve the required fire resistance, Japanese fire-resistant S490SM-FR construction steel was used. For cost-efficiency reasons, the shear loading capacity of the fasteners on exposure to fire could not be allowed to govern the design. Stainless steel fasteners with a high temperature resistance were

Figure 97. The nailed folded-sheet structure of the ship terminal at Yokohama

thus selected for the job. These fasteners had a shear resistance of about 11 kN at 600 °C, which is about 60% of their loading capacity when cold (see Figure 9) [27, 94]. The stainless steel fasteners were galvanized to reduce friction when driving and thus facilitate penetration of the steel and ensure achievement of the correct depth of penetration.

The use of powder-actuated fasteners as a means of joining the butt ends of the tubular sections of electricity pylons was investigated at the University of Toronto [127-129]. A joint type was investigated that could be used on remote sites with a poor infrastructure. The tubular sections to be joined could be of the same diameter, with the joining piece taking the form of an external tubular sleeve. Alternatively, the diameters may be such that one tubular section slides inside the other (Figure 98).

Tubular sections with a wall thickness of up to 8 mm can be joined in this way. Plates of this thickness can be nailed together without predrilling due to the geometry of the tubular section. Although the tendency for a gap to form between steel of this thickness is normally considerable (see Figure 79) and the depth of penetration of the fastener in the inner tube is small, a high shear loading capacity was achieved in the tests as the stiffness of the tubular sections prevents lifting of the pipes. The tensile resistance of the anchorage obtained by the fastener in the inner tubular section is also of secondary importance in this type of joint as the fastener is securely anchored in the outer tubular section, thus reliably preventing "jumping out" as a result of shear force.

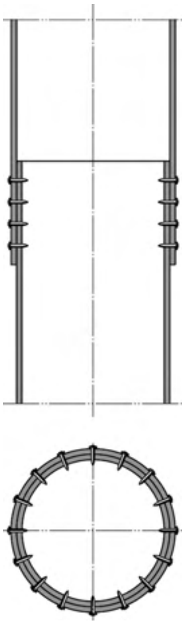


Figure 98. Nailed tubular connection

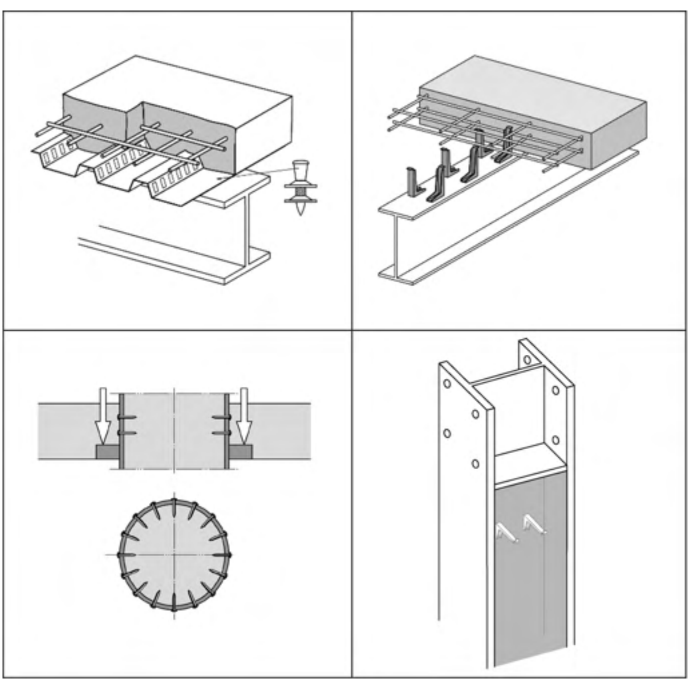
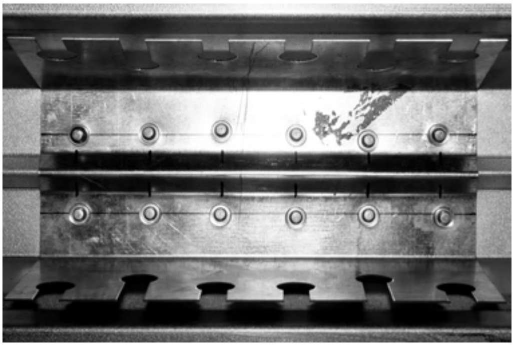


Figure 99. Use of powder-actuated fasteners in composite structures



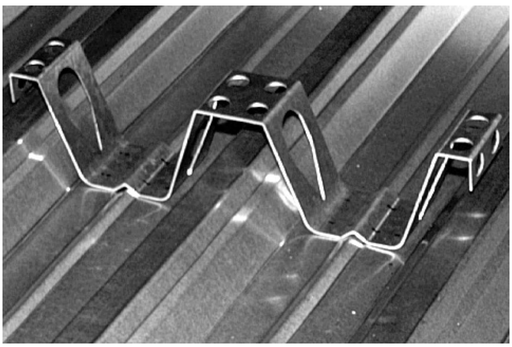


Figure 100. Prototypes of nailed shear connection: *Stripcon* and *Ribcon*

5.11 Applications in steel/concrete composite construction

Figure 99 shows the possible applications of powder-actuated fasteners in steel/concrete composite construction.

- Nailed shear connectors for composite beams
- Temporary tacking of profiled steel sheeting of composite slabs or sheeting used as formwork
- Nailed shear connection for composite tubular columns
- Applications with concrete encased steel beams

5.11.1 Nailed shear connection in composite beams

The main application for powder-actuated fasteners in composite construction is with nailed shear connectors in composite beams used in building construction. In general nailed shear connectors act like cantilevers in the same way as headed studs. Alternatively, also bigger perforated strips of metal sheet or toothed strips may by nailed to the steel beams. These act like frames if the strips span over several ribs of the composite slab or act like a plate in case a toothed strip is embedded within a solid concrete slab (see the concepts *Stripcon* and *Ribcon* according to [130, 131]). Further scientific research – with a focus on numerical investigations with regards to minimum required degree of shear connection – was done by *Bärtschi* and *Fontana* and is amongst others

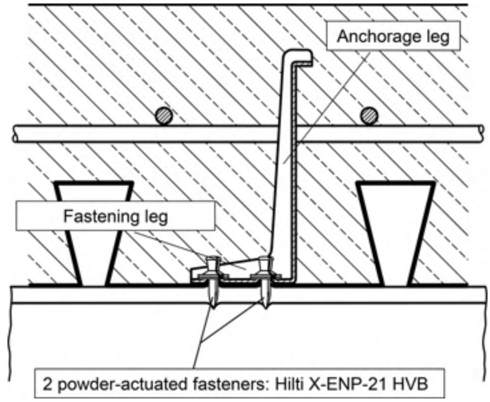


Figure 101. Example of a nailed shear connector: Hilti X-HVB

documented in [132]. However, serial product solutions of nailed strip connectors are not yet offered to date on the market.

Cantilever type nailed shear connectors are the Hilti X-HVB shear connector [95] and the Tecnaria products Diapason and CTF, respectively [133, 134]. The X-HVB shear connector is an L-shaped, deep-drawn sheet metal "bracket" consisting of a fastening leg and an anchorage leg cast into the concrete. The fastening leg is fixed to the steel beam by means of 2 powder-actuated fasteners Hilti X-ENP-21 HVB (Figure 101). The product CTF consists of a headed stud with a shank diameter of 12 mm and a head diameter of 18 mm. The shank is pressed together with a base plate, which itself is fixed by 2 powder-actuated fasteners Spit HSBR 14. These fasteners are also used with the Diapason shear connector, where a formed sheet metal part is fixed by means of 4 powder-actuated fasteners. The firm metal part features supplemental perforations for direct load transfer to the concrete also allowing positioning of the transverse concrete reinforcement.

Since 2016, a European Assessment Document (EAD 200033-00-0602 [151]) is released for nailed shear connectors, which determines the essential characteristics and the respective experimental tests as basis for a European Technical Assessment. The procedure is described in detail in Section 10. To date 3 ETAs for nailed shear connectors were issued on the basis of [151] (see Table 18).

Nailed shear connectors are applied as alternative solution for welded headed studs. When comparing the cost efficiency of nailed shear connectors and headed studs, the effect the method selected has on the whole construction procedure must be taken into account. A prerequisite for the cost-efficient use of nailed shear connectors is that the connectors are installed on the jobsite. Continuous profile sheets can then be used. This reduces the profile cross section that's required compared with single-span sheets and it also reduces the amount of work required to seal the joints between the metal sheets. If headed studs are already welded on in

Table 15. Comparison of the design values for headed studs and nailed shear connectors X-HVB for C30/37

Means of shear connection	P_{Rd} [kN]		
	Solid slab	Composite slab	
		Perforated profile metal sheet	Profile metal sheet with through-welded studs or driven nails
Headed studs d = 19 mm [1)]	69.4	41.6	48.6
Shear connectors X-HVB 125 [2)]	30.0	30.0	30.0

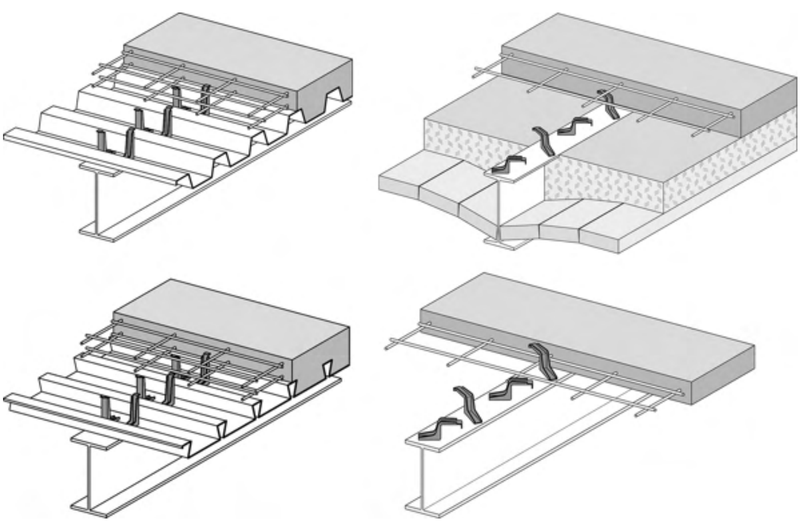
[1)] where $\alpha = 1$, $n_r = 2$, $t \leq 1$ in accordance with DIN EN 1994-1-1 [138] and $\gamma_V = 1.5$ according to German NA [139]

[2)] positioned longitudinally relative to the beam [95] in profile sheet with $k_{tl} = 1.0$ (Table 28)

the workshop, continuous sheets must have holes at the points where the headed studs are positioned. This leads to more planning and prefabrication work for the metal sheets used in the composite structure. This extra work can be avoided through use of nailed shear connectors. Comparison of the applicable design values for these two applications shows that headed studs clearly lose ground to nailed shear connectors as allowance must be made for a reduction in loading capacity in accordance with [138] when perforated sheets are used or when studs are welded through the sheets. With nailed shear connectors, however, the method results in no loss of loading capacity. Table 15 shows an example for comparison.

Cost-efficient use of X-HVB shear connectors or, respectively, all other nailed solutions for composite structures, demands that the installation of these items is done on the jobsite, driving the fasteners through the sheet metal. Compared with welded studs, the fastener driving operation can be carried independent from the weather conditions.

Another area where nailed shear connectors can be used cost-efficiently is in the renovation or strengthening of floor decks in old buildings, especially those subject to regulations on the protection of historic buildings. Only limited height is available for the necessary strengthening, which points towards the need to form a bond between the old steel beams and a new layer of concrete. In cases such as this, the flexibility and mobility during the installation that the nailed shear connectors allow are an additional advantage. The question of whether or not the old steel (e. g. structural iron) can be welded must also be taken into account. Nailed shear connection is applied for many years in France and Italy for refurbishment of old buildings. For these composite beams very thin concrete solid slabs made from light-weight concrete with a minimum thickness of 50 mm are partially used. Shallow shear connectors with a height of 40 mm are available for these applications (e. g. X-HVB 40 and X-HVB 50 according to [95]). The



New construction: Composite beams with composite slabs and with installation of shear connection on the job-site.

Renovation of existing buildings: E.g. refurbishment of Gründerzeit houses with shallow height of slabs and utilization of existing non weldable steel profiles (sections greater IPE 120, thin solid concreted slabs made from normal- or light-weight concrete with thickness beyond 5 cm)

Figure 102. Cost-efficient use of nailed shear connection

Figure 103. Application of shear connection for building renovation

European Assessment Document EAD 200033-00-0602 [151] also considers specific aspects of shear connection in old buildings, e. g. the effect of lower strength of old construction steel on the shear resistance of the connectors is taken into account, in detail see Section 10.2.4.
Powder-actuated fasteners and fastening screws can generally also be used for composite beams made from thin cold-formed profiles with a wall thickness of 2 to 4 mm. The relative gain in loading capacity and rigidity is particularly high when the composite principle is used with thin, cold-formed profiles [135]. Mature solutions in the form of approved products, in which powder-actuated fasteners or metal construction screws are used to fasten sheet metal parts are, however, not available in Germany. In terms of their strength and ductility, powder-actuated fasteners are more suitable for this application than fastening screws [44]. As an alternative to shaped sheet metal parts that are fastened in place, screws of a suitable length can also be used as connectors in their own right, like the product Shearflex® used in the North American market [136]. In that case the steel beam is a truss made from thin-wall profiles and double-angles as top chords (similar with Figure 139).

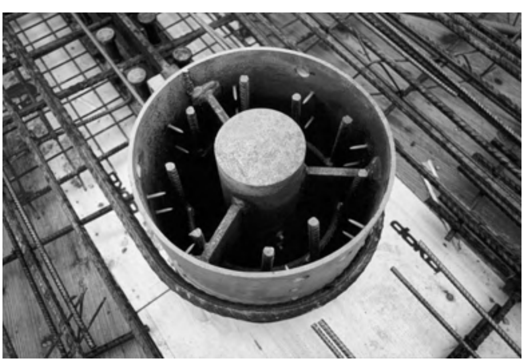


Figure 104. Example: Cross-section of a column in the Millennium Tower, Vienna

5.11.2 Temporary tacking of profiled sheeting of composite slabs

Temporary tacking of profiled sheeting of composite slabs is required in order to secure the position of the sheet during construction. In case the profiled sheeting needs to also resist against wind uplift loading during assembly, powder-actuated fasteners or fastening screws covered by a European Technical Assessment are to be used for these temporary fixings. The transient design situation is to be checked where applicable with reduced wind actions according to DIN EN 1991-1-6 [137].

5.11.3 Shear connection in composite tubular columns

The use of powder-actuated nails is an alternate method of creating shear connection at areas where loads are introduced into composite tubular columns. The powder-actuated fasteners are driven through the tube walls from the outside and then protrude approx. 20 mm on the backside of the tube wall (Figure 99). The connection between the surrounding tubular section and the concrete inside is then provided by the direct pressure of the concrete against the shanks of the nails. The main advantage of this solution is that it is quick and easy to apply – especially for columns which are continuous over several stories. The work involved with conventional methods, e. g. welded studs or gusset plates stuck through the pipe, is no longer necessary.
This nailed shear connection was developed in a research project conducted at the Technical University of Innsbruck [140, 141]. The system was used in practice for the first time in 1999 in the construction of the Millennium Tower in Vienna [142–144].
Its use has been limited to a few projects with individual approval. Neither national technical approvals nor ETAs have been issued to date. With regard to details of load displacement behavior or, respectively, design concepts, please refer to [145, 146]. Further push tests addressing the static and cyclic load-displacement behavior in combinations with hollow sections made from high-strength S460 to S700 steel are documented in [147].

6 European Technical Assessments and national technical approvals

6.1 Assessment criteria

The legal basis for European Technical Assessments (ETAs) is laid down in the EU-Construction Product Regulation CPR 305/2011/EU [12] from the year 2011. The CPR became effective on July 1st, 2013 in all EU member states and replaced the EG Construction Product Directive CPD 89/106/EWG [148]. European Technical Assessment offer manufacturers the opportunity to bring construction products into the market with CE marking for which no harmonized standard serving as assessment basis exists. In that aspect European Technical Assessments don´t differ from the previous European Technical Approvals. The latter were still issued till July 1, 2013 und expired after a 5 year transition period latest on June 30, 2018. Compared with European Technical Approvals – but also the German national technical approvals – the link of the product to its application is less pronounced in case of the European Technical Assessments. A national technical approval delivers the comprehensive check of the product for a defined intended use. Compared with this, the European Technical Assessment is limited to those essential characteristics, for which the manufacturer wants to the declare performances, which are relevant related with the fulfillment of the basic requirements for construction works according to the CPR [12].

Annex 1 of the CPR lists the following 7 basic requirements for construction works.

Basic requirement 1: Mechanical resistance and stability
Basic requirement 2: Safety in case of fire
Basic requirement 3: Hygiene, health and the environment
Basic requirement 4: Safety and accessibility in use
Basic requirement 5: Protection against noise
Basic requirement 6: Energy economy and heat retention
Basic requirement 7: Sustainable use of natural resources

Based on applications by manufacturers it was decided by the European Commission to further regulate powder-actuated fasteners and fastening screws by means of European Technical Assessments. The criteria for the assessment of the performances of the fasteners are provided in a respective European Assessment Document (EAD). Such EADs formally replace the previously necessary CUAPs or ETAGs required for the release of a European Technical Approval.

The Construction Product Directive dated December 12, 1988 [148] defined Essential Requirements ER to works instead of the basic requirements applied today. Relevant for fasteners were: Essential Requirement No 1: Mechanical resistance and stability and the Essential Requirement No 4: Safety in use. The interpretation of these requirements was uniform. Essential Requirement No 1 concerned structural failure, e. g. in case of use of a powder-actuated fastener within a steel deck diaphragm. Essential Requirement No 4 addressed the failure of members not being part of the structure of the building and the respective danger for persons, e. g. in case of falling parts.

At beginning of the transition from the CPD to the CPR [12] a consistent interpretation of the basic requirements was missing. Therefore, the allocation of

Table 16. Relevant European assessment documents

Type of fastener	Material fastened	Base material	Approval criteria per Construction Product Directive [148]	Assessment Documents EADs per Construction Product Regulation [12]	Conformity procedure per Construction Product Regulation [12]
powder-actuated fastener	steel sheet	construction steel	CUAP 06.02/05, February 2004 [155]	EAD 330153-00-0602 [150]	2+
powder-actuated fastener	shear connector	construction steel	–	EAD 200033-00-0602 [151]	2+
powder-actuated fastener	i. a. steel sheet	concrete	CUAP 06.01/28, December 2010 [156]	EAD 330083-01-0601 [152]	2+
fastening screws	steel sheet aluminium	construction steel sheet steel aluminum timber	CUAP 06.02/07, October 2007 [157]	EAD 330046-01-0602 [153]	2+
sandwich panel screws	sandwich panels	construction steel sheet steel aluminum timber	CUAP 06.02/12, June 2010 [158]	EAD 330047-01-0602 [154]	2+
fastening screws	waterproofing membrane with insulation	sheet steel concrete timber	ETAG 006 [159]	ETAG 006 [159]	2+

the product performances – within the EADs listed in Table 16 – to the respective basic requirements was not consistently implemented. In the meanwhile, however, the allocation of the characteristic resistances as well as aspects on durability to basic requirement 1, "Mechanical resistance and stability" has established. This interpretation applies now for both structural as well as non-structural connections. Therefore, newer EADs don´t show any link anymore with the basic requirement No 4: Safety and accessibility in use. Regarding further details on the procedure related with European Technical Assessments, it is referred e. g. to the website www.eota.be of EOTA (*European Organization of Technical Assessment*) or the website www.dibt.de of DIBt (*Deutsches Institut für Bautechnik*).

Table 16 provides a survey on European Assessment Documents for powder-actuated fasteners and fastening screws as well as their context to previous approval criteria according to the Construction Product Directive. All applications are limited to predominantly static loading.

Both EADs [150, 153] for powder-actuated fasteners and fastening screws for connections of profile metal sheet are basically identical with the old CUAPs [155, 157] per Construction Product Directive. On the other hand these CUAPs are based on the local German approval criteria which have been proven for many decades for connecting thin sheet metal. These were developed in the early 1970s. The first German national technical approval for a powder-actuated fastener (ENP3-21L15) as well as fastening screws was granted in 1974 [162]. Scientific support of this development was provided by *Seeger* und *Klee* from the Institute of Materials Science of the Technical University Darmstadt. They lead the basic experimental investigations on the behavior of powder-actuated fasteners driven into steel (e. g. [43]) and setup the basics of the test and verification concept of the fasteners [163]. These provisions were adopted in the draft standard E-DIN 18807-Part 4 [164]. E-DIN 18807-4 [164] and DIN 18807-7 [161] specified type and scope of the approval tests required for the German national technical approval (collective approval Z-14.1-4 held by IFBS – *Industrieverband für Bausysteme im Stahlleichtbau* – since 1974, current issue [169]). The national rules further defined the data evaluation as well as the applicable safety factors.

This national German concept was incorporated – without losing any of its content – into the first CUAP for powder-actuated fasteners [155] which in turn was transferred virtually unchanged into the current EAD [150]. Concerning the provisions for fastening screws, the new EADs [153, 154] – compared with the predecessor CUAPs [157, 158] – explicitly limit the use of connections exposed to weather or moisture to screws made from stainless steel.

The motivation of this historical review is to show that EADs for the connection of thin gauge profiled steel sheeting have kept their close context with the requirements in the specific application. Provided all performances for the product are declared by the manufacturer, the European Technical Assessment implicitly verifies the product use in the application.

Similar conclusions can be drawn for the EAD for fastening of sandwich panels [154] and for the EAD of nailed shear connectors [151]. Use and verification of powder-actuated fasteners are always strongly linked with the application and the details specified in the intended use. Therefore, application specific assessment criteria are technically correct and necessary. The EADs listed in Table 16 meet that criterion as in the past, although the Construction Product Regulations and the European Technical Assessment would allow just the declaration of selective single product performances.

EAD [152] covers the use of powder-actuated fasteners on concrete. The respective provisions are conceptually based on the approval guideline ETAG 001, part 6 [160], which defines the rules for multiple anchor fastenings in concrete. Based on that EAD, fastening of profiled steel sheeting to concrete with powder-actuated fasteners could be assessed resulting to an ETA. The tests to determine the loading capacity of the metal sheet are then to be carried out in accordance with [150] and those to determine the loading capacity of the anchorage in the concrete are to be carried out in accordance with [152].

Approval of construction products only at a national level for Germany will still remain possible, provided

Table 17. European Technical Assessments and national technical approvals for powder-actuated fasteners, status 07/2018

Type of fastener	Materials fastened	Base material	Approval guideline	Conformity procedure
powder-actuated fasteners	base profiles of glass facades made from steel or aluminum, wood and wood materials	construction steel	Following EAD 330153-00-0602 [150]	ÜZ
fastening screws	brackets and bearing profiles of ventilate facades	metal and wood	Following EAD 330046-01-0602 [153]	ÜZ
fastening screws	wood	sheet steel	Following EAD 330046-01-0602 [153] and DIN EN 1995-1-1 [96]	ÜZ

that no European Assessment Document exists for the assessment of the respective product performances. Examples of this are the use of powder-actuated fasteners and screws for fastening wood materials to steel or the fastening of base profiles of glass facades by means of stainless powder-actuated fasteners.

Table 17 provides an overview of applications and fasteners for which the products are approved nationally and for which no EAD exists. All these applications are again limited to predominantly static loading in building construction.

As a result of national standards, in terms of their content, moving closer to the Eurocodes over the past years, there is essentially no longer any difference between national and European approval procedures. As an example, the assessment of the anchorage and the application limit of powder-actuated fasteners used for fastening of base profiles of glass facades is done in keeping with European criteria (CUAP [155] and EAD [150], respectively). Application specific aspects, which are not covered by the European provisions, e. g. the local bearing resistance of the base profile itself or geometric provisions, are then addressed within the national technical approval procedure. A similar procedure is applied in case of fastening of wood or timber materials to steel. The assessment of the fixed timber material was defined within the national approval procedure and it is not formally covered within an EAD. However, also that assessment is derived from European provisions given in DIN EN 1995-1-1 [96] for nailed timber connections.

The national technical approvals require unchanged the conformity assessment system ÜZ. For all EADs of powder-actuated fasteners and fastening screws the system 2+ is specified for the assessment and verification of constancy of performance according to CPR [12]. The system 2+ was already determined for all powder-actuated fasteners, which were approved according to the old Construction Product Directive [148], and it was transferred unchanged into all new EADs. A change concerns the conformity system of fastening screws. The old provision offered system 3 for European Technical Approvals, however, as part of the transfer of the assessment rules into EAD [153] the conformity system was adjusted to the usually for fasteners applied system 2+.

The verifications to be provided within the scope of the manufacturer's own inspection and testing are, as before, based on regulations for the existing national technical approval Z-14.1-4 [169]. These were specified in the DIBt announcement issued in 1999 [71]. That procedure was correspondingly adopted as part of the control plans within the respective EAD. The EADs specify the so called corner stones of the factory production control to be observed by the manufacturers.

An EAD is drawn up by the European Technical Assessment Body (TAB) that receives the first application for European assessment. All EADs for powder-actuated fasteners and fastening screws were worked out by DIBt. Formal approval of an EAD and its content is given by the members of the EOTA (*European Organization for Technical Assessment*) – these are the national technical assessment bodies of each member state (DIBt for Germany) – as well as by the Services of the European Commission. After that coordination process – observing all the required review periods – the process of drafting a European Technical Assessment based on the status of an adopted EAD can be started. After the first ETA is granted the EAD will be finalized and if necessary adjusted considering the gained experience. The last administrative step is the formal adoption of the final EAD by EOTA and further submittal to the EC to start the publication process in the Official Journal of the European Union (OJEU) (in detail see www.eota.be).

An EAD comprises the following:

- Product description, definition of the intended use of the product and its application range
- Definition of the essential characteristics and their type of expression
- Allocation of the essential characteristics to the basic requirements for construction works
- Type and scope of tests and performance assessment
- Design procedure
- System for assessment and verification of constancy of performance
- Cornerstones of factory production control to be observed by the manufacturer
- Tasks of notified bodies

Also within EADs the product to be assessed is described in a generic way that the assessment criteria are also applicable for products of other manufacturers. Although some of the details are product-related (e. g. stipulation of the minimum thickness of the base material in the tests or the nail stand-off tolerance bandwidth), the description of the tests and the basic assessment concept covered by an EAD are product-independent and thus apply to all powder-actuated fasteners and fastening screws used for the same intended use.

6.2 Overview of relevant ETAs and approvals, status 07/2018

The following tables provide an overview of ETAs and national technical approvals for fastenings made with powder-actuated fasteners on steel or, respectively, for fastenings made with fastening screws on steel, aluminum or timber.

Until 2010, most fastening screws were covered by the national technical collective approval Z-14.1-4 [169] held by IFBS. This approval included fasteners used to join several layers of thin sheet metal together (self-drilling screws, blind rivets, screws) as well as the fasteners used to fasten profile metal sheet to steel and timber substructures (self-drilling screws, self-tapping screws and powder-actuated fasteners).

In 2010, DIBt issued European Technical Approvals for a number of fastening screw manufacturers. These

Table 18. European Technical Assessments and national technical approvals for powder-actuated fasteners, status 07/2018

European Technical Assessment / national technical approval	Manufacturer	Powder-actuated fastener	Minimum base material thickness t_{II} [mm]	Application
ETA-04/0101	Hilti	X-ENP-19 L15	6	fastening thin, cold-formed profile metal sheets
ETA-08/0040	Spit	HSBR 14	6	fastening thin, cold-formed profile metal sheets
ETA-10/0462	Würth	W-HMF 14	6	fastening thin, cold-formed profile metal sheets
ETA-13/0172	Hilti	X-ENP2K-20 L15	3	fastening thin, cold-formed profile metal sheets
ETA-15/0876	Hilti	X-HVB shear connector with fasteners X-ENP-21 HVB	6	nailed shear connectors
ETA-16/0082	Hilti	X-U16 S12	6	fastening thin, cold-formed profile metal sheets (single layer)
ETA-18/0355	Tecnaria	Shear connector DIAPASON with fasteners Spit HSBR14	8	nailed shear connectors
ETA-18/0447	Tecnaria	Shear connector CTF with fasteners Spit HSBR14	6	nailed shear connectors
DIBt Z-14.4-453	ITW	Ballistic nails	1.5	wood materials on steel
DIBt Z-14.4-517	Hilti	X-U	4	sheet steel, wood and wood materials on steel
DIBt Z-14.4-766	Hilti	X-R14	4	base profiles for glass facades

Table 19. European Technical Assessments for fastening screws, status 07/2018

European Technical Assessment	Manufacturer	Product [1)]	Diameter [mm]	Material	Base material
ETA-10/0020	Ipex Beheer B.V.	SD	4.8 – 6.5	carbon steel, stainless steel	steel, timber
ETA-10/0021	Red Horse	SD	4.8 – 5.5	carbon steel	steel, timber
ETA-10/0047	Aztec	SD	4.8	carbon steel	steel
ETA-10/0181	Etanco	SD, ST	5.5 – 6.5	carbon steel, stainless steel	steel, timber
ETA-10/0182	Hilti	SD, ST	4.2 – 6.3	carbon steel, stainless steel	steel, timber, aluminum
ETA-10/0183	RAWLPLUG S.A.	SD	4.8 – 5.5	stainless steel	steel, timber
ETA-10/0184	Adolf Würth Gmbh	SD, ST	4.2 – 7.2	carbon steel, stainless steel	steel, timber, aluminium
ETA-10/0198	SFS intec AG	SD, ST	4.8 – 6.5	carbon steel, stainless steel	steel, timber, aluminium
ETA-10/0199	MAGE AG	SD, ST	4.8 – 6.5	carbon steel, stainless steel	steel, timber
ETA-10/0200	EJOT Baubefestigungen GmbH	SD, ST	4.2 – 8.0	carbon steel, stainless steel	steel, timber, aluminium
ETA-11/0174	Guntram End GmbH	SD, ST	4.8 – 6.5	stainless steel	steel, timber
ETA-17/0321	Fastener Point B.V.	SD, ST	4.8 – 6.3	carbon steel, stainless steel	steel, timber

[1)] SD … self-drilling screw ST … self-tapping screw

ETAs were harmonized along the lines of the German collective approval in terms of the text they contain and how the approval annexes are presented. As described in Section 6.1 these European Technical Approvals were transferred into European Technical Assessments. The new ETAs now also include provisions for connections with aluminium sheets, which were covered in the past by the IFBS technical collective approval Z-14.1-537 [170]. A survey of European Technical Assessments of fastening screws most relevant in the German market is provided in Table 19.

The approvals for sandwich panel screws developed similar as for the fastening screws. European Technical Assessments granted to individual manufacturers de-

Table 20. European Technical Assessments for sandwich panel screws, status 07/2018

European Technical Assessment	Manufacturer	Product [1]	Diameter [mm]	Material	Base material
ETA-13/0177	EJOT Baubefestigungen GmbH	SD, ST	5.5 – 6.5	carbon steel, stainless steel	steel, timber
ETA-13/0179	Hilti	SD, ST	5.5 – 6.5	carbon steel, stainless steel	steel, timber
ETA-13/0180	Etanco	SD	5.5 – 6.5	stainless steel	steel, timber
ETA-13/0181	Guntram End GmbH	SD, ST	5.5 – 6.5	stainless steel	steel, timber
ETA-13/0182	MAGE AG	SD, ST	5.5 – 6.5	carbon steel, stainless steel	steel, timber
ETA-13/0183	SFS intec AG	SD, ST	5.5 – 6.5	carbon steel, stainless steel	steel, timber
ETA-13/0210	Adolf Würth GmbH	SD, ST	5.5 – 6.5	carbon steel, stainless steel	steel, timber
ETA-13/0211	Ipex Beheer B.V.	SD, ST	5.5 – 6.5	carbon steel, stainless steel	steel, timber
ETA-17/0293	Fastener Point B.V.	SD, ST	4.8 – 6.3	stainless steel	steel, timber

[1] SD ... self-drilling screw ST ... self-tapping screw

Table 21. Current national technical collective approvals for fastening and sandwich panel screws held by IFBS, status 07/2018

Approval	Holder of the approval	Connections	Fastener	Manufacturer
Z-14.1-4 [169]	IFBS	fastening sheet steel to each other or to steel or timber substructures	blind rivets	Avdel, Titgemeyer, Würth
			self-drilling screws	End, Hilti, Reca, Reisser, Würth, PMJ-tec, Evolution Fastener, Ro-seter/NES [1]
			self-tapping screws	End, Meusel, Reisser, Würth, Ferriere, PMJ-tec [1]
Z-14.1-537 [170]	IFBS	fastening sheet aluminum items to each other or to aluminum, steel or timber substructures	self-drilling screws	PMJ-tec, QP Fastening Works
			self-tapping screws	Reisser, PMJ-tec
Z-14.1-407 [171]	IFBS	fastening sandwich panels to steel or timber substructures	self-drilling screws	End, Reisser, Würth, Wattson, Meusel [1]
			self-tapping screws	End, Reisser, Würth, Wattson, Meusel [1]

[1] Not every manufacturer offers screws for steel and timber substructures

Table 22. Current national technical approvals for fastening screws held by individual manufacturers, status 07/2018

Approval	Holder of the approval	Product [1)]	Component I	Base material
DIBt Z-14.4-426	EJOT Baubefestigungen GmbH	SD	aluminum clips (stand-ing-seam pro-files), solid wood, metal components	steel, timber, timber materials, aluminum
DIBt Z-14.4-440	SFS intec GmbH	SD	wood battens	steel profile sheet
DIBt Z-14.4-532	EJOT Baubefestigungen GmbH	ST	solar panel mounting clamps	steel, timber
DIBt Z-14.4-555	Reisser Schraubentechnik GmbH	ST	solar panel mounting clamps	steel, timber
DIBt Z-14.4-598	Adolf Würth Gmbh	ST	screw for solar facade panels	steel, timber
DIBt Z-14.4-616	SFS intec GmbH	SD	solar panel fastening system	steel profile sheet
DIBt Z-14.4-617	SFS intec GmbH	SD	solar panel fastening sys-tem	steel profile sheet
DIBt Z-14.4-696	Adolf Würth Gmbh	ST	solar panel mounting clamps	steel, timber

[1)] SD ... self-drilling screw ST ... self-tapping screw

veloped from the national technical collective approval Z-14.4-407 [171]. A survey of European Technical Assessments for sandwich panel screws most relevant in the German market is provided in Table 20.

Table 21 further summarizes current national technical collective approvals held by IFBS, including the intended use and the list of manufacturers covered within IFBS industrial association. Besides these a variety of national technical approvals for specific fastenings screws are available within the German market. Table 22 offers a respective survey.

Since 2007 European Technical Approvals were granted for flat roof fasteners and were subsequently replaced by respective European Technical Assessments, e. g. EJOT (ETA-07/0013), SFS intec (ETA-08/0262, ETA-08/0321), MAGE (ETA-08/0077), Etanco (ETA-08/0239), Kölner (ETA-09/0346), Trufast (ETA-09/0375) or Hilti (ETA-17/0346).

7 European Technical Assessment (ETA) for fasteners used to join thin, cold-formed profile sheets

7.1 Test concept and mathematical approach

The tests have been defined so that the ultimate resistance is determined for all modes of failure. Figure 71 shows the types of fastening and loading, taking joints made with powder-actuated fasteners as an example, and Figure 105 shows the possible types of failure of the powder-actuated fasteners or, respectively, fastening screws relative to the direction of loading.

In accordance with DIN EN 1993-1-3 [35], loading capacities are to be determined by tests or by calculation using the formulas given in Table 8.2 or, respectively, 8.3 from DIN EN 1993-1-3 [35]. These formulas often clearly underestimate the real loading capacities and they cover for powder-actuated fasteners only the types of failure applicable to the sheet metal fastened, see formulas (4), (5) and (6). Also in accordance with DIN EN 1993-1-3 [35], the nail resistance itself and the pullout loads can only be determined in tests. A formula for the pullout resistance depending on thread pitch is given for connections made with fastening screws. The loading capacity of the fastening screw itself, in terms of shear as well as tensile loading, must also be determined by conducting tests.

Formulas in accordance with Table 8.2. or, respectively, 8.3 from [35] (nomenclature in accordance with [35]):

Bearing resistance in shear:

$$F_{b,Rd} = \alpha \cdot f_u \cdot d \cdot t / \gamma_{M2} \qquad (4)$$

where:
$\alpha = 3.2$ for powder-actuated fasteners
$\alpha \leq 2.1$ for fastening screws

With self-tapping screws, while taking a minimum base material thickness into account, the maximum value for the coefficient α is 2.1. With powder-actuated fasteners, material in the part to be fastened is displaced when the fastener is driven and thus becomes slightly thicker in the area immediately surrounding the shank of the nail. This is the reason for the applicable coefficient being higher than that for screws, which drill through the part to be fastened, removing material as they do so. [182] shows, in a direct comparison, the significant influence that the penetration of powder-actuated fasteners has on the shear loading capacity of the sheet metal. The effective α-values for powder-actuated fasteners, determined from tests, are clearly above the calculated value of 3.2.

In connections made with fastening screws, the coefficient α depends on the diameter of the screw and the ratio of the thickness of the metals to be connected. Figure 106 shows the course followed by the coefficient

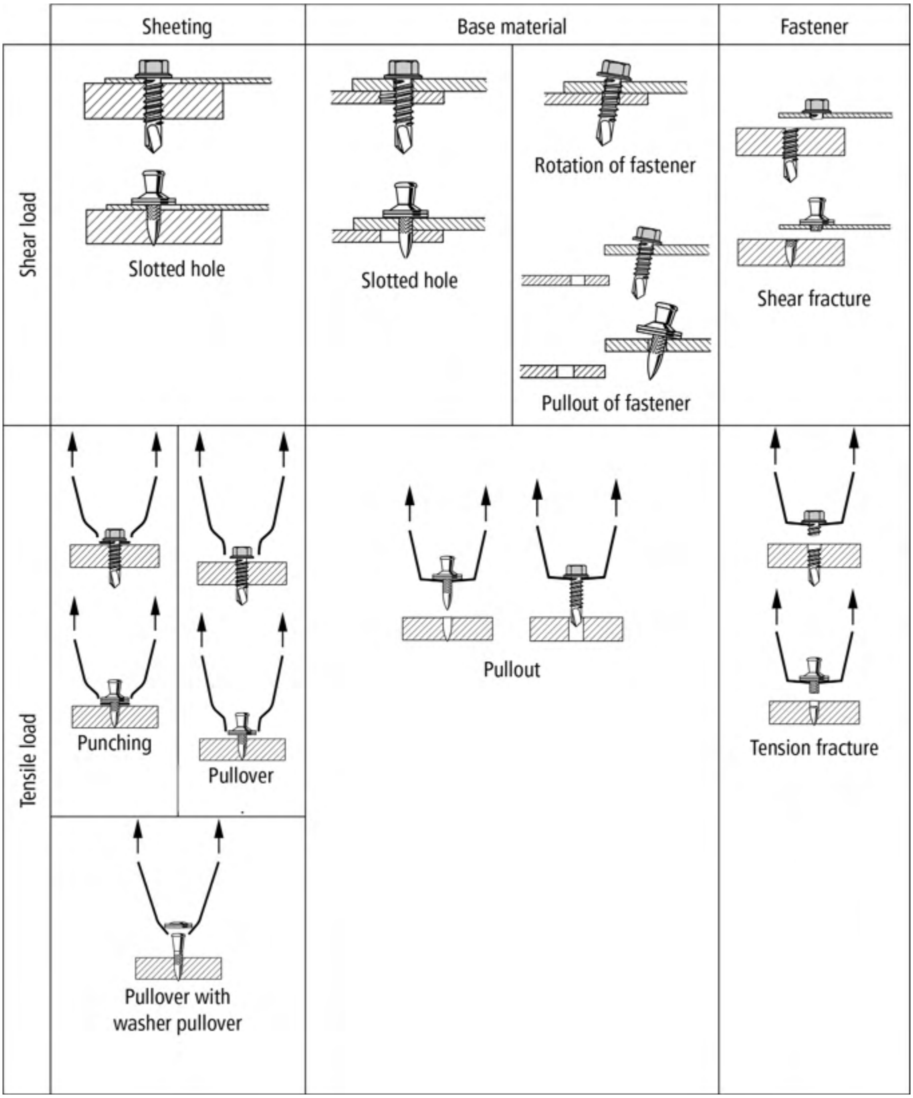


Figure 105. Failure modes for fastenings made with powder-actuated fasteners or fastening screws

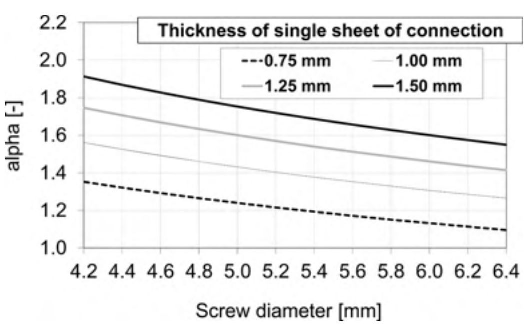


Figure 106. Coefficient α for screw-fastened joints in accordance with Table 8.2 from DIN EN 1993-1-3 [35] with $t_I = t_{II}$

α for overlap joints made with sheet metal of equal thickness ($t_I = t_{II}$).

Pullover resistance for static tension loads:

$$F_{p,Rd} = d_w \cdot t \cdot f_u/\gamma_{M2} \tag{5}$$

Pullover resistance for repeated wind loads:

$$F_{p,Rd} = 0.5 \cdot d_w \cdot t \cdot f_u/\gamma_{M2} \tag{6}$$

Pullout resistance of self-tapping screws:

$$F_{p,Rd} = 0.45 \cdot d \cdot t_{sup} \cdot f_{u,sup}/\gamma_{M2} \quad \text{for } t_{sup}/s < 1 \tag{7}$$

$$F_{p,Rd} = 0.65 \cdot d \cdot t_{sup} \cdot f_{u,sup}/\gamma_{M2} \quad \text{for } t_{sup}/s \geq 1 \tag{8}$$

where

d_w is the diameter of the washer or head of the screw

t, f_u is the thickness and strength of the thinner sheet in the joint

d is the nominal diameter of the screw

t_{sup}, $f_{u,sup}$ is the thickness and strength of the part of the structure into which the self-tapping screw is driven

s is the thread pitch

Remark related with ductility requirement according to DIN EN 1993-1-3 [35]:

The use of the design formula per [35] requires that the design shear resistance of the fasteners exceeds 1.5 times the design bearing resistance of the connected sheets. The intention of that rule is to ensure a minimum ductility of the shear connection with powder-actuated fasteners. The demand on minimum ductility was covered in the former national technical approvals and is also addressed within the European Technical Assessment as described in the following section. However, a shear resistance for the fastener itself is not explicitly published in the ETAs. Nevertheless, for the powder-actuated fasteners available on the market and their declared performances in the European Technical Assessments (Table 18), the required ductility criterion per DIN EN 1993-1-3 [35] is implicitly covered. In order to close that formal inconsistency between the design standard and the ETAs a respective adjustment of EAD 330153-00-0602 [150] is recommended to allow explicit declaration of the fastener characteristic resistance.

7.2 Overview of tests for assessment of fastener performance

Table 23 provides an overview of the approval tests to be carried out for powder-actuated fasteners and their purpose. Generally speaking, all relevant parameter combinations are to be covered by their own series of tests. The characteristic shear force V_{Rk} and tensile force N_{Rk} then cover the most unfavorable conditions of the entire area of application. It is not necessary to derive an analytical formula from the results of the tests. Static tests should generally be carried out. Verification of resistance to dynamic stressing as a result of cyclic wind loads must be provided only in the form of resistance to pullover failure.

Table 24 provides an overview of the assessment tests to be carried out for fastening screws, and the purpose of the tests. The sheet metal's pullover resistance and the screw's pullout resistance are to be verified in the same way as for powder-actuated fasteners. In the case of connections made with powder-actuated fasteners,

Table 23. Assessment tests for powder-actuated fasteners in accordance with EAD [150]

Tests according to EAD [150]	Sheeting (component I)		Base material (component II)		Purpose
	t_I	f_u	t_{II}	f_u	
static pullover tests, single layer	each relevant thickness	lower tolerance	optional	optional	static pullover resistance
dynamic pullover tests, single layer [1)]	each relevant thickness	lower tolerance	optional	optional	dynamic pullover resistance
pullout tests [2)]	4 x t_I or max $\sum t_I$	optional	each relevant thickness	lower tolerance	static pullout resistance
shear tests, single layer	each relevant thickness	lower tolerance	optional	optional	shear resistance sheeting – minimum ductility
shear tests, four layers	4 x t_I or max $\sum t_I$	upper tolerance	minimal (≥ 6 mm)	lower tolerance	base material and fastener shear resistance, verification of fastening types, minimum ductility
			maximal (≤ 20 mm)	upper application limit	
combined shear and tension test	2 x t_I or max t_I	upper tolerance	minimal (≥ 6 mm)	lower tolerance	verification of fastening types without explicit check of thermal constraints
			maximal (≤ 20 mm)	upper application limit	
pullout tests, upper application limit [2)]	4 x t_I or max $\sum t_I$	optional	each relevant thickness	upper application limit	verification of driving operation and pullout resistance at the upper application limit
	single layer	optional	each relevant thickness	upper application limit	

[1)] performance of tests optional

[2)] verification necessary for every fastening tool to be assessed

Table 24. Assessment tests for metal construction screws as per EAD [153]

Test according to EAD [153]	Component I		Component II		Purpose
	t_I	f_u	t_{II}	f_u	
static pullover tests, single layer	each relevant thickness	lower tolerance	optional	optional	static pullover resistance
dynamic pullover tests [1)], single layer	each relevant thickness	lower tolerance	optional	optional	dynamic pullover resistance
pullout tests	4 x t_I or max $\sum t_I$	optional	each relevant thickness or screw-in length	lower tolerance	static pullout resistance
shear tests, single layer	each relevant combination with component II	optional	each relevant combination with component I	optional	shear loading capacity of component I and II, screw angulation, minimum ductility
shear tests, four layers [1)]	4 x t_I or max $\sum t_I$	upper tolerance	each relevant thickness	optional	shear loading capacity of screw and component II, verification of types of fastening without mathematical verification of forces of constraint, screw angulation, minimum ductility

[1)] Test is optional

the thickness of the base material is generally several times that of the thickness of component I. In connections made with self-drilling screws the thicknesses of components I and II are in many cases approximately the same. Separation into component I and component II failure, in technical terms for the purpose of the tests, is then no longer considered to be a reasonable approach. Accordingly, the shear loading tests should be carried out as a single layer with the relevant thickness combinations in order to be able to appreciate and correctly record the reciprocal influences that components I and II have on the shear loading capacity of the connection.
The tests necessary in order to determine the loading capacity of the screw in timber are to be carried out in accordance with DIN EN 1995-1-1 [96] and the test standards cited in these documents.
In contrast to powder-actuated fasteners, verification of application limits for metal construction screws is not regulated in detail in the EAD. The applicable verifications are, however, to be carried out and documented within the scope of the initial type testing [153] by an accredited laboratory. In doing so it must be checked whether the screws can still be driven correctly at their application limits (maximum drilling thickness and maximum sheet metal strength).
The test results must be statistically evaluated in accordance with the DIN EN 1990 [172] and corrected to the minimum value (strength and thickness) for the specified steel grades. More details can be found in the EADs [150, 153].

The static tests must be carried out sufficiently slowly. Tensile loading tests are generally to be carried out on a force-controlled basis at a load application speed of ≤ 20 kN/min, and shear loading tests on a displacement-controlled basis at a deformation speed of ≤ 1 mm/min [173].

7.3 Assessment tests – examples of load bearing behavior

7.3.1 Static resistance of sheet metal under tensile load

Resistance to pullover failure is determined using strips of sheet metal – shape of test specimen see Figure 107

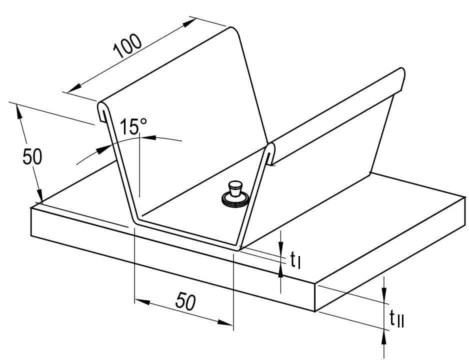


Figure 107. Shape of sheet specimen for tensile testing of sheeting

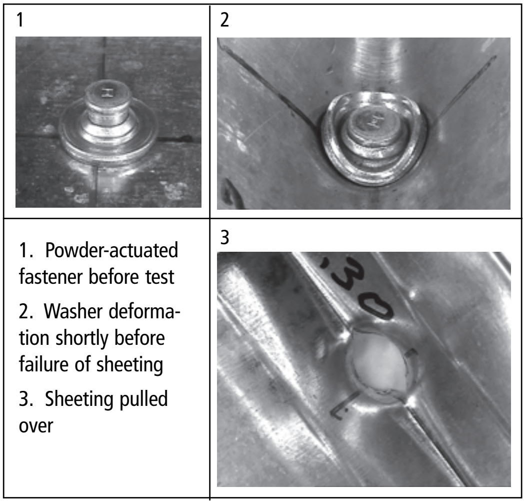


Figure 108. Typical pullover failure

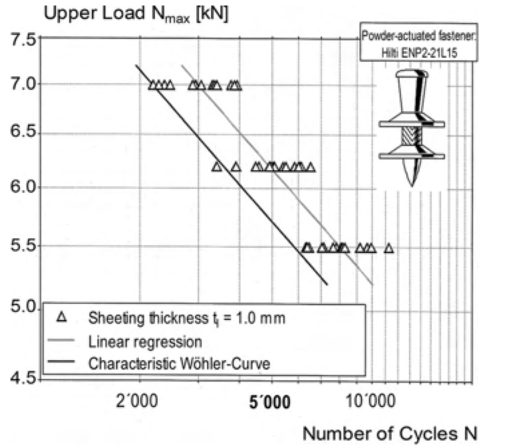


Figure 109. Example of the dynamic pullover resistance of a connection made with a powder-actuated fastener with a sheet metal thickness t_I of 1.0 mm

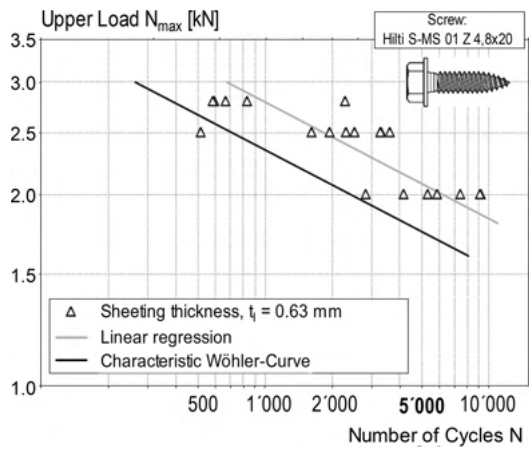


Figure 110. Example of the dynamic pullover resistance of a screw fastening with a sheet metal t_I of 0.63 mm

[173] – of each relevant thickness. Typical nominal test thicknesses are 0.75, 1.0 und 1.25 mm. In case of powder-actuated fasteners other sheet metal thicknesses between these sizes do not have to be tested as linear interpolation of the values for the intermediate thicknesses is permissible so long as the difference to the thickness tested is no greater than 0.25 mm.
Figure 108 shows the failure mode of the sheet metal from a pullover test in a connection made with a powder-actuated fastener. The characteristic pullover failure force N_{Rk} derived from the tests can exceed the values calculated using the formula (5) by more than 50% (see Figure 119 for sheet metal thickness t_I up to 1.25 mm) as the calculation method does not take the load-optimizing features of specific fastener types into account.

7.3.2 Dynamic resistance of sheet metal under tensile load

The characteristic pullover loading capacity of powder-actuated fasteners and fastening screws is defined for 5´000 load cycles. This number of cycles was defined in [163] as the decisive limiting number of load cycles for the coverage of wind loads. This rule has been confirmed in practice over decades to be on the conservative side. Harmonically pulsating tensile loading tests (with R = 0) with a test frequency of 5 Hz are to be carried out at at least three upper load levels. Figure 109 shows an example of a Wöhler curve for a sheet metal (component I) with a thickness of 1.0 mm for a connection made with powder-actuated fasteners. Figure 110 shows a corresponding example for the connection made with a metal construction screw.
It must be noted that carrying out dynamic pullover loading tests is not obligatory. If no dynamic loading tests are carried out with powder-actuated fasteners, the influence of wind loads must be taken into account by applying a reduction factor of 0.5 as with formula (6) in accordance with DIN EN 1993-1-3 [35]. In the EAD [150] this factor is generally defined as the coefficient a_{cycl} – formula (9) – and is also stated explicitly as such in the ETA and is to be taken into account in calculation of the design values (see [30, 31]).

$$\alpha_{cycl} = 1.5 \cdot (N_{k,dyn}/N_{k,stat}) \leq 1{,}0 \qquad (9)$$

$$\alpha_{cycl} = \alpha_{cycl} \text{ (sheet metal thickness } t_I)$$

$N_{k,dyn}$ and $N_{k,stat}$ stand for the static and dynamic pullover loading capacity of each of the sheet metal thick-

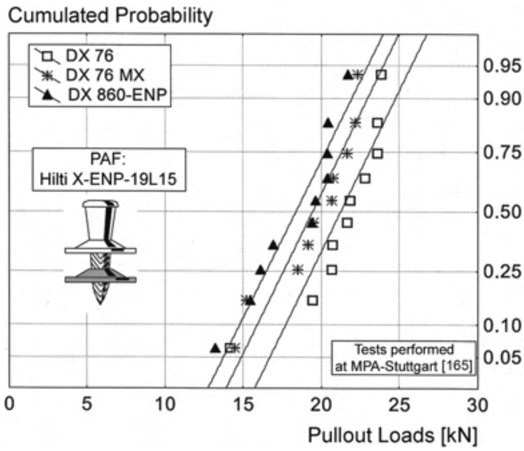


Figure 111. Pullout resistance on 20 mm thick base steel

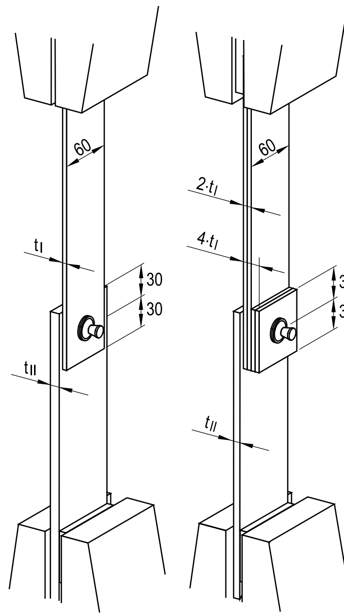


Figure 112. Shear test specimens for testing single layer and 4 layers of sheet metal

nesses developed in the tests. The constant 1.5 corresponds to the – conservatively rounded down – ratio of the global safety factors of 2 and 1.3 for static or dynamic pullover failure as implemented in the national approval Z-14.1-4 in the 1990-ties [163, 164].
With screws, the reduction due to the dynamic influence is handled somewhat differently to that of powder-actuated fasteners. The tests, however, are identical and also optional with screws. If no test results for screw fastened connections are available, the reduction factor α_{cycl} is 2/3. Although this value deviates from the figure given in DIN EN 1993-1-3, it was adopted into the EAD [157] with 2/3 based on the long-term German application experience. The reduction for screws is in general already made in the characteristic loading resistance N_{Rk} published in the ETA. It is thus not necessary to explicitly specify a α_{cycl} value in the assessments.

7.3.3 Static pullout resistance

The pullout resistance must be determined for the most unfavorable conditions. These generally occur when the strength of the base material lies within the lower tolerance range for S 235 construction steel and the maximum thickness is to be fastened (fastening type d, Figure 71). For powder-actuated fasteners this results in the minimum depth of penetration and for fastening screws this results in the minimum screw-in length. In order to take all factors influencing the system into account, these tests must be carried out for powder-actuated fasteners with all types of fastening tool to be included in the ETA (see Section 2.3). A different guidance of the fastener during the driving process – e. g. by means of a single fastener guide or by means of a fastener magazine – defines a separately to check fastening tool, also when using the same tool body in both cases. For connections made with screws, the data given in the ETA generally apply irrespective of the screw driving tools used. The tightening torque to be applied is given in the appendix of the approval and must be adhered to during the installation.
The powder-actuated fastener can be pulled either directly by the head using suitable clamping jaws or by way of pullover specimen with additional sheet metal inserts. Figure 111 shows the results of the pullout tests on 20 mm thick base material for three different fastening systems [165].

7.3.4 Static shear resistance with single layer and four layers of sheet metal

Figure 112 shows the sheet metal layers and the relevant specimen dimensions. The test arrangements for powder-actuated fasteners and fastening screws are identical. In the four layer test only the two lower layers are pulled – covering fastening type b – and the two upper layers ensure that the fastener is conservatively driven with to the greatest fastening height.
The shear resistance is defined in both EADs [150, 153] as the relative maximum within the displacement range of 0.5 to 3.0 mm (Figure 113). This rule thus implicitly covers the criteria for minimum ductility (displacement at V_u greater than 0.5 mm) as well as serviceability state. Limitation of the upper value for slip then covers cases where the load continues to rise even after displacement of 3 mm and the ultimate resistance is reached only when greater displacement occurs. With screw fastenings, a maximum screw inclination of 10° must be additionally verified.

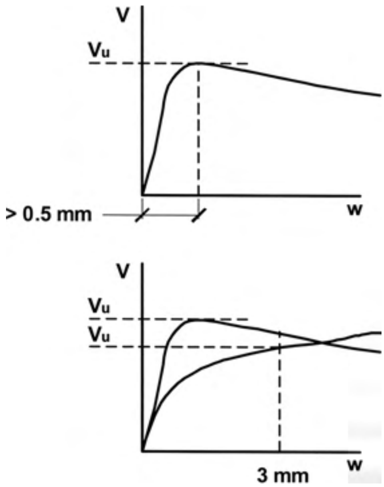


Figure 113. Displacement criteria for shear testing

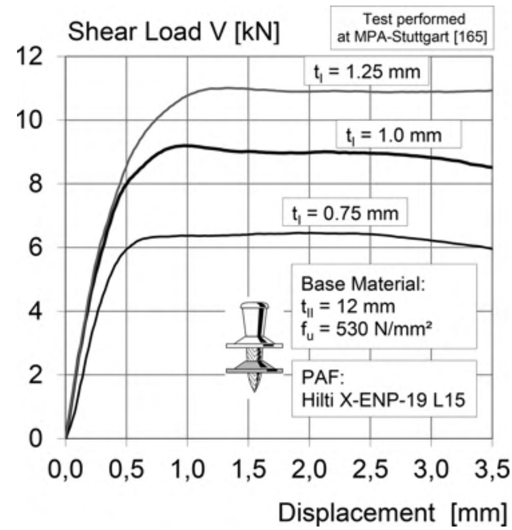


Figure 114. Single layer shear tests: Examples of load-displacement characteristics of powder-actuated fastener

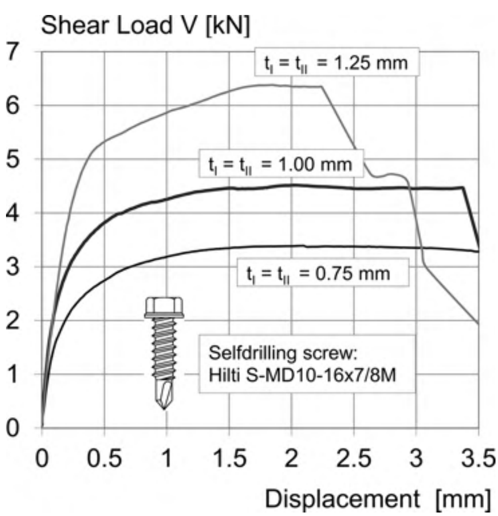


Figure 115. Example showing the shear loading capacity of an overlap joint made with a self-drilling screw.

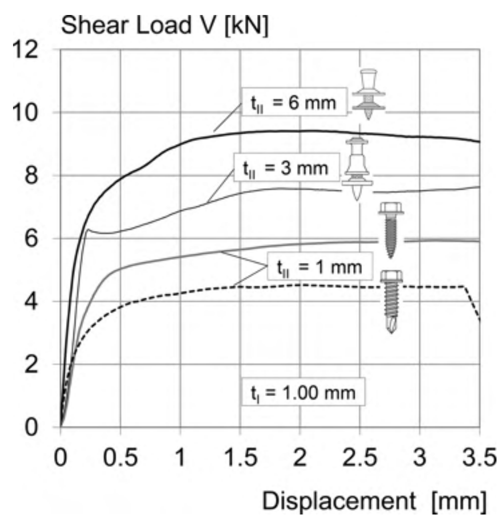
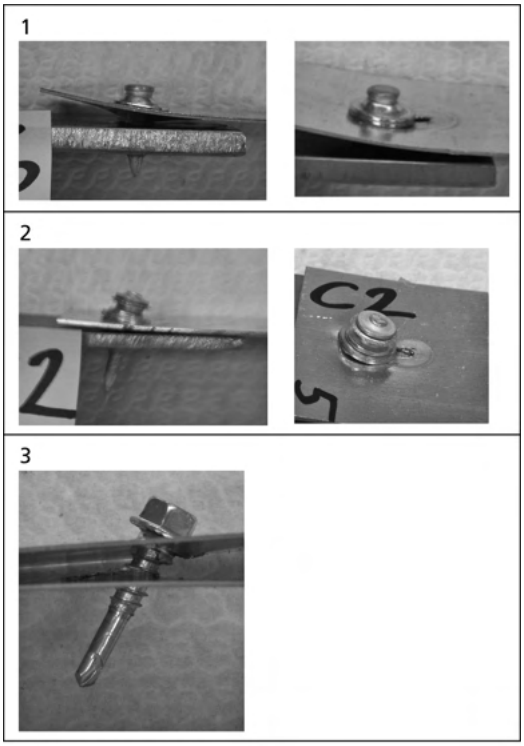


Figure 116. Comparison of the shear loading capacity of a single-layer sheet metal fastening.

With the powder-actuated fasteners, the component I shear loading capacities are provided by the single-layer tests. The base material must be adequately rigid and thick so that its share of the total displacement is negligibly low. Failure due to hole elongation thus results in very ductile load displacement characteristics (Figure 114).

Figure 115 shows examples of shear loading tests of overlap joints made with self-drilling screws. Due to the lower restraint in the thin base material, connections made with screws remain more flexible than those made with powder-actuated fasteners. So long as the shear loading capacity of the screw is not reached, the screwed connection is also very ductile.

Figure 116 shows, in addition, a comparison of the shear loading capacities of powder-actuated fasteners and self-drilling screws, in which the same sheet metal with a thickness of approx. 1 mm was fastened for all of the tests. The fastening technology and the associ-



1 Powder-actuated fastener t_{II} = 6 mm
2 Powder-actuated fastener t_{II} = 3 mm
3 Fastening screw $t_I = t_{II}$ = 1 mm

Figure 117. Shear deformation behavior dependent on the thickness of component II

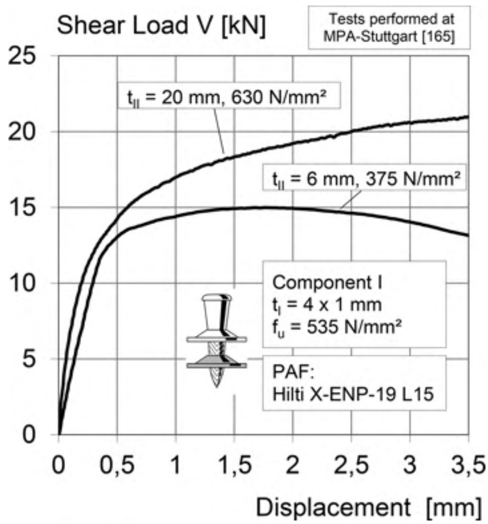


Figure 118. Examples of load-displacement characteristics

ated base material thicknesses were varied for the comparison, with the following findings:

- The highest sheet metal loading capacity was achieved by the powder-actuated fastener in base material with a thickness of 6 mm due to the positive effect of penetrating the component without drilling.
- Reduction of the base material thickness is accompanied by an increase in deformation of the base material, which results in a rotation of the fastener and thus reduced rigidity as well as a decrease in loading capacity.
- Figure 117 shows the corresponding deformation behavior and the increasing rotation that results from reduction of the base material thickness.
- Comparison of both curves for the screws also shows the positive effect of the self-drilling screw without drill point (Figure 57) compared to the conventional self-drilling screw which drills a hole as it is driven.

With powder-actuated fasteners, the tests with multiple layers have the purpose of verifying the loading capacity of the base material and the fastener itself as well as the minimum ductility of the connection. The parameters of the base material should be chosen so that the most flexible (minimum t_{II} with lower strength) as well as the hardest configuration (solid steel at the upper limits) is tested (Figure 118).

The objective of testing with low strength base metal is to investigate the base metal effect on the shear resistance of the connection. Neither the two layers of sheet metal fastened $2.t_I$ nor the powder-actuated fasteners are rigid enough to cause elongation of the hole right through (Figure 105) the 6 mm thick base material. Local plastic deformation is concentrated at the points of highest pressure in the upper half of the thickness of base material. As a result of this deformation, the powder-actuated fastener tilts and may be subsequently pulled out of the base material. This type of failure occurs when the fastened component does not previously fail due to hole elongation. Accordingly, these tests are to be carried out with multiple layers of sheet metal with a high tensile strength.

The shear loading tests on hard base material investigate the shear resistance at the upper application limit. The high strength of the base material could damage the powder-actuated fastener as it is driven or cause the fastener to be driven at an angle. The shear capacity of the fastener shank itself as well as compliance with minimum ductility requirements are therefore also covered by this test.

The motivation for carrying out the tests with the fastening screws is basically the same. The objective is to provide verification of the limits of fastening thick, high-strength steel sheet to thin base material. In addition to the screw loading capacity, the loading capacity of component II and the minimum ductility, the tests

also provide verification of the maximum screw rotation of 10°.
With the screws, the tests with four layers of sheet metal also serve to verify the robustness or resistance of the joint to thermal forces of constraint, i. e. expansion or contraction. If the screw connection remains intact up to a relative displacement of 3 mm, it is not necessary to take thermal forces of constraint into account in the design calculation of fastening types a, b, c and d (Figure 71).
As the keyed hold of the screw is retained even when the screw is slightly angulated relative to the base material, it is not necessary to check the residual pullout loading capacity of the screw.

7.3.5 Combined shear and tensile loading tests with double layers of sheet metal with powder-actuated fasteners

This test serves to check the influence of temperature-dependent forces of constraint. The test consists of two steps. In the first step, a shear loading test specimen (fastening type b or maximum single sheet thickness, respectively) is loaded until a relative displacement of 2 mm occurs. This limiting value originated from investigations of roof structures installed in the 1970s and was thus adopted in old national provisions [164] and later also in the EADs. The relative displacement simulates the temperature-dependent longitudinal expansion of the metal sheets in the erection state, in which a temperature difference of up to 50 °C can be expected [166]. In the second step subsequent to shear displacement, the remaining pullout resistance of the powder-actuated fastener is then determined.
If the requirements for verification under forces of constraint are fulfilled, it is then not necessary to provide an explicit check of temperature-dependent constraints – for those combinations of fastening types explicitly stated in the ETA – within structural analysis for this fastening situation.

7.3.6 Application limit

Verification of the upper application limit of the fastening system is provided by means of pullout tests. These tests are carried out for all relevant thicknesses of the base material with material of the strength corresponding to the application limit, with a single sheet metal layer as well as with the maximum fastenable thickness. The tests with the single layer indicate in addition whether the fastener can be driven to the required depth of penetration without breakage. As with the static pullout tests, explicit verification must be provided for all of the fastening tools to be covered by the ETA in order the address the system interdependency (see Section 2.3).
With fastening screws the application limits are checked by carrying out drill-drive tests and the corresponding loading capacity tests (see also Section 6.1) within the scope of the initial type testing.

7.4 Structure and content of an ETA

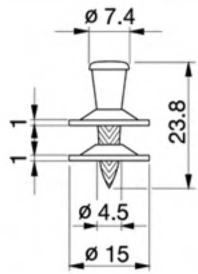
7.4.1 General points

The front page of the assessment defines – besides manufacturer and product – the underlying EAD in its applied revision state.
The specific text section of the ETA comprises:
- technical description of the product
- specification of the intended use
- performance survey of the product
- definition of the applied system for assessment and verification of constancy of performance

The complete declaration of the performance is made following the essential characteristics in relation to the basic requirements for the construction works. If no performance is declared, the assessment "no performance determined" needs to be stated in the performance table.
The annexes of ETAs for powder-actuated fasteners are in general structured in 3 sections.
- Section A: These annexes describe the product (powder-actuated fasteners, fastening screws, powder-actuated fastening tools and other installation tools).
- Section B: These annexes specify the intended use, boundary conditions for the application and design provisions. Furthermore, annex B includes the instructions for use.
- Section C: These annexes summarize the product performance in detail.

7.4.2 Powder-actuated fasteners

Figure 119 shows an example of an annex C1 of a European Technical Assessment for a powder-actuated fastener [30].
This contains the following:
- Drawing and designation of the powder-actuated fastener with its external dimensions
- Designations of the suitable powder-actuated fastening tools and the corresponding pistons
- Details of cartridge selection and tool energy setting
- The fastener driving energy specified covers the area of application under observance of the permissible fastener stand-off to the top surface of the sheeting. It is recommended that trial fastenings are made and, if necessary, the driving energy should be adjusted to suit the applicable conditions.
- Area of application and application limits (see Section 2.4.2)
- Characteristic shear and tension resistances
  These are given as a function of the individual sheet metal thickness and apply to the specified minimum sheet metal grade or higher. In accordance with previous verification practice, no explicit information is given about the influence of higher-grade sheets or the load-increasing influence of multiple sheet layers. With thin sheet metal, the resistance of the sheet metal is decisive. Loading capacity does not continue to rise beyond a certain thickness of component I.



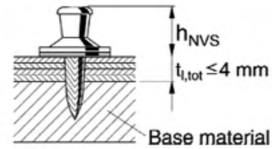
Powder-actuated fastener and fastening tool:

X-ENP-19 L15 with **DX 76**
X-ENP-19 L15 MX with **DX 76 MX**
X-ENP-19 L15 MXR with **DX 860-ENP**

Piston: **X-76-P-ENP**

Cartridges: **6.8/18 M10 (DX 76, DX 76 MX)**
6.8/18 M40 (DX 860-ENP)

Installation control:



h_{NVS} = 8.2 to 9.8 mm

A piston mark on the top washer is clearly visible.

Characteristic shear and tension resistance V_{Rk} and N_{Rk}			
sheeting thickness t_I [mm]	Shear V_{Rk} [kN]	Tension N_{Rk} [kN]	Types of connnection
0.63	4.0	4.1	a,b,c,d
0.75	4.7	6.3	a,b,c,d
0.88	5.4	7.2	a,b,c,d
1.00	6.0	8.0	a,b,c,d
1.13	7.0	8.4	a,c
1.25	8.0	8.8	a,c
1.50	8.6	8.8	a
1.75	8.6	8.8	a
2.00	8.6	8.8	a
2.50	8.6	8.8	a

Design shear and tension resistance V_{Rd} and N_{Rd}

$V_{Rd} = V_{Rk} / \gamma_M$

γ_M = 1.25 in the absence of national regulations

$N_{Rd} = \alpha_{cycl} \cdot N_{Rk} / \gamma_M$

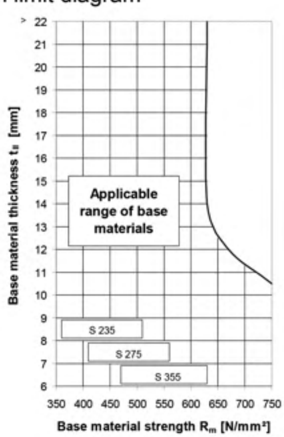
$\alpha_{cycl} = 1.0$

α_{cycl} considers the effect of repeated wind loads

α_{cycl} = 1.0 for all sheeting thickness t_I

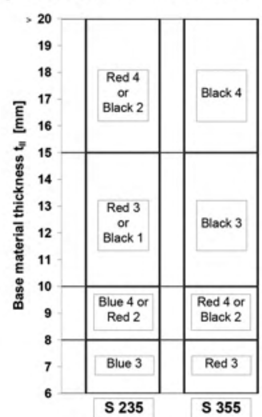
γ_M = 1.25 in the absence of national regulations

Application limit diagram



Base material:
Structural steel S235, S275 and S355 in qualities JR, JO, J2, K2 according to EN 10025-2; minimum thickness = 6 mm

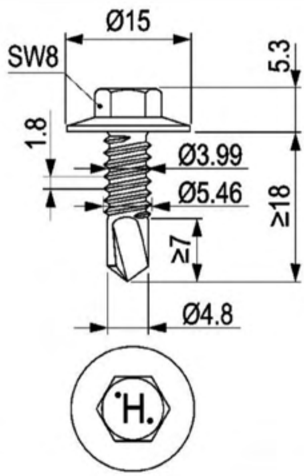
Cartridge selection and tool energy setting



Note for S 275: Start with recommendation for S 355.
In case of too much energy: Reduction of tool energy setting or change of cartridge colour till correct stand-offs h_{NVS} are achieved.

Hilti powder-actuated fastener X-ENP-19 L15 (MX, MXR)	**Annex C1**
Performances X-ENP-19 L15 with tools DX 76, DX 76 MX and DX 860-ENP: Characteristic and design resistance, application limit, cartridge selection and nail head standoff	

Figure 119. Example of an annex sheet from a European Technical Assessment for a powder-actuated fastener



Material:

Fastener:	carbon steel, case hardened and galvanized or coated
Washer:	none
Component I:	S280GD, S320GD, S350GD - EN 10346
Component II:	S235, S275, S355 - EN 10025-1 S280GD, S320GD, S350GD - EN 10346

Drilling capacity: $\Sigma t_i \leq 6{,}00$ mm

Timber substructures:

no performance determined

	t_I [mm]	t_{II} [mm] 1,00		1,50		2,00		2,50		3,00		4,00		5,00		6,00	
$V_{R,k}$ [kN]	0,50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0,55	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0,63	1,88	—	1,88	—	2,60	ac	2,60	ac	2,60	ac	2,60	—	2,60	—	—	—
	0,75	2,06	—	2,06	—	3,70	ac	3,70	ac	3,70	ac	3,70	—	3,70	—	—	—
	0,88	2,13	—	2,13	—	4,50	—	4,50	ac	5,00	ac	5,00	—	5,00	—	—	—
	1,00	2,20	—	2,20	—	4,50	—	4,50	ac	6,50	a	6,50	—	6,50	—	—	—
	1,13	2,20	—	2,76	—	4,90	—	4,90	—	7,00	—	7,90	—	—	—	—	—
	1,25	2,20	—	3,28	—	5,30	—	5,30	—	7,40	—	9,30	—	—	—	—	—
	1,50	2,20	—	4,36	—	6,20	—	6,20	—	8,30	—	9,50	—	—	—	—	—
	1,75	2,20	—	4,36	—	6,20	—	6,20	—	8,30	—	9,50	—	—	—	—	—
	2,00	2,20	—	4,36	—	7,80	—	7,80	—	9,40	—	9,50	—	—	—	—	—
$N_{R,k}$ [kN]	0,50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0,55	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0,63	1,07	—	2,28	—	2,61	ac	3,11	ac	3,11	ac	3,11	—	3,11	—	—	—
	0,75	1,07	—	2,28	—	2,61	ac	3,75	ac	4,61	ac	4,61	—	4,61	—	—	—
	0,88	1,07	—	2,28	—	2,61	—	3,75	ac	4,90	ac	6,25	—	6,25	—	—	—
	1,00	1,07	—	2,28	—	2,61	—	3,75	ac	4,90	a	6,25	—	6,25	—	—	—
	1,13	1,07	—	2,28	—	2,61	—	3,75	—	4,90	—	6,25	—	—	—	—	—
	1,25	1,07	—	2,28	—	2,61	—	3,75	—	4,90	—	6,25	—	—	—	—	—
	1,50	1,07	—	2,28	—	2,61	—	3,75	—	4,90	—	6,25	—	—	—	—	—
	1,75	1,07	—	2,28	—	2,61	—	3,75	—	4,90	—	6,25	—	—	—	—	—
	2,00	1,07	—	2,28	—	2,61	—	3,75	—	4,90	—	6,25	—	—	—	—	—
$M_{t,nom}$ [Nm]		$\Sigma t \leq 3{,}00$ mm: 7 Nm										$\Sigma t > 3{,}00$ mm: 8 Nm					

No additional regulations.

Self drilling screw	
Hilti S-MD 23 Z 5,5 x L Hilti S-MD 23 C 5,5 x L with hexagon head	Annex 32

Figure 120. Example of a page from an annex of a European Technical Assessment for a self-drilling screw

The loading capacity is then cut off by the governing pullout or shear loading capacities. The values are applicable within the complete application range. Also in this case, in the interest of simplicity, no explicit information is given about the influence of the thickness or strength of the base material.

- Types of fastening
  These determine the maximum fastenable thickness in case of multiple layer fastenings as well as the combinations for which shear forces due to temperature fluctuations are allowed to be neglected within structural analysis.
- Design resistances
  Shear force:

$$V_{Rd} = V_{Rk}/\gamma_M \quad (10)$$

Tensile force:

$$N_{Rd} = \alpha_{cycl} \cdot (N_{Rk}/\gamma_M) \quad (11)$$

with

α_{cycl} ... factor to consider the effect of repeated wind loads on design tension strength

In accordance with DIN EN 1993-1-3 [35], a partial factor γ_M of 1.25 is applicable to powder-actuated fasteners. In this particular case (Figure 119), the coefficient α_{cycl} for all sheet thicknesses is 1.0. This means that the dynamic tension resistance of the sheet metals is not governing the design resistance of this type of fastener.

- Information about fastening inspection
  The projection of the head of the fastener (stand-off) h_{NVS} beyond the fastened component I serves as a means of checking the quality of the fastening (here h_{NVS} = 8.2 to 9.8 mm). In this particular case, an additional means of visual control of fastening quality also exists: the mark left by the piston on the washer should be clearly visible, as with this system (Figure 119), the piston of the tool is stopped by contact with the work surface (see Section 2.5.3.1).

7.4.3 Self-drilling screws

Figure 120 shows, as an example, a page from an annex of an ETA for a self-drilling screw [174].
The information on the page is formally presented in the same way as for powder-actuated fasteners. Points specific to screws are:

- The figure given for maximum drilling performance.
- The application limits are stated in terms of the combinations of sheet thickness and the given material specification. Materials S235, S275 and S355 in accordance with EN 10025-1 are covered within their full tolerance range of base material strength.
- The given tightening torque.

The design value for tensile force differs from that for powder-actuated fasteners and is calculated as follows:

$$N_{Rd} = N_{Rk}/\gamma_M \quad (12)$$

According to the EAD [153], a possible reduction intended to take the influence of repeated wind loads into account has already been incorporated in the characteristic resistance N_{Rk}. It is thus not necessary to explicitly state a reduction factor α_{cycl}. According to the EAD [153], the partial factor γ_M for metal construction screws is 1.33.

7.4.4 Self-tapping screws

Figure 121 shows, as an example, a page from an annex of an ETA for a self-tapping screw [174].
The information on the page is formally presented in the same way as for self-drilling screws. Points specific to self-tapping screws are:

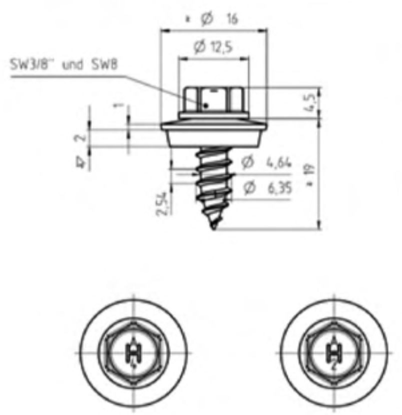
- The diameter of the hole, dependent on the sheet metal thickness, to be drilled in advance.
- If the screw is also suitable for driving into timber substructures, the characteristic plastic bending moment $M_{y,Rk}$, the characteristic pullout parameter $f_{ax,k}$ and the minimum effective screw-in length l_{ef} are given.

7.4.5 Special applications and interaction

These are understood to include fastening applications in which the powder-actuated fastener and fastening screws are positioned off center rather than in the middle of the corrugation in the sheet metal. This is most often the case when fastening liner trays to steel columns. As rules about this are now given in DIN EN 1993-1-3 [35], it is no longer explicitly mentioned in the European Technical Assessment. Instead, a reference is made to the corresponding paragraph in [35].
The off-center position of the fasteners is covered by the load-reducing factors given in Figure 122. The load-reducing factor of 0.7 N_{Rd} should then, logically, be applied to wall liner trays.
The interaction between tension and shear force is also handled by DIN EN 1993-1-3 [35]. Unless some other behavior can be proven by way of tests, the following linear interaction should be used:

$$N_{Sd}/N_{Rd} + V_{Sd}/V_{Rd} \leq 1.0 \quad (13)$$

Figure 123 shows the results of tension-shear interaction tests. When executing such tests special care needs to be taken that the specimen is precisely positioned on the inclined swivel plate to ensure that the force Z of the test engine will be introduced centrally into the powder-actuated fastener. Besides the reference test results for centric tension ($\alpha = 90°$) and pure shear ($\alpha = 0°$) the results for inclined loading with angles α = 30, 45 and 60° are shown.
The results confirm the conservative assumption of a linear interaction according to DIN EN 1993-1-3 [35]. In all tests sheet pullover combined with slotting of the sheet was the controlling mode of failure. Figure 124 shows additionally the results from interaction tests of blunt-tip threaded studs with conical shank to investigate the effect of inclined loading on the anchorage of



Material:

Fastener:	stainless steel (1.4301, 1.4401, 1.4404, 1.4567) - EN 10088
Washer:	stainless steel (1.4301) - EN 10088
Component I:	S280GD, S320GD - EN 10346
Component II:	S235 - EN 10025-1 S280GD, S320GD - EN 10346 Structural timber - EN 14081

Predrill diameter: see Table below

Timber substructures:

performance determined with

$M_{y,Rk}$ = 9,742 Nm
$f_{ax,k}$ = 8,575 N/mm² for $l_{ef} \geq 26,0$ mm

	t_I [mm]	0,63 mm ≤ t_{II} ≤ 3,00 mm													$V_{I,R,k}$
		0,63	0,75	0,88	1,00		1,13		1,25		1,50		≥ 2,00		$N_{I,R,k}$
$V_{R,k}$ [kN]	0,50	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0,55	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0,63	1,30	1,50	1,80	2,00	ac	2,30	ac	2,50	ac	2,90	ac	2,90	ac	2,90
	0,75	1,40	1,60	1,90	2,20	ac	2,50	ac	2,60	ac	3,10	ac	3,50	ac	3,50
	0,88	1,50	1,70	2,00	2,30	ac	2,60	ac	2,80	ac	3,20	ac	3,70	ac	3,70
	1,00	1,50	1,80	2,10	2,50	—	2,80	—	3,10	—	3,60	—	3,90	ac	3,90
	1,13	1,60	1,80	2,20	2,60	—	2,90	—	3,20	—	3,80	—	4,00	ac	4,00
	1,25	1,60	1,90	2,30	2,70	—	3,00	—	3,30	—	4,00	—	4,10	ac	4,10
	1,50	1,60	1,90	2,40	2,80	—	3,20	—	3,50	—	4,00	—	4,30	—	4,30
	1,75	1,60	1,90	2,40	2,80	—	3,20	—	3,50	—	4,00	—	4,30	—	4,30
	2,00	1,60	1,90	2,40	2,80	—	3,20	—	3,50	—	4,00	—	4,30	—	4,30
$N_{R,k}$ [kN]	0,50	0,49	0,59	0,70	0,76	ac	0,86	ac	0,97	ac	1,13	ac	1,19	ac	1,19
	0,55	0,61	0,75	0,89	0,95	ac	1,09	ac	1,23	ac	1,43	ac	1,50	ac	1,50
	0,63	0,90	1,10	1,30	1,40	ac	1,60	ac	1,80	ac	2,10	ac	2,20	ac	2,20
	0,75	0,90	1,10	1,30	1,40	ac	1,60	ac	1,80	ac	2,10	ac	2,80	ac	2,80
	0,88	0,90	1,10	1,30	1,40	ac	1,60	ac	1,80	ac	2,10	ac	3,50	ac	3,50
	1,00	0,90	1,10	1,30	1,40	—	1,60	—	1,80	—	2,20	—	3,60	ac	3,60
	1,13	1,00	1,20	1,40	1,50	—	1,70	—	1,90	—	2,30	—	3,60	ac	3,60
	1,25	1,00	1,20	1,40	1,50	—	1,70	—	1,90	—	2,30	—	3,60	ac	3,60
	1,50	1,00	1,20	1,40	1,50	—	1,70	—	1,90	—	2,30	—	3,60	—	3,60
	1,75	1,00	1,20	1,40	1,50	—	1,70	—	1,90	—	2,30	—	3,60	—	3,60
	2,00	1,00	1,20	1,40	1,50	—	1,70	—	1,90	—	2,30	—	3,60	—	3,60
$M_{t,nom}$ [Nm]		3 Nm							5 Nm						
d_{pd} [mm]		t_{II} ≤ 0,75 mm d_{pd} = Ø4,0 mm			0,75 mm < t_{II} ≤ 1,50 mm d_{pd} = Ø4,5 mm						t_{II} ≥ 1,50 mm d_{pd} = Ø5,0 mm				

The values listed above in dependence on the screw-in length l_{ef} are valid for k_{mod} = 0,90 and timber strength grade C24 (ρ_a = 350 kg/m³). For other combinations of k_{mod} and timber strength grades see Annex 3.

Self tapping screw

Hilti S-MP 53 S 6,5 x L / Hilti S-MP 53 SS 6,5 x L
Hilti S-MP 63 S 6,5 x L / Hilti S-MP 63 SS 6,5 x L
Hilti S-MP 73 S 6,5 x L / Hilti S-MP 73 SS 6,5 x L
with hexagon head and sealing washer ≥ Ø16 mm

Annex 71

Figure 121. Example of a page from the annex of a European Technical Assessment for a self-tapping screw

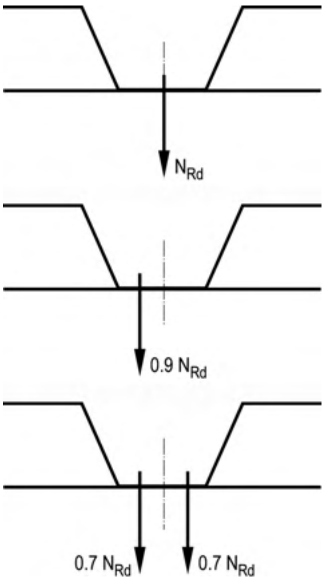


Figure 122. Reduction factors due to the position of fasteners in accordance with DIN EN 1993-1-3 [35]

the fasteners. Tests were performed with the same load angles $\alpha = 30$, 45 and 60°. For these tests with blunt-tip studs the strength of the base material was varied, too. Also in that case the test results prove the linear interaction as conservative assumption.

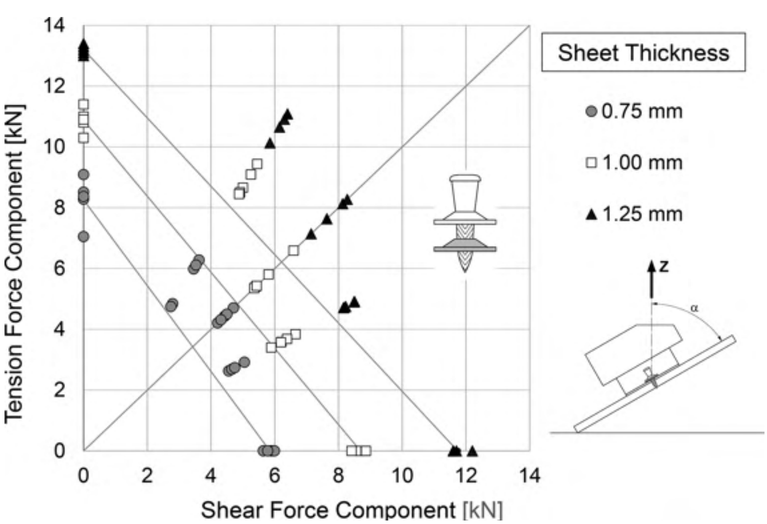
7.5 Deviation from the conditions applicable to the European Technical Assessments

7.5.1 Substructures made from of thermomechanically-rolled and high-strength materials

Construction steels per DIN EN 10025-2 [33] are generally specified in ETAs and national technical approvals as base materials (e. g. [28, 30]). These are the standard construction steel grades S235, S275 and S355 in the qualities JR, J0, J2 and K2 [33]. The thermo-mechanically rolled construction steel grades S355M/ML, S420M/ML and S460M/ML currently covered by DIN EN 10025-4 [167] are thus not explicitly covered by these ETAs.

In terms of the loading capacity of the fastener anchorage these types of steel are very suitable for use as base materials for powder-actuated fasteners. Figure 125 shows an example of the comparison of two series of tests on steels of the same nominal tensile strength. Due to the manufacturing procedure involved, thermomechanically-rolled steels are harder at the surface (the outer approx. 2 to 3 mm) than at the core of the material. Consequently, the application limit for powder-actuated fasteners on thermomechanically-rolled steels is lower than on standard types of construction steel. As a guide, the application limit determined for construction steel type S355 as per DIN EN 10025-2 [33] must be reduced by about 50 N/mm^2 in order to cover thermo-mechanically rolled steel of the type S355M/ML as per DIN EN 10025-4 [167].

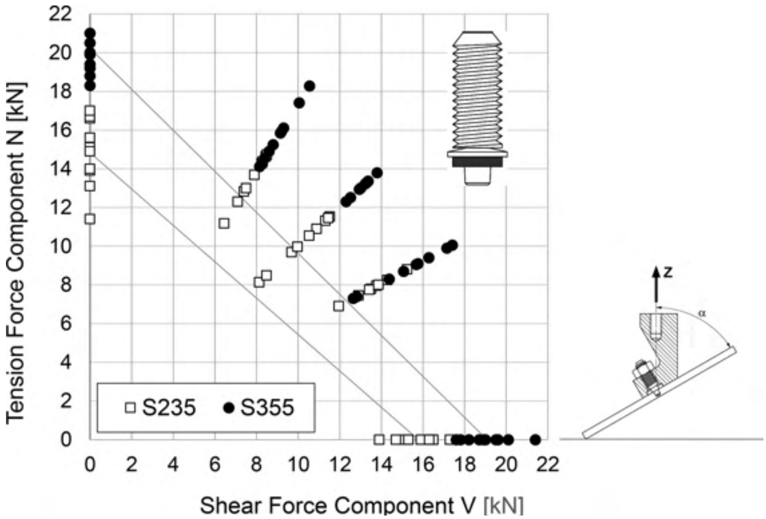
Construction steel up to S460M is used in building construction for long-span beams with thick flanges or for



Tested powder-actuated fastener: Hilti X-ENP-19 L15, base material thickness $t_{II} = 8$ mm.

The lines connect the mean values of 5 tests for pure tension and shear force and show the linear interaction for comparison.

Figure 123. Results of interaction tests of powder-actuated fastener for sheet metal fastening



Tested power-actuated threaded stud: Hilti X-BT-MR M10/15 SN 8 with conical shank, d = 5.2 mm (Figure 10)
Base material thickness t_{II} = 8 mm, S235 (f_u = 400 N/mm^2) and S355 (f_u = 620 N/mm^2)
The lines connect the mean values of 10 tests for pure tension and shear force.

Figure 124. Results of interaction tests of blunt-tip power-actuated threaded studs

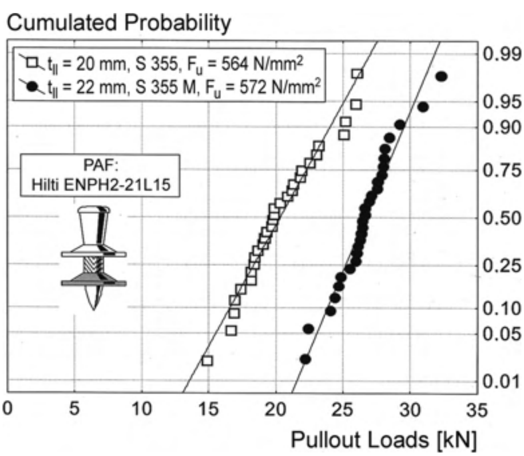


Figure 125. Loading capacity of the anchorage in thermo-mechanically-rolled steel (t_I = 0.75 mm)

heavy columns. Already the upper tolerance of 720 N/mm^2 of the nominal strength of S460M clearly exceeds the upper application limit of powder-actuated fasteners [30, 31]. Therefore, in order to use the fasteners on solid steel made of S460M a project-specific approval (ZiE) granted for the respective case [168] is required. Condition of use is the knowledge of the actual strength of the used material batches.

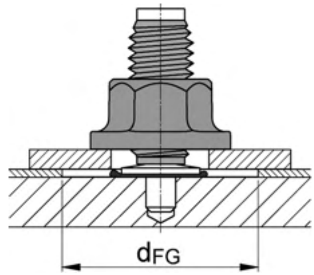
The actual nominal strength values should be in middle and lower range of the strength bandwidth of the grade S460M (530 bis 630 N/mm^2) and should be covered by the application limit published for standard construction steel. For the verification of the used material batches the upper application limit needs to be confirmed for the specific case. When doing these tests all relevant project-specific parameters are to be considered: base material samples representative for the used batches, actual sheet metal thickness, use of applied powder-actuated fastening system. It is essential to ensure the quality during assembly in order to confirm and track the use of the suitable material batches. The installation quality of the powder-actuated fasteners during assembly and execution is to be ensured by means of supplemental checks defined in the project-specific approval.

The typical field of application of thermo-mechanically construction steel up to S700M is currently with thinner plates in the range between 3 and 12 mm. These plates are used to manufacture longitudinally welded hollow sections, which are economically used for trusses of commercial steel halls. Figure 126 shows a typical application example (by Ruukki Construction Oy).

In the range of the thin plates of thermo-mechanically rolled grades S500M to S700M the upper application limit can be extended beyond the upper tolerance range of 630 N/mm^2 of the standard S355. However, current powder-actuated fastening technology reaches its limits in that range, e. g. plates of the most commonly used grade S550M cannot be covered for thickness of 10 or 12 mm.

For individual cases blunt-tip power-actuated threaded studs might be used for the fastening of profiled steel sheeting loaded by wind suction, as these studs cover

Figure 126. Steel hall construction with trusses made of steel grades up to S700M



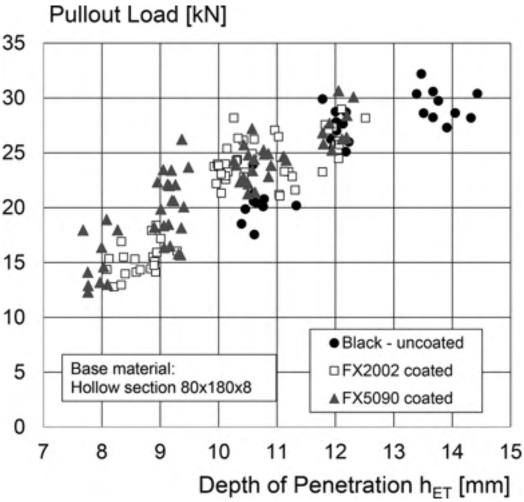
Blunt-tip powder-actuated fasteners: Hilti X-BT MF M10
d_{FG} = 28 – 30 mm

Figure 127. Alternate fastening of profiled steel sheeting to high-strength construction steel

the complete ultimate strength range of steel grades up to S960Q. With regards to the practical execution it must be considered that the studs cannot be driven from above right through the metal sheet. Therefore, the metal sheet needs to be prepunched at the intended fastening locations with sufficiently big holes with a diameter d_{FG}. This diameter d_{FG} needs to be selected big enough in order to allow access of the fastener guide of the fastening tool to the surface of the base material. In that case the blunt-tip powder-actuated threaded studs can be installed after the panels of metal sheet were laid. The bigger opening d_{FG} is to be closed by washers or platelets.
Fastening screws or screw-in threaded studs are not suitable for fastenings made to thermo-mechanically higher-strength construction steel.

7.5.2 Divergent types of connection

Component I combinations not covered by the ETA may also occur in practice. The maximum fastening thickness given in Figure 119 is 4 mm when there are four layers. With a single layer of sheet metal, however, this is only 2.5 mm. The reason for this limitation is that no shear loading tests or forces of constraint tests have been carried out with single layers of this kind or, respectively, the figures could not be verified. With regard to the classical type of profile metal sheet fastening, this limitation is not relevant as the maximum thickness of a single layer amounts in general 1.5 mm.
The data given in the ETAs can serve as an indication of technical feasibility for thicker single layers of approximately 2 to 4 mm. In each specific case, considerations have to be made on:
a) whether the fastener can be driven correctly (no gap between the sheet metal and the base material),
b) the required ductility in the shear direction is achieved,
c) which forces of constraint may occur and whether they must be taken into account explicitly within the structural analysis and,
d) whether the same partial safety factors can be used for the characteristic tensile and shear forces as for sheet metal fastenings.
Increasing the span of load-carrying profile metal sheet results in more frequent use of thicker sheets with a thickness of 1.25 and 1.5 mm, respectively. Multiple layer connections (fastening type d of quadruple layers and fastening type b of double layer at the panel side lap) are currently not covered by any ETA [30, 31]. According to the ETAs shear forces due to thermal elongation of the metal sheets need to be considered in the design of the connections.
Such a consideration can be done analytically. A guide value of $\Delta T = 50$ K for the temperature difference to be considered in the state during construction is given in [166]. For efficient utilization it is recommended to consider the flexible shear displacement characteristics of the connection in the analytic static design model. The respective stiffness is to be determined based on experimental tests with lap shear test samples. The analytic design actions due to thermal elongations are then verified against the design shear resistance V_{Rd} given in the ETA.
Alternatively the tension resistance N_{Rk} can be based on the supporting length of the panel (see n_{Rk} [kN/m] according to [99]). Applying this pragmatic and conservative approach, the double layer connection type b is carried out for constructive reasons but the fastening point is neglected in the structural design.
A further possibility to consider thermal elongations is to perform directly an experimental validation – combined shear- and tension test according to Table 23 – for the respective configuration. In general the soft base material (t_{II} = 6 mm, f_u = 350 bis 400 N/mm²) controls the coverage of fastening types in the ETAs. However, in combination with long-span thicker panels also thicker and stronger base materials are typically used, which reduce substantially the sensitivity of powder-actuated fastener against its tilting caused be local base material deformations offering the possibility of experimental validation.



Base material: hollow section 8 mm made of S500MH

Types of reactive coating: Sherwood Williams FIRETEX FX2002 and FX5090 in thickness of 1.5 bis 3.5 mm

Fixed sheeting: 1 x 1 mm, 2 x 1.25 mm und 4 x 1 mm

Powder-actuated fastener: Hilti X-ENP-19 L15

Figure 128. Resistance of powder-actuated fasteners on base materials with reactive fire coating

7.5.3 Base materials with a reactive fire-protective coating

The use of conventionally coated base materials (e. g. powder-coated or liquid paint coatings with a dry coating thickness of up to approx. 160 μm) is covered by the assessment procedure. Fire protective coatings, however, may have a thickness of about 1 mm or more. As a result of the thickness of the coating, it is possible that the loading capacity of the anchorage obtained is reduced. This must be verified by carrying out tests within the scope of project-specific approval considering the used steel base materials.

Figure 128 shows examples of tension pullout tests made with construction steel with reactive fire protective coating. In the specific example the coating leads to a reduction of the effective depth of penetration with a respective reduction of the resistance of the anchorage. Here, the values are sufficiently high – due to the high strength of the based material – that no reduction of the published resistances would be required. When using powder-actuated fasteners on steel with reactive fire coating it is also relevant to check if driving of the fasteners is possible without damaging or spalling the reactive coating.

When checking the fastener stand-off it should be considered that the powder-actuated fasteners locally compress the thick coating next to the driving location. Therefore, the metal sheet will be slightly drawn around

Figure 129. Hint on fastener inspection

the fastener shank. This effect needs to be observed during fastener inspection. The target value of the fastener stand-off must be measured next to the edge of the washer of the fastener. The use of a stiff plastic gauge – which is well suitable to check driving energy in case of single layer connection on uncoated base material – might indicate too high fastener depth of penetration although the fastener is perfectly driven. In these cases – especially if detrimental effects of excess energy can be excluded for base material thickness greater 8 to 10 mm – the optical fastener inspection is clearly to be preferred. In the specific case it is easy and reliable the inspect the piston mark on the top washer of the powder-actuated fastener.

Where a coating is hard and several millimeters thick, the coating may be removed at the point where the fastener is to be driven (e. g. using a Forstner bit) so that the fastening is made on bare, uncoated steel. This method, however, requires that the fire protection coating is subsequently correctly re-applied at the points where fasteners are driven. Generally speaking, with all fastening methods, it must be ensured that the presence of a powder-actuated fastener or screw has no negative influence on the effectiveness of the fire protection coating.

8 European Technical Assessment of sandwich panel fastenings

EAD 330047-01-0602 specifies the required tests for the fastening of sandwich panels to metal or timber substructures with self-drilling or self-tapping screws. With this fastening method, the sandwich panels are penetrated directly by the screws. The tests carried out cover the relevant failure modes for sandwich panel fasteners in accordance with Figure 130.

Table 25 provides an overview of the tests to be carried out with sandwich panel screws and the purpose of the tests. Put simply, the tensile loading capacity of the sandwich panel fastening is assessed by determining the

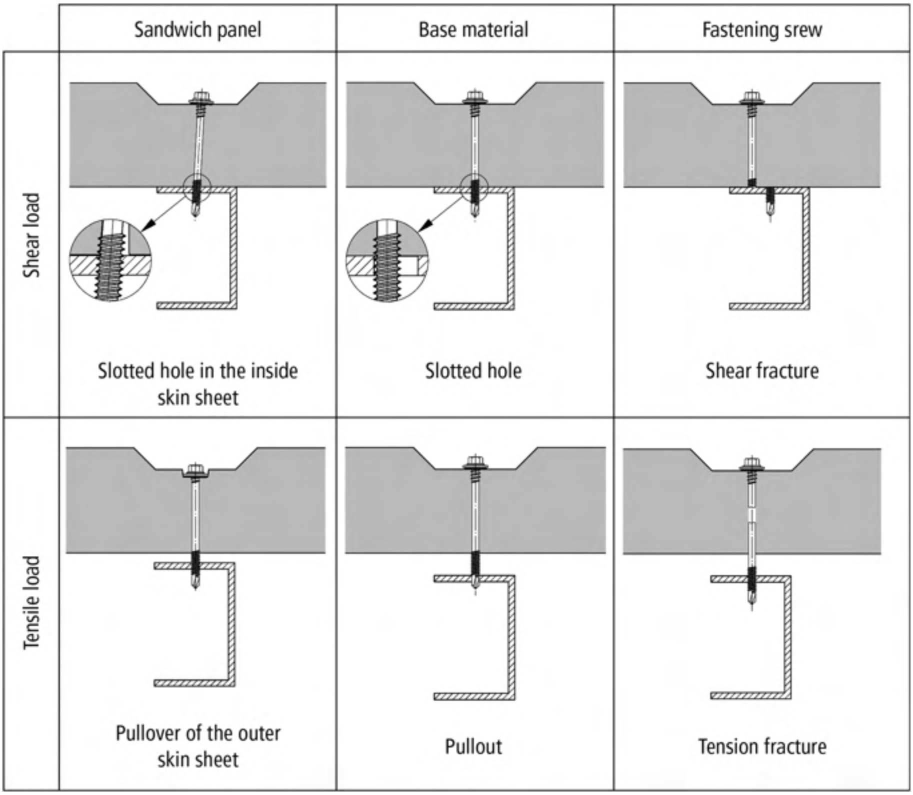
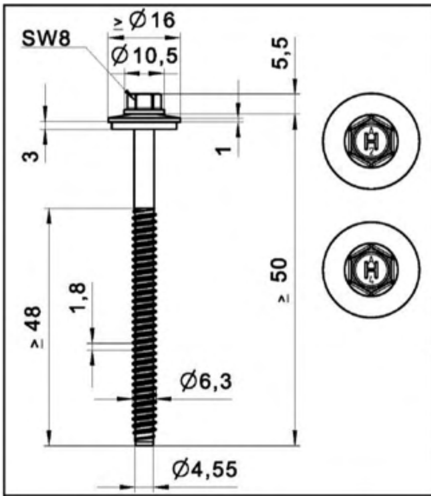


Figure 130. Sandwich panel fastener failure modes

Table 25. Tests per EAD 330047-01-0602 [154] for screws to fasten sandwich panels

Tests according to EAD 330047-01-0602 [154]	Component I		Component II		Purpose
	t_I	f_u	t_{II}	f_u	
static pullover test [1)]	each relevant thickness of outer sheet metal skin	optional	–	–	static pullover loading capacity
dynamic pullover test (optional)	each relevant thickness of outer sheet metal skin	optional	–	–	dynamic pullover loading capacity
pullout test	– [2)]	–	each relevant thickness or, respectively, screw-in length	optional	static pullout loading capacity
shear loading test	each relevant combination of inside skin sheet with thickness of component II	optional	each relevant combination of inside skin sheet with thickness of component I	optional	shear loading capacity of components I and II, shear loading capacity of the screw
dynamic testing of screw head displacement	– [3)]	–	each relevant thickness	optional	verification of resistance to repeated thermal expansion

[1)] Tests with sheet metal strips of a thickness equal to that of the outer skin of the panel
[2)] The screw is pulled out using an appropriate pulling device
[3)] The screw itself is eccentrically loaded using various cantilever lengths to simulate the relevant sandwich panel thicknesses



Material:

Fastener: stainless Steel (1.4301, 1.4401, 1.4571) - EN 10088
Washer: stainless Steel (1.4301) - EN 10088
Component I: S280GD, S320GD, S350GD - EN 10346
Component II: S235, S275, S355 - EN 10025-1
S280GD, S320GD, S350GD - EN 10346

Predrill diameter: see Table below

Timber substructures:
no performance determined

	t_{N1}, t_{N2}, d, D [mm]	t_{II} [mm]								
		1,50	2,00	2,50	3,00	4,00	5,00	6,00	8,00	≥ 10,0
$V_{R,k}$ [kN]	0,40	1,14	1,14	1,14	1,14	1,14	1,14	1,14	1,14	1,14
	0,50	1,54	1,54	1,54	1,54	1,54	1,54	1,54	1,54	1,54
	0,55	1,70	1,70	1,70	1,70	1,70	1,70	1,70	1,70	1,70
	0,60	1,83	1,83	1,83	1,83	1,83	1,83	1,83	1,83	1,83
	0,63	1,90	1,90	1,90	1,90	1,90	1,90	1,90	1,90	1,90
	0,75	2,07	2,07	2,07	2,07	2,07	2,07	2,07	2,07	2,07
	0,88	2,07	2,07	2,07	2,07	2,07	2,07	2,07	2,07	2,07
	1,00	2,07	2,07	2,07	2,07	2,07	2,07	2,07	2,07	2,07
$N_{R,k}$ [kN]	0,40	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51
	0,50	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51	1,51
	0,55	1,59	1,91	1,91	1,91	1,91	1,91	1,91	1,91	1,91
	0,60	1,59	2,47	2,47	2,47	2,47	2,47	2,47	2,47	2,47
	0,63	1,59	2,80	2,80	2,80	2,80	2,80	2,80	2,80	2,80
	0,75	1,59	3,43	3,60	3,60	3,60	3,60	3,60	3,60	3,60
	0,88	1,59	3,43	3,80	3,80	3,80	3,80	3,80	3,80	3,80
	1,00	1,59	3,43	4,00	4,00	4,00	4,00	4,00	4,00	4,00
u [mm]	30	20,0	12,0	4,0	4,0	3,0	3,0	3,0	3,0	3,0
	40	25,0	13,5	5,0	5,0	3,5	3,5	3,5	3,5	3,5
	50	33,0	15,5	6,5	6,5	4,0	4,0	4,0	4,0	4,0
	60	40,0	18,0	8,0	8,0	5,0	5,0	5,0	5,0	5,0
	70	40,0	20,5	10,0	10,0	6,0	6,0	6,0	6,0	6,0
	80	40,0	24,0	12,0	12,0	6,5	6,5	6,5	6,5	6,5
	100	40,0	30,0	15,0	15,0	8,5	8,5	8,5	8,5	8,5
	120	40,0	36,0	18,0	18,0	10,0	10,0	10,0	10,0	10,0
	≥ 140	40,0	40,0	21,0	21,0	11,5	11,5	11,5	11,5	11,5
$N_{R,k,II}$ [kN]		1,59	3,43	4,63	5,82	8,23	8,23	8,23	8,23	8,23
d_{pd} [mm]		Ø5,0	Ø5,3				Ø5,5		Ø5,7	

No additional regulations.

Self tapping screw	Annex 29
Hilti S-MP 54 S 6,3 x L Hilti S-MP 54 SS 6,3 x L Hilti S-MP 64 S 6,3 x L Hilti S-MP 64 SS 6,3 x L Hilti S-MP 74 S 6,3 x L Hilti S-MP 74 SS 6,3 x L with hexagon head and sealing washer ≥ Ø16 mm	

Figure 131. Example of a page from the appendix of a European Technical Assessment for a sandwich panel tapping screw

pullover resistance of the outer skin of the panel and by determining the shear load resistance of the inner skin. A topic specific to sandwich panels is verification of the dynamic displacement of the screw head. This covers the influence of repeated lateral movement (expansion and contraction) of the outer skin due to temperature fluctuations and the resulting stresses to which the screw is subjected. The total dynamic displacement of the screw is based on the following assumed temperature cycles over a period of 50 years [114]:
– 20,000 at 40 °C
– 2,000 at 60 °C
– 100 at 70 °C

After subjection to this dynamic loading, the pullout loading capacity of the screw must be still at least 80% of its reference loading capacity.

Evaluation and normalization of the test results is carried out essentially in the same way as for the self-drilling and self-tapping screws. The characteristic dynamic pullover loading capacity of sandwich panel screws is defined for 5´000 load cycles. For determination of the Wöhler curve harmonically pulsating tensile loading tests (with R = 0) with a test frequency of 5 Hz are to be carried out with at least three upper load levels. The test results serve to evaluate the reduction factor $\alpha_{cycl.}$

The performance of dynamic pullover loading tests is not obligatory. However, the effect of repeated wind loading on the design resistance needs to be considered. If no dynamic tensile loading tests are carried out, the influence of repeated pullover loading is taken into account by applying a constant reduction factor α_{cycl} = 2/3. The characteristic tension resistance N_{Rk} published in the ETAs in general already considers that reduction. In these cases the reduction factors α_{cycl} are not explicitly listed in the ETAs or national technical approvals. As for the fastening screws, the partial safety factor γ_M is 1.33. Figure 131 shows, as an example, a page from the appendix of a European Technical Assessment for a sandwich panel tapping screw [175].

9 European Technical Assessment for fastening waterproofing membranes

European Technical Assessment of components of mechanical fastening systems for waterproofing membranes has been regulated in ETAG 006 since the year 2000. The components of the system are (Figure 96):
– the waterproofing membrane
– mechanical fasteners
– thermal insulation

ETAG 006 was revised in 2012 [159]. For the time being ETAG 006 is used by the Technical Assessment Bodies (TABs) as basis for issuing European Technical Assessments [176]. For mechanical fasteners for fastening waterproofing membranes such ETAs are required and possible, respectively. When using the fastener in a kit, the ETA of the mechanical fastener must be referenced in the ETA of the waterproofing membrane system.

For mechanical metal fasteners, the following tests are to be carried out:
– static centric tension tests
– resistance to unwinding the fastener due to dynamic loading of the waterproofing membrane
– 15 Kesternich test cycles with correctly installed fasteners

Please refer to ETAG 006 [159] for details of how the tests are to be carried out and the results evaluated.

At least one wind uplift test must be carried out on the entire system for the purpose of verifying the suitability of the fastening system for use. If only one test is carried out its parameters must be selected in such a way that the combination of the components used result in the highest characteristic loading capacity available. The ETA provides the loading capacity per fastening point for the entire system (kit) as well as the loading capacity of the fastener alone (component resistance) which was used in the wind uplift test.

The system loading capacity with other fasteners not tested in the wind uplift test is calculated by way of linear interpolation relative to the loading capacities of the components. Extrapolation is not permissible.

10 European Technical Assessment of nailed shear connectors

10.1 Intended use and survey of tests

Nailed shear connectors are intended to be used for shear connection of composite beams or as means to provide end anchorage in composite slabs for applications in building construction according to DIN EN 1994-1-1 [138]. The EAD 200033-00-602 [151] for nailed shear connectors determines the essential characteristics for the Basic requirement 1: Mechanical resistance and stability and the Basic requirement 2: Safety in case of fire. As usual, the product under consideration is generically described, but not explicitly designated with its trade name. EAD 200033-00-602 [151] specifies a cold-formed L-shape connector which is fixed to the steel beam by means of 2 powder-actuated fasteners, e. g. applicable for the Hilti shear connector X-HVB which is fastened by means of X-ENP-21 HVB fasteners. The provisions given in EAD 200033-00-602 [151] are obligatory – as European harmonized specification – for all nailed shear connectors, for which product performance will be declared in a European Technical Assessment. Table 26 provides a survey about the essential product characteristics and the allocated testing required.

10.2 Tests and examples of load-bearing behavior

The following sections describe in detail the required tests and exemplify – using the Hilti shear connector X-HVB – the load bearing behavior of nailed shear connectors.

Table 26. Survey of required tests for nailed shear connectors

Essential characteristics	Testing
characteristic resistance in composite beams with solid concrete slab and composite slabs with profiled steel sheeting	push tests with the shear connector, lap shear tests with powder-actuated fastener
characteristic resistance of the end anchorage of composite slabs	shear tests with sheet metal
effect of base material with ultimate strength $f_y < 235$ N/mm²	shear tests with sheet metal
resistance to fire	shear tests with powder-actuated fasteners at elevated temperatures
resistance in case of seismic loading	no specific testing is required, provided the intended use according DIN EN 1998-1[68] as defined in the EAD is observed
application limit	installation tests with the shear connector and tension pullout tests with the powder-actuated fasteners

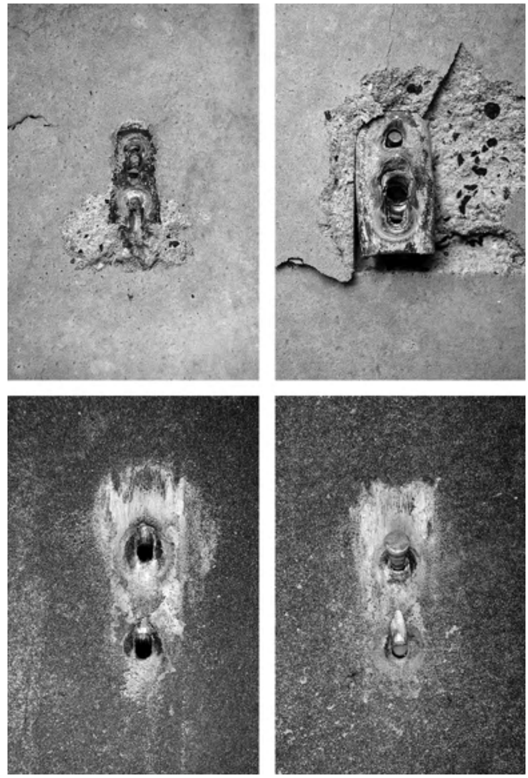
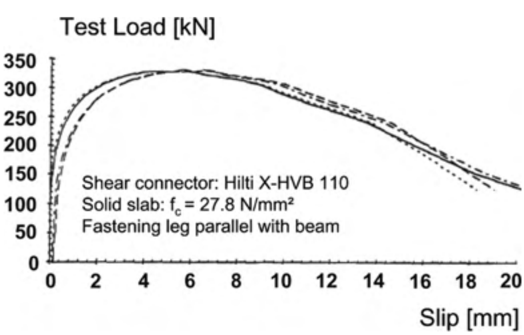


Figure 133. Shear connector X-HVB: Failure in the nailed joint

10.2.1 Resistance in solid concrete slab

The evaluation of the load-displacement characteristics of nailed shear connectors is based for long time on the provisions of Eurocode 4, DIN EN 1994-1-1 [138], Annex B.2. These determine setup and execution of push tests with welded headed studs and were adopted unchanged into EAD 200033-00-0602 [151] for nailed shear connectors.



Shear connector: 8 pieces X-HVB 110

Mean resistance P ≈ 40 kN per X-HVB

Figure 132. Load-displacement diagrams for the X-HVB shear connector [177]

DIN EN 1994-1-1 also specifies the evaluation and the threshold value of the characteristic deformation capacity δ_{uk}. As for headed studs, nailed shear connectors are considered as ductile if the characteristic deformation capacity exceeds 6 mm. The EAD does not state a fixed predefined test program, but rather requires that the relevant influencing parameters like type and height of the shear connector or type and compressive strength of the concrete are covered by the test program. Table 27 provides a survey of test parameters be considered for the strength evaluation of shear connectors used in solid concrete slabs and slabs with profiled sheeting.
The evaluation of the test results is to be done according to the provisions of test assisted design per DIN EN 1990, Annex D [172]. Alternatively, a simplified evaluation per push test series according to DIN EN 1994-1-1 [138], Annex B 2.5 is also permitted. The latter may be reasonable if the shear connector strength should be determined for certain profiled sheeting types with specific geometries or features.
Figure 132 shows examples of load-displacement curves from push tests performed with the Hilti X-HVB 110 nailed shear connector [177]. The load-displacement characteristics is ductile meeting the conditions of DIN EN 1994-1-1 [138] as prerequisite for the assump-

Table 27. Parameters be considered for push tests according to EAD 200033-00-602 [151]

Shear connector	Type of slab	Concrete	Profiled steel sheeting
type and height positioning: parallel or transverse with beam axis positioning: one row or multiple rows, spacings	solid concrete slab composite slab with profiled steel sheeting	normal weight concrete or lightweight concrete concrete strength class	type: trapezoidal or dovetail geometry rib geometry and height positioning: parallel or transverse with beam axis

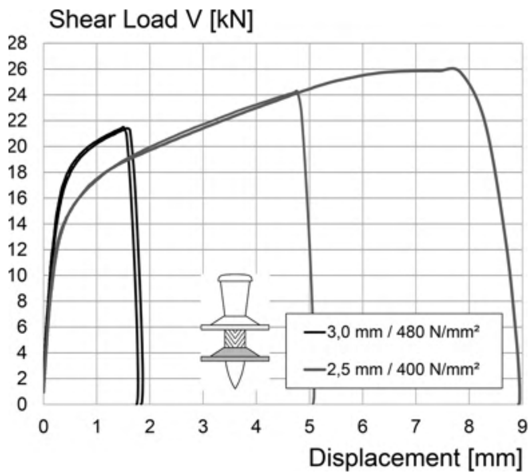


Figure 134. Shear resistance of powder-actuated fasteners X-ENP-21 HVB

tion of ideal plastic behavior of the shear connection in composite beam design.

The connector's load-bearing capacity in solid concrete slabs beyond a thickness of approximately 10 cm is primarily determined by the nailed joint. The total deformation capacity results from superposition of

- bearing deformations in the fastening leg,
- local concrete deformations in the compression areas of the metal connector and the heads of the powder-actuated fasteners,
- bending deformations of the fasteners combined with local bearing deformations in the steel base material.

As the nailed connection mainly determines the resistance, the effect of the concrete strength is then comparatively minor in case of solid slabs. Increasing concrete strength only slightly increases the shear connector resistance. For example, the characteristic resistance P_{Rk} – given in ETA-15/0876 [95] for the X-HVB shear connector – are independent on the concrete strength class. The pure shear strength of the powder-actuated fasteners must be determined in addition to the push tests by means of single layer lap shear tests (see Figure 112). The thickness of the fixed sheet needs to be minimum 3 mm to ensure that pure shear of the powder-actuated fasteners controls the failure. The characteristic shear strength of the fastener represents the upper threshold for the resistance of the shear connector embedded in the concrete. This approach corresponds with the design provisions for welded headed stud shear connectors according to DIN EN 1994-1-1 [138]: both the anchorage of the stud in the concrete as well as the shear resistance of the stud shank needs to be verified in design.

Figure 134 shows the shear resistance of the powder-actuated fastener X-ENP-21 HVB from shear tests performed with a thickness of 3 mm, such as required per EAD [151]. In addition to these tests also results from shear tests with a sheet thickness of 2.5 mm are shown. This thinner sheet still fails by bearing and achieves higher plastic deformation and higher strength when comparing with the strength of the 3 mm sheet. Therefore, EAD [151] requires a sheet thickness great enough that only negligible slotting in the sheet develops and that pure shear of the fastener shank controls the behavior. When performing push tests in solid concrete slabs made from higher strength class, the resistance of the shear connectors might achieve values which are about 15% greater than the pure shear resistance of the fasteners [182]. That higher resistance is caused by the inclination of the powder-actuated fasteners and the supplemental superimposed friction contribution. The reliable statistical prediction of that maximum utilization for design purposes is complex and time consuming. Furthermore, in case of maximum strength utilization the ductility of the nailed shear connection will decrease. Therefore, the maximum strength of the shear connector was capped in the EAD [151] with the pure shear resistance of the powder-actuated fasteners.

The design resistance of the nailed shear connector P_{Rd} in solid concrete slabs results from the minimum of the strength from the push tests and the fastener shear tests.

$$P_{Rd} = \min (P_{Rd,SC}; n \cdot P_{Rd,PAF}) \quad (14)$$

with:

$P_{Rd,SC}$ Design resistance from push tests (with γ_V = 1.25)

$P_{Rd,PAF}$ Design resistance from shear tests with powder-actuated fasteners (with γ_V = 1.25), $P_{Rd,PAF}$ = 16 kN for the X-ENP-21 HVB

n Number of powder-actuated fasteners per nailed shear connector, n = 2 for Hilti X-HVB

The design shear resistance of the powder-actuated fastener must be corrected to the minimum material strength of the fastener specified by the manufacturer. Furthermore, the actually according to DIN EN 1990 [172] evaluated partial factor is to be considered for the determination of the characteristic resistance published in the ETA. In case the actual partial factor exceeds $\gamma_V = 1.25$, the characteristic resistance evaluated from the tests needs to be reduced accordingly for being published as characteristic value P_{Rk} in the ETA.

Remarks on push test:

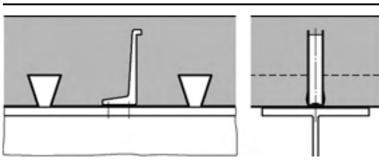
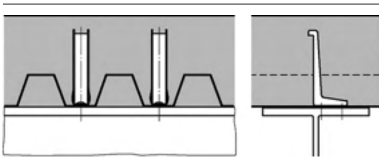
Recent investigations on further development of push tests [183] suggest a modification for tests with headed studs. These proposals consider the restricted uplift of the concrete slabs by means of lateral movement constraints of the concrete in the push test. However, EAD 200033-00-602 [151] adopted unchanged the currently in DIN EN 1994-1-1 [138] specified push test geometry without any means of lateral constraints. It is assumed that applying such lateral constraints in push tests with nailed shear connectors may lead to disproportionately favorable results. Such beneficial confinement effects were observed in push tests with powder-actuated nails used for shear connection in composite tube columns [145]. The results of push tests simulating lateral constraint of the concrete slab cannot be directly utilized for the evaluation of the shear resistance of nailed shear connectors. For justification of that test modification also for nailed shear connection further research on that subject is required. Especially an accurate understanding of the acceptance of lateral constraints in the test related with the real behavior of composite beams is required.

10.2.2 Resistance in slabs with profiled steel sheeting

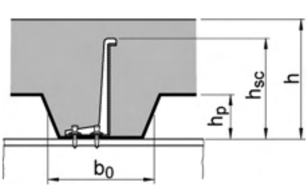
The resistance of nailed shear connectors in combination with profiled steel sheeting is also to be determined experimentally by means of push tests under consideration of the relevant parameters given in Table 27. Compared with headed studs, the shear resistance of nailed shear connection in solid concrete slabs is clearly smaller. Therefore, the strength reducing effect of profiled steel sheeting is then primarily relevant for narrow rib steel sheeting. For example, the shear resistance of X-HVB shear connectors combined with dovetail composite decking Holorib HR51 is identical with the performance in solid concrete slabs. Observation of positioning rules according to [95] – minimum distance to the profile sheet as well as minimum height of shear connector – ensures ductile shear load bearing behavior. The resistance of the ribs only controls in case of comparatively narrow ribs, the anchorage leg of the X-HVB shear connector will then be plastically bent, see beam tests according to [179].

Provided a sufficient number of push tests is available, the effect of profiled sheeting can be considered with reduction factors k_t and k_l analogically as with headed studs per DIN EN 1994-1-1 [138]. As an example the

Table 28. Design resistance of Hilti X-HVB shear connectors with profiled steel sheeting and ribs transverse to the supporting beam [95]

X-HVB Positioning	Design resistance $P_{Rd,t}$
 X-HVB positioning parallel with beam axis	$P_{Rd,t,l} = k_{t,l} \cdot P_{Rd}$ $k_{t,l} = \frac{0.66}{\sqrt{n_r}} \cdot \frac{b_0}{h_p}\left(\frac{h_{sc}}{h_p} - 1\right) \leq 1.0$ (15)
 X-HVB positioning transverse to beam axis	$P_{Rd,t,t} = 0.89 \cdot k_{t,t} \cdot P_{Rd}$ $k_{t,t} = \frac{1.18}{\sqrt{n_r}} \cdot \frac{b_0}{h_p}\left(\frac{h_{sc}}{h_p} - 1\right) \leq 1.0$ (16)

with



and n_r = number of shear connectors within the rib of the profiled sheeting

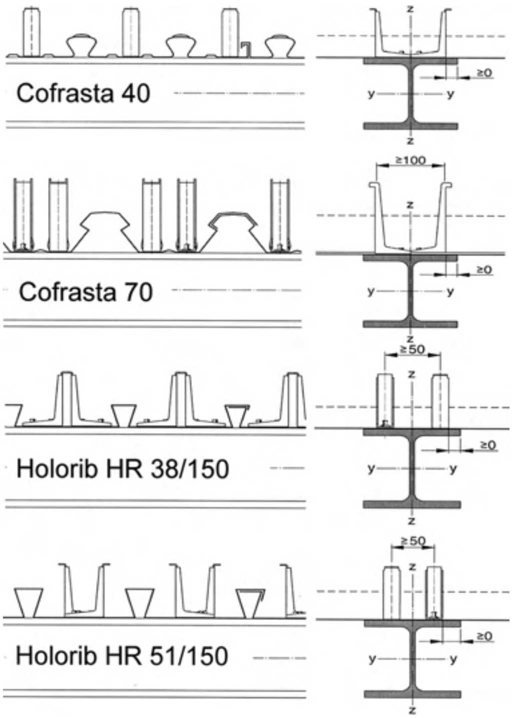


Figure 135. Optimum positioning of X-HVB shear connectors

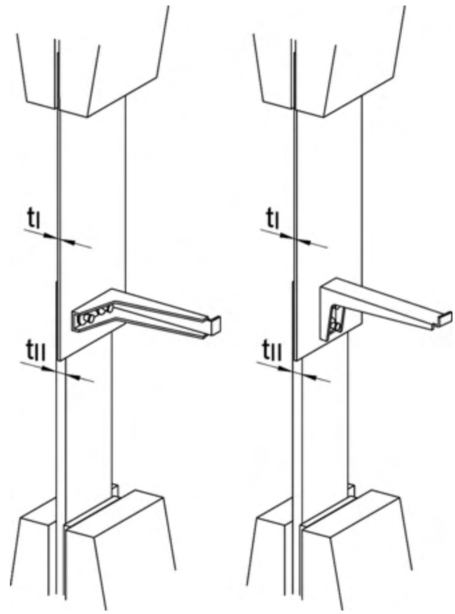


Figure 136. Shear test for the determination of the resistance of the end anchorage

design resistance of the Hilti X-HVB shear connector is provided in Table 28 for profiled steel sheeting with ribs transverse to the supporting beam. The deviations of the factors compared with Eurocode 4 (e. g. 0.66 instead of 0.7) are explained by the actual mathematical fitting of the test results against the applied theoretical function of the resistance of the nailed shear connector. Whenever possible the X-HVB shear connector should be positioned parallel with the beam axis, as then a slightly higher strength of the connector can be utilized compared with its positioning transverse to the beam axis. However, X-HVB positioning transverse to the beam axis is required in case of narrow rib sheeting or for profiled sheeting with stiffeners in the bottom flange. Figure 135 shows the optimum positioning of two rows of X-HVB shear connectors when used with typical profiled steel sheeting.
With respect to further publications on push tests or beam tests with X-HVB shear connectors it is referred to [178-181].

10.2.3 Resistance of the end anchorage of composite slabs

Nailed shear connectors may also be utilized for the end anchorage of the composite slabs. The tension force which can be transferred via the composite steel sheeting is determined by means of shear tests with steel sheeting, as shown in Figure 136. The steel sheet is fixed together with the shear connector in order to realistically simulate the local connection between the powder-actuated fastener and the sheet. The local deformation restriction of the composite sheet by the shear connector is then considered. Furthermore, the potential effect of the group of two powder-actuated fasteners with small spacing is covered as well.
The resistance of the end anchorage results from these shear tests. Furthermore, the resistance is capped by the resistance of the shear connector in the solid concrete slab for the respective positioning parallel or transverse to the force direction.

10.2.4 Resistance for old building renovation

In case of building refurbishment or strengthening of existing slabs (e. g. roof conversions) the existing steel beams should often be re-used as part of the new composite beams. In case the old steel does not reach the minimum strength of current S235 ($f_u = 360$ N/mm^2 und $f_y = 235$ N/mm^2), the strength of the nailed shear connector needs to be adjusted.
This reduction factor may be determined by means of lap shear tests with single layer of sheeting (see Figure 112). These tests are to be setup such that the effect of the base material strength on the shear pullout of the powder-actuated fastener from the base material is determined, details see EAD [151]. This reduction factor is then applied independent on the controlling failure mode observed in the push tests. Alternatively and in

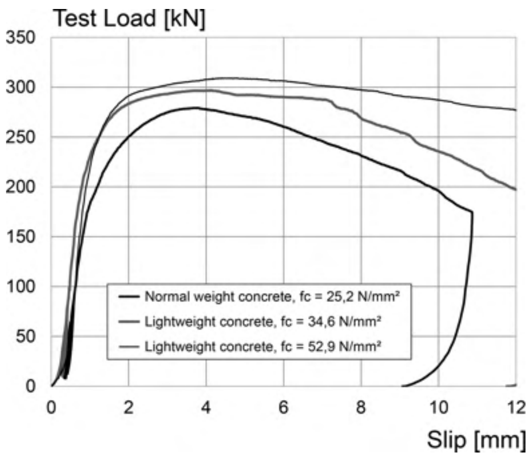


Figure 137. Load-displacement curves with narrow beams IPE 120 and thin solid concrete slabs

compliance with EAD [151] (see EAD section 2.2.7, option A), push tests may be performed with original material samples to optimize shear resistance.

Remark: The determination of the reduction factor concerns the performance of the nailed shear connector. The suitability of the existing steel as part of the composite beam (e. g. application of plastic design) needs to be validated by the structural engineer for the respective individual case.

In renovation application shallow steel beams are often used with respective thin solid slabs with a thickness of 5 or 6 cm. In order to save weight also lightweight concrete is applied. Figure 137 shows for example load-displacement curves from push tests performed with shallow shear connectors X-HVB 40 and a correspondingly thin solid concrete slab with a thickness of 5 cm. The steel base material corresponds regarding width (64 mm) and thickness (6 mm) with a profile IPE 120 with an ultimate tensile strength of 420 N/mm^2. The shear connectors were placed in so-called "duck-walk" position diagonal to the beam section but centered above the beam flange (see Figure 102, right).

The load-displacement characteristics of shallow shear connectors X-HVB 40 is also ductile in thin solid concrete slabs. The resistance is controlled by concrete failure of the 5 cm slab [184]. The powder-actuated fastener connection with the base material remained intact apart from slight tilting of the fastener in the 6 mm material. The results achieved with lightweight concrete with a density of approximately 1750 kg/m^3 are with respect to the strength at least equivalent with those achieved with normal weight concrete of the same compressive strength. The ductility with lightweight concrete tends to be higher, probably caused by higher local compressibility of the lightweight aggregates.

10.2.5 Resistance in case of a fire

Following the concept of DIN EN 1994-1-2 [185] the EAD [151] specifies the determination of temperature dependent reduction factor $k_{u,\Theta,NSC}$ for nailed shear connectors. That values corresponds – independent on the observed failure mode in the cold state – with the respective minimum value $k_{u,\Theta}$ for steel failure, $k_{c,\Theta}$ for concrete failure and $k_{u,\Theta,PAF}$ for shear failure of the powder-actuated fastener. The reduction factors $k_{u,\Theta}$ and $k_{c,\Theta}$ apply according to DIN EN 1994-1-2 [185]. Type and performance of the shear tests at elevated temperatures for the determination of the temperature dependent reduction factor $k_{u,\Theta,PAF}$ are specified in the EAD [151]. In generally the reduction $k_{u,\Theta,PAF}$ will control the reduction factor $k_{u,\Theta,NSC}$, see Section 2.2.4, Figure 9.

10.2.6 Application limits

As for profiled sheet metal fasteners both the lower as well as the upper application limit (see Figure 12) must be validated for the nailed shear connector in combination with the powder-actuated fastening system to be assessed. Installation and pullout tests are to be performed with the powder-actuated fasteners, whereby these are fixed together with the shear connectors. At the upper application limit no shear fractures of the fasteners must occur during the driving process and the powder-actuated fasteners must achieve a characteristic pullout resistance of 8.8 kN. That value is derived from the achievable resistances of powder-actuated fasteners for sheet metal fastenings in case of multi-layer sheet fastenings. Applying that analogy the proper installation of the fasteners is proven when used in combination with the shear connector. It is to note that the resistance needs to be checked separately for both powder-actuated fasteners 1 and 2 of the connector, as the outset condition for the driving process is different.

In case the shear connectors are also intended to be used on thin top flanges with a thickness less than 8 mm – e. g. in case of refurbishment of old buildings – the resistance of the powder-actuated fasteners is then also to be checked at the lower application limit by means of installation and pullout tests. In order to consider the flexibility of the top flanges correctly, those tests are to be performed with the respective base profiles applying the connector positioning recommended by the manufacturers.

10.3 Structure and content of the ETA

European Technical Assessments for nailed shear connectors correspond with the ETA structure described in section 7.4.1 with Annex A covering the product description, Annex B detailing the intended use and guidance on product assembly and Annex C summarizing the product performances.

11 Powder-actuated fastener and metal construction screw suitability checklist

11.1 Powder-actuated fasteners

Apart from the applications covered by ETAs – e. g. profile metal sheet fastenings and composite construction – it is not always possible for planners and specifiers to quickly assess the fundamental suitability of a powder-actuated fastener for a new application. Accordingly, the clarifying questions to be asked are summarized and discussed in the following paragraphs in the form of a checklist. These questions help to assess quickly in advance whether the powder-actuated fastening technology may or may not be suitable for the fastening or connecting application in question.

Question 1: To which ambient conditions will the fastening be subjected?

The answer to this question leads directly to the choice of material. In accordance with Section 2.8, galvanized powder-actuated fasteners may be used only in dry interiors for permanent, safety-relevant fastenings. Corrosion-resistant fasteners must be used in moist environments or in situations where exposure to the weather cannot be avoided. Stainless steel fasteners must, of course, also meet the actual corrosion-resistance requirements. Generally speaking, powder-actuated fasteners made from stainless steel are less hard than those made from carbon steel. Accordingly, stainless steel powder-actuated fasteners have a more limited application range (see Section 2.4.2).

Question 2: What is the thickness and strength of the base material (component II)?

Question 3: What is the thickness and strength of the component to be fastened (component I)?

This information confirms whether a powder-actuated fastening system is available, based on manufacturers information, for the application concerned. The combination of component I and component II determine the required total fastener length. If the powder-actuated fastener is available as a standard item or to special order, a suitable fastening tool capable of driving the fastener in a reproducible manner, without failure, must also be available. The actual configuration must be within the upper and lower application limits of the system (see Section 2.4.2).

Question 4: Is the base material covered by reactive fire protective coating?

The presence of a reactive fire protective coating is not yet generally covered by any ETA and must be addressed for the specific case. One aspect is the potential influence of the coating on the tension pullout resistance of the powder-actuated fastener. Furthermore, driving the fasteners must not damage or lead to spalling of the coating.

Question 5: Does a hole have to be drilled in advance in the part to be fastened (component I)?

This question relates, on the one hand, to the upper application limit. The thickness and strength of base material that can be covered decreases as the thickness and strength of the part to be fastened increases. Predrilling the hole has a positive effect on the upper application limit. On the other hand – if predrilling is not applied – attention must also be paid to the formation of a gap between component I and the supporting material (see Section 5.6).

The powder-actuated fastening system must be suitable for driving fasteners in predrilled holes. The decisive factor here is that the fastener can be positioned in the fastening tool with the point of the fastener protruding, so that it can be easily positioned centrally in the predrilled hole in component I. Fastening systems in which the fasteners are contained within the tool, e. g. as is the case when nail magazines are used, fail to meet this requirement.

Question 6: Is the base material sufficiently thick and stiff?

At the point where the fastener is driven, the base material must meet the minimum thickness requirement. Apart from this, especially with thin base materials (3 to 6 mm), the flexibility of the supporting structure must also be taken into account. Rigid tubular sections have more favorable characteristics than open angles or cold-rolled profiles in terms of reproducibility of the driving process. The position of the fastener relative to the profile cross section is particularly relevant. The energy required to drive the fastener increases along with the increase in the distance of the fastener from a rigid profile corner as inadequate driving velocity leads to local plastic deformation of the angle or profile, which can result in a gap forming between component I and the base material.

In situations where the position of the fastener in the profile cross section can be clearly ascertained, the fastener driving energy can also be determined accurately by making test fastenings. Selection of the correct driving energy is more difficult when the exact position of the fastener is not obvious at the moment it is driven (Figure 138). This is the case, for example, when fastening profile metal sheets on lattice girders Figure 139) with a top flange consisting of a thin double-angle profile (wall thickness: 3 to 5 mm, leg width ≥ 40 mm).

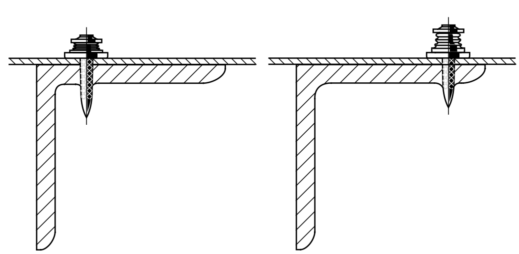


Figure 138. Fastener positioned close to the edge or web of an angle profile

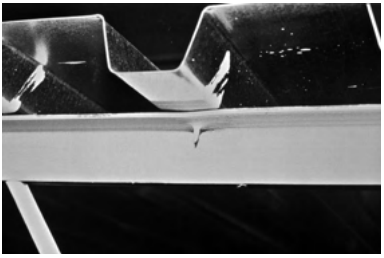


Figure 139. Fastening profile metal sheets on thin-walled, flexible angle profiles

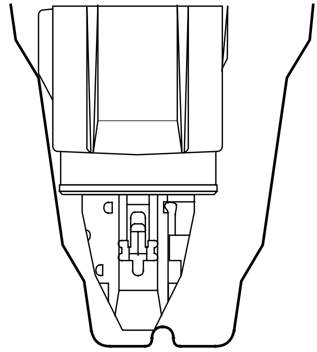


Figure 140. Insufficient space in case of contact of tool body

Supporting materials of this kind are typical of the type of structure used for industrial buildings in North America.
The energy required to drive a fastener close to the web of the profile is considerably lower than that required at the edge of the profile. The optimum driving energy for fasteners positioned close to the web of the profile may result in inadequate depth of penetration at the edge of the profile. On the other hand, the optimum driving energy for fasteners positioned at the edge of the profile may cause excess energy effects at the profile web, resulting in damage to the fastener anchorage. Fastening tools equipped with a built-in piston brake are capable of fulfilling these opposing requirements. These fastening tools are always set to a sufficiently high power level so that fasteners positioned close to edge areas can also be driven correctly. When driving a fastener at the corner of a profile, the excess driving energy is dissipated by way of a predefined stop piece (buffer) within the tool. Detrimental excess energy effects can thus be reliably avoided.
Flexibility of the base material influences the reproducibility of the anchorage obtained by the powder-actuated fastener. The previous brief digression into construction practice in the North American market shows that fastening systems optimized for the local conditions, which allow fasteners to be driven reliably into flexible base materials, are available on the market. When assessing question 6, the technical characteristics (see Section 2.5.3.1) of the applicable fastening system must thus be taken into account.
Question 7: Does the size / shape of the fastening tool allow access to the fastening points?
To ensure that the fastener is driven correctly, and for safety reasons, powder-actuated fastening tools must always be held perpendicular to the work surface. Space around the fastening point must be sufficient to allow the tool to be brought into position and to be pressed against the surface before triggering. Figure 140 shows an example from a practical situation where, although the front end of the fastening tool could be brought into position in the corrugation at an angle, it was difficult or almost impossible to trigger the tool in a perpendicular position due to contact between the top edge of the corrugation and the body of the fastening tool.
Question 8: Can the required productivity be achieved in practice with the available powder-actuated fastening solution?
For standard applications, powder-actuated fastening is a highly productive fastening method. In the case of new applications, the time taken to produce a suitable fastening while taking into account all steps of operation, should be checked. Allowance must be made for the fact that manufacturers of powder-actuated fasteners do not offer collated fasteners for their entire range of fasteners.
Question 9: Is adequate technical data available for the assessment of loading behavior and for a project-related approval?
The performance of the powder-actuated fastening solution determines cost-efficiency while the availability of the required data influences whether or not the project can be completed on schedule.

11.2 Fastening screws

The questions relevant to powder-actuated fasteners, regarding assessment of suitability for use, also basically apply to connections made with fastening screws. Generally speaking these questions concern the systematic examination of the following aspects: durability (question 1), usability (questions 2 to 7), cost-efficiency (question 8) and on-time implementation (question 9).

12 Summary

Powder-actuated fasteners and fastening screws have been used cost-efficiently in lightweight metal construction for many years. This report deals with the technology involved, the verification of suitability, the applications for which the systems are used and the associated European technical assessments.

Powder-actuated fasteners are driven into the base material by the fastening tool in a one step operation – safe piston-type tools have been in use in the construction industry for decades. The base material is displaced by the high-strength fastener during the driving operation. Fastening screws, on the other hand, must be driven into a predrilled hole. With self-drilling screws, drilling and thread cutting take place in one operation.

The decisive parameter for the anchorage of powder-actuated fasteners is the correct driving depth in the base material. The parameters influencing fastener anchorage are discussed and explained together with the test results. Research on the subject of the influence of stress on the base material show that connections made with powder-actuated fasteners are robust. The influence of the fastener itself on the base material is generally good-natured. This has been confirmed by experimental investigations. Stainless steel blunt-tip or screw-in threaded studs also allow fastenings to be made in coated materials without damage to the coating.

Powder-actuated fasteners and fastening screws are suitable for a wide range of applications in steel construction. These range from the simple fastening of wood and plasterboard without structural relevance through the classical profile sheet metal fastening applications to high-performance applications of powder-actuated fasteners in composite construction. The core application for both technologies is their use in lightweight metal construction.

The economic advantage of powder-actuated fastening is its high system productivity, even on thick, high-strength base materials. This is the decisive factor in the decision to use this technique. Although the material costs per fastening point may often be higher than with fastening screws, this is more than compensated by other factors when the entire chain of operations is taken into account. The thinner the base material, the lesser are the advantages of powder-actuated fastening. The powder-actuated fastening technique cannot be used to join thin, cold-formed profile metal sheets to each other and it cannot be used to fasten sandwich panels. On the other hand, there are no screw fastener solutions available on the market for composite shear connectors..

Assessment of the fastening solution's system productivity takes the following into account:

- The speed with which the fastenings can be made on the construction site.
- Almost complete freedom from influence by the weather.
  This applies, to a very great extent, to powder-actuated fasteners as well as screws.
- Independence from electric power supplies. This allows great flexibility on the jobsite and applies not only to powder-actuated fastening, as fastening screws can also be driven with complete freedom when suitable cordless (battery powered) screwdrivers are used.
- The simplicity and ease of use of powder-actuated fastening tools and screwdrivers ensure that operators can be trained quickly and reliably.
- Reproducible fastening quality achievable even by semi-skilled personnel.
- Simple means of visual/geometric inspection for fastening quality assurance.

A checklist has been drawn up for the assessment of new applications in order to allow a quick decision to be made about the general suitability of the powder-actuated fastening technology or, respectively, to allow formulation of a description of the requirements to be met by the fastening and the fastener driving operation. The logic behind this checklist applies equally to the assessment of the suitability of fastening screws.

The three key aspects of a good powder-actuated fastening are:

- Use of the specified system components (keyword: system interdependency)
- Observance of the application limits
- Use of materials suitable for the ambient conditions

Observance of the application limits and selection of the right materials are equally relevant when making connections with metal construction screws. With screw fastening, a system approach is not explicitly required, i. e. there are no mandatory instructions within the approvals to use screws in combination with a specific screwdriver. Screwdrivers, nevertheless, thanks to their ergonomic design and the performance they offer, make a very significant contribution toward achievement of reliable, reproducible screw fastenings.

National technical approvals or European Technical Assessments are required for use in areas of application where construction authority approval is relevant. The technological basis for use in the fastening of profile metal sheets and subsequent applications was developed about 40 years ago. At this point we would again like to extend special thanks and recognition to those who began with a blank sheet: *Prof. Timm Seeger* and *Dr. Stefan Klee* of the Technical University of Darmstadt and in memory of *Elmar Thurner* of the Hilti Corporation.

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