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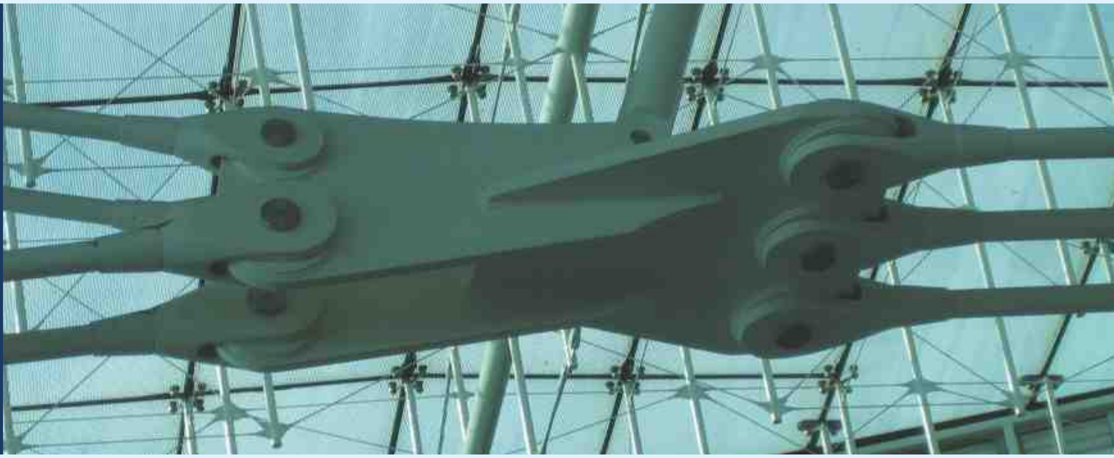

Powder-actuated fasteners and fastening screws in steel construction

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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.

Contents

1 Introduction

This publication is an updated and extended version of the article "Powder-actuated fasteners in steel construction" [1] from the "Stahlbau-Kalender 2005". Powder-actuated fasteners are nails or threaded studs made from high-strength steel, used to fasten components to steel, concrete and masonry [2–4]. The materials most commonly 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. Powder-actuated fastening to steel is a familiar technique that has been in use for decades. The classical applications in steel construction are the fastening of thin gauge metal sheets in single or multi-story buildings [5]: load-bearing sheeting of roof structures, liner trays for walls or sheeting of composite decks.

As an alternative to powder-actuated fasteners, fastening screws (self-drilling or self-tapping screws) can also be used to fasten profile metal sheets. Self-drilling screws can also be used at joints between thin-gauge metal profile framing. Accordingly, in addition to bringing powder-actuated fastening topics up to date, we have decided to integrate the subjects of fastening screw technology, applications and approval in this "Stahlbau-Kalender" and to compare the method with powder-actuated fastening.

Fastening screws, like powder-actuated fasteners, are made from hardened carbon steel or stainless steel. The various screw types are differentiated mainly in the ways in which they are used. A self-tapping screw, for example, is driven in a pre-drilled hole. The screw forms its own thread in the base material as it is driven. A self-drilling screw, on the other hand, is equipped with a drill point, so no predrilling is necessary. The screw drills the hole and forms a thread simultaneously in a single operation.

Figure 1 shows typical examples of powder-actuated fastening and screw 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.

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, the material into which powder-actuated 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.

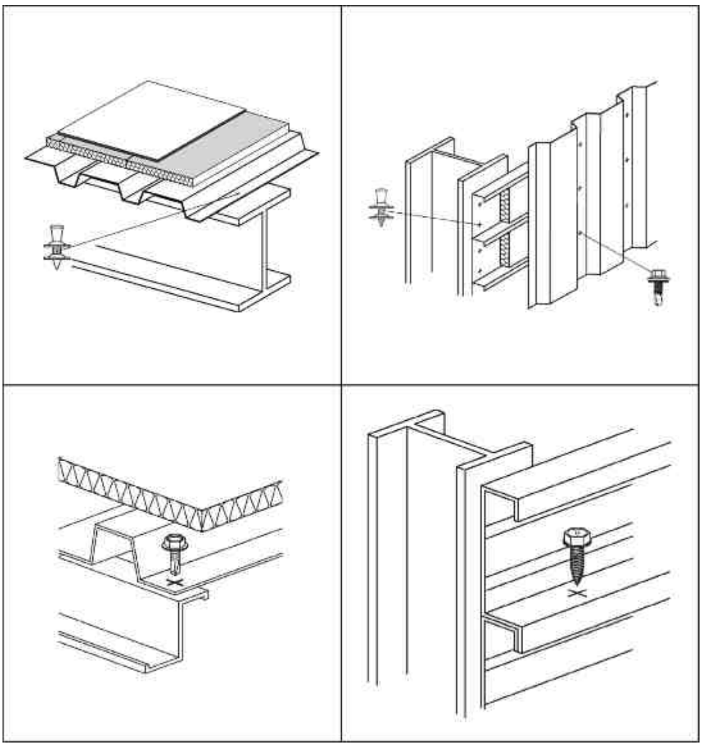


Figure 1. Use of powder-actuated fasteners and screws in light-gauge steel construction

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 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 currently approved fasteners.

Other possible areas of use for powder-actuated fasteners and fastening screws, e.g. as a means of joining materials, fastening wood or wood materials or fastening base profiles for glass facades, will be discussed in this report in conjunction with the corresponding applications.

The first European Technical Approval for fastening profile metal sheets was granted in 2004 to a powder-actuated fastener [6]. Since 2005, the basis for European Technical Approval of metal construction screws and sandwich panel screws has been under development. The first European Technical Approval for fastening screws was granted in the year 2010 and approval for sandwich panel screws is expected to be awarded in 2011. When DIN EN 1993-1-1 [7] comes into force there will then be complete formal agreement with the European Technical Approvals. In many cases, these will take over completely from the previous national means of product qualification in the form of general construction supervisory authority approvals Z-14.1-4 [8] or, respectively, Z-14.4-407 [9]. The European approval specifications are thus presented alongside the previous national German regulations in order to allow comparison of the earlier German approval concept with the new European Technical Approval provision both for powder-actuated fasteners as well as fastening screws.

Nevertheless, the relevance and influence the individual parameters have on loading capacity can be interpreted from the approval data – especially for powder-actuated fasteners – only to a certain extent. A further motivating reason for writing this article is thus to illustrate, by means of example, the influence 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

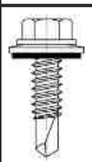
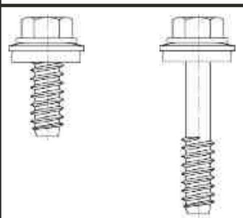
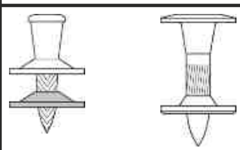
2.1 Basic principles

2.1.1 Methods and terminology

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 are compressed air or gas combustion. In the construction industry, so-called piston-type (Class A) tools are used exclusively [10]. In tools of this type, the piston functions as an inter-

Table 1. Fasteners for metal sheets and liner trays

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

t_I Thickness of each individual sheet

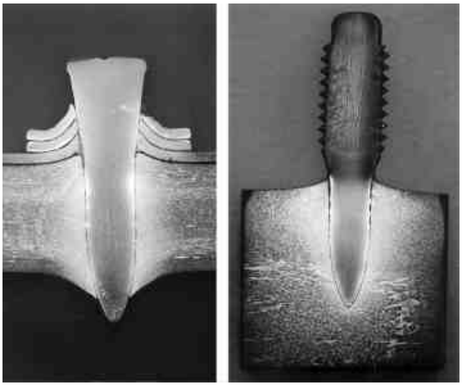


Figure 2. Ground cross-sections of fasteners after driving

mediate element between the fastener and the propellant cartridge, with the effect of reducing the velocity at which the fastener is driven.

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

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. For comparison: The maximum driving energy provided by compressed-air tools is approx. 250 J while gas combustion tools achieve approx. 100 J.

Propellant cartridges are available in various calibers and lengths. The calibers in common use are 6.3 and 6.8 mm. Cartridge power levels are indicated by a cartridge color code in accordance with [11] and by a number, as follows:

White/Brown	– extra low	– power level 2
Green	– low	– power level 3
Yellow	– low/medium	– power level 4
Blue	– medium	– power level 5 (in Europe)
Blue	– medium	– power level 4.5 (in USA, CDN)
Red	– medium high	– power level 6 (in Europe)
Red	– medium high	– power level 5 (in USA, CDN)
Black	– extra high	– power level 7 (in Europe)
Black/Purple	– extra high	– power level 6 (in USA, CDN)

The driving velocity is the key physical parameter that determines whether it is possible to drive a fastener into a hard supporting material such as steel. Even a technically "perfect" fastener could never be pressed statically into solid steel or driven by hand into a hard supporting material with a few hammer blows.

The terminology used has not been standardized. In English, the fasteners are known as "powder-actuated fasteners" or "cartridge-fired pins". In German, the word *"Setzbolzen"* has become established as the generic term for all types of powder-actuated fasteners. These terms refer to the nails equipped with steel washers for fastening

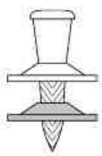
Power-actuated fastener	Direct fastening tool	Energy
	 Powder driven	
	 Gas driven	

Figure 3. Components of direct fastening systems

profile metal sheets and the nails for general (non-removable) fastening applications as well as the threaded studs used to create removable fastenings (Figure 6).

2.1.2 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 [12]. 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 4). 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) [13] 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 [14]. 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.

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.

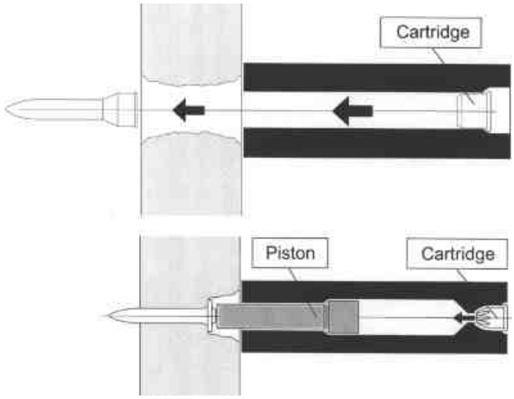


Figure 4. High-velocity tool principle versus low-velocity piston principle

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 for almost all powder-actuated fastening tools available today come in plastic magazine strips. Gas-actuated tools, which use a combustible gas propellant contained in a replaceable canister (the so-called "gas can"), are fully-automatic fastening tools capable of high productivity. The capacity of the gas can is sufficient for approx. 750 fastenings.

2.1.3 CE marking and C.I.P. approval of powder-actuated fastening tools

Powder-actuated fastening tools were integrated in the new edition of the Machinery Directive [15] for the first time in 2006. Until then, the legal basis for the approval of tools of this kind in European states was, for historical reasons, provided by weapon laws. The necessary approvals for powder-actuated fastening tools were issued in accordance with the resolutions [16] of the C.I.P. – The *Permanent International Commission for the Proof of Small-Arms* [1].

The Machinery Directive [15], generally speaking, defines the most important requirements to be met by machinery. The detailed safety requirements, the necessary tests and how they are to be evaluated are laid out in a harmonized standard. These requirements to be met by powder-actuated tools have been worked out by CEN over the last few years on the basis of a European Commission mandate. The current version takes the form of preliminary standard (FprEN 15895:2010 [17]) and is expected to be issued as the standard EN 15895 in the very near future. This standard will cover only powder-actuated fastening tools equipped with a piston and with a maximum fastener exit speed (muzzle velocity) of 100 m/s. In accordance with the nomenclature used in [10] und [16], these powder-actuated fastening tools are powder-actuated tools of the class A.

The first powder-actuated fastening tools carrying CE marking were brought onto the market on the basis of FprEN 15895 in the year 2010. Assessment of their conformity was carried out in accordance with [15] on the basis of EC type testing [18] which had to be carried out by an accredited, independent testing agency. In Germany this agency is the *Physikalische Technische Bundesanstalt Braunschweig und Berlin (PTB)*. As of mid 2011, all powder-actuated tools on the market must bear CE marking.

FprEN 15895 has adopted the previous stringent safety and test requirements of the C.I.P. or, respectively, extended these with the addition of ergonomic requirements. The following points, among others, require to be verified:

- 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.

The C.I.P. is an international organization with European and Non-European member countries. 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. The type identification plates on tools of this kind then bear the C.I.P. mark as well as CE marking as confirmation of their conformity with the Machinery Directive (Figure 5).

The cartridges to be used require their own approval in accordance with the C.I.P. resolutions [16]. The approvals are split between testing of the propellant (the so-called "ammunition" approval), e.g. [19], as well as a system test of the cartridge in conjunction with a certain fastening tool, e.g. [20]. During this test, the influence of unforeseen excessively high pressure on the cartridge and the cartridge magazine strip is tested. This test is to be carried out for all tools in which the cartridge is to be used. The corresponding list of tools with which the cartridge can be used must appear on the cartridge package, stating the system approval number.

PTB S 813	CE
Conformity with C.I.P. resolutions [16]	Conformity with the Machinery Directive [15]
PTB abbreviation indicating the testing agency S abbreviation standing for powder-actuated tool of the Class A 813 approval certificate number	

Figure 5. Conformity marking of powder-actuated tools

Standardizing activities with the objective of introducing CE marking for cartridges are also currently taking place, but in a time frame that differs to that of the tools. The cartridges are covered by the Pyrotechnics Directive 2007/23/EC [21] that was published in 2007. A harmonized European testing standard for cartridges is currently in preparation. It is expected that cartridges bearing CE marking will be brought onto the market as of mid 2013.

In contrast to powder-actuated tools, compressed air or gas-driven fastening tools were covered by the Machinery Directive right from the beginning. Tests and safety requirements for these tools are listed in EN 792-13 [22]. Confirmation of conformity is provided by CE marking.

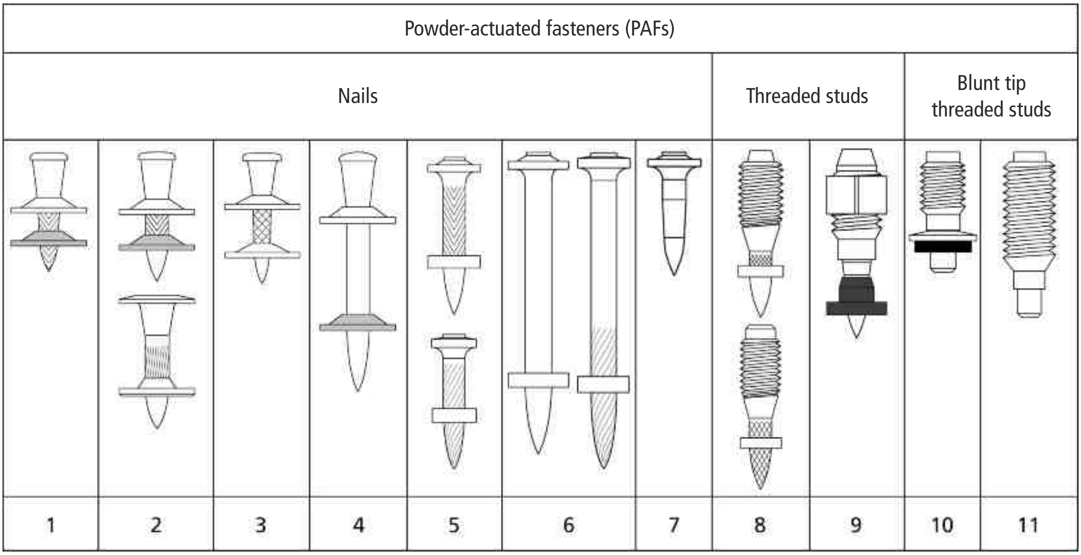
2.1.4 Powder-actuated fasteners: Features and characteristics

Figure 6 provides an overview of the range of fasteners available, their main features and their areas of application.

2.1.4.1 Geometry and form

Powder-actuated fasteners of the types 1 to 9, as shown in Figure 6, 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 63) 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



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) 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 (pre-drilled) 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
11 Stainless, two-part, blunt tip threaded stud

Figure 6. Powder-actuated fasteners for applications on steel

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.

2.1.4.2 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.

Use of smooth-shank, unknurled, galvanized carbon steel fasteners on construction steel is basically possible (see Section 5.6). 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 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.

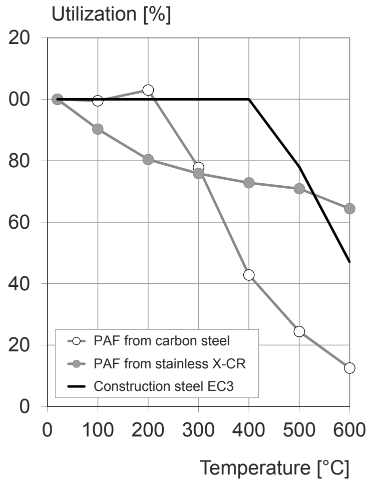
2.1.4.3 Washers

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.

2.1.4.4 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 2 [23–25]. 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 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).

Figure 7 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.



Note: The line representing construction steel shows the influence of temperature on the yield point in accordance with [27].

Figure 7. Influence of temperature on the strength of powder-actuated fasteners.

2.1.4.5 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 fastener is intended for use in safety-relevant fastening applications where the finished fastening is not directly exposed to the weather or moist atmospheres [8, 76] (see Section 2.6).

Stainless steel fasteners suitable for the corresponding ambient conditions should be used in situations where the fastenings are exposed to the weather or dampness. 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.

Table 2. Mechanical properties at room temperature

			Diameter d = 4.5 mm	
Material	Hardness (HRc)	Ultimate strength [N/mm²]	Tensile strength [kN]	Shear strength [kN]
Heat-treatable carbon steel	58	≈ 2200	≈ 35	≈ 21.5
Heat-treatable carbon steel	54	≈ 2000	≈ 32	≈ 20.0
Corrosion resistant steel 1)	49	≈ 1850	≈ 30	≈ 18.5

1) CR-500 according to [26]

2.1.4.6 Blunt tip powder-actuated fasteners

Stainless steel threaded studs are used in environments exposed to the weather or, in some cases, under highly corrosive ambient conditions (e.g. in the petrochemical industry or on off-shore platforms). Sub-structures in these facilities are, of course, coated or hot-dip galvanized in order to meet requirements for their own protection from corrosion. Fastenings made to structures in such facilities therefore often have to be made on materials with a protective coating. Stud welding techniques generally require previous preparation of the surface of the supporting material. This is not necessary with powder-actuated fasteners. Nevertheless, if the powder-actuated fastener penetrates right through the supporting member, the protective coating on the reverse side will also be damaged. The coating then has to be repaired or touched-up at the point of through penetration. The corrosion protection coating also suffers some damage at the point of entry of the fastener into the supporting material.

Blunt tip, stainless steel powder-actuated fasteners which solve this problem of penetration through materials with a thickness of $t_{II} \geq 8$ mm have been on the market since 2003. These fasteners comprise three sections: a cylindrical pin with a diameter of 4.5 mm and upset forged head, a threaded sleeve pushed onto the pin and a sealing washer. Figure 6 shows examples of blunt tip fasteners of this kind.

A blunt tip powder-actuated fastener cannot be driven directly into the supporting material. A pilot hole with a diameter of 4 mm must be drilled in advance at the point where the fastening is to be made. A special stop-type drill bit must be used for this purpose. This drill bit scrapes the coating away on the surface of the supporting material, providing an indication of having reached the correct depth. The ring scraped away by the drill bit (outer diameter 7 mm) is protected from corrosion by the sealing washer once the fastener is driven. When an electric drill suitable for drilling in steel is used (≥ 3500 r.p.m.), it takes about 6 seconds to drill this hole.

The blunt tip fastener is subsequently driven by "conventional" means, using a powder-actuated fastening tool, into the base material at the point where the hole has been pre-drilled. The blunt tip of the fastener is chamfered to facilitate centering in the pre-drilled hole. The system concept mentioned in Section 2.1.5 also applies to this fastening system. Only the fastening tool specified by the manufacturer for this application may be used for driving these fasteners. This tool has a built-in piston brake (see Section 2.3.3.1) which ensures that the very narrow depth of penetration tolerances are adhered to. The effective depth of penetration for the blunt tip powder-actuated fasteners, i.e. the length of contact between the pin and the supporting material is approx. 4.5 mm.

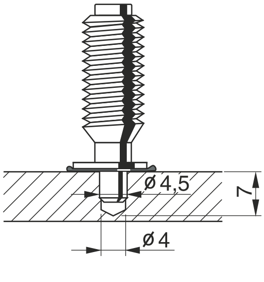


Figure 8. Blunt tip powder-actuated fastener Hilti X-BT after driving

2.1.4.7 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 approval are deposited with the DIBt (or with the corresponding EOTA approval body). The manufacturers of products holding approval are obliged to verify conformity of the products with the provisions of the corresponding approval.

2.1.5 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 [28], 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.

Accordingly, the entire powder-actuated fastening system must be verified as a whole as part of the procedure for European technical approvals. 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 approval.

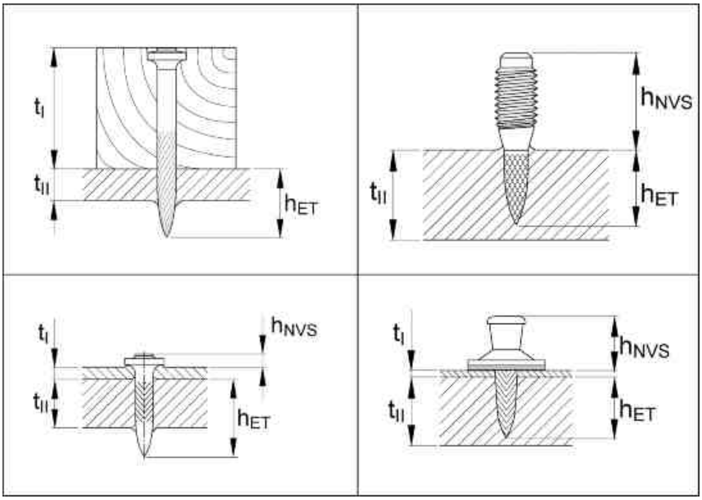


Figure 9. Components I and II, depth of penetration h_{ET} and fastener stand-off h_{NVS}
Component I: fastened component, thickness t_I
Component II: base material, thickness t_{II}

2.2 Powder-actuated fastening terms and definitions

2.2.1 Depth of penetration and fastener stand-off

Figure 9 shows examples of powder-actuated fastenings. In accordance with the nomenclature used in [29], 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. Above a certain base material thickness, i.e. thickness greater than 15 to 20 mm depending on the type of fastener used, any additional increase in the thickness of the material has no further effect on the fastener driving process or the hold it obtains. 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.

Fastener standoff 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 103).

2.2.2 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 10 shows an example for a profile metal sheet fastener ([76] or, respectively, Figure 103). 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 is the decisive cause of failure during the driving operation (see Figure 75).

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 approval procedure.

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

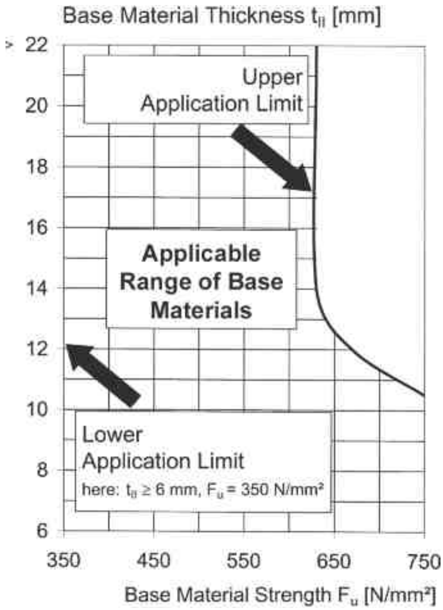


Figure 10. Application limit diagram

incorrect as they do not represent the actual physical behavior.

2.3 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 11).

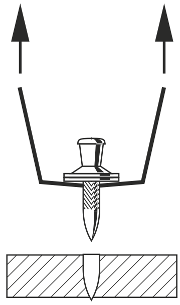


Figure 11. Anchorage failure

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 [30]. Within the scope of the approval process, 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.

2.3.1 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 [31, 32]. 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 12) provides proof of this microkeyed hold and material bonding. The anchorage obtained by stainless steel fasteners takes the form of a friction hold and welding effect.

Analytical computation models for determination of the loading capacity of the anchorage are not published or, respectively, are not part of the applicable regulations. Verification of the loading capacity of the anchorage thus has to be provided by tests. The relative shares of each of

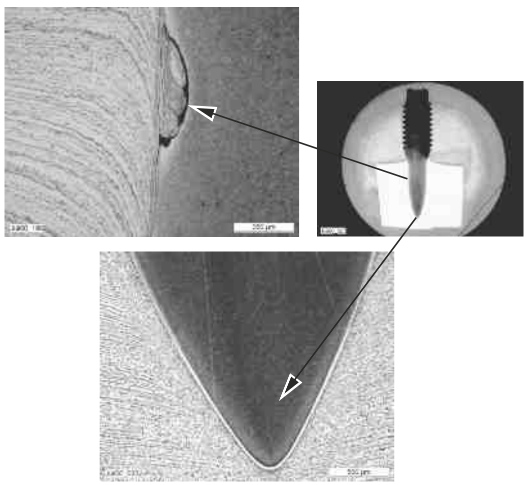
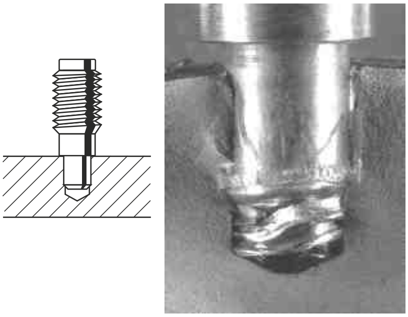


Figure 12. Micrographs of fastener anchorage



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

Figure 13. Cross section of a blunt tip fastener

Figure 14. Base material adhering to a pulled-out fastener

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 [33].

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 13). 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 14 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.

2.3.2 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 15 [34]. 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 16 shows examples of load-displacement curves for S235 and S355 steels.
After reaching loading capacity, which is determined by failure of the welded zones, the blunt tip studs still take up forces approximately equal to the recommended working loads with a displacement of 2 to 3 mm. Loading

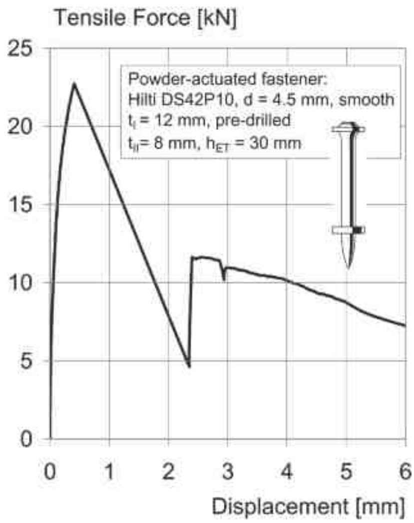


Figure 15. Load-displacement curve for fastener with great driving depth and complete penetration of the base steel

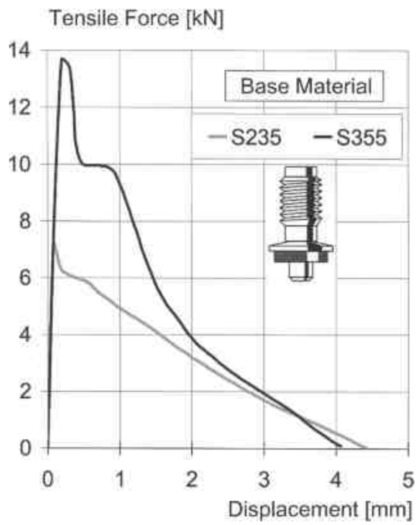


Figure 16. Load-displacement curves for blunt tip fasteners Hilti X-BT in solid steel

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 shank of the fastener (Figure 14).

2.3.3 Parameters influencing anchorage

2.3.3.1 Depth of penetration

Depth of penetration is the key parameter influencing the quality of the fastening. Figure 17 shows a good example of how it influences the pullout loads achieved by threaded studs [35]. 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
- 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 9). The fastener stand-off range to be observed and the maximum permissible thickness of the component to be fastened are defined in the fastener approval or, respectively, in the technical documentation provided by the manufacturer. Observance of these conditions ensures that fasteners are driven to the correct depth.

Figure 18 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 17, 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.

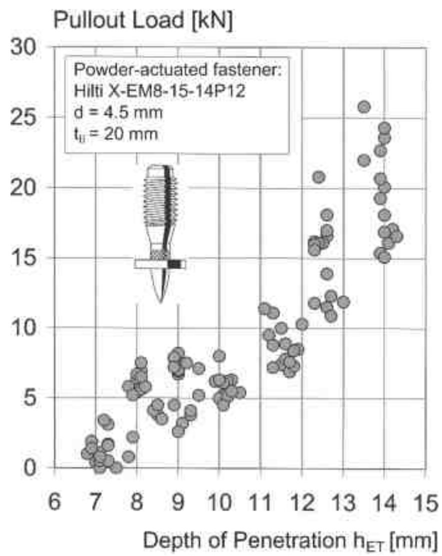


Figure 17. Influence of depth of penetration in solid steel

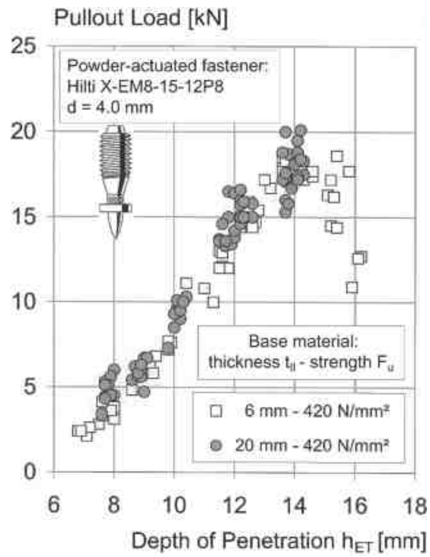


Figure 18. Influence of depth of penetration in base materials with a thickness of 6 mm or 20 mm

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 18 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 pis-ton completes the driving operation.

Figure 19 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.

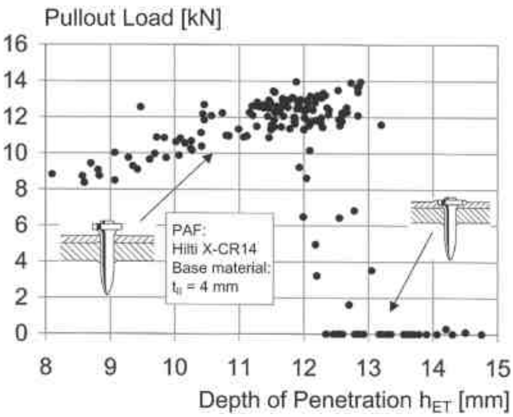


Figure 19. The effect of excess driving energy when fastening to thin materials

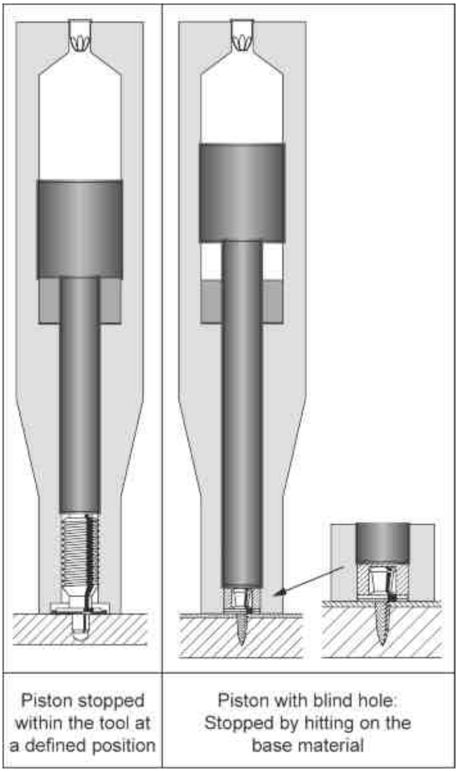


Figure 20. Piston brake concepts

The negative effect of excess energy on fastener anchorage can be avoided when this point has been taken 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 dam-aging 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 inte-gral 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 mm $\leq t_{II} <$ 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 19).

2.3.3.2 Base material thickness

Figure 21 shows the results of tests evaluated according to the thickness of the base steel [35]. 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 materi-als of a thickness in which the point of the fastener only just penetrates right through [36]. 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 21 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 22). 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

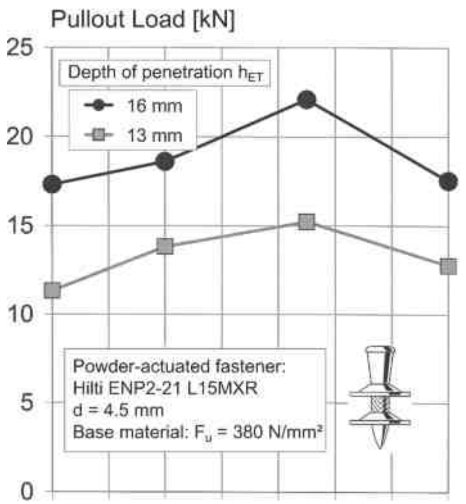


Figure 21. The influence of base material thickness for $t_{II} \geq 6$ mm

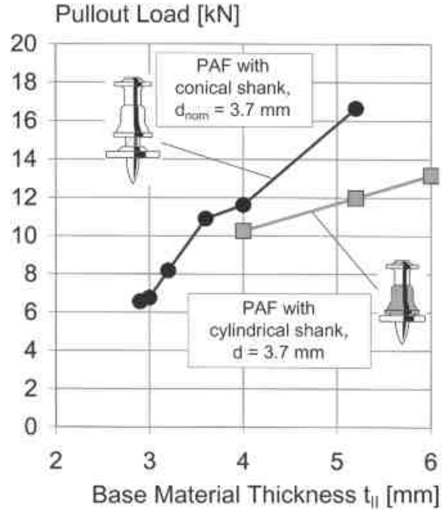


Figure 22. The influence of base material thickness for $t_{II} < 6$ mm

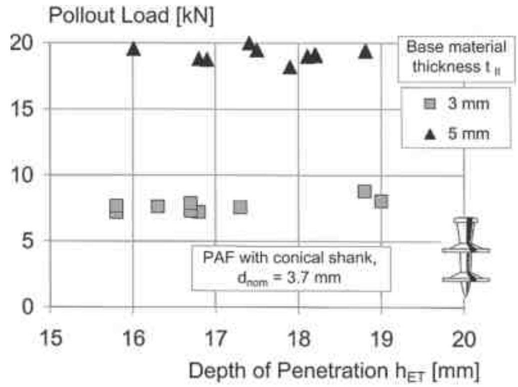


Figure 23. The influence of depth of penetration for $t_{II} < 6$ mm

anchorage loading capacity becomes independent of depth of penetration, is exceeded (Figure 23) – subject consideration of excess energy effect in accordance with Figure 19.

2.3.3.3 Base material strength

The loading capacity of the anchorage generally increases as the strength of the base material is increased [35] (Figure 24). 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 approval procedure, 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

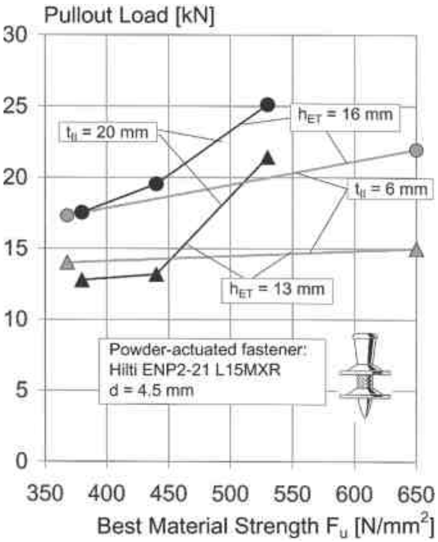


Figure 24. The influence of base material strength

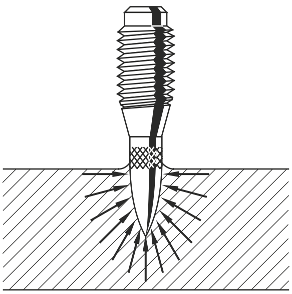


Figure 25. Elastic reaction (resilience) when depth of penetration is inadequate

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 25) [37]. As part of the European approval 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 16 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 capac-ity in the area of the welded zone (Figure 14). For example, more than half of the blunt tip fasteners driven into high-strength S960 steel achieve an ultimate load of about 30 kN in tests with mode of failure being breakage of the fastener shank.

2.3.3.4 Knurling

The effect of knurling on the fastener (see Section 2.1.4.2) is shown as an example in Figure 26, with data from pull-out tests using fasteners with knurled and smooth shanks in which all other test parameters re-mained 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. An advantage of fasteners with knurled tips (see Figure 6, 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 27 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 17).

2.3.4 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

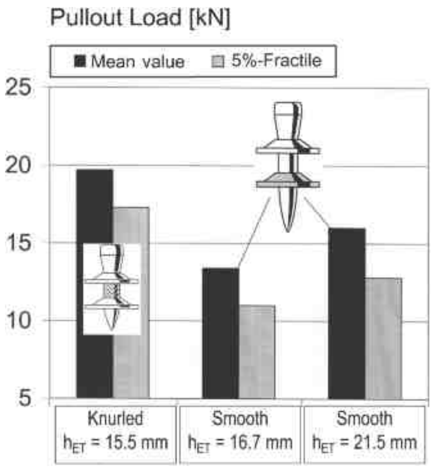


Figure 26. The influence of knurling on the fastener

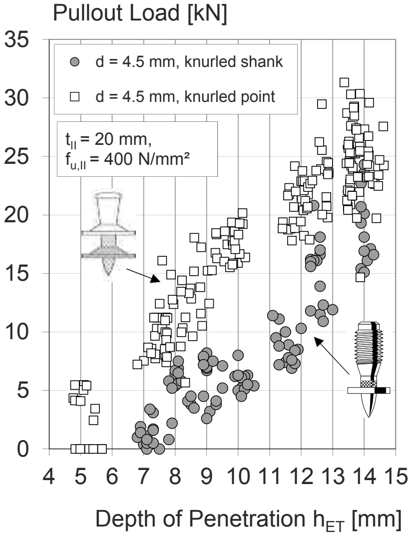
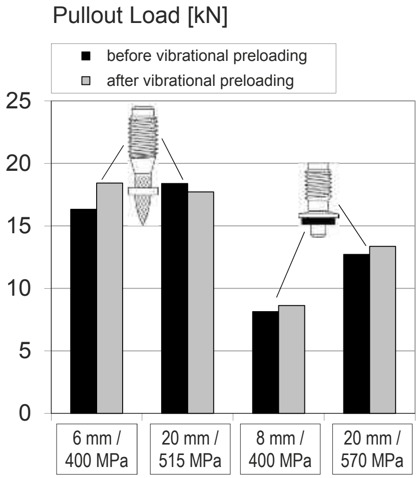


Figure 27. Influence of tip knurling on the required fastener driving depth



Carbon steel fastener with knurled tip: Hilti X-EM8H
Blunt-tip stainless steel fastener: Hilti X-BT

Figure 28. The influence of vibrational preloading

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 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 to their specified depth of penetration.

2.3.4.1 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.

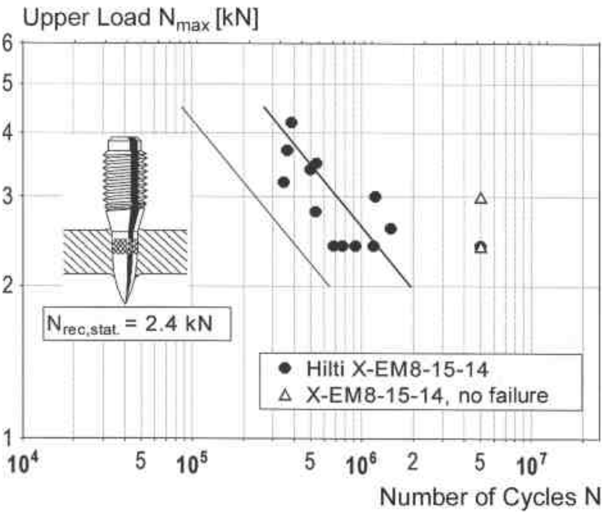


Figure 29. Pulsating tensile tests with galvanized carbon steel threaded stud

Figure 28 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 pre-loading. 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.

Dynamic testing using strips of sheet metal forms part of the testing 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 8.3.2).

The test results available ([31, 38] 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 and, in the tests of the threaded

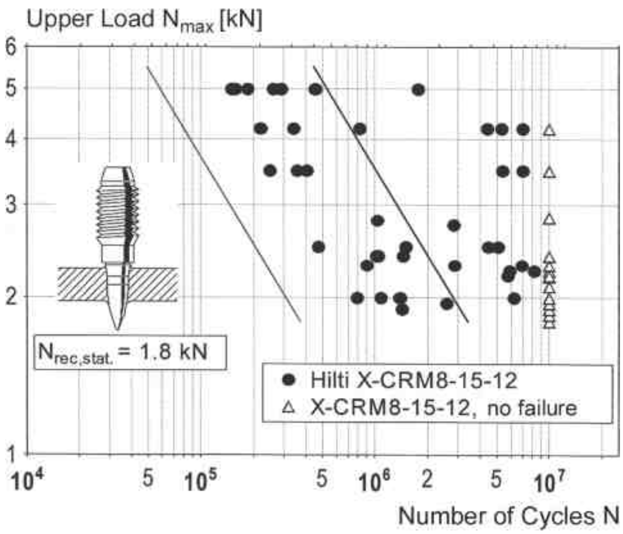


Figure 30. Pulsating tensile tests with stainless steel threaded stud

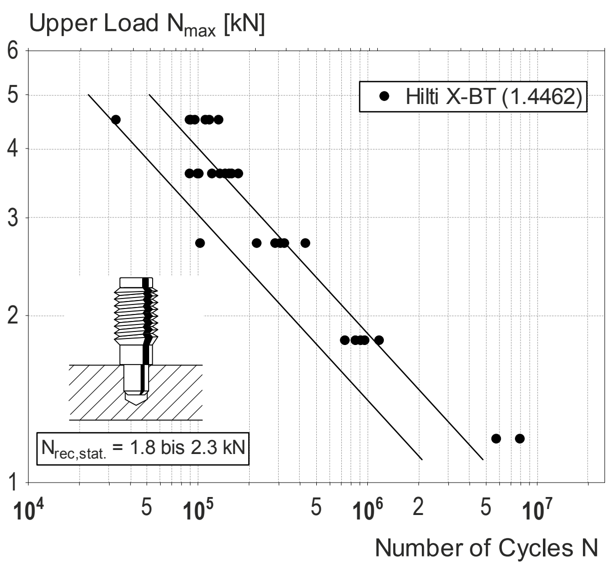


Figure 31. Pulsating tensile tests with stainless steel blunt tip threaded studs made from material 1.4462

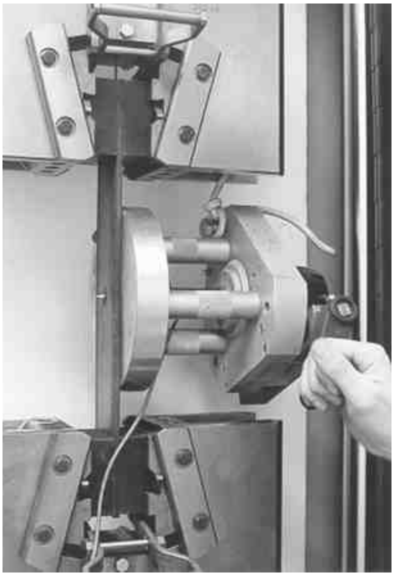


Figure 32. Test setup for pullout tests from base material subjected to stress

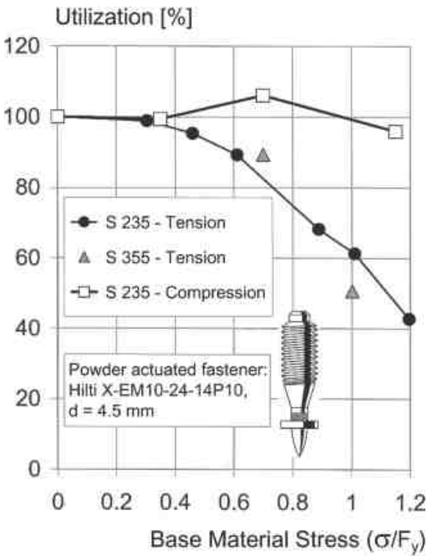


Figure 33. The influence of stress in the base material on loading capacity of the anchorage

studs, the threaded stud itself failed due to fatigue fracture of the material from which the fas-tener is made. Figures 29 to 31 show the results (individual values, linear regression and characteristic Wöhler curve) of pulsating tensile loading tests ($R = N_{min}/N_{max} \approx 0$) in which the tensile load is centrically applied to galvanized, stainless steel and blunt tip 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 durability 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 [31].

The tests also show that a generally applicable value cannot be given for the fatigue strength of powder-actuated fasteners. This 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). The blunt-tip fasteners, for example (with shanks made from 1.4462 material, Figure 31), show lower scatter and a less steeply rising Wöhler curve than the stainless steel threaded studs (made from CR500 material in accordance with [26], Figure 30). In both cases the steel pin fails due to breakage. With the blunt-tip fasteners this occurs, in every case, about 1 mm below the surface of the base material. With the threaded studs, however, breakage occurs at various places along the length of the shank, depending on the geometry of the notches present.

Please refer to Section 4.1.2.1 for verification of fastener fatigue strength.

2.3.4.2 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 [39]. 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 32).

Figure 33 shows fastener pullout loading capacity relative to tension or compression on the base material. For

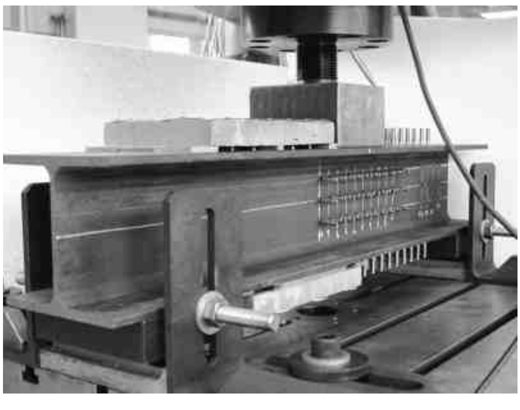


Figure 34. Test setup for application of dynamic stress to the base material

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.

Compressive stress in the base material has neither a negative nor positive (load-increasing) effect on the pull-out 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 [39].

2.3.4.3 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 [40]. 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.

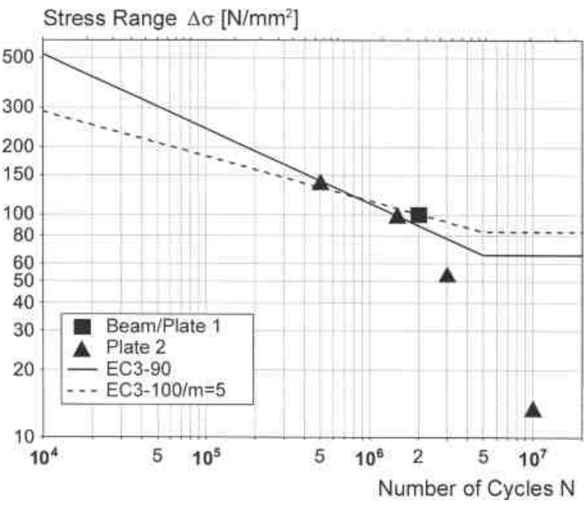


Figure 35. Stress ranges corresponding to the loading protocol

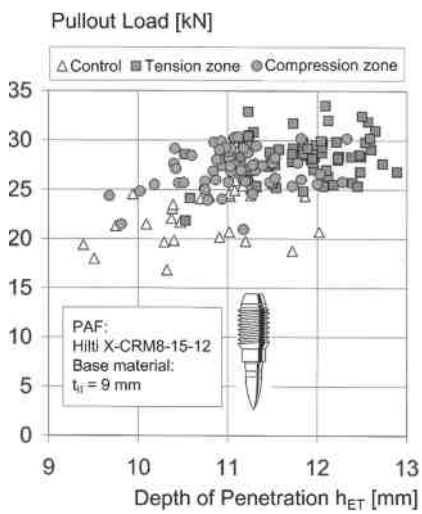


Figure 36. Influence of vibration of the base material on stainless steel threaded studs

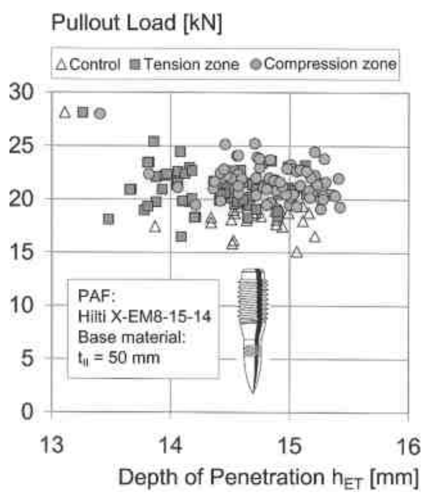


Figure 37. Influence of vibration of the base material on carbon steel threaded studs

Stainless steel and carbon steel fasteners were tested in [40]. These fasteners were driven into two different test beams, an HE-A 140 steel profile (Figure 34) 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 35) was oriented toward the fatigue strength of steel with powder-actuated fasteners (see Section 2.5.2). 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 36 and 37 show examples of the results from [40]. 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.

2.3.4.4 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 [41] resulted to the reduction of pullout resistance according to Table 3.
Grinding off the points does not cause uncontrolled damage to the fastener anchorage. However, the influence on allowable loads shall be taken into account by applying load reductions for the applicable fastener type.

2.3.4.5 The influence of temperature

Table 4 shows the influence of temperature on the loading capacity of blunt-tip stainless steel threaded studs. Up to a temperature of 400 °C, pullout resistance increases as temperature rises. At 600 °C the pullout loading capacity is still about 70 % of the original loading capacity in a cold state. Therefore, the presence of such temperatures will in general not control design of the threaded stud connection. A verification at elevated temperatures 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.
The loading capacity of the fastener anchorage also remains largely unaffected at low temperatures. The stainless steel material's higher coefficient of thermal expansion has no negative effect on the hold obtained by the fastener under these conditions.

2.4 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-

Table 3. Influence of ground fastener points [41]

	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

Table 4. The influence of temperature on the anchorage

	Characteristic pullout load N_{Rk} [kN]	
Temperature [°C]	S 235	EH 36
20	10.5	10.2
–50	12.8	15.0
200	11.7	14.9
400	12.6	14.5
600	7.5	8.7

PAF: Hilti X-BT M8
Base material: S 235: t_{II} = 8 mm, f_u = 455 N/mm²
EH 36: t_{II} = 8 mm, f_u = 535 N/mm²

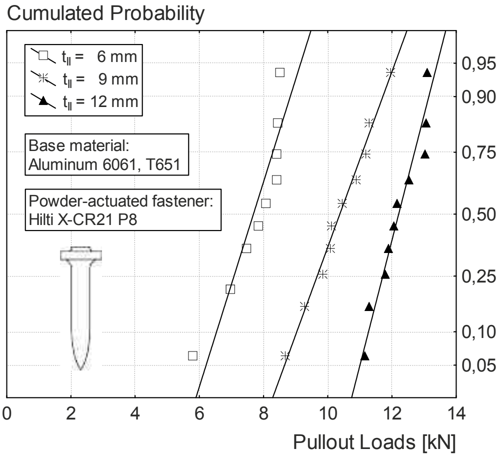


Figure 38. Example of the loading capacity of stainless steel powder-actuated fasteners in aluminum

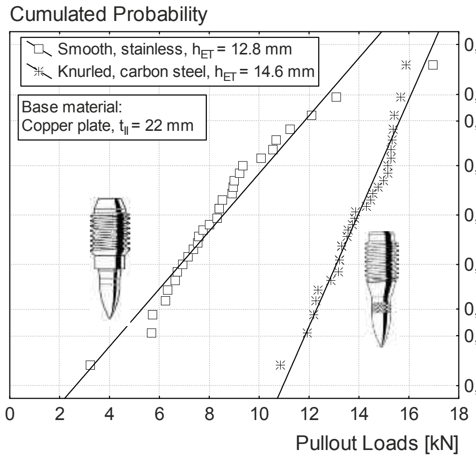


Figure 39. Loading capacity of threaded studs set in a copper plate

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 [42–44]. Figure 38 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 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 (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, predrilling in stainless steel 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 38 provides an appropriate example for a 6061 aluminum alloy with a strength of approx. 330 N/mm² (state T651). The fastener penetrates right through aluminum base material sheet of all thicknesses 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 6, 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 5.7).

A further example of the loading capacity of powder-actuated fasteners driven into a non-ferrous metal is given in Figure 39. 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 manu-

facturing). 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.

2.5 Influence on the base material structural steel

2.5.1 Influence on net section efficiency

The influence of powder-actuated fasteners on the static stress-strain characteristics of construction steel have been systematically analyzed in [45]. Tensile tests were conducted using steel coupons into which various types of powder-actuated fasteners were driven at various spacings. Table 5 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 40 and 41 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 %.

Table 5. Test parameters: Influence of powder-actuated fasteners on the net section efficiency of structural steel [45]

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 (EN 10025) • S 355 (EN 10025) • Grade 50 (ASTM 607)	• 6.0 x 45 mm • 3.5 x 74 mm

1) Hilti ENP2-21L15, X-EM10, X-EDNK22 THQ12, X-CRM8

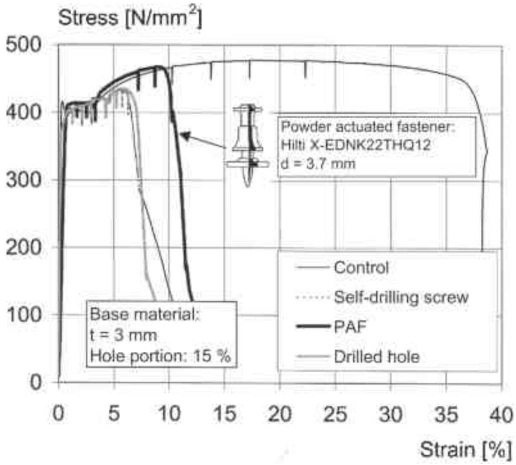


Figure 40. Stress-strain characteristics of steel with high tensile strength

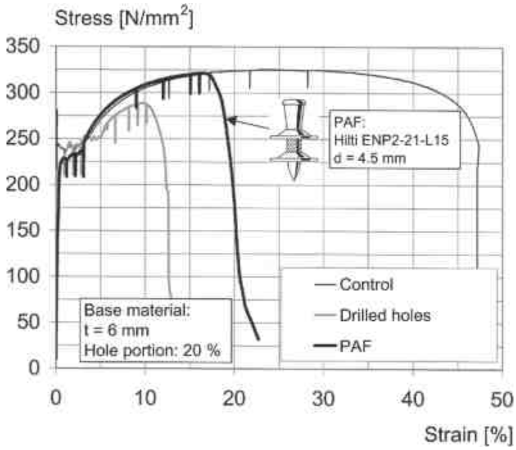


Figure 41. Stress-strain characteristics of steel with low tensile strength

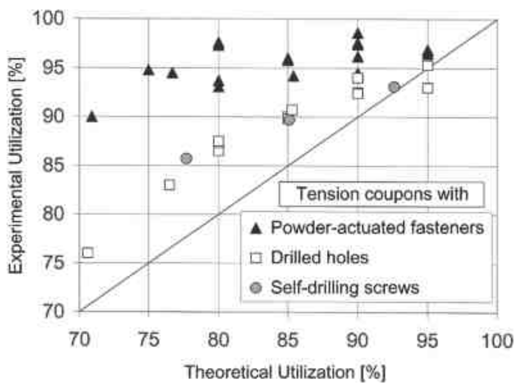


Figure 42. Theoretical and experimental utilization of structural steel with powder-actuated fasteners

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 42). 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

N_u Ultimate tension load determined from tests

F_u Tensile strength of the (unweakened) steel tested

Figure 42 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.

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 maximum permissible values for the ratio A_{gross}/A_{net} for S235 and S355, up to which the deduction for holes can be neglected, is given in the old DIN standard 18800-1:1990 [46] (element 742). This limiting ratio can be calculated from the current basic standard 18800-1:2008 or, respectively, the future basic standard DIN EN 1993-1-1:2010. Table 6 provides an overview of the maximum permissible (limiting) values. For comparison, the corresponding ratios for typical American construction steel in accordance with [48] are also given.

These maximum permissible values are lower in accordance with the new basic standard as, on the one hand [49], a partial safety factor γ_{M0} of 1.00 was specified and, on the other, the minimum strength for S355 was reduced to 490 N/mm².

With S235 and S275, in many cases in practice, the weakening effect of holes made by powder-actuated fasteners is still clearly below the maximum permissible values according to the new basic standard [7]. 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 [7] (see formula (6.7)).

In accordance with the new basic standard DIN EN 1993-1-1 [7], on the other hand, verification of breakage in the net cross-section in general controls design of tensile members made from S355. From previous considerations it was deduced that the design rules for drilled holes can be conservatively applied for powder-actuated fasteners [1]. Applying these rules, in cases where components made from S355 are under high tensile stress, the presence of a powder-actuated fastener must, strictly speaking, be taken into consideration in verification calculations. The influence of powder-actuated fasteners on the tensile strength of construction steel is, however, much more favorable than that of drilled holes. Figure 42 shows an overview of the results. The explanation for this is that the base material is not removed, but simply displaced in the area around where the fastener is driven, forming favorable compressive residual stresses within the material (Figure 45). For good agreement between theory and practice, only a fraction of the full calculated weakening caused by holes made by fasteners would need to be applied to the theoretical model. If this reserve is taken into account, the general approach to consider the presence of powder-actuated fasteners in the verification of

Table 6. Comparison of the 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 18800-1:1990 [46]	DIN 18800-1:2008 [47]	DIN EN 1993-1-1:2010 [7]	AISC Steel Construction Manual [48]
S 235	1.20	1.20	1.10	–
S 275	1.15	1.19	1.12	–
S 355	1.10	1.04	1.00	–
ASTM A36 2)	–	–	–	1.35
ASTM A572 Grade 50 3)	–	–	–	1.08

1) S235, S275, S355 as per EN-10025-2 [30]

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

breakage is too conservative. 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 approvals for fasteners.

In addition to the tensile tests of steel coupons described in [45], *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 [39] and [50] for details.

2.5.2 Influence on fatigue strength

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 [51]. This structure consisted of the loadbearing components of the bridge, covered by a thin layer of insulating material and an outer skin of 2 to 3 mm thick sheet metal. This outer layer of sheet metal had to be fastened permanently to the substructure by way of mechanical fasteners. During the course of preliminary investigations [51], it was determined that the powder-actuated fastening method would be most suitable for this purpose. Other alternatives investigated included threaded studs welded on with circular fillet

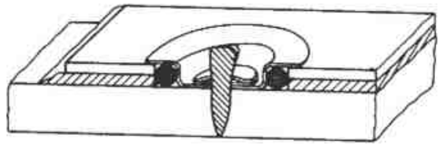


Figure 43. Retaining pieces, from [52]

Table 7. Test parameters: Fatigue tests of structural steel containing powder-actuated fasteners [52]

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

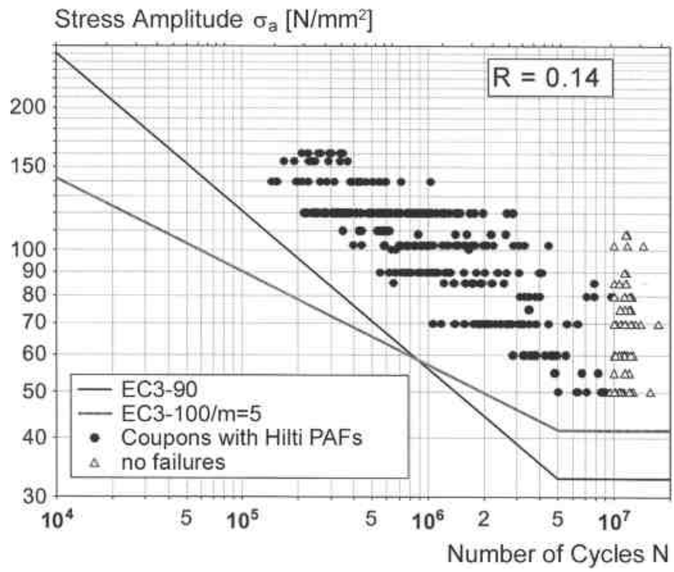


Figure 44. Fatigue strength test results of base steel containing powder-actuated fasteners for R = 0.14

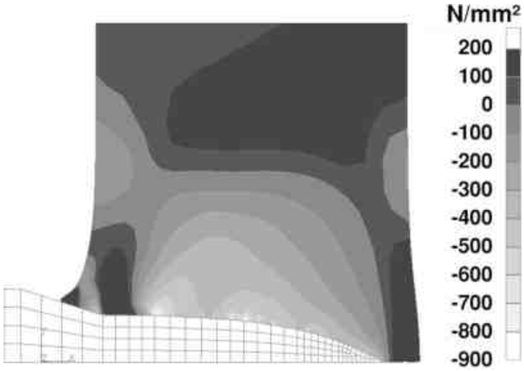


Figure 45. Residual compressive stresses acting toward the circumference in the vicinity of the fastener

welds or, respectively, countersunk-head screws. The powder-actuated fasteners fixed the outer sheet metal skin to the steel substructure by way of special retaining pieces (Figure 43).

Further systematic analysis to determine the fatigue strength of a base material containing powder-actuated fasteners was conducted in the early 1980s by *Melber* [52]. An overview of the test parameters for more than 1´000 fatigue tests is provided in Table 7. Figure 44 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 [53, 54]. 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.

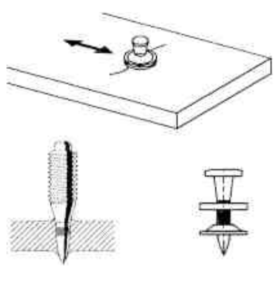
The qualitative explanation for this behavior is given in [51]: On the one hand, strain-hardening of the plastically deformed base material occurs locally in the vicinity of the powder-actuated fastener while, on the other hand, residual compressive stresses in the base material acting toward the circumference 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 [32], and the result of a numerical simulation of the driving process is shown in Figure 45 [55].

The results of tests [52] were evaluated by *Niessner* und *Seeger* [57] in accordance with Eurocode 3 [56] 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 [53, 54], see Table 8, which was taken from [53].

2.6 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

Table 8. Fatigue classification of the constructional detail "base steel with powder-actuated fasteners" in keeping with Eurocode 3 (table taken from [53])

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.

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 ºC). 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) [58]. 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.

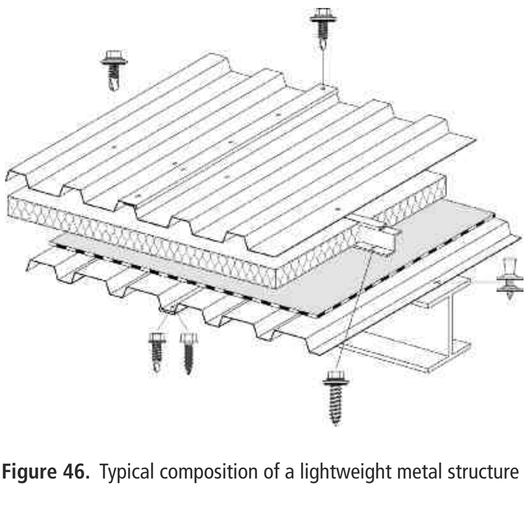


Figure 46. Typical composition of a lightweight metal structure

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 [8, 76] 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 [59].
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 classes A2 and A4 can be found, for example, in acidic atmospheres containing chloride (e.g. in indoor swimming pools or in road tunnels).
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 [60], 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 negligible.

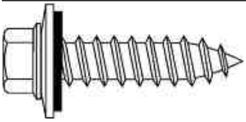
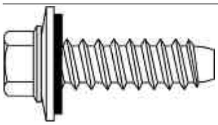
3 Fastening screw technology

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 and sandwich panels to the supporting substructures and to fasten

Table 9. Areas of application for self-tapping screws

Screw	Base material thickness t_{II}	Example of application
	0.63 – 3.0 mm (steel) ≥ 26 mm (screw driving depth in timber)	Overlap joints and profile metal sheets and sandwich panels on timber
	≥ 1.25 mm	Profile metal sheets or sandwich panels on steel beams

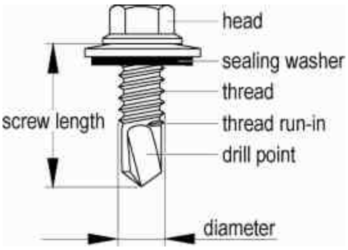


Figure 47. Fastening screw designations

Figure 48. Self-tapping screws with a point or blunt tip

sheet metal to sheet metal, e.g. at overlap joints. 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 the screws are subjected to wind loads and must be designed accordingly. Screws at longitudinal and transvers 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.
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 pre-drilling 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 47.

3.1.2.1 Self-tapping screws

Self-tapping screws are either made with a point or have a blunt tip (Figure 48). 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 3.0 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 pre-drilled hole diameter required depends on the thickness of the base material and are specified in construction supervisory authority approvals.

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. In order to ensure that the sheet metal can be clamped

properly against the base material, further measures are necessary, as described in [61].

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.

There is also a new type of screw that penetrates the steel base material without drilling (type 3 shown in Table 10). It does so by displacing the metal around it in the part to be fastened and in the supporting structure, thereby achieving an optimum keyed hold and thus the ability to take up higher loads (Figure 100). 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.

Figure 49. Self-drilling screw

Figure 50. Self-drilling screw without drill point

Table 10. Areas of application for self-drilling screws

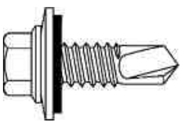
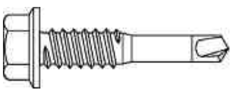
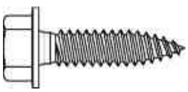
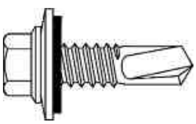
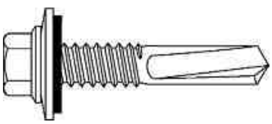
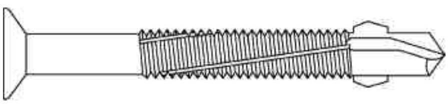
Screw type	Total sheet metal thickness Σt_i	Examples of applications
 (1) With short drill point	2 x 0.63 mm – 3.0 mm	Overlap joints and profile metal sheets on C- and Z-profiles
 (2) With reduced diameter drill point	2 x 0.50 mm – 2 x 1.50 mm	Overlap joints
 (3) Without drill point	2 x 0.50 mm – 2 x 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 51. Screw for fastening sandwich panels

Figure 52. Roofing membrane fastener: screw and load distribution plate

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 a secondary 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.

3.1.2.4 Screws for fastening roofing membranes

Roofing membrane fasteners (screw with load distribution plate, see Figure 52) 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 [62]. 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. 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).

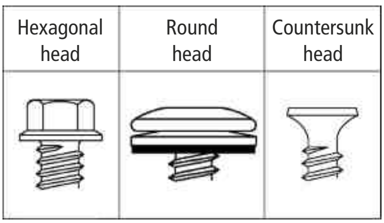


Figure 53. Screw heads

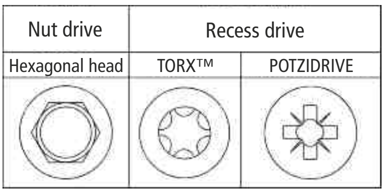


Figure 54. Drive types

3.1.2.5 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 [61].

3.1.2.6 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

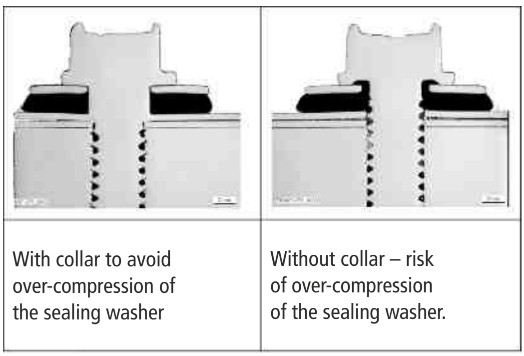


Figure 55. Screws with sealing washer, with and without collar

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 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.

3.1.2.7 Materials and their mechanical characteristics

Fastening screws are manufactured from carbon steel standardized in accordance with DIN EN 10084 (so-called carbon steel screws, typically with a carbon content of about 0.2 %), or from stainless steel in accordance with DIN EN 10088. 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/mm² and a shear strength of 600 – 700 N/mm². Stainless steel screws have a mean tensile strength of about 800 – 900 N/mm² and a shear strength of 400 – 500 N/mm².

3.1.2.8 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/mm²). The same technical relationships, as described in Section 2.6, 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 coating (e.g. KwikCote as per [63]) which provides greater protection against corrosion, thus making the screws suitable for use in situations where they are directly exposed to the weather. Stainless steel screws should, however, be used in situations where the screws are exposed to damp environments or weathering in corrosive or very corrosive atmospheres. Stainless steel screws generally meet the requirements of corrosion resistance class A2. Screws of the class A4 are also available for use under the most demanding conditions.

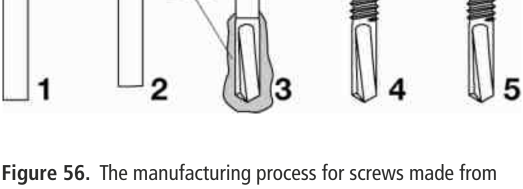


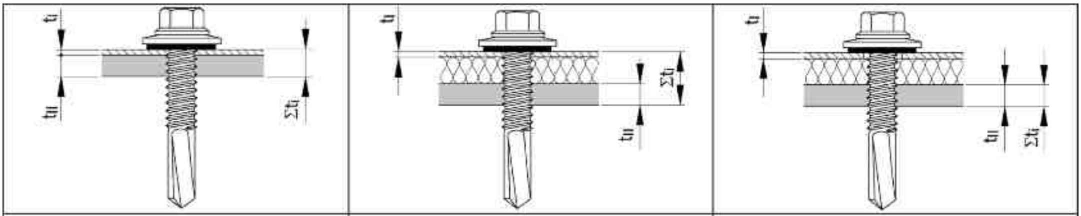
Figure 56. The manufacturing process for screws made from carbon steel

3.1.2.9 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 56. 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 is 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 56. During the heat treatment process, only the tip and the thread run-in are hardened.

3.1.3 Interdependency: Screws – screwdrivers

The quality of a screw fastening and the driveability 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



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

Figure 57. Drilling capacity Σt_i

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).

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 fastened, 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 Σt_i in order to be able to drill all the way through the total stack to be fastened. 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 57.
The minimum sheet metal thickness for use of screws is 0.5 mm, which results in a minimum fastening stack of 2 x 0.5 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 58 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

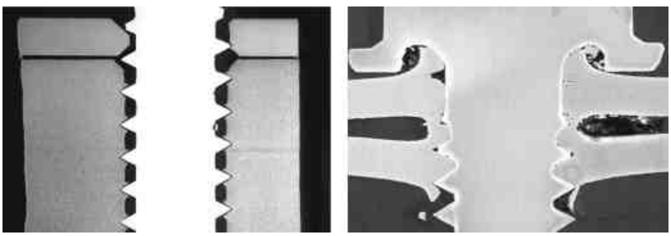


Figure 58. Anchorage in thick steel and joining thin metal sheets

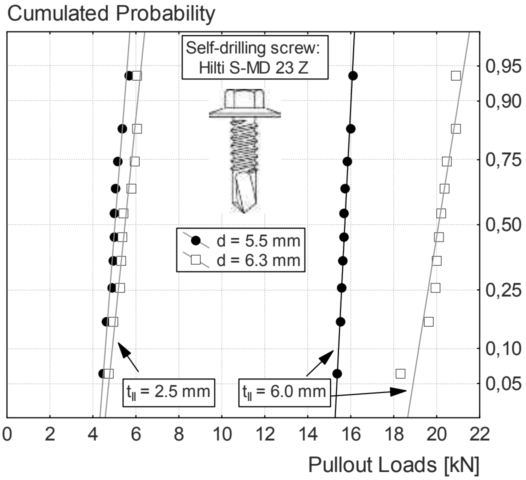


Figure 59. The influence of screw diameter and base material thickness on the anchorage

assessments require to be carried out in order to investigate the robustness of the anchorage obtained by 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 2.3.4). 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 0.63 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 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.

4 Verification concepts

4.1 Loading capacity

4.1.1 Predominantly static loading

Definite guidelines are applicable to the approved applications. The semi-probabilistic safety concept with the general verification equation (1) has now also been implemented in all national approvals. The characteristic loading capacity can be calculated in accordance with DIN EN 1993-1-3 [64] for certain types of failure, e.g. hole elongation in the sheets fastened. With certain types of failure, however, e.g. the pullout loading capacity of powder-actuated fasteners and fastening screws, the loading capacity can be determined reliably only by experiment. The corresponding tests must then be carried out in accordance with the relevant approval criteria (see Sections 8 to 10). Evaluation of these test results then provides the characteristic loading capacities with the corresponding partial safety factors.

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

with

S_d design value of actions
R_d design value of resistance

For applications not regulated by approvals, the manufacturers of powder-actuated fasteners generally publish recommended working loads in their technical documentation [31, 65]. These are based on the manufacturers' own safety concepts. Verification then takes place at working load level:

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

with

S_k characteristic action
R_{rec} recommended working load

For verification at design load level, the partial safety 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:

$$\gamma_F \cdot S_k = S_d \leq \gamma_F \cdot R_{rec} \quad (3)$$

Steel deck diaphragms can be designed either in accordance with DIN EN 1993-1-3 [64] or, as before, in accordance with DIN 18807-3 [66]. The latter will remain in force in future and will not be superseded by EN 1993-1-3. EN 1993-1-3 covers general points concerning the design of steel deck diaphragms: 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, EN 1993-1-3 makes references to ECCS publication no. 88 [67].

4.1.2 Dynamic loading

4.1.2.1 Vibrational loading

For fatigue strength design of powder-actuated fasteners and fastening screws, apart from pullover tests with dynamic loading (see Section 8.3.2), there are neither notch classifications in EN 1993-1-9 [56] nor general testing guidelines listed in the approval criteria. For specific applications it is recommended that verification of fatigue strength is calculated in accordance with the Eurocode 3 regulations [56] 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 safety factors for the applicable actions, taking damage tolerance into account.

In accordance with Section 2.3.4.1, the anchorage of powder-actuated fasteners is generally not the decisive factor in the fastening's resistance to fatigue. This is determined 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, must be taken into account.

For the sake of clear comparison, Wöhler diagrams for powder-actuated fasteners (Figures 29 to 31) use the load range (upper load N_{max} for $R = 0$) of the oscillating force and not a nominal stress range.

4.1.2.2 Seismic loading

The current approvals for powder-actuated fasteners and fastening screws do not cover dynamic loading subsequent to earthquakes. For example, such loading will be relevant if the fasteners are used as part of a steel deck diaphragm, which secures lateral stability of a building in the seismic event. In Europe at present no specific seismic rules for use of powder-actuated fasteners and fas-

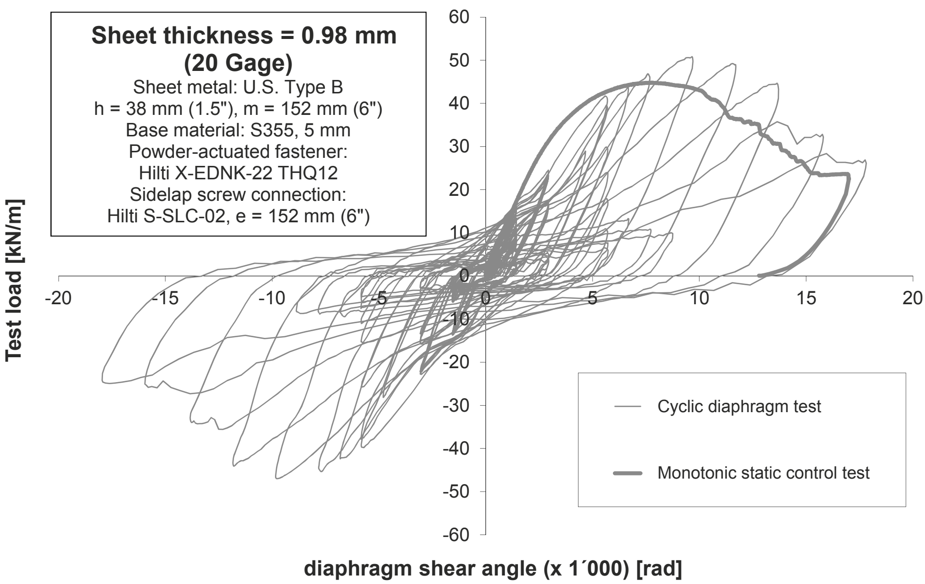


Figure 60. Cyclic load-displacement behavior of a steel deck diaphragm under seismic loading [70]

tening screws in steel deck diaphragms are available as well.

In the USA, on the other hand, powder-actuated fasteners and fastening screws have been used for decades as mechanical fasteners of steel deck diaphragms of non-dissipative structures. 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 [68–71]. 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 2.3.4.1).

Figure 60 shows an example of a plastic, cyclic load-displacement behavior of a steel deck diaphragm. With profile metal sheets with a thickness of up to about 1.0 mm the result is a hysteresis curve that is characterized by the effects of elongation of the holes in the metal sheets at the fastening points (Figure 61). Figure 60 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 curve. This good-natured behavior can thus also be taken advantage of in dissipative structures by making use of the capacity method [72]. However, the corresponding approval criteria for this application are not yet available in the USA.

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, dynamic verification would require a project specific approval for the selected fastening solution.

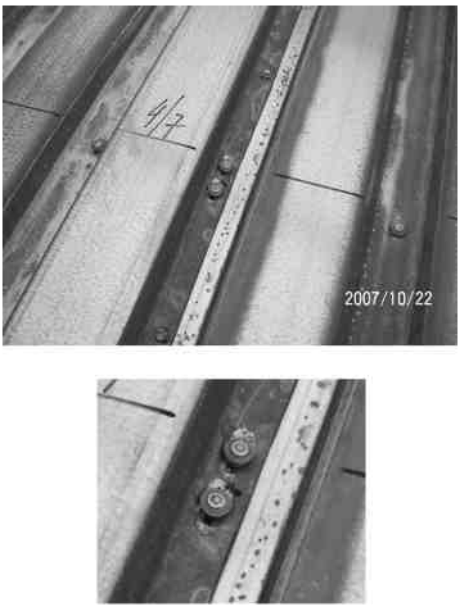


Figure 61. Hole elongation during cyclic shear loading tests

4.1.3 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 2.3.4.5).

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 82 [73]). This verification procedure is also used with the X-HVB shear connector. The corresponding temperature-dependent reduction factor $k_{\theta,X\text{-}HVB}$ specific to the powder-actuated fastener is given in the German approval of this shear connector [74]. 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 7).

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 approval 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 8.3.4).

The deformation of the fastenings are also neglected when determining the total deformation of a steel deck diaphragm in accordance with DIN 18807-3 [66] or [75]. Verification of diaphragm, on the other hand, is determined by deformation limits of the profile metal sheets.

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 the approvals. Use of

high-strength carbon steel powder-actuated fasteners for permanent, safety-relevant applications is restricted to dry interiors [76, 77]. Stainless steel fasteners are mandatory where the powder-actuated fastening technique is used for fastening of base profiles for glass facades in building construction [78].
The stainless steel fasteners available on the market are not suitable for use in safety-relevant, permanent fastenings in acidic 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.
According to approval Z-14-1-4 [8], stainless steel screws must be used for fastenings of exterior profile sheets that are exposed to the weather. In accordance with the currently applicable European Technical Approvals (Table 16), use of carbon steel screws with corrosion protection coatings is permissible for indoor and outdoor applications. The corrosion protection of the screws must, however, meet the durability requirements of EN 1090-2 and EN 1993-1-3 while taking the applicable environmental class in accordance with EN ISO 12944-2 into account. The ability to reliably produce well-sealed fastenings is also of great significance. It is the manufacturer's responsibility to ensure that planners and contractors are informed of the corresponding requirements and installation regulations.

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 1052 [79] or DIN EN 1995 [80] are to be applied for the purpose of the verification of connections incorporating timber and wood materials. Corresponding design resistances (Figure 105) 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 approval guidelines (see Section 7.1). The load-bearing capacities and partial safety factors are then given in the approvals themselves.

5 Applications in steel construction

5.1 General information

Figure 62 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, sandwich panels)
- 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 the direct fastening of Z-purlins.
- Fastening wood and wood materials
- Fastening sandwich panels using fastening screws
- Fasteners with a connecting thread, e.g. threaded studs for the suspension of components used in mechanical and electrical installations or the fastening of gratings.
- Structural connections of thick sheets or plates.

As a basic rule, the redundancy principle must be applied to fastenings or connections made using powder-actuated fasteners and fastening screws. The saying "One bolt is no bolt" also applies to fastening screws and, in the same sense, also to powder-actuated fasteners, although the fasteners are, of course, viewed as single points for the purpose of verification of their static loading capacity. The design load value must be lower than the design resistance. The design resistance is based on the characteristic ultimate resistance, which corresponds to at least the 5 % fractile calculated for the given application situation. From a design point of view, however, multiple fastenings must be made in such a way that failure of a single screw or powder-actuated fastener cannot lead to failure of the entire component. In this sense, fastenings made with single threaded studs from which rigid, continuous runs of pipes are suspended are, of course, also viewed as redundant multiple fastenings.
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 approvals, must be observed. The area of application that can be covered 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. Such limitations should be taken into account right at the planning stage. The varying application limits depend on the system, e.g. on the use of various powder-actuated fastening tools. In addition to this, stainless steel

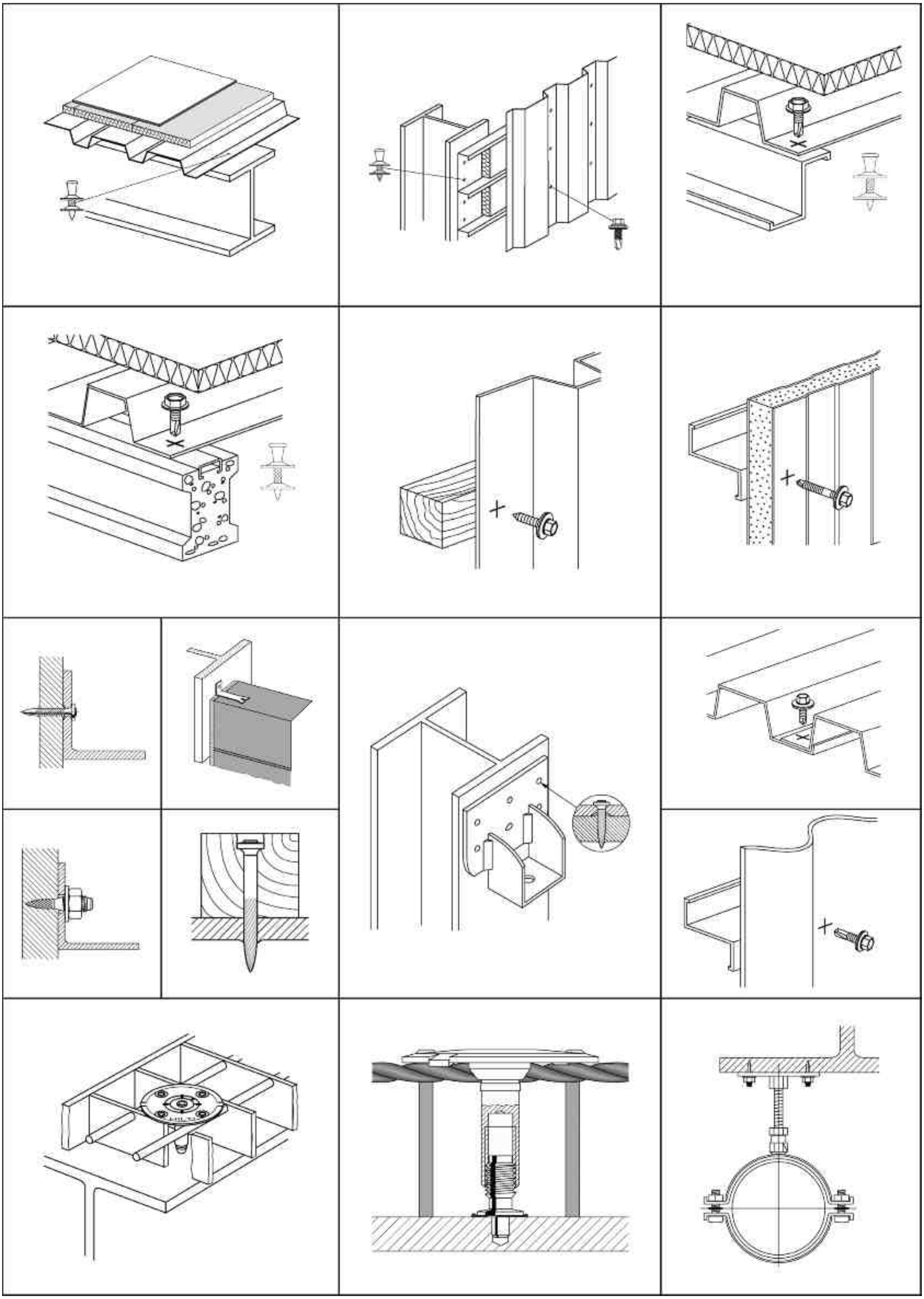


Figure 62. Uses for powder-actuated fasteners and fastening screws in steel construction

fasteners – with the exception of blunt-ended 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 5.9). 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.

5.2 Fastening thin gauge cold-rolled profiles

Trapezoidal profile metal sheets may be fastened in single or multiple layers. In the applicable approvals, 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. Figure 63 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) so only a single layer requires to be fastened. In accordance with [81], 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 ([67, 82–86] and others) as well as the information brochures published by the IFBS (Industrieverband für Bausysteme im Stahlleichtbau, www.ifbs.de) [81].

The choice between powder-actuated fasteners and fastening screws depends, from a technology point of view, on the thickness of the metal sheets to be fastened and the environmental conditions.

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

The currently approved powder-actuated fasteners (e.g. [76, 77]) are preferred for fastening the loadbearing profile steel sheeting of insulated, built-up roofs or, respectively, the inner liner trays on insulated walls. These are suitable and approved for use on steel base materials with a thickness of at least 6 mm. 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

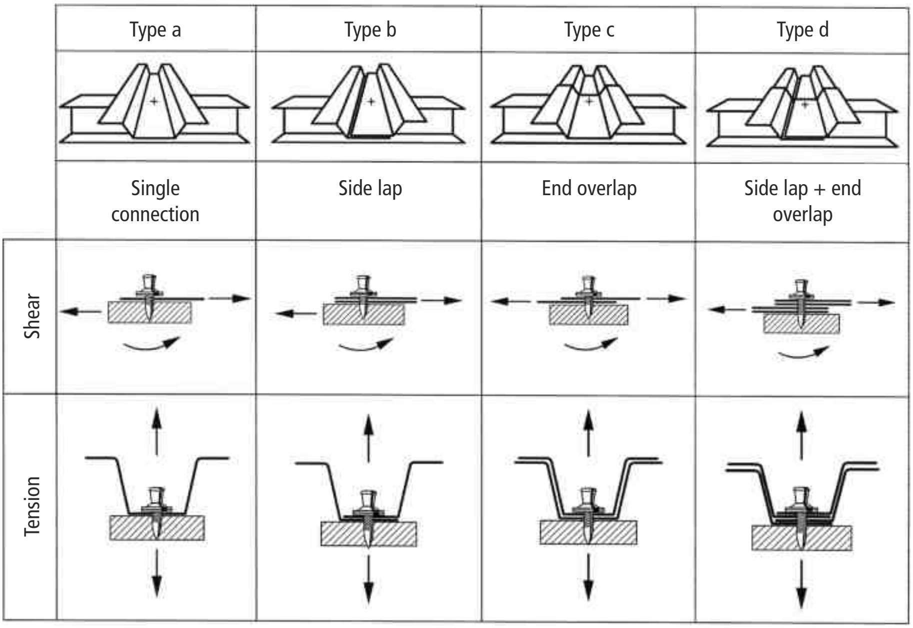


Figure 63. Types of fastening and loading

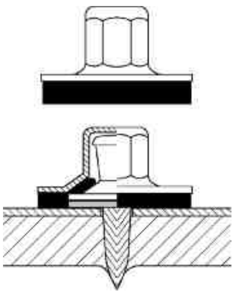


Figure 64. Powder-actuated fastener with sealing cap

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, have also been available for several years [76].
With S355 steel, the maximum drilling capacity of a self-drilling screw is 14 mm [87]. 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 [87, 88] productivity sinks due to the need to predrill the hole in a separate operation.
A comprehensive range of stainless steel fastening screws is also 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 [59], e.g. application of sealing caps.
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 [59]) 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 20, 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. Powder-actuated fasteners have not yet received approval for use in this thickness range. Manufacturers nevertheless offer powder-actuated fasteners for use on materials with a minimum thickness t_{II} of about 3 mm [31]. If these fasteners are to be used reliably on thin materials it is important that the powder-actuated fastening tool is equipped with a built-in piston brake (Figure 20, 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 2.3.3.1 and Figure 19).
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 50). Screw fastenings of this kind, requiring no pre-drilling, achieve a greater shear loading capacity (Figure 100). The maximum drilling capacity possible with this type of screw is 2.5 mm 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 [66] and installation guidelines [81].

5.2.3 Timber and concrete supports

5.2.3.1 Fastening to timber

Self-tapping screws with a coarse thread (Table 9) are normally used to fasten profile metal sheets to timber. The loading capacity of the metal sheets is stated explicitly in the applicable approvals. 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 1052 [79] or Eurocode 5 [80]. 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 pre-drilled holes, e.g. like seating plates, could be nailed onto timber in one operation [89], but there is currently no fully-developed product solution for this type of application available on the market.

5.2.3.2 Fastening to concrete

Figure 62 shows how profile metal sheets can be fastened to steel sections cast into concrete using either self-drilling screws or powder-actuated fasteners. A minimum steel thickness of 6 mm is currently required for use of powder-actuated fasteners. Powder-actuated fasteners with a slim, tapered and knurled shank are also capable of achieving a secure hold in cast-in sections with a nominal thickness of only 3 mm.
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 65.
It is important that this method of fastening is taken into consideration at the planning stage, before the pre-cast 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 (Figure 63) 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 reduce accordingly [90]. In the cracked tension zone of the concrete, the pullout loading capacity of the fastener is the decisive factor.

5.3 Fastening of base profiles of glass facades

This application involves fastening of the base profiles of glass facade to a steel substructure. The wall thickness of commonly-used steel or aluminum profiles varies between 1.5 and 3.0 mm. Figure 66 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 approval requirements for profile metal sheet fastenings [91]. The only basic difference to the tests of powder-actuated fasteners for profile metal sheets given in Table 19 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

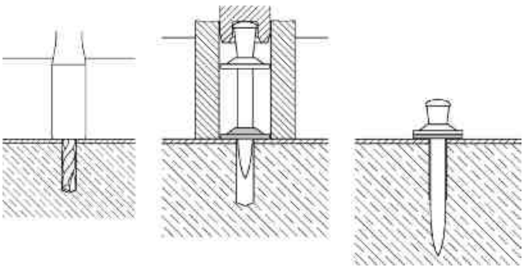


Figure 65. Procedure: Fastening profile metal sheets to concrete using powder-actuated fasteners

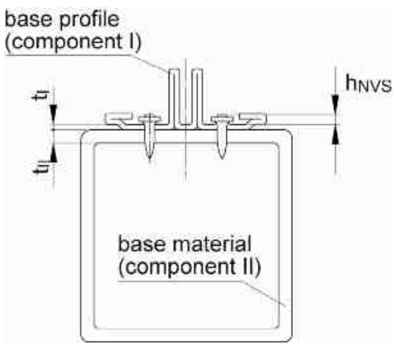
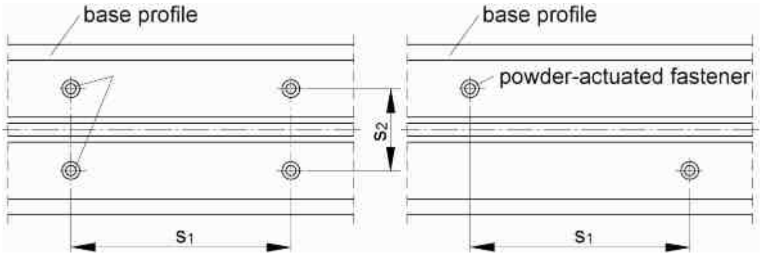


Figure 66. Example of application: Base profile with powder-actuated fasteners Hilti X-CR14



$s_1 \leq 250$ mm with aluminum base profiles [78]

Figure 67. Position relative to the screw channel and spacing. Left: Symmetrically positioned relative to the screw channel. Right: Alternately positioned

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 general construction supervisory authority approval [78], 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 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 67). 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 66). A further prerequi-site 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 general construction supervisory authority approval [78], the minimum thickness of the base material is 5 mm. If the base profiles are fastened to rigid tubular profiles, the base material thickness my be reduced from 5 to 4 mm if the geometric constraints are adhered to [92]. The limiting values for the width of the tubular profiles (= width of the support to which the base profile is attached), i.e. 80 to 100 mm or, respectively, the edge distance of 30 to 40 mm, must be adhered to. The differences in the values are a result of the tests carried out with various base profiles (Ferro-Wictec, Wicona, Raico) and tubular profiles. Please refer to [93–95]

In order to avoid damage of the anchorage by excess energy (see Section 2.3.3.1), fastener driving power must be set carefully in accordance with the manufacturer's instructions [78]. 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 [78] and adhering to the geometric conditions in accordance with [93–95].

Notes:

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.

Fasteners are correctly driven, within the required stand-off range, when they are not absolutely tight and flush against the part fastened (see Figure 68). 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.

Base profiles can also be fastened with fastening screws. Screws have the disadvantage of forming metal cuttings. With a view to avoiding obstruction problems (clearance or space for the screw head), facade system manufacturers also offer special screws for this purpose (e.g. in

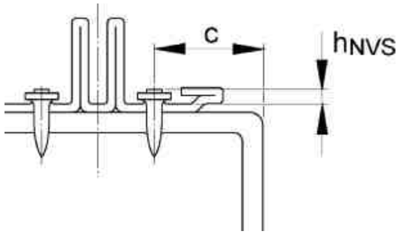


Figure 68. Edge distance for fastening base profiles to tubular sections

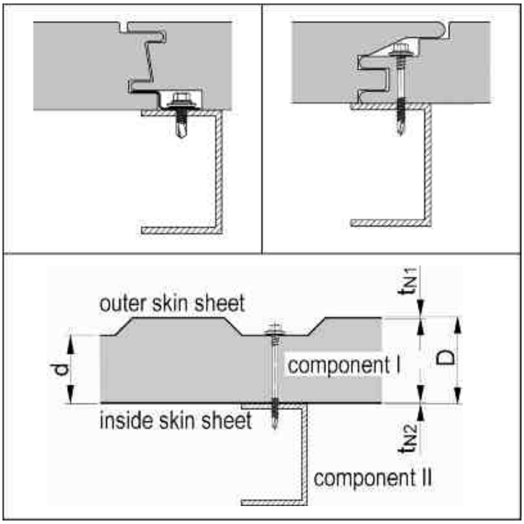


Figure 69. Methods that can, in principle, be used to fasten sandwich panels

accordance with [96] for fastening aluminum profiles to timber). MAG spot welding is also used to fasten base profiles to steel substructures (see [97]).

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 69 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 [98].

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 [85, 99], 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 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

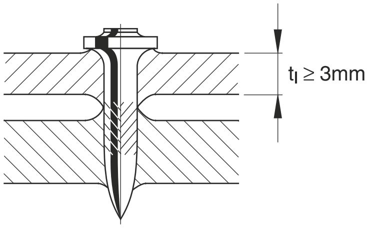


Figure 70. Formation of a gap between component I with t_I ≥ 3 mm and component II

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. 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 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 ≥ 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. 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.

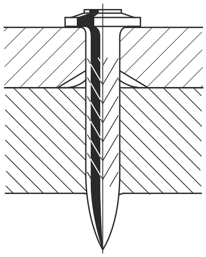


Figure 71. Fastening components with predrilled holes, countersunk on the reverse side

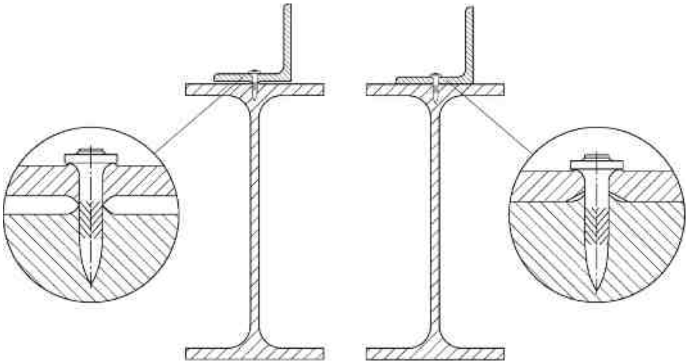


Figure 72. Angle bracket designed to prevent a steel beam from lateral buckling; left: unacceptable design

Figure 72 shows a practical example. The nailed-on angle bracket is intended to prevent the steel beam from lateral buckling. The angle bracket was too narrow to allow the fasteners to be offset. It was thus essential that holes were predrilled in the angle bracket so that the required shear forces could be taken up without transferal of bending forces.

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 [34]. 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 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. It can thus be ensured that all 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 Approvals for metal construction screws (Table 16) 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 approvals. 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 pre-drilled 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 [100].

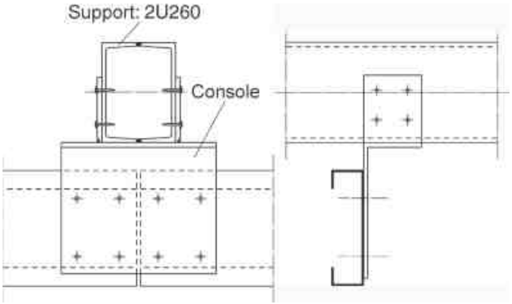


Figure 73. Example of a connection (console fixed to column) consisting of a group of fasteners

5.6 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 74). In accordance with construction supervisory authority approvals [101], 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 10) [102]. If, on the other hand, conventional metal construction screws are used, the timber must be predrilled to a diameter large enough to allow

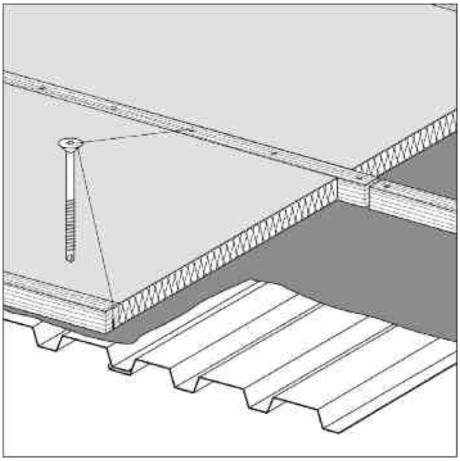


Figure 74. Fastening square timber to trapezoidal sheet liner trays

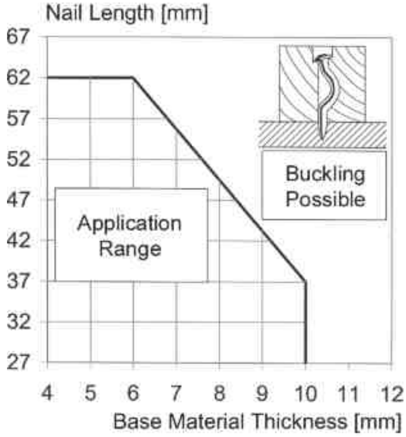


Figure 75. Application range for fastening wood

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} = 15–25 mm) than knurled powder-actuated fasteners. Despite being driven to 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 11 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 are required to provide in accordance with DIN 1052 [100].

Compared with the values given in Table 11., the characteristic tensile loading capacity of a screw fastening as per [101], 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 75).

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

Table 11. 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

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 [100]. 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 construction supervisory authority approvals [103]. 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 [104, 105].

5.7 Detachable fastenings with threaded studs

5.7.1 General points

This application is currently covered only by powder-actuated fasteners in the form of threaded studs (see Figure 6). Threaded studs are a preferred fastening method used for the suspension of components in mechanical and electrical installations in buildings (pipes and ducts etc.) or, in conjunction with suitable retaining pieces, for fastening floor gratings. Conventional nuts and washers are used to attach the components to the threaded studs. Threaded studs are available in a variety of materials, thread lengths and thread diameters. Common thread sizes are M6, M8 and M10. The various shank diameters available depend on the fastening tool used as each manufacturer offers ranges of threaded studs that can be driven with the fastening tools of the different power levels.

Threaded studs make detachable fastenings possible. Oversize holes in the parts to be fastened allow adjustment of their position during installation. In contrast, a nailed connection is immediately immovable and cannot be released without destroying the connection. Due to the clearance in the hole around the threaded stud, the design of statically fully effective groups of fasteners is more difficult as the interplay within the group, in a shear loading situation for example, is not clearly defined. The feasibility of the fastening must thus be assessed on the basis of the conditions for the situation in question. The following points must be taken into account:

- The number of threaded studs simultaneously in contact with the plate
- The amount of clearance in the holes
- The points of contact between the fixed steel and the threaded studs with assessment of the moment acting on the shanks of the threaded studs
- The possibility of load redistribution, taking plastic deformation of the threaded studs into account
- Effective utilization of the loading capacity of each threaded stud

The main difference between threaded powder-actuated studs and conventional bolts is that far higher prestressing can be applied to high-strength bolts. The manufacturers give in general a figure for the torque that can be applied to the nuts. The order of magnitude of the torque is about 5 to 10 Nm. The possible effective prestressing is thus relatively low. The tightening torques given for threaded studs are not high enough to clamp thick steel components (approximately 5 to 10 mm) tightly against the supporting structure or to generate any appreciable forces of friction at the joints.

Although threaded studs are made from high-strength material, they cannot be pretensioned like high strength bolt joints. 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. Tightening torque applies a high tension force to the stud, particularly when the nut is new and well lubricated. The application of an uncontrolled torque beyond the recommended values may thus 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 a new stud.

Problems of this kind can be avoided in practice by:

a) Training the workforce.
b) Driving the studs correctly to the specified depth. This ensures that the stud achieves the required pullout resistance.
c) 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.

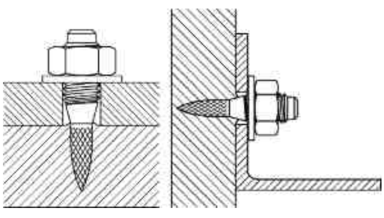


Figure 76. Fastening with threaded studs

5.7.2 Blunt tip threaded studs

Blunt tip threaded studs can be used on coated materials with a thickness of $t_{II} \geq 8$ mm without causing damage to the back side of the base material (see Section 2.1.4.6 for information about this technology). The point of penetration is sealed by the 12 mm diameter sealing washer after the fastener is driven. With regard to loading capacity, blunt tip studs can also be used on materials with a thickness of approximately 6 mm. The coating on the reverse side of the base material, however, will then suffer damage.

Advance preparation of the base material – with the exception of drilling the required hole – as well as subsequent finishing or repairs to the coating, are thus not required. The use of blunt tip studs raises productivity significantly. Further technical advantages of the blunt tip stud technique are:

a) They are suitable for use on all types of unalloyed steel in use in construction. Their range of use is not limited by the tensile strength of the base material. Their suitability for use on steel with a tensile strength of approx. 1100 N/mm² has been verified in tests [106]. Blunt tip studs thus raise application limits significantly compared to stainless steel pointed studs.
b) Due to their relatively ductile load-displacement characteristics, they are more robust when tightening the nut as slight overtensioning does not lead to failure of the stud's anchorage.
c) They can be positioned very accurately and very close to edges (≥ 6 mm) without reduction of the permissible working load [26, 107]. 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 77).
d) Very ductile load-displacement characteristics are displayed by the way in which shear loads are taken up via the sealing washer (Figure 78). This allows the load to be distributed over several threaded studs in the group making up the connection.

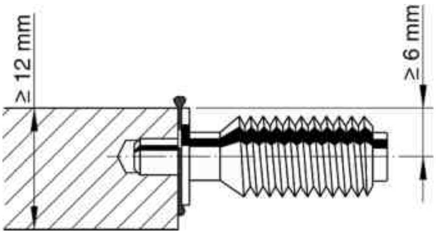


Figure 77. Installation of blunt tip studs in the butt end of a beam flange

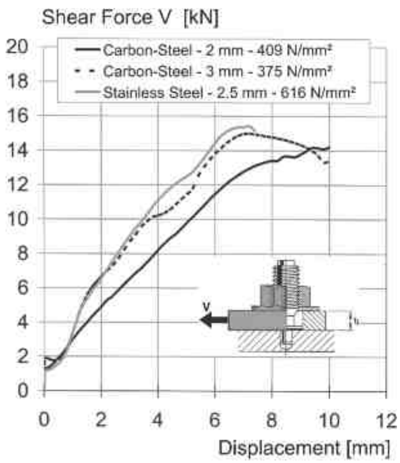


Figure 78. Shear loading capacity of blunt tip studs with a load introduction via the sealing washer in dependence of thickness and strength of the fixed steel

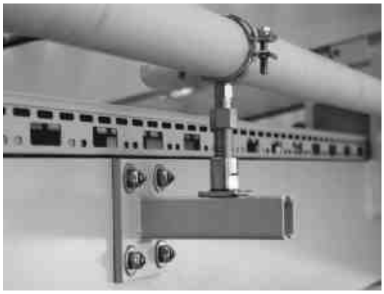


Figure 79. A bracket fastened by a blunt-tip threaded stud

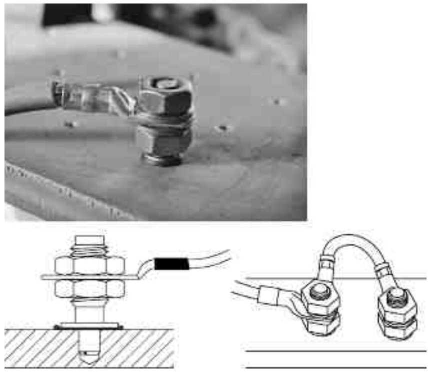


Figure 80. Grounding point provided by a blunt-tip stud

Figure 79 shows the example of a sprinkler support bracket fastened to a coated material.

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.

In compliance with EN 60439-1 and EN 60204-1, a single blunt-tip stud has been verified as being suitable for a 10 mm² copper wire connection and two coupled studs for a 16 mm² copper wire connection [108].

5.8 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 81 shows the composition of a typical roof with the sealing membrane and the 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.

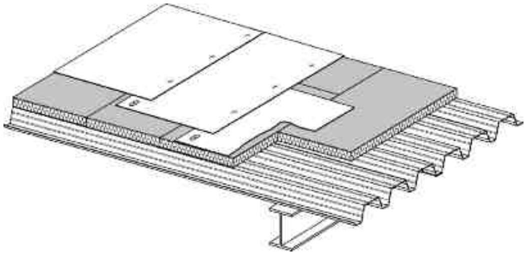


Figure 81. Roof composition with sealing membrane and integrated thermal insulation

5.9 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 82). 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 up to now 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 S490 SM-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 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 7) [25, 73]. 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.

Figure 82. The nailed folded-sheet structure of the ship terminal at Yokohama

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 [109–111]. The incentive for this was the need to develop a method of joining 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 83).

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 70) and the depth of penetration of the fas-

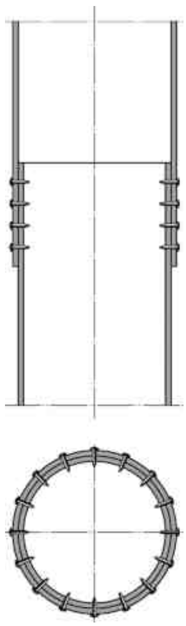


Figure 83. Nailed tubular connection

tener 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.

6 Applications in steel/concrete composite construction

6.1 General points

Figure 84 shows the possible applications of powder-actuated fasteners in steel/concrete construction.

- Nailed shear connectors for composite beams
- Nailed shear connection for composite tubular columns
- Applications with concrete encased steel beams

The main application for powder-actuated fasteners in this field is with nailed shear connectors in composite beams, which are used as an alternative to welded headed studs. The nailed shear connectors act either like cantilever arms in the same way as headed studs or, when perforated sheet metal strips are nailed on, like toothed strips [112]. In Germany, only the shear connector discussed in Section 6.2 has construction supervisory authority approval. In other European countries, above all in Italy, other nailed solutions are also available. Another new development is the ductile connector known as Diapason from Tecnaria [113], in which a sheet metal part is fastened with four powder-actuated fasteners. This sturdy sheet metal connector features openings to facilitate bonding with the concrete and to hold the connecting rebars. The basic variants of this presented in [112] and [114], known as Stripcon and Ribcon, in which large perforated sheet metal parts are fastened with 8 to 10 powder-actuated fasteners, are solutions that have not yet been offered on the market as products.

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 [115]. 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 [39]. 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. In the USA there is a product on the market that uses this solution, see [116] for details.

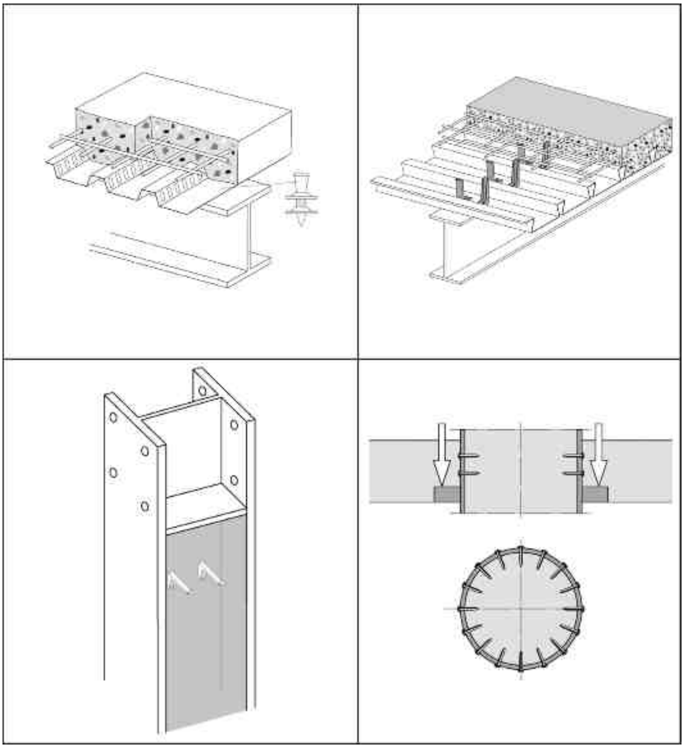


Figure 84. Use of powder-actuated fasteners in composite structures

6.2 The Hilti X-HVB shear connector

The X-HVB nailed shear connector allows for shear connection in composite beams. This L-shaped, deep-drawn sheet metal "bracket" consists of the fastening leg and the anchorage leg cast into the concrete. The fastening leg is fixed to the steel beam by 2 powder-actuated fasteners as shown in Figure 85. The shear connector, its basic load-bearing characteristics and the design provisions in accordance with [74] are described comprehensively in [112]. The following section provides a brief overview of its load-displacement characteristics and design information about the positioning of the connector on profile metal sheets.
Figure 86 shows examples of load-displacement diagrams (from [117]) for push-out tests conducted with the X-HVB shear connector. Its load-displacement characteristics meet the requirements of Eurocode 4 [118] for connectors with plastic properties. Please refer to [119–123] for further results of push-out tests, beam tests and tests of the end anchorage of composite slabs.

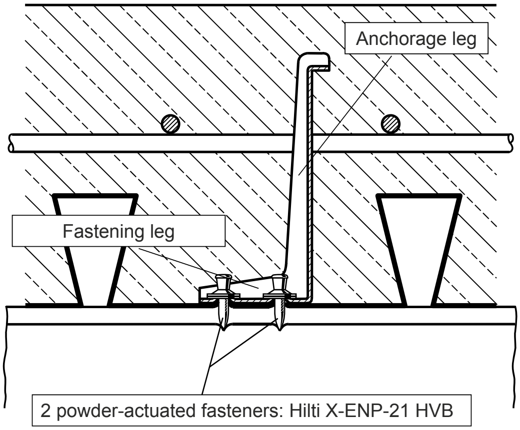


Figure 85. Shear connection in composite beams with Hilti X-HVB shear connector

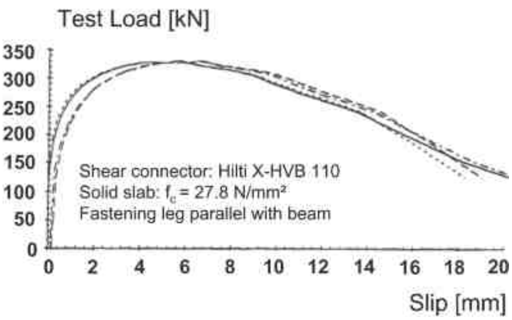


Figure 86. Load-displacement diagrams for the X-HVB shear connector [117]

The connector's load-bearing capacity in solid concrete slabs is determined by the nailed joint. Deformation capacity is the result of a combination of hole elongation in the fastening leg of the connector, bending of the fasteners and local deformation of the concrete in the contact zone with the connector. As the load-bearing capacity of each connector in the solid concrete slab is clearly lower than that of headed welded studs with d ≥ 19 mm, the presence of sheet metal – as part of the composite deck – only has a resistance-reducing influence with very narrow concrete ribs. The load-bearing capacity of the X-HVB in conjunction with Holorib HR51 undercut composite decking sheet, for example, is identical to its loading capacity in solid concrete slabs.
When comparing the cost efficiency of 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 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 shear connectors as allowance must be made for a reduction in loading capacity in accordance with [118] 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 12 shows an example for comparison.

Table 12. Comparison of the maximum 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)]	70.6	42.4	49.4
Shear connectors X-HVB 125 [2)]	32.0	32.0	32.0

1) where $\alpha = 1$, $n_r = 2$, $t \leq 1$ in accordance with [137]
2) positioned longitudinally relative to the beam [74]

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. The fastener driving operation can be carried independent from the weather conditions.
Another area where shear connectors of this type 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. In France, use of nailed shear connectors on old structural iron beams that are unsuitable for welding has been approved for many years [124]. Shear connectors of this type with a height of only 50 mm are available for use where a thin layer of concrete is to be applied. These old beam materials are not explicitly covered by [74] today.
The connector's ductile load-bearing characteristics are ensured by the design provisions [74], such as observance of the minimum distance to the edge of the steel sheet, minimum connector spacings and minimum connector height. The loading capacity of the concrete rib governs design only with narrow corrugations resulting to a plastic bending of the anchorage leg of the X-HVB shear connector, see beam tests in [121].
As far as the design of the structure will allow, the fastening legs of the X-HVB shear connectors should be aligned in parallel with the axis of the beam as the achievable loading capacity is then slightly higher than with transverse positioned connectors. Transverse alignment of the shear connectors is necessary in the case of very narrow ribs or, respectively, with profile sheets with rigid base corrugations. Figure 87 shows the optimum positioning of shear connectors when two rows of shear connectors are applied for metal sheets approved for use in Germany in composite structures.

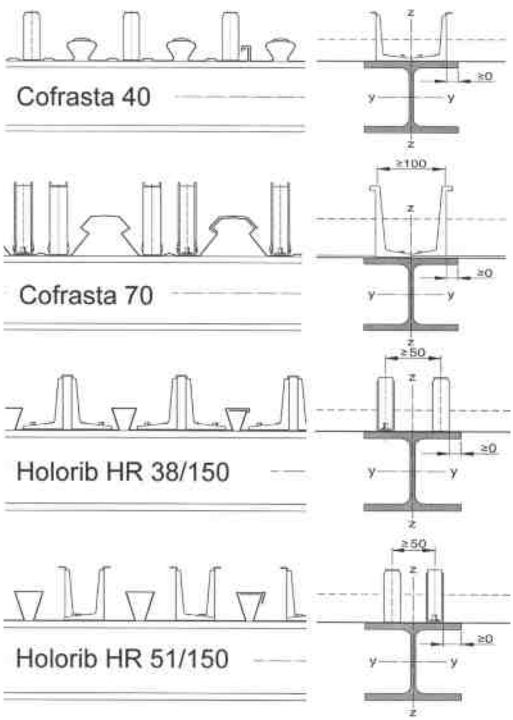


Figure 87. Optimum positioning of X-HVB shear connectors

6.3 Shear connection in composite tubular columns

The use of Hilti X-HVN 32P10 powder-actuated nails is a relatively new 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 84). 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 [125, 126]. The system was used in practice for the first time in 1999 in the construction of the Millennium Tower in Vienna [127–129].
Up to now, however, the method has not become established in the construction market. Its use has been limited to a few projects with individual approval. General con-

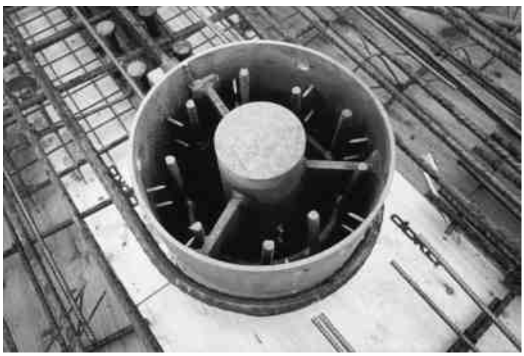


Figure 88. Example: Cross-section of a column in the Millennium Tower, Vienna

struction supervisory authority approval has not been issued. With regard to details of load displacement behavior or, respectively, design guidelines or regulations, please refer to [1] and the literature listed there.

7 European Technical Approval and other national approvals

7.1 Basis for approval

The legal basis for European Technical Approval is provided by the EU Construction Products Directive 89/106/EWG [130] from the year 1989. If the use of the connector falls under the essential requirements for the structure concerned (Essential Requirements ER 1 to 7 of [130]), then the product must be in conformance with a European technical specification when put on the market. European technical specifications are either harmonized European Standards (hEN) or European Technical Approvals (ETA).

After requests from manufacturers of fastening products, the European Commission decided that powder-actuated fasteners and fastening screws should be regulated by European Technical Approvals. The criteria for approval are regulated in accordance with either an ETAG (European Technical Approval Guideline) or in a CUAP (Common Understanding of Assessment Procedure) in accordance with section 9.2 of the Construction Products Directive [130]. For formal details, please refer to, e.g. the EOTA (European Organization of Technical Approvals) Web site at www.eota.be. Table 13. provides an overview of the relevant basis for European approval of powder-actuated fasteners and fastening screws. All applications are limited to predominantly static loading.

The DIBt is presently drawing up a CUAP on the use of powder-actuated fasteners on concrete [134]. This is based on approval guideline ETAG 001, part 6 [135], which defines the rules for multiple anchor fastenings in concrete. Once this new CUAP becomes available, which is expected to be mid 2011, fastening profile metal sheet to concrete with powder-actuated fasteners will then be able to be given European approval. The tests to determine the loading capacity of the metal sheet are then to be carried out in accordance with [91] and those to determine the loading capacity of the anchorage in the concrete are to be carried out in accordance with [134].

The essential requirements affected are:

ER 1: Mechanical strength and static stability

ER 2: Fire protection

ER 4: Safety in use.

ER 1 applies to failure of the loadbearing structure, for example, when powder-actuated fasteners or screws are used in steel roof deck diaphragms which secure the lateral stability of a single story steel building. ER 4 applies to failure of parts of a structure that are not structurally relevant and to the danger to persons that this presents, e.g. through parts falling (please refer to "Interpretative Documents" on the European Commission Web site [136] for details).

Approval of products only at a national level for Germany will still remain possible. Examples of this are the use of powder-actuated fasteners and screws for fastening wood materials to steel or use of nailed shear connectors. Table 14 provides an overview of applications for which the products are approved nationally and for which neither a formal ETAG nor a CUAP exist. 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 few years, there is essentially no longer any difference between national and European approval procedures. The push-out test used to determine the loading capacity of shear connectors, for example, has been regulated by

Table 13. Relevant European approval guidelines

Type of fastener	Material fastened	Base material	Approval guideline	Applicable essential requirements	Conformity procedure
powder-actuated fasteners	steel sheet	construction steel	CUAP 06.02/05, February 2004 [91]	ER 1, ER 2, ER 4	2+
fastening screws	steel or aluminum sheet	construction steel sheet steel aluminum timber	CUAP 06.02/07, October 2007 [131]	ER 1, ER 2, ER 4	3
sandwich panel screws	sandwich panels	construction steel sheet steel aluminum timber	CUAP 06.02/12, June 2010 [132]	ER 1, ER 2, ER 4	2+
fastening screws	waterproofing membrane with insulation	sheet steel concrete timber	ETAG 006 [133]	ER 4	2+

Table 14. Basis for national approvals for applications without CUAP or ETAG

Type of fastener	Materials fastened	Base material	Approval guideline	Conformity procedure
powder-actuated fasteners	sheet steel, aluminum, wood and wood materials	construction steel	following the example of CUAP 06.02/05 [91]	ÜZ
fastening screws	wood	sheet steel	following the example of CUAP 06.02/07 [131] or DIN 1052	ÜZ
powder-actuated fasteners	shear connectors	construction steel	EN 1993-1-1 EN 1994-1-1	ÜZ for powder-actuated fasteners and ÜHP for the X-HVB connector [74]

Eurocode 4 for decades, and provides the technical testing basis for the design of composite beam structures in accordance with EN-1994-1-1 [118] or DIN 18800-5 [137].

In addition, when drawing up the CUAPs for powder-actuated fasteners [91] and fastening screws [131] the objective was to take the German regulations, which had been incorporated in E-DIN 18807-4 [29] or, respectively, in DIN 18807-7 [138] and well proven over decades, without losing any of their content, and to adopt these in the new European regulations. This procedure was agreed to by all EOTA member countries.

The previous basis for national approvals for profile metal sheet fastenings und connections was developed during the early 1970s. The first powder-actuated fasteners for profile metal sheets (ENP3-21L15) were granted German general construction supervisory authority approval in 1974 [139]. The scientific background and support for this development work was provided by *Seeger* and *Klee* of the Institute for Materials Science at the Technical University of Darmstadt. Testing and basic research on the behavior of powder-actuated fasteners in steel were carried out (e.g. [38]) and the necessary testing and verification concepts drawn up [140]. These provisions for powder-actuated fasteners were incorporated in the German standard E-DIN 18807 part 4 [29]. E-DIN 18807 part 4 [29] and DIN 18807-7 [138] cover type and scope of the tests to be carried out for the German approval, the evaluation of results and the safety factors to be considered.

A deviation exists regarding the conformity procedure for fastening screws which has been defined by the commission in accordance with System 3 rather than the usual System 2+. The amount of work involved with System 3, which demands regular checks and inspections by the manufacturer at the production plant and initial testing by an accredited testing agency, is less than with System 2+ or, respectively, less than with the ÜZ conformity procedure applied nationally. With a view to avoiding a loss of quality, the CUAP [131] defined the required tests for fastening screws which are to be carried out within the scope of the manufacturer's own testing and inspection. For example, verification must be provided that the screw can be driven even at its upper application limit (i.e. using its maximum drilling capacity measured on steel of the maximum specified strength rating) and that the loading capacities published in the ETA are achieved. Furthermore, the screw's ductility and its sensitivity to hydrogen embrittlement must also be verified.

The verifications to be provided within the scope of the manufacturer's own inspection and testing are, as before, based on the existing national approval regulations Z-14.1-4 [8]. These are specified in the DIBt announcement issued in 1999 [58].

A CUAP is drawn up by the European approval authority that receives the first application for European approval. In the case of powder-actuated fasteners and sandwich panel screws this was the DIBt and for fastening screws it was the VTT (the Finnish approval authority). However, the CUAP was then drawn up jointly by the VTT and the DIBt working in cooperation.

Formal approval of a CUAP and its content is given by the members of the EOTA (*European Organization for Technical Approvals*): these are the national approval authorities of each member state (DIBt for Germany). The final step in this coordination procedure is the endorsement of the CUAP by the Technical Board of the EOTA. After endorsement of this *"Common Understanding"* by all member states, European Technical Approval of the defined product is then formally possible on the basis of the procedure stipulated in the CUAP.

A CUAP comprises the following:

- Product description, definition of the intended use of the product and its application range
- Type, scope and evaluation of the tests to be carried out
- Classification of the tests designed to fulfill the essential requirements of the construction product directive
- Verification concept
- Attestation of conformity procedure

The first CUAP [91] defined the basis for approval of a powder-actuated fastener for sheet metal attachment. The applicable powder-actuated fastener is described in this document by way of its features (shank diameter of 4.5 mm, a tapered head and two steel washers with a diameter of 15 mm). 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 concept for verification covered by this CUAP [91] are product-independent and thus generally apply to all powder-actuated fasteners used for the same purpose.

The product descriptions in the CUAPs [131, 132] for fastening screws are formulated in a general way and cover all products available on the market from all manufacturers. The first applications for European Technical Approval of powder-actuated fasteners and fastening screws were made about the same time at the end of 2001. The European Commission originally decided that metal construction screws should not be regulated by an ETA but, instead, by a harmonized European standard. This decision, however, was revised a few years later and the CUAP procedure for fastening screws was thus was also laid down in accordance with paragraph 9.2 of the construction products directive.

There was thus an interval of about 4 years between the drawing up of the CUAP for powder-actuated fasteners and the CUAP for fastening screws. This explains the slight difference between the European Technical Approvals for powder-actuated fasteners and fastening screws. The CUAP for powder-actuated fasteners differs from the CUAP for metal construction screws in that it is fully in conformance with EN 1993-1-3 [64] (see Section 8) regarding the used partial safety factors as well as the consideration of the influence of wind loads.

CUAPs, in contrast to ETAGs, are not officially published by the EOTA. Accordingly, an overview of the tests to be carried out is given in the following Sections 8 and 9. The CUAPs are, however, made available to applicants and interested parties by the corresponding approval authorities.

7.2 Overview of relevant approvals, status 10/2010

The following tables provide an overview of the national approvals and European 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 expiry of the collective approval Z-14.1-4 [8] at the end of August 2010, most fastening screws were covered by this approval. Holder of the approval is the IFBS (*Industrieverband für Bausysteme im Stahlleichtbau* – the German industrial association for building systems used in light steel construction). Z-14.1-4 was issued for the first time in 1974 and it covers the 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).

It was not possible to issue a collective European Technical Approval based on the example set by Z-14.1-4. The DIBt therefore issued European Technical Approvals for a number of manufacturers in mid August 2010 (Table 16). These ETAs are harmonized along the lines of previous German collective approvals in terms of the text they contain and how the approval annexes are presented. The content of these ETAs is essentially a transcript from the current national approval Z-14.1-4.

As an interim measure, the period of validity of collective approval Z-14.1-4 [8] has been extended by the DIBt to beyond 30.8.2010. An extension of this national approval for a further full period is presently in preparation. Z-14.1-4 forms a platform for all manufacturers operating primarily in the German market. It is expected that most European manufacturers who have obtained European Technical Approvals for their products will no longer extend the national approvals for their products.

Table 15. Approvals for powder-actuated fasteners, status 10/2010.

Approval	Holder of the approval	Product	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
DIBt Z-14.4-456	Hilti	X-CR14	5	base profiles for glass facades
DIBt Z-14.4-517	Hilti	X-U	4	sheet steel, wood and wood materials on steel
DIBt Z-14.4-453	Spit	ballistic nails	1.5	wood materials on steel
DIBt Z-26.4-46	Hilti	X-HVB shear connector with X-ENP-21 HVB powder-actuated fasteners	8	nailed shear connectors

Table 16. European Technical Approvals for fastening screws, status 10/2010

Approval	Holder of the approval	Product	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	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	Koelner S.A.	SD	4.8 – 5.5	stainless steel	steel, timber
ETA-10/0184	Adolf Würth Gmbh	SD, ST	4.2 – 6.3	carbon steel, stainless steel	steel, timber
ETA-10/0198	SFS intec AG	SD, ST	4.8 – 6.5	carbon steel, stainless steel	steel, timber
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

SD self-drilling screw
ST self-tapping screw

Table 17. Current national trade association approvals for fastening screw construction and sandwich panel screws, status 10/2010

Approval	Holder of the approval	Connections	Fastener	Manufacturer
Z-14.1-4 [8]	IFBS	fastening sheet steel to each other or to steel or timber substructures	blind rivets	Avdel, Bralo, Gesipa, MAGE, Reisser, SFS, Titgemeyer, Würth
			self-drilling screws	End, EJOT, Etanco, Hilti, MAGE, Reca, Reisser, SFS, Würth
			self-tapping screws	End, EJOT, Etanco, Ferrier, Hilti, HOSI, MAGE, Meusel, Reca, Reisser, Schürmann, SFS, Würth [1)]
			powder-actuated fasteners	Spit
Z-14.1-407 [9]	IFBS	fastening sandwich panels to steel or timber substructures	self-drilling screws	End, EJOT, Etanco, Hilti, IPEX, Koelner, MAGE, Reca, Reisser, SFS, Würth [1)]
			self-tapping screws	End, EJOT, Hilti, MAGE, Meusel, Reisser, Schäfer+Peters, SFS, Würth [1)]
Z-14.1-537 [141]	GDA	fastening sheet aluminum items to each other or to aluminum, steel or timber substructures	blind rivets	SFS
			self-drilling screws	EJOT, MAGE, Reisser, SFS, Würth
			self-tapping screws	EJOT, MAGE, SFS, Würth
Z-14.1-548 [142]	GDA	fastening and joining corrugated aluminum	self-drilling screws	EJOT, SFS

[1)] Not all manufacturers supply screws for use on steel and timber, see [9]

The national collective approval Z-14.1-537 [141], which includes the subject of fastening aluminum sheets, was issued for the first time in 2008. The owner of the approval is the GDA (*Gesamtverband der Aluminiumindustrie e.V.* – i.e. the German aluminum industry association). In addition to joining aluminum sheet to aluminum sheet, this approval also covers fastening to aluminum, steel and timber structures. The GDA also holds an approval for corrugated aluminum, in which the screws from several manufacturers are listed. Table 17 provides an overview over the current approvals issued by trade associations, the applications and the manufacturers represented through the association. In addition to the trade association approvals there is also a series of national approvals which are held by the manufacturers themselves. Table 18 provides the corresponding overview.

Up to now, no ETAs have been issued for sandwich panel screws. The procedure will be similar to that for the metal construction screws, i.e. with adaptation of the national trade association approval Z-14.4-407 to manufacturer-specific ETAs. The first ETAs are expected to appear before Z-14.4-407 expires (November 2011). At present, also in the case of the sandwich screws, it appears that the existing Z-14.4-407 national approval will again be extended by a reduced number of manufacturers who have not applied for an ETA. The material aluminum is included in the CUAP [131] for fastening screws. Therefore, it is expected in the medium term that national trade association approvals of the GDA will be adapted to become manufacturer-specific ETAs.

The manufacturers EJOT (ETA-07/0013), SFS intec (ETA-08/0262, ETA-08/0321), MAGE (ETA-08/0077), Etanco (ETA-08/0239) and Kölner (ETA-09/0346) have held European Technical Approvals for flat roof fasteners since 2007.

7.3 Future developments

Future developments will, on the one hand, refer to the subject matter of the approval criteria and, on the other, will concern changes in European legislation. The CUAP [91] for powder-actuated fasteners refers to the fastening of thin, cold-formed profiles in situations where loading is mainly static. Forthcoming changes to the CUAP have the objective of extending its scope to include the general use of threaded studs or, respectively, extension to cover dynamic loading, especially as a result of earthquakes.

The European Construction Products Directive [130] is currently under revision. The draft of the new European Construction Products Regulations [143] is now available and will be discussed by the European Parliament [144]. The new regulations will become mandatory for all member countries. This will accelerate the implementation process and will avoid different national interpretations in national law, as has previously been the case with the current Construction Products Directive.

With regard to approvals, the objective of the regulations is to simplify and accelerate the process and to make it less costly for the manufacturers. In future, the approval criteria will be summarized in product-specific *European Assessment Documents* (EAD), following the example of the CUAPs. Transitional regulations from [143] provide for the fact that approval guidelines as well as approvals issued on the basis of a CUAP before July 1, 2013 shall be accepted as being in conformance with the Construction Products Regulation. The future European Construction Products Regulations will thus, in terms of technical content, have no influence on the products and approvals discussed here. Also in future it is very likely that it will be possible to have the products approved only at a national level as well as in accordance with the European regulations.

Table 18. Current national approvals held by manufacturers of fastening screws, status 10/2010

Approval	Holder of the approval	Product	Component I	Base material
DIBt Z-14.4-440	SFS intec GmbH	SD	wood battens	steel profile sheet
DIBt Z-14.4-426	EJOT Baubefestigungen GmbH	SD	aluminum clips (standing-seam profiles), solid wood, metal components	steel, timber, timber materials, aluminum
DIBt Z-14.1-519	MAGE AG	SD	aluminum standing-seam profile retaining clips, metal components	steel, timber, OSB board
DIBt Z-14.1-538	Hilti AG	SD	trapezoidal profile and corrugated aluminum or steel sheets	steel, aluminum, timber
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

SD self-drilling screw
ST self-tapping screw

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

8.1 Test concept and mathematical approach

The tests have been defined so that the ultimate resistance is determined for all modes of failure. Figure 63 shows the types of fastening and loading, taking joints made with powder-actuated fasteners as an example, and Figure 89 shows the possible types of failure of the powder-actuated fasteners or, respectively, fastening screws relative to the direction of loading.

In accordance with EN 1993-1-3 [64], loading capacities are to be determined by tests or by calculation using the formulas given in table 8.2 or, respectively, 8.3 from EN 1993-1-3 [64]. 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 EN 1993-1-3 [64], 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.

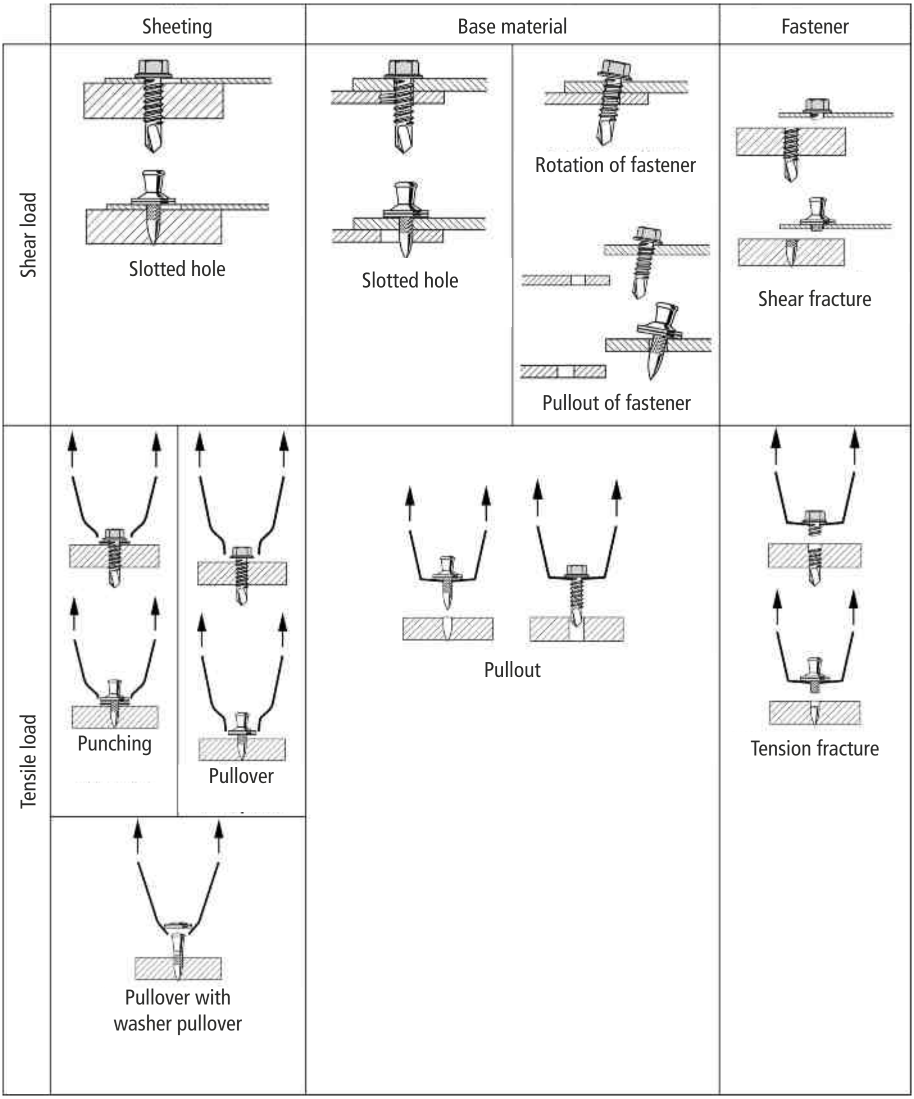


Figure 89. Failure modes for fastenings made with powder-actuated fasteners or fastening screws

Formulas in accordance with table 8.2. or, respectively, 8.3 from [64] (nomenclature in accordance with [64]):

Bearing resistance in shear:

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

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. [145] 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 90 shows the course followed by the coefficient α for overlap joints made with sheet metal of equal thickness ($t_I = t_{II}$).
Pullover resistance for static tension loads:

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

Pullover resistance for repeated wind loads:

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

Pullout resistance of self-tapping screws:

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

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

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

8.2 Overview of approval tests

Table 19 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 – in agreement with [29] – only in the form of resistance to pullover failure.

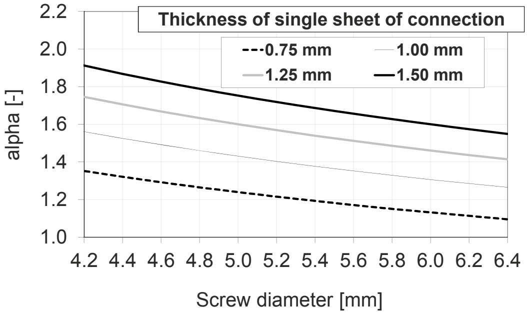


Figure 90. Coefficient α for screw-fastened joints in accordance with Table 8.2 from EN 1993-1-3 [64] with $t_I = t_{II}$

Table 20 provides an overview of the approval 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, 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 1052 [79] or, respectively, EN 1995 [80] 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 CUAP. The applicable verifications are, however, to be carried out and documented within the scope of the initial type testing 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) and that the specified loading capacity in accordance with the ETA is achieved.
The test results must be statistically evaluated in accordance with the Eurocode [146] and corrected to the min-

Table 19. Approval tests for powder-actuated fasteners in accordance with CUAP [91]

Tests according to CUAP [91]	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 Σ 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 Σ 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	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 Σ 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 all fastening tools to be approved

Table 20. Approval tests for fastening screws as per CUAP [131]

Test according to CUAP [131]	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 Σ 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 Σ 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)] performance of tests optional

imum value for the specified steel grades. More details can be found in the CUAPs [91, 131].
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.

8.3 Approval tests – examples of load bearing behavior

8.3.1 Static resistance of sheet metal under tensile load

Resistance to pullover failure is determined using strips of sheet metal of each relevant thickness. The previously used form of test specimen, in accordance with [29], remains applicable (Figure 91). 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 92 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 NRk derived from the tests can exceed the values calculated using the formula (5) by more than 50 % (see Figure 103 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.

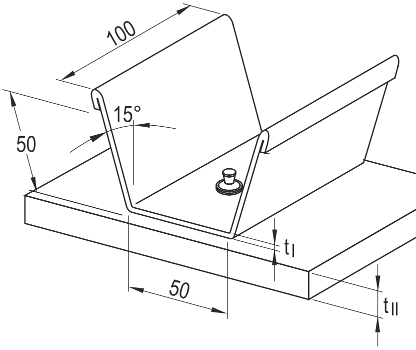


Figure 91. Shape of sheet specimen for tensile testing of sheeting

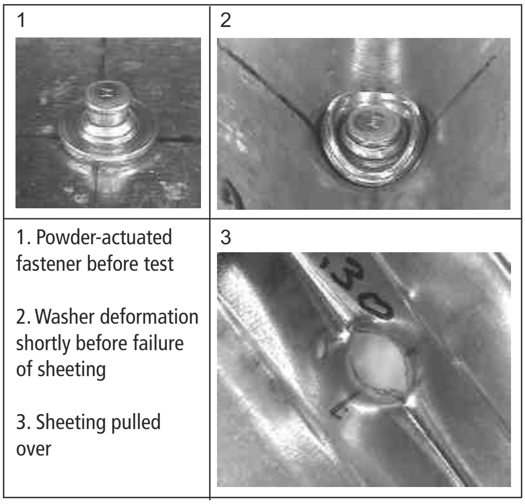


Figure 92. Typical pullover failure

8.3.2 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 as in [29]. This number of cycles was defined in [140] 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, and was thus adopted unchanged in the CUAPs [91, 131] as no corresponding harmonized European rulings have been drawn up within the last 25 years. 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 93 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 94 shows a corresponding example for the connection made with a metal construction screw.

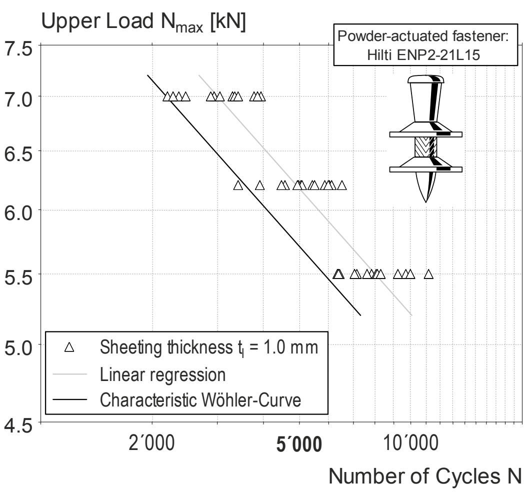


Figure 93. Example of the dynamic pullover resistance of a connection made with a powder-actuated fastener with a sheet metal thickness t_I of 1.0 mm

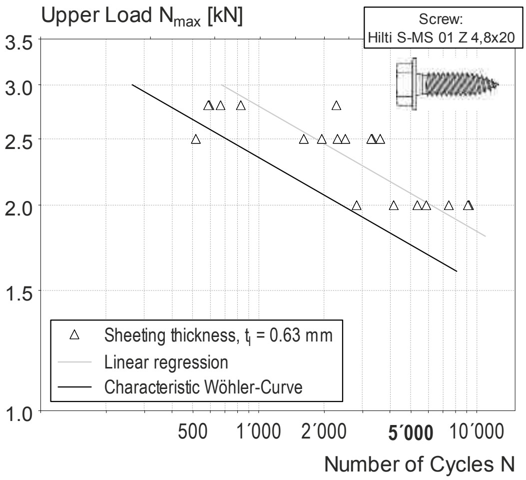


Figure 94. Example of the dynamic pullover resistance of a screw fastening with a sheet metal thickness t_I of 0.63 mm

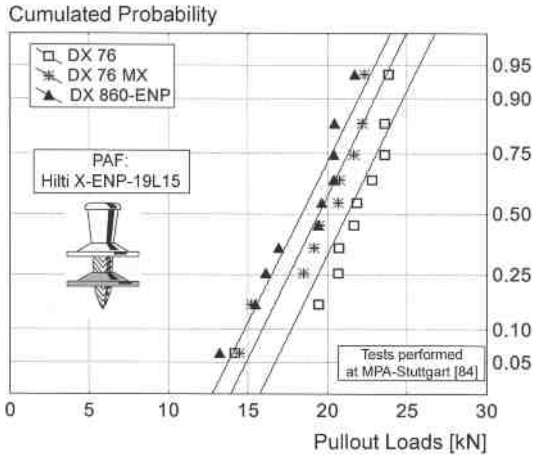


Figure 95. Pullout resistance on 20 mm thick base steel

It must be noted that carrying out dynamic pullover loading tests – as in [29] – is not obligatory. The influence of cyclic wind loads on static design resistance, however, must be taken into account. This is done either by way of tests or by conservative application of higher safety factors, which are to be applied to the static characteristic loading resistances.

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 [64]. In the CUAP [91] this factor is generally defined as the coefficient α_{cycl} – formula (9) – and is also stated explicitly as such in the approval and taken into account in calculation of the design values (see [76, 77]).

$$\alpha_{cycl} = 1.5 \cdot (N_{k,dyn}/N_{k,stat}) \leq 1.0 \qquad (9)$$

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

$N_{k,dyn}$ and $N_{k,stat}$ stand for the static and dynamic pullover loading capacity of each of the sheet metal thicknesses 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 [29].

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 Eurocode, it corresponds to the reduction factor that has been used on a national basis for decades and has been included in the CUAP [131] for screws. The reduction for screws was already made in the characteristic loading capacity N_{Rk} published in the ETA. It is thus not necessary to explicitly specify a α_{cycl} value in the approvals.

8.3.3 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 S235 construction steel and the maximum thickness is to be fastened (fastening type d, Figure 63). 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 approval (see Section 2.1.5). For connections made with screws, the data given in the approval 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 95 shows the results of the pullout tests on 20 mm thick base material for three different fastening systems [147].

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

Figure 96 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

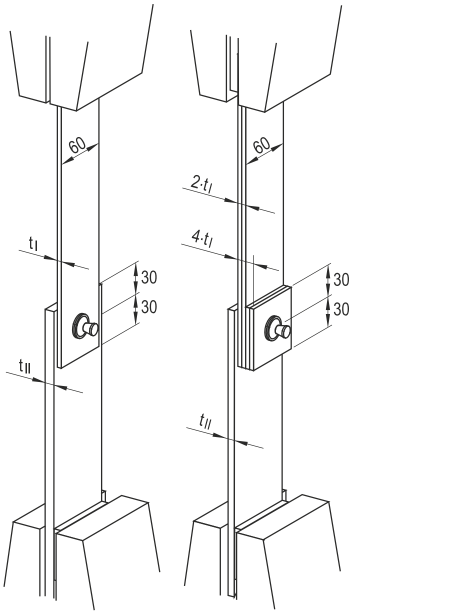


Figure 96. Shear test specimens for testing single layer and 4 layers of sheet metal

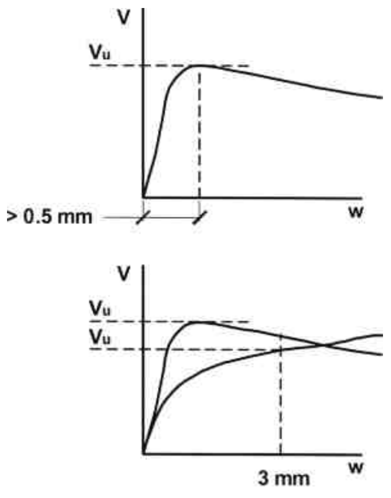


Figure 97. Displacement criteria for shear testing

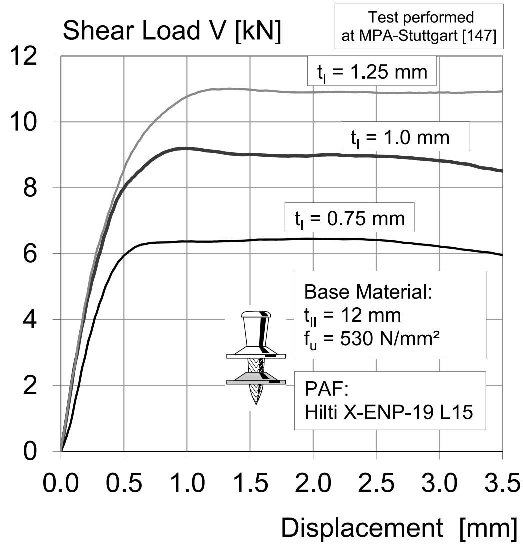


Figure 98. Single layer shear tests: Examples of load-displacement characteristics of powder-actuated fastener

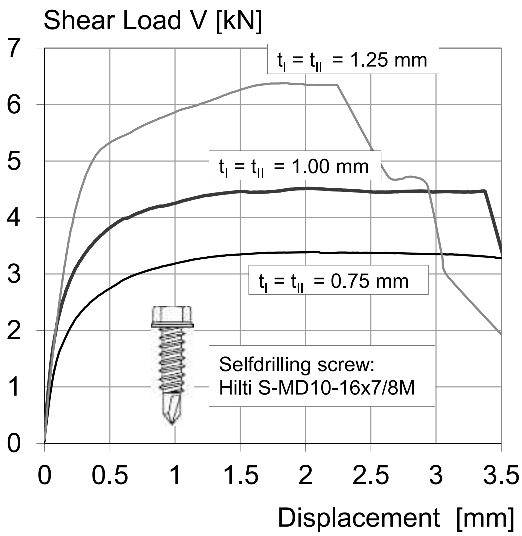


Figure 99. Example showing the shear loading capacity of an overlap joint made with a self-drilling screw.

– 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 CUAPs – as in [29] – as the relative maximum within the displacement range of 0.5 to 3.0 mm (Figure 97). 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.

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 98).

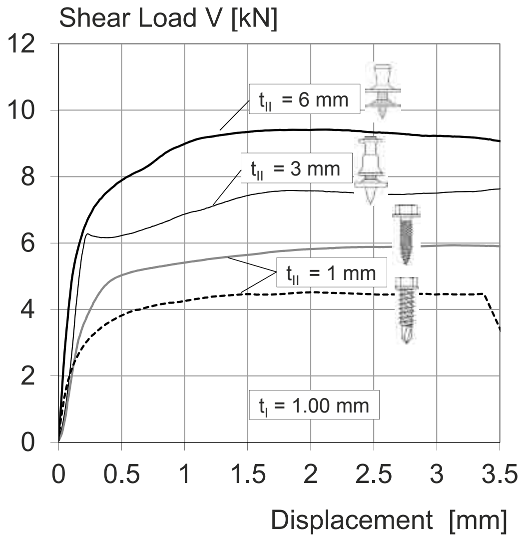


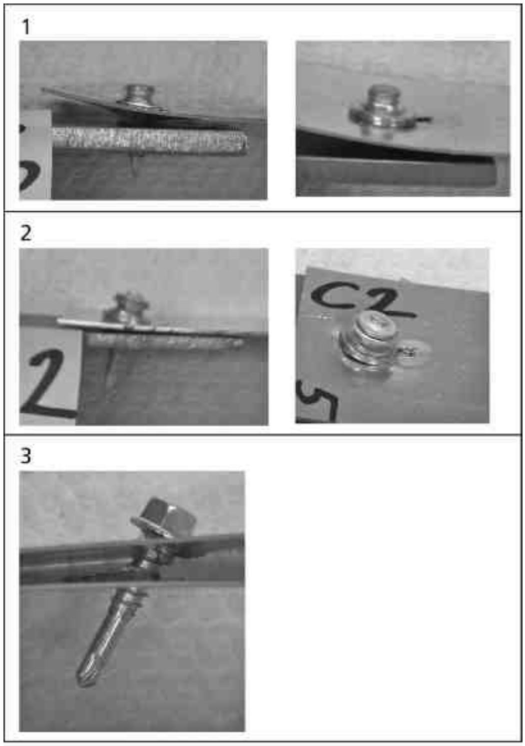
Figure 100. Comparison of the shear loading capacity of a single-layer sheet metal fastening.

Figure 99 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 100 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 associated 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 101 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 50) 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



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 101. Shear deformation behavior dependent on the thickness of component II

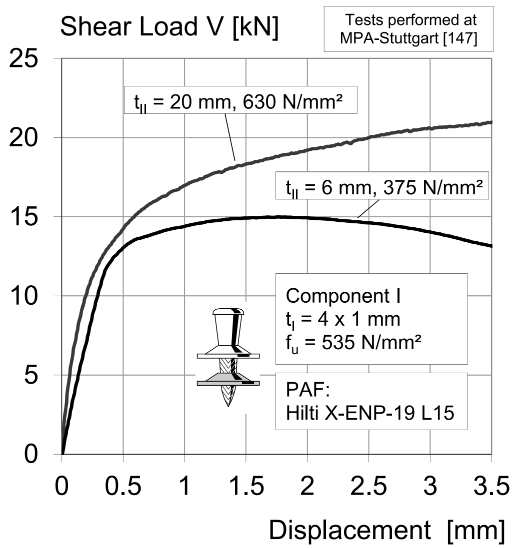


Figure 102. Examples of load-displacement characteristics

the base material should be chosen so that the most flexible (t_{II} = 6 mm, with lower strength) as well as the hardest configuration (solid steel at the upper limits) is tested (Figure 102).

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 89) 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 63).

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.

8.3.5 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) 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 [29]. 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 [148]. 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 within structural analysis for this fastening situation.

8.3.6 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 approval in order the cover the system interdependency (see Section 2.1.5).

With fastening screws the application limits are checked by carrying out drill-drive tests and the corresponding loading capacity tests (see also Section 7.1) within the scope of the initial type testing.

8.4 Structure and content of an ETA

8.4.1 General points – attestation of conformity procedures

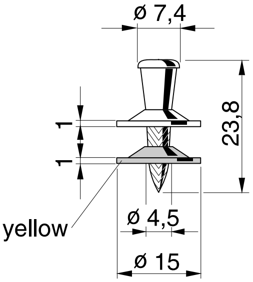
The text section of the ETA defines the legal basis and general conditions, the product and its intended use, the characteristics of the product and the methods of verification, the system of attestation of conformity to be applied and the assumptions under which the fitness for use of the product is given. The formal reference to the Construction Product Directive [130] is provided by listing the applicable Essential Requirements (mechanical resistance and stability – safety in case of fire – safety in use) of the CPD. If European harmonized rulings already exist for some of the points in question, such as special cases of use and N-V interaction, reference will be made to these. The product-specific technical data is summarized in the appendices.

8.4.2 Powder-actuated fasteners

Figure 103 shows an example of an annex sheet from a European Technical Approval for a powder-actuated fastener [76].

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



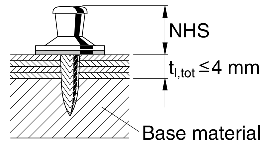
Powder-actuated fastener and fastening tool:

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 / 18M (DX 76, DX 76 MX)**
6.8 / 18M40 (DX 860 ENP)

Installation control:

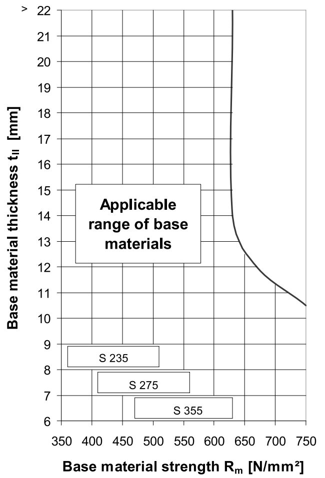


NHS = 8.2 to 9.8 mm

A piston mark on the top washer is clearly visible.

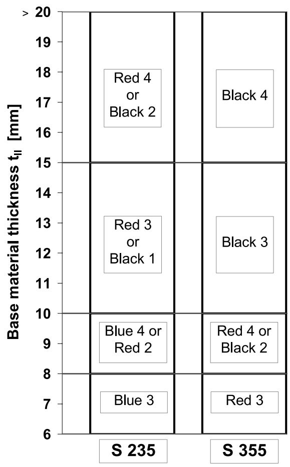
Characteristic shear and tension resistance V_{Rk} and N_{Rk}				**Design shear and tension resistance V_{Rd} and N_{Rd}**	
sheeting thickness t_I [mm]	Shear V_{Rk} [kN]	Tension N_{Rk} [kN]	Types of connnection	$V_{Rd} = V_{Rk} / \gamma_M$	$N_{Rd} = \alpha_{cycl} N_{Rk} / \gamma_M$
0.63	4.0	4.1	a,b,c,d	γ_M = 1.25 in the absence of national regulations	$\alpha_{cycl} = 1.0$ 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
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		

Application limit diagram



Base material:
Structural steel S235, S275 and S375 in qualities JR, JO, J2, K2 according to EN 10025-2; minimum thickness = 6 mm

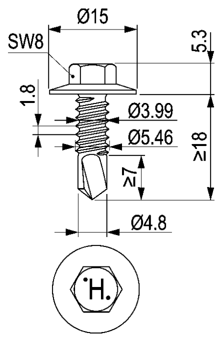
Cartridge selection and tool energy setting



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 til correct stand-offs NHS are achieved.

Powder actuated fastener	**Annex 4**
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	to European technical approval **ETA 04/0101**

Figure 103. Example of an annex sheet from a European Technical Approval for a powder-actuated fastener



<u>Materials</u>

Fastener: carbon steel
case hardened and galvanized

Washer: none

Component I: S280GD, S320GD or S350GD - EN 10346

Component II: S235, S275 or S355 - EN 10025-1
S280GD, S320GD or S350GD - EN 10346

<u>Drilling capacity</u> $\Sigma t_i \leq 6{,}00$ mm

<u>Timber substructures</u>

no performance determined

	$t_{N,II}$ [mm]	1,50		2,00		2,50		3,00		4,00		5,00		6,00		—	
	$M_{t,nom}$	—		$\Sigma t \leq 3{,}00$ mm: 7 Nm $\Sigma t > 3{,}00$ mm: 8 Nm										—			
$V_{R,k}$ [kN] for $t_{N,I}$ [mm]	0,50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0,55	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0,63	—	—	2,60	ac	2,60	ac	2,60	ac	2,60	—	2,60	—	—	—	—	—
	0,75	—	—	3,70	ac	3,70	ac	3,70	ac	3,70	—	3,70	—	—	—	—	—
	0,88	—	—	4,50	—	4,50	ac	5,00	ac	5,00	—	5,00	—	—	—	—	—
	1,00	—	—	4,50	—	4,50	ac	6,50	a	6,50	—	6,50	—	—	—	—	—
	1,13	—	—	4,90	—	4,90	—	7,00	—	7,90	—	—	—	—	—	—	—
	1,25	—	—	5,30	—	5,30	—	7,40	—	9,30	—	—	—	—	—	—	—
	1,50	—	—	6,20	—	6,20	—	8,30	—	9,50	—	—	—	—	—	—	—
	1,75	—	—	6,20	—	6,20	—	8,30	—	9,50	—	—	—	—	—	—	—
	2,00	—	—	7,80	—	7,80	—	9,40	—	9,50	—	—	—	—	—	—	—
$N_{R,k}$ [kN] for $t_{N,I}$ [mm]	0,50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0,55	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0,63	—	—	1,71	ac	1,71	ac	1,71	ac	1,71	—	1,71	—	—	—	—	—
	0,75	—	—	2,26	ac	2,26	ac	2,26	ac	2,26	—	2,26	—	—	—	—	—
	0,88	—	—	2,91	—	2,91	ac	2,91	ac	2,91	—	2,91	—	—	—	—	—
	1,00	—	—	3,09	—	3,57	ac	3,57	a	3,57	—	3,57	—	—	—	—	—
	1,13	—	—	3,09	—	4,35	—	4,35	—	4,35	—	—	—	—	—	—	—
	1,25	—	—	3,09	—	4,35	—	5,11	—	5,11	—	—	—	—	—	—	—
	1,50	—	—	3,09	—	4,35	—	5,61	—	6,89	—	—	—	—	—	—	—
	1,75	—	—	3,09	—	4,35	—	5,61	—	6,89	—	—	—	—	—	—	—
	2,00	—	—	3,09	—	4,35	—	5,61	—	6,89	—	—	—	—	—	—	—

Self drilling screw

Hilti S-MD 23 Z 5,5 x L
with hexagon head

Annex 22

of European technical approval

ETA-10/0182

Figure 104. Example of a page from the appendix of a European Technical Approval for a self-drilling screw

- 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 2.2.2)
- Characteristic resistances
  These are given as a function of the individual sheet metal thickness and apply to the specified 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. The loading capacity is then cut off by the governing pullout or shear loading capacities. 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 as well as the combinations for which no explicit check of temperature dependent forces of constraint is required within structural analysis – taking the grade of steel of component I into account.
- Design resistances
  The design values should be calculated as follows:
  For shear force:

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

  For tensile force

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

  with

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

  In accordance with Eurocode, a partial safety factor γ_M of 1.25 is applicable to powder-actuated fasteners.
  In this particular case (Figure 103), 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
  As previously laid down in national regulations, projection of the head of the fastener (stand-off) beyond the fastened component I serves as a means of checking the quality of the fastening (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 103), the piston of the tool is stopped by contact with the work surface (see Section 2.3.3.1).

8.4.3 Self-drilling screws

Figure 104 shows, as an example, a page from the appendix of a European Technical Approval for a self-drilling screw [149].
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 CUAP [131], a possible reduction intended to take the influence of repeated wind loads into account has already been incorporated in the characteristic loading capacity N_{Rk}. It is thus not necessary to explicitly state a reduction factor α_{cycl}. According to CUAP [131], the partial safety factor γ_M for metal construction screws is 1.33.

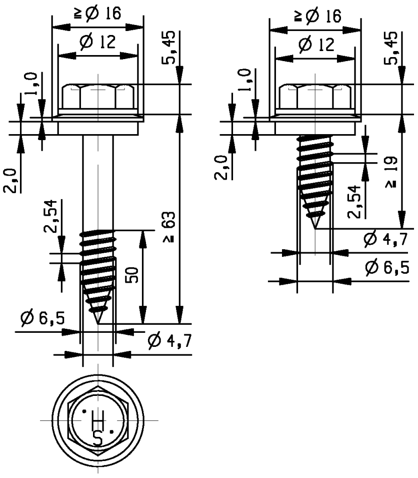
8.4.4 Self-tapping screws

Figure 105 shows, as an example, a page from the appendix of a European Technical Approval for a self-tapping screw [149].
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 lef are given.

8.4.5 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 EN 1993-1-3 [64], it is no longer explicitly mentioned in the European Technical Approval. Instead, a reference is made to the corresponding paragraph in [64].
The off-center position of the fasteners is covered by the load-reducing factors given in Figure 106. The load-reducing factor of 0.7 N_{Rd} should then, logically, be applied to wall liner trays.
The interaction between N_{Sd} and V_{Sd} is also handled by EN 1993-1-3 [64]. Unless some other behavior can be



Materials

Fastener:	stainless steel (1.4301) - EN 10088
Washer:	stainless steel (1.4301) - EN 10088
Component I:	S280GD or S320GD - EN 10346
Component II:	S235 - EN 10025-1 S280GD or S320GD - EN 10346

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} ≥ 26,0 mm

	$t_{N,II}$ [mm]	0,63		0,75		0,88		1,00		1,13		1,25		1,50		≥ 2,00		
	$M_{t,nom}$	3 Nm										5 Nm						
$V_{R,k}$ [kN] for $t_{N,I}$ [mm]	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
bearing resistance of component I																		
$N_{R,k}$ [kN] for $t_{N,I}$ [mm]	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
pull-through resistance of component I																		

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 section 4.2.2.

predrill diameters:	$t_{N,II}$ ≤ 0,75 mm d_p = ø4,0 mm	0,75 mm < $t_{N,II}$ < 1,50 mm d_p = ø4,5 mm	$t_{N,II}$ ≥ 1,50 mm d_p = ø5,0 mm

Self tapping screw

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

Annex 40
of European technical approval
ETA-10/0182

Figure 105. Example of a page from the appendix of a European Technical Approval for a self-tapping screw

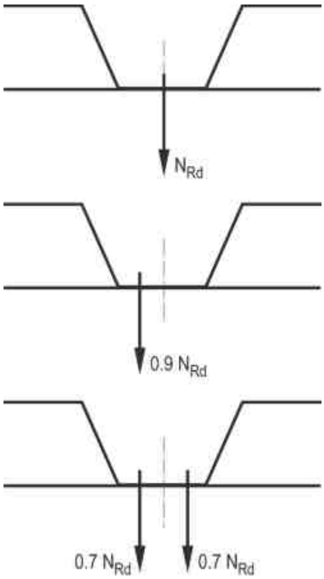


Figure 106. Reduction factors due to the position of fasteners in accordance with EN 1993-1-3 [64]

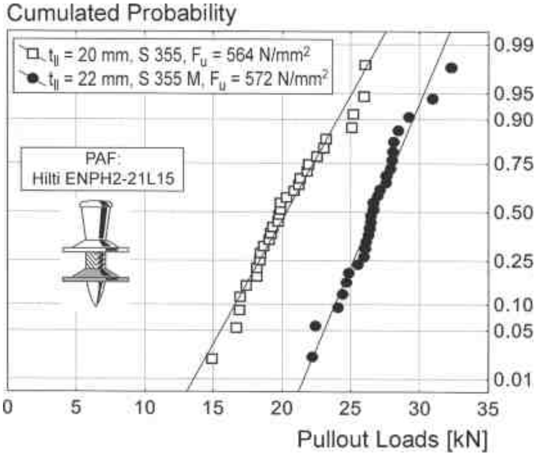


Figure 107. Loading capacity of the anchorage in thermomechanically-rolled steel (t_I = 0.75 mm)

proven by way of tests, the following linear interaction should be used:

$$N_{Sd}/N_{Rd} + V_{Sd}/V_{Rd} \leq 1{,}0 \quad (13)$$

8.5 Deviation from the conditions applicable to the approval

8.5.1 Substructures made from thermomechanically-rolled materials

Construction steels as per EN 10025-2 [30] are generally specified in approvals as the base material (e.g. [76, 78]). These are the standard construction steel grades S235, S275 and S355 in the qualities JR, JO, J2 and K2 [30]. The thermo-mechanically rolled construction steel grades S355 M/ML, S420 M/ML and S460 M/ML currently covered by EN 10025-4 [150] are thus not explicitly covered by these approvals.
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 107 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 EN 10025-2 [30] must be reduced by about 50 N/mm² in order to cover thermo-mechanically rolled steel of the type S355 M/ML as per EN 10025-4 [150].

8.5.2 Divergent types of fastening

Component I combinations not covered by the approval may also occur in practice. The maximum fastening thickness given in Figure 103 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 makes sense as single layers of this thickness are not used in practice.
The approval can serve here as an indication of technical feasibility. 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.

8.5.3 Base materials with a fire-protection 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 approval procedure. Fire protection coatings, however, may have a thickness of about 1 mm or more. As a result

Table 21. Approval tests for screws to fasten sandwich panels

Tests in accordance with CUAP [132]	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
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 with thickness of inside skin sheet 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

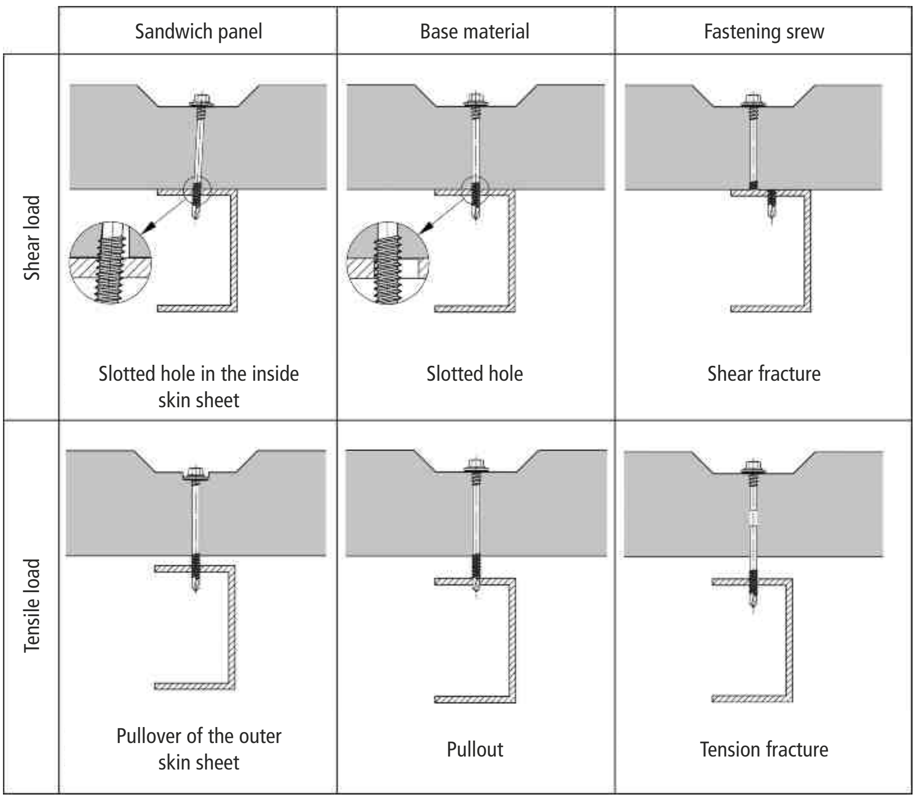


Figure 108. Sandwich panel fastener failure modes

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 approval on an individual basis.
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.

9 European Technical Approval of sandwich panel fastenings

9.1 Approval tests and approval regulations in accordance with CUAP [132]

Approval tests for the fastening of sandwich panels to metal or timber substructures with self-drilling or self-tapping screws are regulated by the CUAP. 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 108.
Table 21 provides an overview of the approval 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 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 [98]:

- 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 standardization of the test results is carried out essentially in the same way as for the self-drilling and self-tapping screws. No dynamic tensile loading tests are carried out – the influence of repeated pullover loading due to wind loads is taken into account by applying a constant reduction factor $\alpha_{cycl} = 2/3$. As for the fastening screws, the partial safety factor γ_M is 1.33.
Figure 109 shows, as an example, a page from the appendix of a European Technical Approval for a sandwich panel screw.

10 European Technical Approval for fastening waterproofing membranes

European Technical Approval 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 81):

- the waterproofing membrane
- mechanical fasteners
- thermal insulation

ETAG 006 was revised, above all formally, in 2007 [133]. In accordance with the new edition, independent European Technical Approval is now required or, respectively, is now possible for mechanical fasteners of this kind. When used in a kit, the means of fastening (with the corresponding ETA) must be stated in the European Technical Approval for the waterproofing membrane system. This formal change makes operational procedures easier with regard to the comprehensive possibilities for the combination of waterproofing membranes and fasteners from various manufacturers.
For the purpose of verifying the reliability of mechanical metal fasteners, the following tests are to be carried out:

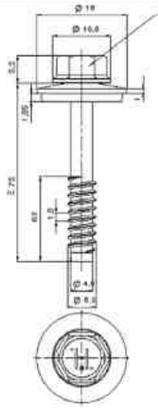
- static centric tension tests
- resistance to unwinding the fastener due to dynamic loading of the waterproofing membrane
- 15 Kesternich test cycles with correctly installed fasteners

Please refer to ETAG 006 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, e.g. [151]. 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.

11 Powder-actuated fastener and fastening screw suitability checklist

11.1 Powder-actuated fasteners

Apart from the approved applications (profile metal sheet fastenings and composite construction) it is not always possible for planners and specifiers to assess the suitability of a powder-actuated fastener for a new application. Accordingly, the clarifying questions to be asked are summarized and discussed in the follow-ing 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.



Verbindungs-element S-MP54S 6,3 x L
mit Dichtscheibe ≥ Ø16 mm

Werkstoffe Schraube:
nichtrostender Stahl, DIN EN 10088
Werkstoff-Nr. 1.4301

Scheibe:
nichtrostender Stahl, DIN EN 10088
Werkstoff-Nr. 1.4301
mit aufvulkanisierter EPDM-Dichtung

Hersteller Hilti AG
Feldkircherstrasse 100
FL - 9494 Schaan

Vertrieb Hilti Deutschland GmbH
Hiltistraße 2
D - 86916 Kaufering
Tel.: +49 (0) 800 888 5522
Fax: +49 (0) 800 888 5523
Internet: www.hilti.de

Bauteil II aus Stahl mit t_{II} in [mm]:
S235Jxx, S275Jxx oder S355Jxx nach DIN EN 10025-2
S280GD+xx, S320GD+xx oder S350GD nach DIN EN 10326

		1,50	**2,00**	**2,50**	**3,00**	**4,00**	**5,00**	**6,00**	**8,00**	**≥ 10,0**
Ø Bohrloch		5,0	5,3				5,5		5,7	
Bauteil I, Blechdicke t_{N1} bzw. t_{N2} in [mm]: S280GD+xx bis S350GD nach DIN EN 10326 — **Querkraft $V_{R,k}$ in [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
	0,63	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
Zugkraft $N_{R,k}$ in [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
	0,63	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
max. Kopfauslenkung u in Abhängigkeit von der Sandwichelementdicke d oder D alle Maße in [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

Weitere Festlegungen:

Schrauben	Charakteristische Tragfähigkeitswerte für das Verbindungselement S-MP54S 6,3 x L	Anlage 3.16 zur allgemeinen bauaufsichtlichen Zulassung Nr. Z-14.4-407 vom

Notes to Figure 109: The sheet covers a stainless self-tapping screw with sealing washer. The table gives characteristic tension values $N_{R,k}$ and shear values $V_{R,k}$ dependent on component I (*Bauteil I*) and component II (*Bauteil II*) thickness. The required drill diameter (∅ *Bohrloch*) is stated in the header of the table. Component I is structural steel and component II is steel sheet. Additionally the maximum nail head deflection u is given depending on the thickness of the sandwich panel D (range from 30 to ≥ 140).

Figure 109. Example of a page from the appendix of the German approval Z-14.4-407 [9] for a self-tapping screw used to fasten sandwich panels

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 2.6, 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 2.2.2).

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. It must meet the given requirements within the upper and lower application limits of the system (see Section 2.2.2).

Question 4: 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 attention must also be paid to the formation of a gap between component I and the supporting material (see Section 5.5).

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 5: 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

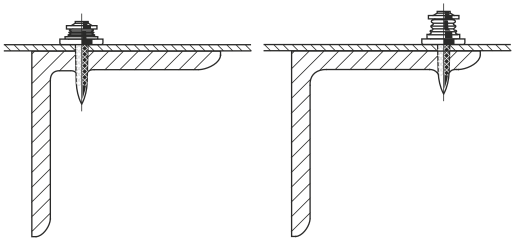


Figure 110. Fastener positioned close to the edge or web of an angle profile

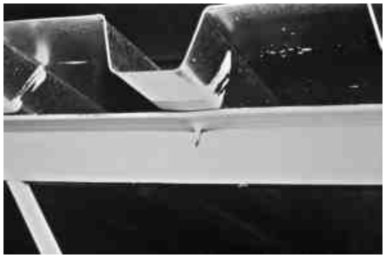


Figure 111. Fastening profile metal sheets on thin-walled, flexible angle profiles

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 110). This is the case, for example, when fastening profile metal sheets on lattice girders Figure 111) with a top flange consisting of a thin double-angle profile (wall thickness: 3 to 5 mm, leg width ≥ 40 mm). 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

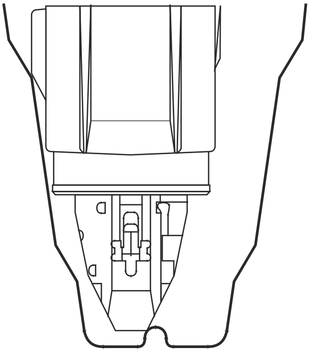


Figure 112. Insufficient space in case of contact of tool body

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 5, the technical characteristics (see Section 2.3.3.1) of the applicable fastening system must thus be taken into account.

Question 6: 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 112 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 7: 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 magazined fasteners for their entire range of fasteners.

Question 8: Is adequate technical data available for the assessment of loading behavior and for a project specific construction supervisory authority 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 6), cost-efficiency (question 7) and on-time implementation (question 8).

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 as well as national construction supervisory authority regulations.
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 pre-drilled 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 fasteners 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 or for fastenings where an external connecting thread is required.

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.

After initially being granted to powder-actuated fasteners in 2004, European Technical Approvals were awarded to fastening screws for the first time in mid 2010. The new European approval procedure for profile metal sheet fastening as well as sandwich panel fastening was presented. The previous national approval regulations were adopted in the European approval process without any loss of content. Tables provide an overview of the products with national and European approval (status 10/2010).

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 or European technical approvals are required for use in areas of application where construction supervisory 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 to *Elmar Thurner* of the Hilti Corporation.

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