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Anchorage in Concrete Construction

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Preface

Modern fastening technology is becoming increasingly important in civil and structural engineering worldwide. Cast-in-place fastenings, which are placed in the formwork before the concrete is poured, as well as post-installed fastening systems, which are installed in hardened concrete or masonry, have found widespread use in construction practice.

Anchor bolts transfer applied tension loads to the anchorage material through mechanical interlock, friction, bond, or a combination of these mechanisms. Regardless of the load-transfer mechanism, however, fastening systems rely on the tension strength of the concrete or masonry. This fact must be accounted for both in the design of the fastening and the design of the supporting (or supported) concrete or masonry member.

Every fastening element is designed for optimal performance for a specific application. When a fastening element is used for an application for which it was not intended, its performance can be negatively affected. Knowledge of the behaviour of different fastenings is therefore necessary to select the proper fastening system for a given application and to implement the design of the fastening correctly. Fastening behaviour may be influenced by many parameters. Environmental conditions such as chemical attack, temperature fluctuation, and fire exposure must also be considered.

Although each year millions of anchors are installed in concrete and masonry elements on construction sites around the world, the state of knowledge about this technology in the practice is often very poor. It is therefore the goal of this book to present the state of the art relative to fastening technology for concrete. Fastening products currently available on the market, as well as their intended areas of application, are discussed. The fundamentals of their load-bearing behaviour under short- and long-term loading, dynamic loading including seismic loading, and the dependence of the behaviour on the loading direction and failure mode are presented. The influence of the condition of the concrete, non-cracked versus cracked, as well as the behaviour of fastenings under fire loading and the corrosion behaviour of fasteners is examined. Additionally, a detailed discussion of the design of fastenings is provided.

This book builds on the volume '*Befestigungstechnik in Beton- and Mauerwerk*' by Eligehausen, Mallée (2000) and translated into the English by Philip Thrift (Hannover). Extensive editing of the translated text was performed by John Silva. The content in this book, however, has been significantly extended and updated.

Research in the field of fastening technique from around the world is brought together in this book. Much of this research was conducted at the Department of Fastening Technology at the University of Stuttgart. The department was founded in the 1970's by Professor Emeritus Dr.-Ing. Dr.-Ing. E.h. (mult) Gallus Rehm and flourished under his oversight until his retirement in 1989. The authors owe him a great deal of gratitude.

This book would not have been possible without the support of many individuals. We would like to thank Mr. M. Hoehler, M.Sc., who contributed to section 10 on seismic loading, and edited the completed manuscript as well as Dr.-Ing. J. Asmus and Dr.-Ing. T. Sippel for supplying numerous figures. Furthermore we would like to thank Ms. Dipl.-Ing. A. Clauss, Ms. Dipl.-Ing. Y. Grewin, Ms. Dipl.-Ing. I. Simons, Dipl.-Ing. J. Appl, Dipl.-Ing. L. Bezecny, Dipl.-Ing. J. Hofmann, Dipl.-Ing. T. Huer, Dipl.-Ing. M. Potthoff, Dipl.-Ing. K. Schmid, for their tireless effort preparing and editing figures.

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1 Introduction

1.1 A historical review

The task of connecting building components is as old as building itself. Throughout history, the job has been handled in different ways depending on the building material, the structural system and the particular requirements of the construction.

In wood construction traditional joinery began with timbers bound with tough natural fibres and developed into various types of interlocking, screwed and doweled joints, glued and finger joints as well as embedded steel plates and ring connectors.

Steel construction, a comparatively 'young' discipline, employs connection techniques ranging from cast-iron fittings to rivets, bolts and welding, whereby only bolting and welding are in common use today.

In concrete and masonry construction, various means of anchoring are in regular use (Fig. 1.1).

The mortar used in masonry assemblies can be regarded as the oldest type of connection material. In fact, the hewn dovetails, cast metal joints and embedded metal studs or sleeves historically employed in stone masonry may be considered to be the predecessors of today's modern fastening technology. Today, these methods have been largely replaced by plastic and/or metal elements of sophisticated design inserted into pre-drilled holes and secured via friction, mechanical interlock, chemical bond, or a combination thereof. Today there are systems available that are suitable for practically any type of masonry.

Concrete and reinforced concrete construction initially borrowed fastening techniques from other building trades, either unchanged or only slightly modified. Wood lathe placed in the formwork was anchored in the concrete via predriven nails and served as an attachment point for the entire range of building systems, as well as for suspended ceilings. Later, threaded

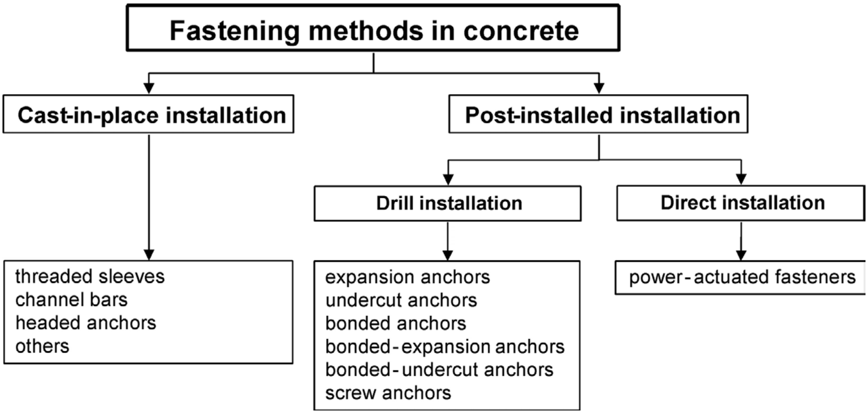

Fig. 1.1 Fastening methods in concrete

sleeves, anchor channels and headed studs welded to steel plates were employed, these being secured inside the formwork and cast into the concrete.

These so-called "cast-in-place" techniques were later rivalled by systems designed to be installed after the concrete had cured. The evolution of drilling technology from chisels to rotary-percussion tools and the more recent development of diamond core drilling has opened up new opportunities for the field of post-installed anchoring technology.

For minor loads, the ubiquitous plastic anchor, successor to hemp and lead plugs, has all but replaced other techniques. To cope with higher loads, various types of metal expansion anchors have been developed that employ, in principle, the same functional principles but with varying construction details and attendant variations in installation and application conditions.

Bonded anchors, in which a steel rod is grouted into a pre-drilled hole, continue to be frequently used. Representing the latest stages in this chain of development are undercut anchors, hybrid systems employing bond, friction and/or mechanical interlock, and second-generation self-tapping screws.

Parallel with the development of anchors for pre-drilled holes, the technology of high-strength steel nails or studs driven into steel and concrete by an explosive or pneumatic energy source (so-called power-actuated fastening) has seen growing use over the past four decades. These systems serve to simplify the attachment of piping systems, lightweight suspended ceilings, etc., and are also widely employed for the attachment of metal deck to steel framing.

Clearly, post-installed fastening in concrete and masonry is a relatively young discipline, meaning that the state of the art is generally in a state of flux. Consequently, these systems typically cannot be regulated via prescriptive standards, as is done, say, with high-strength structural bolts. Consequently, in the member states of the European Community, the U.S. and other countries the design and installation of post-installed fastenings is usually carried out in accordance with product-specific approvals.

1.2 Requirements for fastenings

Fastenings must be designed in such a way that they do the job for which they are intended, are durable and robust, and exhibit sufficient load-carrying and deformation capacity. Fastenings for less critical applications, e.g. securing lightweight duct, lighting, and wiring, can be selected on the basis of the user's experience and do not usually require analysis or structural review (outside areas of seismic hazard). On the other hand, fastenings that are relevant to life safety, i.e. whose failure could pose a hazard to life or result in significant economic loss, must generally be selected on the basis of structural considerations and are typically designed and detailed by a structural engineer. The design establishes whether the requirements of the serviceability and ultimate limit states are met. The serviceability limit state includes requirements for limiting deformation, and requirements on durability (corrosion, chemical resistance). At the ultimate limit state it must be proven that the design value of the actions does not exceed the design value of the fastening resistance. Analyses of the serviceability and ultimate limit states generally make a distinction between the type and direction of the load. Section 1.3 deals with loads acting on connections and section 3.7 with the distribution of these loads to the fasteners. The capacities of the fastenings are explained in relation to the type of fastener and type of base material as well as failure mode in sections 4 to 9. The behaviour of fasteners under seismic excitations and under fire is dealt with in sections 10 and 11 respectively. Corrosion and corrosion protection is discussed in section 12 and the influence of fastenings on the capacity of concrete members in which they are installed is explained in section 13. Requirements on the suitability of fasteners for the application in question and the design of fastenings are discussed in section 14.

1.3 Nature and direction of actions

Actions (loads) can be classified according to the frequency of their occurrence and their duration. In addition, we can make a distinction as to whether or not inertial forces are involved. Table 1.1 provides an overview of various actions. Dynamic forces arise in cases of

Table 1.1 Classification of actions

Number of load cycles				
None (constant)	Low		High	
	Without inertial forces	With inertial forces	Without inertial forces	With inertial forces
• Self-weight • Partitions • People • Fixtures and fittings • Stored materials • Snow • Water • Wind • Restraint of deformations	• Restraint of deformations	• Impact • Earthquake • Explosion	• Traffic loads on bridges and basement roofs • Crane rails • Lifts • Machines without inertial acceleration	• Machines generating high inertial accelerations (punches, presses, rams, forges)
	• Primarily static actions	• Dynamic actions	• Frequently alternating actions	• Dynamic actions

impact, earthquake, explosion or machines that generate large inertial loads. If the load is permanent or occurs only a few times and does not include inertial forces, then the action is considered to be static. If the number of load cycles is large but, again, inertial loads are not present, then we refer to fatigue loading. If inertial forces are involved, then the action is dynamic, regardless of the number of load cycles.

Static actions are the sum of permanent and semi-permanent (slowly changing) actions. These actions are sometimes referred to as dead and live loads. The permanent actions result from the weight of the structural components to be anchored and any other constant loads that the attached components must carry, e.g. backfill, floor coverings, and plaster. Semi-permanent actions include, for example, foot traffic, fixtures and fittings, non-load-bearing lightweight partitions, stored materials, wind and snow. Given values for the applicable permanent and semi-permanent actions can be found in the relevant national and international standards (e. g. DIN 1055, Eurocode 1: EN 1990: 2002 (2002), ASCE 7 (*American Society of Civil Engineers* (2002)) .

Deformations can occur in anchored components, e.g. due to temperature fluctuations or due to shrinkage and creep of the concrete components. Temperature fluctuations may be due to weather conditions, as with building facades, or may simply be a result of the component function, as in the case of chimneys, silos, boiler rooms and cold storage rooms. Restraint of these deformations gives rise to stresses in the fasteners, the magnitude of which depends on the geometry and position of the fastenings as well as the mechanical properties of the materials involved. These stresses may be relevant to the fatigue-resistance of the fastener, depending on the number of temperature-induced strain cycles. For example, in the case of facade support structures, assumptions of 10^4 to $2 \cdot 10^4$ load cycles are often used in design.

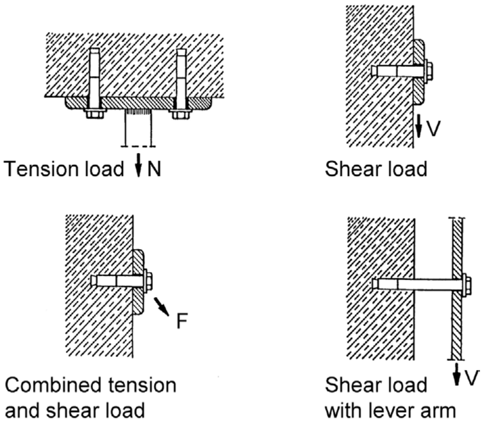

Fig. 1.2 Actions on fasteners

Frequently alternating actions (fatigue loads) are caused by, for example, traffic loads, crane rails, lift and machines. The magnitude of the changing action required for design is again to be found in the relevant national and international standards. These standards also define whether a changing action should be viewed as a static action or as a fatigue load. For example, a wind load frequently changes in magnitude and direction but is often regarded as a static load for design purposes.

The essential difference between dynamic and static actions lies in the presence of inertial and attenuation forces. These forces arise from the induced accelerations and must be taken into account when determining the forces on the fastening. Dynamic forces are brought about by earthquakes, sudden actions such as impacts and explosions, and by machines with high inertial acceleration, e.g. printing presses. Dynamic actions generated by machines are also regarded as relevant for fatigue.

Loads can occur as tension, shear or a combination of tension and shear. In the case of shear, we distinguish between loading with or without bending of the fastener (Fig. 1.2).

2 Fastening systems

2.1 General

Fasteners transfer applied tension loads to the base material in various ways. Load-transfer mechanisms are typically identified as mechanical interlock, friction or bond (Fig. 2.1).

Mechanical interlock involves transfer of load by means of a bearing interlock between the fastener and the base material. Mechanical interlock is the load-transfer mechanism employed by headed anchors, anchor channels, screw anchors, and undercut anchors.

Friction is the load-transfer mechanism employed by expansion anchors. During the installation process, an expansion force is generated which gives rise to a friction force between the anchor and the sides of the drilled hole. This friction force is in equilibrium with the external tensile force.

In the case of chemical interlock, the tension load is transferred to the base material by means of bond, i.e. some combination of adhesion and micro-keying. Chemical interlock is the load-transfer mechanism employed by bonded anchors.

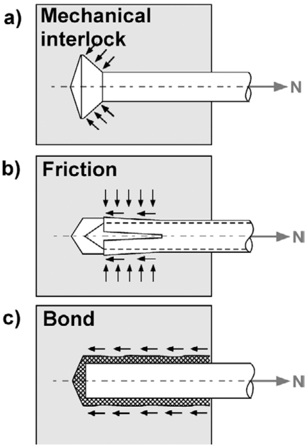

Fig. 2.1 Anchor load-transfer mechanisms

The majority of commercially available fasteners resist tension loads via one or more of the above described mechanisms.

Another way of differentiating anchor systems is by the way they are installed. A distinction is made between cast-in-place, drilled-in and direct installation. Cast-in-place components are secured in the formwork prior to casting. Drilled-in anchors are installed in holes drilled into the hardened base material. Direct installation refers to studs or nails driven into the base material with powder cartridges or pneumatic action.

The following sections describe anchors commonly used in plain and reinforced concrete.

2.2 Cast-in-place systems

A variety of inserts are used for cast-in-place installations. These include lifting inserts for the transportation of precast concrete components, anchor channels, embedded plates with headed studs, bent reinforcing bars equipped with internally threaded unions, as well as custom components for hanging heavy facade panels and for securing masonry. Sections 2.2.1 to 2.2.4 describe the more common cast-in-place systems listed above. Design procedures for cast-in-place headed anchors and anchor channels are outlined in section 14.

As previously discussed, cast-in-place systems transfer external tension loads into the base material by means of a mechanical interlock between the embedded component and the concrete. Their positions must be coordinated with the reinforcement layout. They can also be installed in heavily reinforced elements without difficulty. The advantage of cast-in-place systems lies in the fact that the location of the anticipated external loads is known and so can be accommodated in the design of the reinforced concrete member through appropriately placed reinforcement. The disadvantage lies in the extra layout and planning required for these systems, as well as in the potential for erroneous placement.

2.2.1 Lifting inserts

Lifting inserts used for the transport of plain and reinforced concrete precast elements must often conform to applicable local specifications regulating their design. Examples include the safety guidelines of Germany's *Hauptverband der gewerblichen Berufsgenossenschaften* (1992) and the *U.S. Occupational Safety and Health Administration (OSHA)* (1989) which specifies capacity requirements for inserts and lifting hardware.

In the case of cast-in cable loops, the crane hook or lifting tackle is simply attached to a loop of cable projecting from the concrete (Fig. 2.2).

A wide variety of commercially available lifting inserts are equipped with flush-set internally threaded sleeves to accommodate lifting tackle (Fig. 2.3). These are anchored in the concrete by various means including deformations, transverse dowels, and hairpins. Lifting inserts may also be constructed by swaging an internally threaded insert directly onto the end of a piece of reinforcing bar (Fig. 2.4).

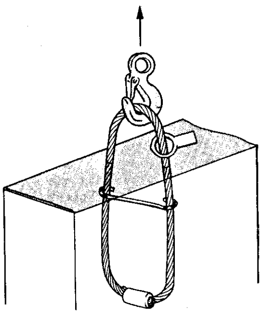

Fig. 2.2 Cast-in cable loop for crane hook (*Bertram* (1997))

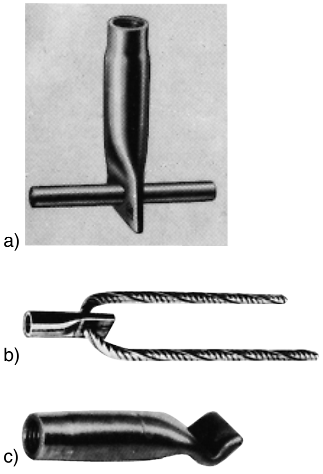

Fig. 2.3 Typical threaded sleeves (*Bertram* (1997))

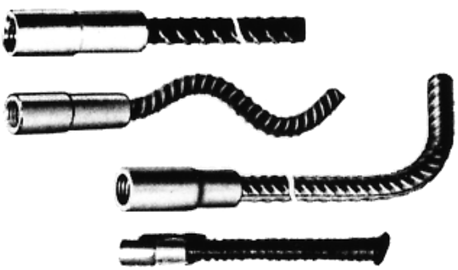

Fig. 2.4 Transport anchors with swaged threaded sleeves (*Bertram* (1997))

A simple form of transport anchor is constructed from bar stock, one end of which has been sheared and bent to form a 'swallow tail'. A hole drilled into the opposite end serves to accommodate the lifting hardware attachment (Fig. 2.5).

Headed anchors with cold-formed heads (Fig. 2.6) at each end are designed to accommodate special lifting hardware that engages the larger head.

There are also systems available in which the lifting tackle can be remotely disconnected (Fig. 2.7).

The installation instructions of the manufacturer must be adhered to when using lifting inserts. These specify permissible load, minimum concrete strength, minimum component

Fig. 2.5 Steel flatbar with “fishtail”

Fig. 2.6 Round-headed transport anchor

Fig. 2.7 Lifting tackle with remote release

thickness, minimum spacing, and edge distance, as well as the necessary reinforcement. As a rule, specific additional reinforcement is required since lifting inserts are often positioned close to edges or in narrow components.

Lifting inserts used to carry permanent loads as part of the finished structure must satisfy additional requirements for such installations (e.g. as per the constraints of the relevant approval).

2.2.2 Anchor channels

Anchor channels (Figs. 2.8 and 2.9) consist of a cold-formed or hot-rolled steel channel equipped with special anchor fittings. These channels, filled with rigid urethane foam to prevent concrete intrusion, are attached directly to

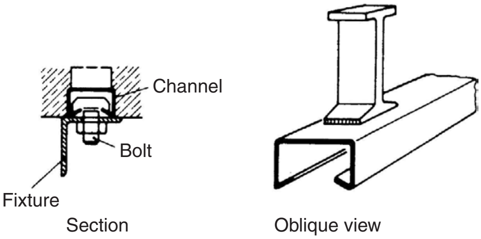

Fig. 2.8 Cast-in-place channel anchor (*Eligehausen, Mallée, Rehm* (1997))

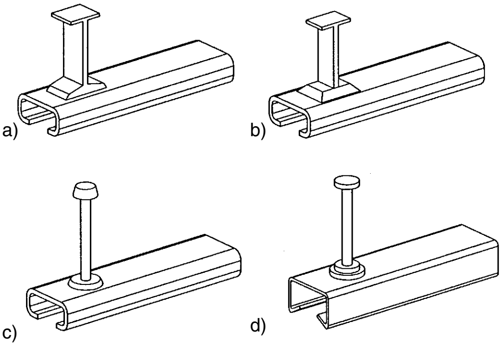

Fig. 2.9 Variants for cast-in-place anchor channels (*Wohlfahrt* (1996))
a) Welded profile
b) Swaged profile
c) Swaged headed stud
c) Welded headed stud
d) Welded special nut with screw

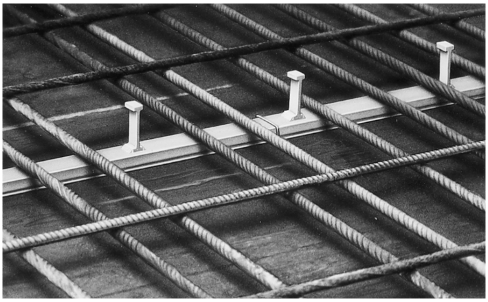

Fig. 2.10 Anchor channel placed in the formwork

the inside of the formwork (Fig. 2.10). Following removal of the formwork and of the rigid foam, a variety of components can be attached with the aid of special T-headed bolts (Fig. 2.11).

Transfer of the load back into the concrete in the case of anchor channels is generally achieved by way of T-, I-shaped or headed anchors welded (Fig. 2.9a) or forged to the channel (Fig. 2.9b, c) or special nuts welded to the channel into which a bolt is screwed (Fig. 2.9d). However, there are also anchor channels available in which the load is transferred into the base material by way of loops of steel with tabs that are passed through the back of the channel and bent. This type of anchorage presents a problem because the anchorage may become effective only after a certain degree of slip of the channel. In addition, it cannot be guaranteed that the steel tabs are bent properly on site. In Germany such anchor channels are not approved for use in safety relevant applications.

The anchor channels described above may only be loaded perpendicular to the axis of the channel because transferring forces along the length of the channel is only achieved by way of friction between the T-headed bolt and the lip of the rail, and the magnitude of this friction force is uncertain. To transfer loads along the length of the channel there are special channels with serrated lips. The matching T-headed bolts also exhibit serrations which engage with those of the channel (Fig. 2.12). To guarantee an interlocking connection which transfers the loads, these bolts have to be prestressed with a defined torque.

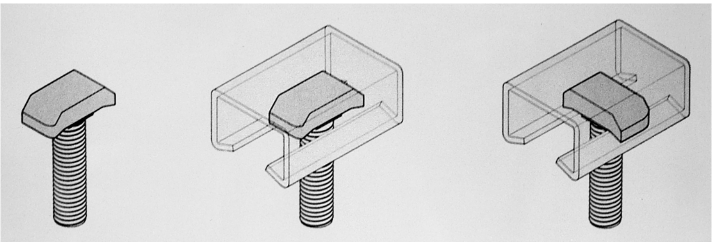

Fig. 2.11 Installing a T-head bolt in a cast-in-place channel

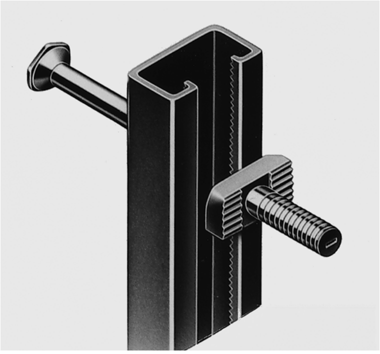

Fig. 2.12 Cast-in-place channel with serrated edges for resisting shear loads along the length of the rail

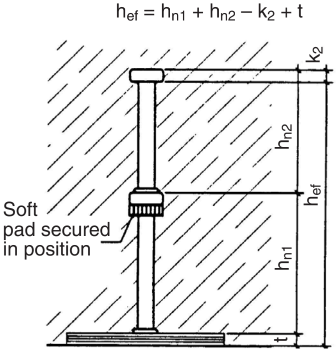

Fig. 2.14 Two headed studs welded together with a soft pad placed beneath the head nearest the surface

2.2.3 Headed studs

Headed stud anchorages (Fig. 2.13) consist of a steel plate with headed studs butt-welded on. Long headed studs can be produced by welding short studs together (Fig. 2.13). In such cases a soft pad should be placed under the intermediate heads in order to prevent a mechanical interlock (Fig. 2.14). However, instead of welding short headed studs together, it is recommended to use longer studs.

Headed studs with smooth shanks are usually welded on using drawn arc stud welding.

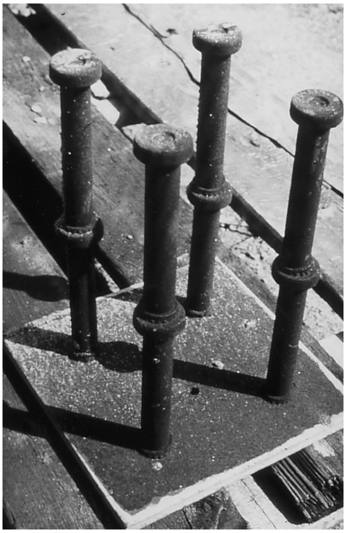

Fig. 2.13 Steel embed plate with welded headed studs

Headed studs can also been made from ribbed reinforcing bars and welded to the steel plate by means of metal arc welding. The welding is not usually carried out on site but rather under controlled factory conditions. The fixture is normally welded to the cast-in steel plate.

2.2.4 Threaded sleeves

Threaded sleeves consist of a tube with an internal thread which is anchored back into the concrete. We distinguish between sockets for lifting eyes and sleeve anchors (Fig. 2.3). Sockets for lifting eyes have a flat section with a hole at one end (Fig. 2.3a,b). They are anchored back into the concrete by passing a steel rod or reinforcing bar through the hole. In the case of sleeve anchors, the flat section at one end includes a hook (Fig. 2.3c). Curved anchors (Fig. 2.15) comprise a bent ribbed reinforcing bar with a threaded sleeve pressed on.

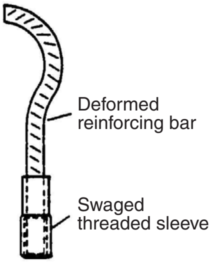

Fig. 2.15 Hooked reinforcing bar with swaged threaded sleeve (*Eligehausen, Mallée, Rehm* (1997))

2.3 Drilled-in systems

2.3.1 Drilling techniques

Advances in drilling technology have contributed significantly to the widespread use of post-installed anchors. Rotary-impact drills (rotary hammers) are most often used for anchoring applications. Diamond core drills are used less frequently, although recent advances in weight reduction, slurry-capture, and dry coring have made these systems more attractive for anchoring applications where existing reinforcement is expendable. In some cases, rock drills are used for large anchorages.

An electro-pneumatic rotary-impact drill employs a piston to generate the percussive action of the drill bit. These drills operate at low rotational speeds but with high impact energy. The speed at which the drill advances is generally not dependent on the applied pressure. Depending on the power rating of the drill, holes with diameters up to 40 mm can be produced easily and economically with carbide tipped bits. Drilling through reinforcing bars of small diameter is possible, although bit life is significantly reduced. Newer models have built-in vacuum systems to capture the dust generated during drilling, thus mitigating the contamination and inconvenience caused by the dust, reducing the drilling time and extending the bit life. Dust capture can also reduce health risks for the drill operator.

Diamond core drills are employed for a variety of applications. The cutting edges of the hollow cylindrical bit are tipped with a diamond matrix. The concrete is removed not through chiselling action, but rather by abrasion. Diamond drilling equipment is often secured to the component being drilled and water is typically used to both cool the bit and transport drilling slurry to the surface. The rate of diamond grit loss during drilling is crucial for proper functioning of the bit and requires the correct pairing of bit type and concrete aggregate hardness. Recently, hand-held core drill rigs more suited to anchoring applications and "dry" bits that do not require water cooling have become widely available. It should be remembered when employing diamond core drilling that reinforcing bars of any diameter can be severed without difficulty or noticeable changes in drill operation. Therefore, particular attention should be paid to coordinating the position of the drilled holes with respect to the reinforcing steel in order to avoid damaging structural reinforcement.

Many anchor systems are sensitive to deviations of the as-drilled hole diameter outside of specified tolerances, and in turn on the dimension of the carbide-tipped drill bit as measured across the tip. Carbide drill bits used for anchoring applications should be checked that their dimensional tolerances, particularly those relating to tip dimensions and concentricity, conform to anchor manufacturer requirements. Typically, national standards such as those of the *Deutsches Institut für Bautechnik* (2002) or the *American National Standards Institute* (1994) are referenced and can be used to confirm drill bit suitability. Drill bits conforming to *Deutsches Institut für Bautechnik* (2002) are marked with a special sign (Fig. 2.16).

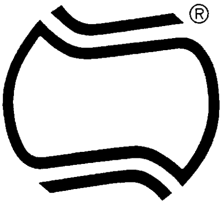

Fig. 2.16 Special mark for drill bits confirming to *Deutsches Institut für Bautechnik* (2002)

Use of diamond core drill bits for anchoring applications should be verified with the anchor manufacturer, since the actual hole diameter associated with a core drill bit of correct nominal diameter may not be within the tolerances necessary for the anchor to function properly. Additionally, some anchor systems, notably bonded anchors, may be sensitive to hole roughness. "Matched tolerance" core bits are tested to verify correct functioning of the anchor in holes drilled with these bits.

2.3.2 Installation configurations

Three types of installation configuration may be distinguished (Fig. 2.17):

- pre-positioned
- in-place
- stand-off

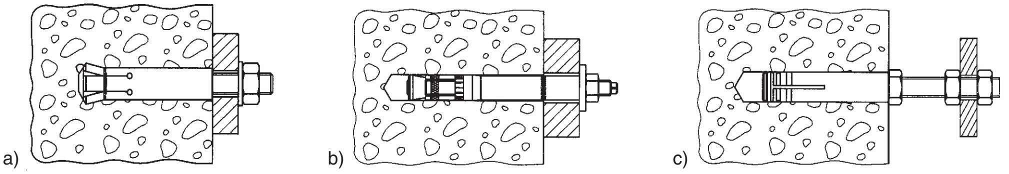

Fig. 2.17 Anchor installation configurations
a) Pre-positioned installation
b) In-place installation
c) Stand-off installation

A pre-positioned installation (Fig. 2.17a) involves drilling a hole, inserting the anchor and subsequently placing and securing the item to be fastened. The drilled hole in the base material is typically larger than the clearance hole in the component being fastened.

An in-place installation uses the element to be fastened as a template for drilling the anchor hole(s). Therefore, the diameter of the hole in the component to be fastened must be at least as large as the required diameter of the drilled hole (Fig. 2.17b).

In a stand-off installation, the item to be fastened is mounted at a distance from the surface of the base material (Fig. 2.17c). It is necessary in this type of installation to ensure that the fastener is capable of delivering both tension and compression loads to the base material. In the case of post-installed mechanical anchors, it is necessary to provide a bearing washer and nut at the surface of the base material to receive compression loads. This is also advisable, although not required, for bonded anchors.

Pre-positioned or in-place installations require that the useable fixing length l_{fix} is at least equal to the thickness t_{fix} of the item to be fastened. If the base material is covered with a non-load-bearing layer (e.g. plaster or insulation), then the fixing length l_{fix} must be selected so that it is at least equal to the thickness of the non-load-bearing layer plus the thickness of the item to be fastened (Fig. 2.18).

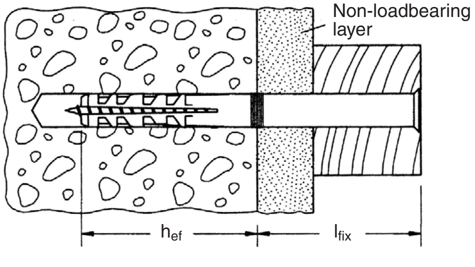

Fig. 2.18 Accounting for non-load-bearing layer in determining the useable fastening length

Although the useable fixing length of an anchor equipped with internal threads can be varied by simply selecting a bolt of suitable length, it is a set dimension for most other types of mechanical anchors. The manufacturer's specification should be consulted to determine the maximum possible useable fixing length of an individual anchor. Note also that with in-place installation the actual embedment length of fasteners with a defined useable fixing length will be equal to the minimum embedment plus the balance of the fixing length not used by the thickness of the item to be fastened and any surface coatings, pads, etc.

2.3.3 Drilled-in anchor types

2.3.3.1 Mechanical expansion anchors

Mechanical expansion anchors can be divided into two groups (Fig. 2.19):

- torque-controlled (Fig. 2.19a)
- displacement-controlled (Fig. 2.19b)

Torque-controlled expansion anchors may be further classified as either sleeve- or bolt-type. Sleeve-type anchors generally consist of a bolt or threaded rod with nut, washer, spacer and expansion sleeve, deformations to prevent spinning of the anchor in the hole, and either one expansion cone (Fig. $19a_1$) or two cones (Fig. $2.19a_2$). Bolt-type anchors typically consist of a bolt, the end of which has been swaged or

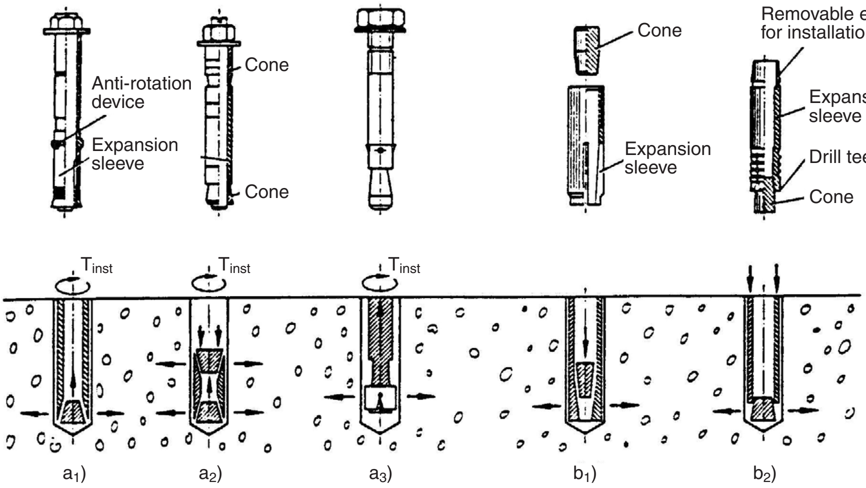

Fig. 2.19 Details and working principles of metal expansion anchors (*Eligehausen, Mallée, Rehm* (1997))
a) Torque-controlled expansion anchor
b) Displacement-controlled expansion anchor

machined into a conical shape, expansion segments nested in the recessed conical end of the bolt, and a nut and washer (Fig. 2.19a$_3$).

Torque-controlled expansion anchors are installed by drilling a hole, removing drilling dust and debris, inserting the anchor into the hole and securing it by applying a specified torque to the bolt head or nut with a torque wrench (Fig. 2.20). Once the bolt or nut achieves bearing against the base material, the further application of torque draws the cone at the embedded end of the anchor up into the expansion sleeve (or expansion segments), thereby expanding the expansion element(s) against the sides of the drilled hole. The ensuing frictional resistance places the bolt in tension. The compression forces acting on the concrete due to the dilation of the expansion elements are known as expansion forces. If the concrete around the anchor is continuous and undisrupted by cracking or a proximate edge, the resulting stresses are distributed roughly symmetrically around the anchor perimeter. In the past, torque-controlled anchors were occasionally referred to as "force-controlled" expansion anchors because the torque generates a tensile force in the anchor. However, "torque-controlled" is a better descriptor for the working principle of the anchor since a prescribed torque is used to set the anchor. Torque also serves as a way of checking the installation of torque-controlled expansion anchors. An anchor that was not set correctly will rotate before achieving the prescribed torque. Rotation is nominally prevented by deformations in the anchor elements contacting the sides of the hole. Oversized holes or local defects in the concrete may reduce their

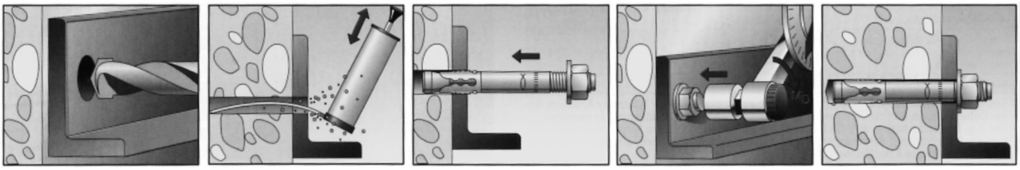

Fig. 2.20 Installation of a torque-controlled stud-type expansion anchor

effectiveness and allow the anchor to spin, thereby preventing attainment of the required expansion force. Alternatively, the anchor may attain the required torque but only after the anchor has been drawn out of the hole to an excessive degree. Either of these conditions is an indication of improper set and could lead to reduced anchor capacity.

Torque-controlled expansion anchors compensate for minor deviations in the diameter and roundness of the drilled hole by variations in the extent to which the cone is drawn into the expansion element (Fig. 2.21). This is known as expansion reserve; it is determined by the geometry of the anchor and is necessarily limited. For this reason, torque-controlled expansion anchors should be installed with drill bits conforming to the tolerances of recognised national standards as discussed above. When this condition is satisfied, normal deviations of drilled hole geometry as caused by e.g., operator position, base material hardness, etc., should have little effect on anchor function.

In the system shown in Fig. 2.19a_2, the expansion sleeve is expanded by cones both the top and bottom of the sleeve. However, although double-cone anchors can exhibit a higher load-carrying capacity than single-cone anchors, they require greater minimum edge distances owing to the greater expansion forces.

The setting process of a torque-controlled expansion anchor results in expansion forces which in turn generate high stresses (Fig. 2.22) and localised deformations in the concrete. The degree of expansion and the magnitude of the deformation of the hole wall both depend on the force with which the cone is drawn into the sleeve (or expansion segments) as well as on the resistance of the concrete to deformation. The deformation of the hole wall may be critical for proper functioning of the anchor. Expansion anchors set in high-strength concrete (concrete compressive strengths ≥ 65 N/mm^2) typically produce deformations of negligible magnitude. Therefore, torque-controlled expansion anchors developed for use in concrete of normal strength may be unsuitable for applications in high-strength concrete.

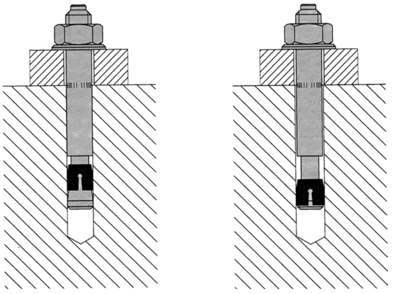

Fig. 2.21 Torque-controlled expansion anchors in drilled holes with different diameters

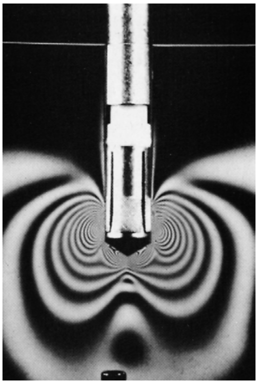

Fig. 2.22 Stress contours in the anchorage zone of a torque-controlled expansion anchor (*Seghezzi* (1983))

Torque-controlled expansion anchors transfer external tensile forces to the base material via friction and, to a limited extent, via mechanical interlock in the region of the deformed concrete. As the torque is introduced, it generates a prestressing force in the bolt or stud which at the same time clamps the item being fastened against the surface of the base material. This prestressing force diminishes after installing the anchor as a result of several factors, including localised relaxation of the concrete. If cracks occur in the base material in the vicinity of the installed anchor, then the prestressing force drops further. As the anchor is loaded externally, most of the load acts to relieve the prestressing, or clamping, force in the anchorage. Loading beyond the point where the residual prestressing force is completely balanced by the external load produces a proportional increase in the force in the bolt, with the result that the cone is drawn further into the sleeve (or segments) and the anchor is expanded further (follow-up expansion). This follow-up expansion generates the necessary additional friction to resist an increasing imposed external load. Follow-up expansion is only possible when the frictional resistance between cone and expansion sleeve (or segments) is less than the friction force generated between the sleeve (or segments) and the sides of the drilled hole. If this is not the case, then the anchor exhibits uncontrolled slip under tension loading, i.e. it is pulled partially or completely out of the hole without any increase in load beyond the onset of noticeable slip. To increase the friction potential between the expansion sleeve and the concrete, some expansion anchors utilise ribs, knurling or other deformations.

Torque-controlled expansion anchors are typically available in a wide range of diameters, from 6 mm to 24 mm. They are typically provided with zinc electroplating (coating thickness ≥ 5 µm) in order to prevent corrosion during storage and transport. Sheradising or hot-dip galvanising may be used to achieve a more robust zinc coating thickness (in the range of 50µm). However care must be taken to prevent uneven coating thickness on friction surfaces and threaded parts. Where additional corrosion protection is required, torque-controlled expansion anchors may also be fabricated in stainless steel, although care must be taken to avoid jamming of threads and friction surfaces. Studs and bolts may be fabricated from a variety of steels depending on the production method used and the desired mechanical properties after fabrication. In Europe, carbon steel anchor bolts are typically fabricated to conform to the requirements of a Grade 8.8 steel according to *ISO 898, Part 1* (1988). Stainless steel bolts generally reference to A4-70 (austinitic steel) as per *ISO 3506* (1979). For anchors fabricated in the U.S., no single standard is universally specified. Reference is often made, however, to *ASTM A510-03* (2003) or *ASTM A108-03* (2003) for the mechanical properties of carbon steel anchor bolts. Stainless steels typically conform to either *AISI 303* (1995)*, AISI 304* (1995) or *AISI 316* (1995) with respect to chemical composition, whereby *ASTM A276-04* (2004) or *ASTM A493-95* (2004) may be referenced for the mechanical properties. When a thorough understanding of the bolt properties is required, the manufacturer should be consulted for detailed information. Commercially available torque-controlled expansion anchors are offered in a wide array of configurations and designs that vary with respect to the number of cones as well as the shape, dimensions and number of expansion sleeves and expansion segments. Additionally, newer designs specifically authorised for applications in cracked concrete may employ special features, e.g. friction-reducing coatings, to improve the follow-up expansion behaviour of the anchor.

Displacement-controlled expansion anchors usually consist of an expansion sleeve and a conical expansion plug, whereby the sleeve is internally threaded to accept a threaded element (bolt, rod, etc.). They are set via the expansion of the sleeve as controlled by the axial displacement of the expansion plug within the sleeve. In the common displacement controlled anchor type as depicted in Fig. 2.19b$_1$, known as a drop-in anchor, this is achieved by driving the expansion plug into the sleeve with a setting tool and a hammer (Fig. 2.23). Alternatively, in the type of displacement-controlled anchor shown in Fig. 2.19b$_2$, setting is achieved by driving the sleeve over the cone. Like torque-controlled expansion anchors, displacement-controlled expansion anchors transfer external tension loads into the base material via friction and, in the zone of the localised deformation, some degree of mechanical interlock.

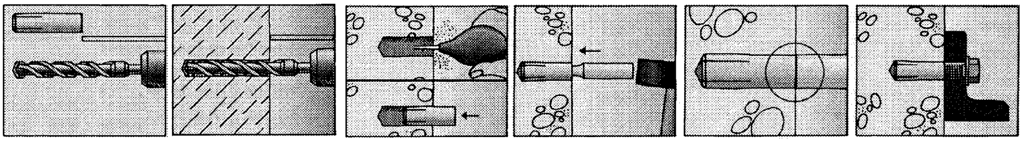

Fig. 2.23 Installation of a drop-in anchor of the type shown in Fig. 2.19b$_1$

In the anchor shown in Fig. 2.19b$_1$, the magnitude of the expansion force depends on the degree of sleeve expansion, the gap between the anchor and the sides of the drilled hole, and the deformation resistance of the concrete. The initial expansion force generated by a fully-installed displacement-controlled anchor of this type is typically considerably greater than that created by a torque-controlled expansion anchor of similar size. This high initial expansion force is substantially reduced through relaxation of the concrete, however, and cannot be renewed except by re-setting of the anchor. In particular, the expansion force does not increase with the introduction of an external load, since the anchor has no follow-up expansion capability. As such, its tension load-bearing behaviour depends substantially on the depth of the localised deformation into the concrete and therefore significantly on the drilled hole tolerance. If the hole diameter is too small, the expansion force generated during setting may be so high that the concrete spalls or is split. Additionally, if the concrete has a high compressive strength (e.g. ≥ 50 N/mm^2), it may be physically impossible to expand the anchor to the required degree. Conversely, if the hole is oversized, the expansion sleeve does not engage the hole wall sufficiently (Fig. 2.24) and the load-carrying capacity of the anchor is correspondingly diminished.

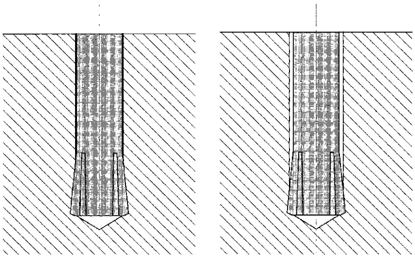

Fig. 2.24 Drop-in anchors in drilled holes with different diameters

Owing to their sensitivity with respect to hole and installation tolerances, displacement-controlled anchors require strict adherence to correct drill bit tolerances, as discussed previously as well as on-site installation checks. For drop-in anchors as depicted in Fig. 2.19b$_1$, proper installation is verified visually when the collar of the setting tool contacts the sleeve of the anchor, as shown in Fig. 2.23. Only in this way can full expansion of the anchor be assured.

A significant amount of driving energy is required to ensure complete expansion of drop-in anchors. According to studies by *Eligehausen, Graf, Meszaros, Lee* (1995), full expansion requires anywhere from 5 to 30 hammer-blows (using a representative hammer size and weight), depending on type and size of the anchor, hole diameter and concrete strength. In overhead installations, (e.g. in a slab soffit), the required number of hammer blows increases roughly 2 to 3 times. In many cases, this level of effort is not achieved in practice. *Eligehausen, Meszaros* (1992) investigated the *in-situ* condition of roughly 220 drop-in anchors (M8-M12) of various manufactures installed on several different building sites. The degree of expansion was found to be approximately 30 % to 70 % (on average 50 %) of full expansion, which is relatively low. Inadequate expansion has roughly the same effect as an oversized hole (see Fig. 2.24) on drop-in anchor tension load capacity.

In anchors of the type depicted in Fig. 2.19b$_2$, the maximum expansion occurs at the extreme end of the sleeve and decreases along the anchor length. The primary action of the setting process is to chip away at the concrete and the expansion force generated is less than that associated with anchors of the type shown in Fig. 2.19b$_1$.

One representative of the anchor type shown in Fig. 2.19b$_2$ is the so-called self-drilling anchor. Its anchor body is designed to serve as a drill bit (it has a removable end for insertion into the drill chuck adapter) with the intent that hole tolerance is eliminated as a factor in the load-carrying capacity of the anchor. Furthermore the required hole depth is automatically ensured. After the anchor has been used to drill the hole, it is removed, the expansion plug is inserted into the end of the sleeve, and the anchor placed back into the hole and hammered over the expansion plug with the rotary-impact drill set to hammer-only mode until the drill chuck adapter touches the concrete surface. This design places high demands on the anchor materials and the manufacturing process. The anchor body must, on the one hand, possess sufficient hardness to facilitate drilling, while at the same time remaining sufficiently ductile to permit expansion.

With sleeve-down type anchors similar to the one shown in Fig. 2.19b_2 the hole is drilled by means of a rotary impact drill. During installation the sleeve is hammered onto the cone until the upper rim of the sleeve sits flush with the concrete surface. To ensure full anchor expansion the proper drill hole depth is essential which should be ensured by using a drill that stops at the required depth (stop-drill).

The load-carrying capacity of deformation-controlled self-drilling or sleeve-down type anchors depends on achieving the required expansion. As this cannot be verified visually after installation, it is essential to check the distance between the rim of anchor sleeve and the top of the expansion plug.

Displacement-controlled expansion anchors are produced in the size range M6 to M20 and are typically provided with zinc electroplating (≥ 5 µm). Drop-in anchors manufactured from stainless steel are available as well. The manufacturer information or approval documentation should be consulted for details of the grade of steel used in a particular anchor.

2.3.3.2 Undercut anchors

As with cast-in-place systems, undercut anchors develop a mechanical interlock between anchor and base material. To do this, a cylindrically drilled hole is modified to create a notch, or undercut, of a specific dimension at a defined location either by means of a special drilling apparatus (Fig. 2.25a, b), or by the undercutting action of the anchor itself (Fig. 2.25c, d). Fig. 2.25 e and f illustrate two further variations of undercut anchors. In terms of the shape of the undercut, a distinction is made between those that widen towards the surface (Fig. 2.25a) and those that widen towards the bottom of the hole (Fig. 2.25 b–d).

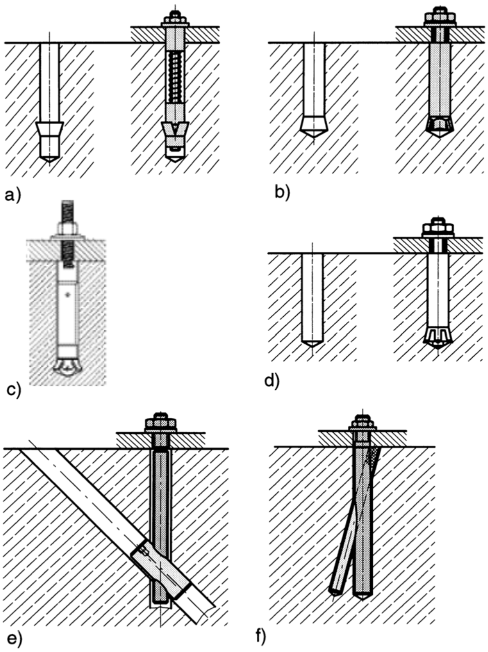

Fig. 2.25 Undercut anchors
a) Reverse undercut
b) to d) Forward undercut
e) and f) Other interlocking systems

The anchor depicted in Fig. 2.25a consists of a threaded rod with hex nut and washer, a cylindrical nut, three curved bearing segments, cone, spacer sleeve, helical spring and a plastic ring

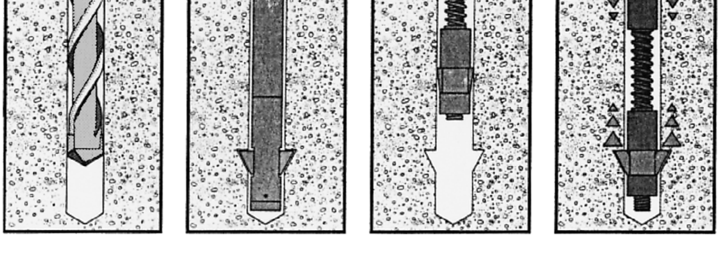

Fig. 2.26 Installation of an undercut anchor of the type shown in Fig. 2.25a (hole cleaning step not shown)

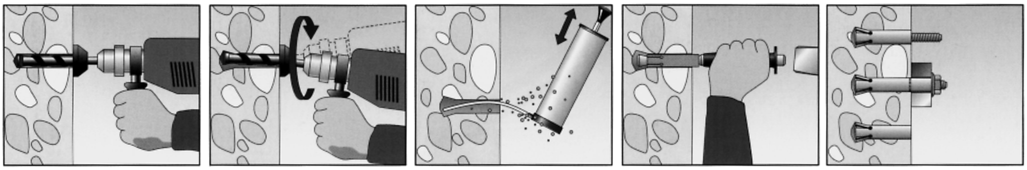

Fig. 2.27 Installation of an undercut anchor of the type shown in Fig. 2.25b

which secures the bearing segments prior to installing the anchor. The installation sequence is shown in Fig. 2.26. After drilling a cylindrical hole, the undercut is created with the help of a water-cooled undercutting tool with diamond grit blades. Afterwards the anchor is inserted into the hole and the bearing elements are allowed to unfold into position at the level of the undercut. Torquing the anchor brings the bearing segments into contact with the undercut surfaces. The tension load-bearing behaviour depends largely on achieving the necessary undercut. This has to be ensured through appropriate checks during the undercutting process. In order to prevent over-torquing and consequent shearing of the undercut surfaces, the number of turns of the nut permitted to achieve the required torque is limited.

The undercut anchor represented in Fig. 2.25b typically consist of a threaded stud with a conical end (cone bolt), expansion sleeve, nut, and washer. Internally threaded versions (not illustrated) accept bolts or threaded rods. One such anchor employs the installation procedure depicted in Fig. 2.27. First, the cylindrical hole is drilled with a special stop-drill bit. When the stop-drill bit limit has been reached, the undercut is created by gyroscopic rotation of the hammer drill. The unique design of the stop-drill bit defines the extent of the gyroscopic rotation and thereby the resultant undercut. After cleaning out the hole, the expansion sleeve is hammered over the cone bolt with a setting tool.

The anchor systems represented by Fig. 2.25c typically consist of a cone bolt, an expansion sleeve designed for undercutting, and either a nut and washer or an internal thread in the sleeve to accept bolts and threaded rods. Fig. 2.28 shows how such an anchor is installed. The cylindrical hole is drilled using a stop-drill. The undercut is generated using the expansion elements of the anchor, which are typically equipped with hardened drilling points. The anchor is mounted in a rotary-impact drill and

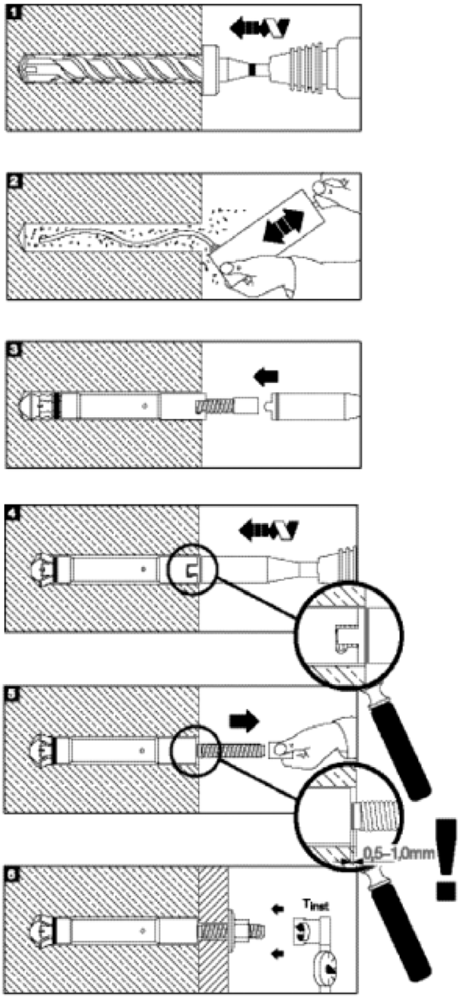

Fig. 2.28 Installation of an undercut anchor of the type shown in Fig. 2.25c

inserted into the pre-drilled hole. Use of rotary-impact action permits the expansion elements to simultaneously undercut the concrete and widen to their fully-installed position. The cone bolt provides at its end space for the drilling dust which accumulates during formation of the undercut. This process results in a precise match between the undercut form and anchor geometry.

Undercut anchors of the type described in Fig. 2.25d are similar to those of Fig. 2.25c with the exception that the undercutting process is accomplished with hammering action only (Fig. 2.29). Typically, the degree of undercutting associated with these systems is smaller than that achieved with the systems utilising both rotary and hammering action to produce the undercut.

The undercut anchors described in Fig. 2.25 b–d all require that the vertical hole depth be controlled with a stop-drill bit. For all anchors with a continuous sleeve (Fig. 2.25 b–d), it is important to check that clearance exists over the top of the sleeve in its final set position to ensure that the sleeve is not placed in compression as the anchor is torqued or loaded in tension. The value of the clearance depends on the anchor system and is on the order of a few millimeters. Note also that if this gap is too large, it could lead to diminished shear capacity. Typically, correct set of undercut anchors utilising a cone bolt is checked by means of a mark on the rod that becomes visible when the anchor is fully expanded. Internally threaded anchor systems are checked via the position of the sleeve relative to the surface of the concrete (Fig. 2.29).

The anchor shown in Fig. 2.25e consists of a threaded bar equipped with an oblique barrel nut, as well as a conventional hex nut and washer. The installation process is depicted in Fig. 2.30. First, a hole is drilled perpendicular to the surface of the concrete with a special diamond core drill. The same drill is then used to drill a second hole at an angle of 45° to the first. The drilling equipment is designed to ensure that the two holes intersect. A special tool is used to position the oblique barrel nut in the 45° hole at the intersection with the vertical hole. The anchor rod is then threaded into the barrel nut.

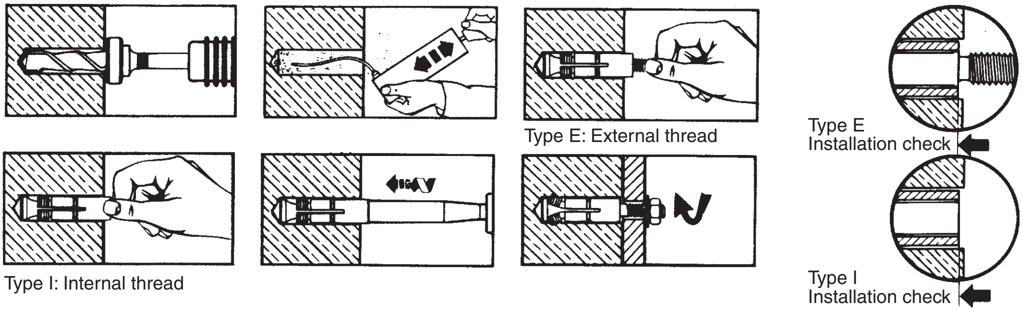

Fig. 2.29 Installation of an undercut anchor of the type shown in Fig. 2.25d

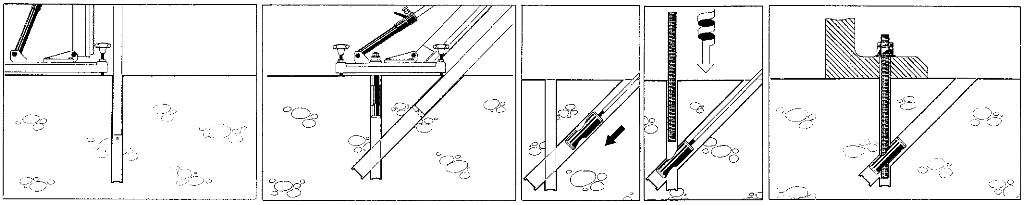

Fig. 2.30 Installation of an undercut anchor of the type shown in Fig. 2.25e (water removal step not shown)