EFRC Report

EFRC
European Forum for
Reciprocating
Compressors e. V.

Office:
EFRC
c/o TU Dresden
01062 Dresden
Germany

Phone: +49(0)351 463 32815
E-Mail: contact@recip.org

Summary of international guidelines, standards and best practices of foundations, anchor bolts and grouting of reciprocating compressor systems

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Content

Foreword

The EFRC is the European Forum for Reciprocating Compressors, founded in 1999 by Neumann & Esser, Leobersdorfer Maschinenfabrik, Hoerbiger Ventilwerke, TNO, TU Dresden, Thomassen Compression Systems, Wärtsila Compression Systems and Burckhardt Compression. The target of the EFRC is to serve as a platform to facilitate exchange of information between vendors, operators and scientists working in the field of reciprocating compressors.
This is achieved by knowledge transfer (conferences, internet, student workshops, training and seminars), standardization work (e.g. API 618, ISO 13707, and ISO 10816) and by joint pre-competitive research projects, aiming at improving the performance and the image of the reciprocating compressor.
In the R&D projects the forces are combined of all interested parties to solve or investigate problems which are beyond the scope of a single player. The basic research and pre-competitive research projects are carried out at research institutes or universities. In this way the R&D group of the EFRC will serve as the scientific arm of the reciprocating compressor community.
The R&D group is open to all EFRC members and the annual budget is funded by participating members. The results are owned by the EFRC and the research results are disclosed to EFRC research group members only.

Reciprocating compressors generate dynamic loads which require a support system that can resist these dynamic loads and the resulting vibrations. When excessive, such vibrations may be detrimental to the machinery and its support system. Foundations shall be designed to be able to withstand the static and dynamic loads to prevent excessive foundation settlement and vibration problems of the compressor system.
Besides an adequate foundation structure, the compressor must be mounted in a correct and sufficient way with anchor bolts to the foundation structure to ensure frame and coupling alignment and providing energy paths for dissipation of dynamic loads. Several international standards, guidelines and best practices on the design of foundations, anchors and grouting of reciprocating compressor systems have been developed.

Unfortunately, most of this material is not available for everybody, is too extended or not directly applicable. For that reason it was decided to start a project of the R&D group of the EFRC, to generate a comprehensive document, consisting of a summary of international guidelines, standards and best practices of foundations, anchors and grouting of reciprocating compressor systems.

Besides a summary of existing standards and guidelines, several equations have been derived for parts of the system e.g. bolt pocket size, edge distance etc. which can be used in the design of a foundation system.

This document is intended to be used by rotating equipment and civil engineers of end users, packagers, EPC contractors, grouting companies and reciprocating compressor OEM's.

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The above disclaimer is not intended to restrict or exclude the liability for death or personal injury caused by own carelessness.

EFRC – European Forum for Reciprocating Compressors e.V.
Institut für Energietechnik
c/o Technische Universität Dresden
01062 Dresden
GERMANY

1 Background and Introduction

1.1 Background

Reciprocating compressors generate dynamic loads which require a support system that can resist dynamic loads and the resulting vibrations. When excessive, such vibrations may be detrimental to the machinery and its support system.
Foundations shall be designed to be able to withstand the static and dynamic loads to prevent excessive foundation settlement and vibration problems of the compressor system.
Besides an adequate foundation structure, the compressor must be mounted in a correct and sufficient way with anchor bolts to the foundation structure to ensure frame and coupling alignment and providing energy paths for dissipation of dynamic loads.

Many engineers with varying backgrounds are engaged in the analysis, design, construction, maintenance, and repair of machine foundations and mountings.
Therefore, it is important that the owner/operator, geotechnical engineer, structural engineer, and equipment supplier collaborate during the design process.
Each of them has inputs and concerns that are important and shall be effectively communicated with each other, especially considering that machine foundation and mounting design procedures and criteria are not covered in standards and guidelines used in civil engineering.
Many firms and individuals have developed their own standards and specifications as a result of research and development activities, field studies, or many years of successful engineering or construction practices.
Besides that there are many documents, procedures, papers, and guidelines available on foundations and mounting methods for reciprocating compressors, all highlighting particular segments of the total procedure.

The Gas Machinery Research Council (GMRC) has carried out extensive research projects on foundations and mountings of reciprocating compressors. The results of these research projects have been summarized in several reports and contain many relevant information, of which much are still up-to-date.
Besides the GMRC reports, many other documents, guidelines, standards, papers etc. are available which contain valuable information which has been used in this project. Unfortunately, most of this material is not available for everybody, is too extended or not directly applicable.
For that reason it was decided to start a project of the R&D group of the EFRC, to generate a comprehensive document, consisting of a summary of up-to-date best practices and engineering rules on foundations and mounting methods for reciprocating compressor systems.

Different guidelines and standards have been developed for different items as summarised and discussed in this document. This results in different values for particular item such as for example the bolt preload. A particular value can be prescribed in a standard and can be different per country. For that reason only a summary of those particular values has been given instead of a recommendation.
Due to the fact that these guidelines and standards contain already very use full information, many parts have been copied or referenced in this report.

It was not the scope of this project to develop detailed design and construction rules for all applicable items. Where relevant, a reference is given to the document containing the detailed design procedure for a certain topic.
However, several guidelines have been derived from existing standards and guidelines which can be used in the design of the anchorage system for the actual foundation system of interest. Examples are pocket size, edge and anchor bolt distance, etc. It shall be noted that the examples as given are based on certain material properties, dimensions, anchor preloads etc. If the values for the foundation system of interest deviate from those of the examples as given in this report, the values shall be adjusted accordingly.

Last but not least it shall be noted that many companies have developed their own guidelines and best practices which have been applied for many years without having major problems. These company guidelines may differ from the summary of the guidelines as given in this report but this does not necessarily mean that the company guidelines are not suitable to use.

1.2 Introduction

To achieve a strong, high-quality yet cost-effective installation which ensures the long term integrity, safety and reliability, it is important to recognize two very important elements in the design of the mounting system.
The first important item is that the compressor and its foundation must form an integrated structure. Vibration energy travels in the form of waves through the foundation where the soil must absorb it. Separations in the integrated compressor/foundation structure will prevent the vibration waves from traveling downward.
The second important item is that the compressor installation must be treated as a series of interacting structures that move and vibrate, see left hand picture from Figure 1.1. Vibration energy actually deforms the structure as it passes through the structure because the compressor unit, driver, skid (if applied), grout, concrete soil are not infinitely stiff. Preventing foundation degradation, cracking of the concrete, loosening of anchor bolt preload leading to unacceptable vibrations and misalignment, means making sure that all mounting components work together and none act to harm the other components or mounting system. For example, the design and installation of the anchor bolts shall not cause the concrete to crack,
the anchor bolt preload shall be large enough to ensure the fixation of the compressor by means of friction to the concrete etc.
The one best word to describe what it means to "form an integrated structure" is monolithic. A monolithic structure is one that is cast as a massive, seamless, uniform, and rigid piece, see also right hand picture of Figure 1.1.
The design objective behind a compressor installation is therefore to create a monolithic structure that clamps the series of interacting pieces together (the compressor and its driver to a well-designed concrete foundation) with enough size and mass to avoid a coincidence between the frequency of the excitation forces and the mechanical natural frequencies (MNF's) of (parts of) the structure.

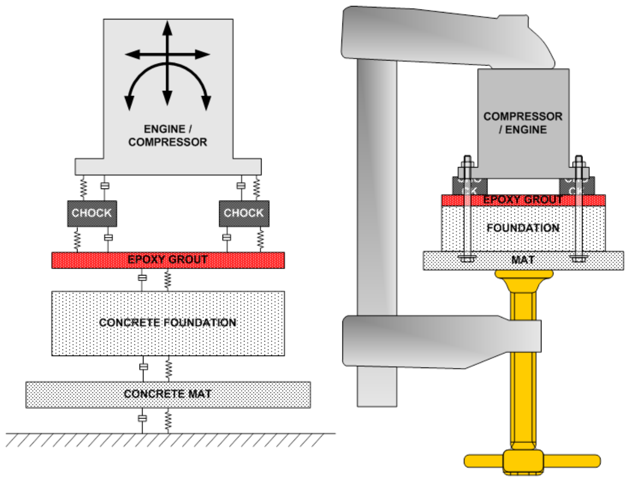


Figure 1.1 Different flexible elements of a compressor foundation and its mounting system [14]

There are also compressor systems which need to be mounted on flexible elements. This is the e.g. the case for systems which need to be mounted on very flexible soil or systems where structure borne noise becomes important w.r.t. legislation e.g. offshore systems. These systems are not monolithic and need to be treated with care w.r.t. to the dynamic design. If not designed well the flexible elements of these systems can lead to unacceptable vibrations leading to fatigue failures.

2 Assumptions and limitations

The summary as given in this report are for reciprocating compressor systems directly mounted to the concrete foundation or on a skid.
In the calculation of the dynamic loads, the assumption has been made that (parts of) the compressor system are not in resonance. This means that the frequency of the excitation loads do not coincide with mechanical natural frequencies (MNF's). This shall be the final target of the dynamic design of the foundation and anchoring system. However, if the system must be able to operate on resonance conditions, it shall be proved with detailed calculations that the system can run safe, reliable for the long term.

Compressor anchor bolts are not intended to act in shear and do not directly transfer horizontal forces via the bolt shank to the concrete. However, shear is something that shall be considered in relation to thermal expansion of the compressor.

Several civil engineering rules and best practices have been determined from standards which are not applicable for machine foundations (e.g. EN 1993 Eurocode 3 "Design of Steel Structures"). However, they have been applied for guidance in this report due to the lack of better standards and guidance. Some notes w.r.t the applied civil engineering codes and standards are therefor made as follows:

- Civil engineering codes and standards typically only include non-preloaded externally loaded anchor bolts. They do not include the preloaded anchor bolts used in machine and compressor applications where friction provides the primary mechanism for transferring the dominant horizontal forces from the compressor to the foundation. The effect of preload, the compression of the clamped parts, on the tensile and compressive stresses in the concrete is generally not considered in these codes and standards.
- Machine foundations and their fastenings do not fall within the scope of the Eurocodes. However, where applicable, parts can and have been used in this report for guidance. For the requirements of fastenings EN 1992 Eurocode 2 "Design of Concrete Structures" refers to Technical Specification "Design of Fastenings for Use in Concrete". Parts from this specification that have been used for reference are CEN/TS 1992 Part 4.1 General and Part 4.2 Headed Fasteners.
- Most standards classify headed anchors, having a nut or plate termination, as cast-in fasteners instead of post-installed anchors. Many anchor bolts used in most compressor applications are of the headed type and post-installed with the anchor bolt pocket filled with grout material. It shall be noted that the grout material has a considerably higher compressive strength than concrete in case of cast-in anchors.
- In the calculations it is assumed that the bolts are cast-in.
- The design based on the recommendations as given in this report such as e.g. the edge distance, bolt termination plate diameter and bolt preload, shall be more than adequate to prevent concrete failure.

3 Definitions

Alignment
Alignment normally refers to the process of adjusting the position of driver and compressor on their mounts so the shafts of each are very close to collinear while avoiding undesired axial or thrust forces and limit crankshaft web deflections at normal operating temperatures. Alignment is further used in this document to refer to the levelling and elimination of twist and bending within the frame of both driver and compressor.

Angular misalignment
The angle between the shaft centre line of two adjacent shafts. This angle is normally reported in slope of mm change per m of linear distance

Anchor bolt
Elements made of steel either cast into concrete or post-installed into a pocket filled with cement or epoxy grout and used to transmit applied loads. In this document “anchor bolt”, “bolt”, “fastener” and “foundation bolt” are used synonymously.

Anchor spacing
Distance between centre lines of the fasteners.
Anti-Vibration Mount (or soft foot)
Flexible element such as a helical steel springs, a rubber blocks or pads on which the compressor is mounted.

Baseplate
A fabricated (or cast) metal structure used to mount, support, and align, machinery and its auxiliary components. Baseplates may be directly grouted to concrete foundations (after levelling) or bolted to pre-grout chock plates.

Blow-out failure
Spalling of the concrete on the side face of the concrete element at the level of the embedded head of the anchor bolt with no major breakout at the top concrete surface. This is usually associated with fasteners with small side cover and deep embedment.

Bolt
See anchor bolt.

Bolt Torque
Twisting or wrenching effect, or moment exerted by force acting at a distance on a body, equal to the force multiplied by the perpendicular distance between the line of action of the force and the centre of rotation at which it is exerted. Bolt torque is typically applied in a controlled manner by means of a manual or hydraulic torque wrench.

Bolt spacing
Distance between the centre lines of the bolts.

Bolt Tension
Stress on a material produced by the pulling forces tending to cause extension. In the case of an anchor bolt, this is the stretch or elongation from a relaxed state.

Bonded anchor
Fastener placed into a hole in hardened concrete, which derives its resistance from a bonding compound placed between the wall of the hole in the concrete and the embedded portion of the fastening.

Canister bolt
An anchor bolt in a sleeve designed for installation in concrete with a termination disk at its lower end for embedment in the concrete and an encasing sleeve covering the entire length of the bolt, which helps protect the bolt. The bolt can usually be temporarily lowered into the canister flush with or below the concrete surface, if needed, then raised up again to interface with mounted equipment.

Cast-in fastener
Headed bolt, headed stud, hooked bolt installed before pouring the concrete, see headed anchor.

Cement grout
A type of grout material that is cement based.

Chock
The chock is normally a solid plate of epoxy grout or metal with a machined top surface that is grouted to a concrete foundation to support and maintain alignment of a machinery structural steel baseplate.

Clamping force
The amount of compression between the underside of the anchor bolt nut and the anchor bolt embedment point in the foundation.

Clamped bolt length
That part of the bolt which clamps different parts together.

Compliance ratio
Ratio of the dynamic (tension) load range carried by the bolt and the applied (tension) dynamic load range on the clamped parts. This is also named bolt load factor.

Concrete breakout failure
Failure that corresponds to a wedge or cone of concrete surrounding the fastener or group of fasteners separating from the base material.

Concrete pry-out failure
Failure that corresponds to the formation of a concrete spall opposite to the loading direction under shear loading.

Concrete related failure modes
Failure modes under tension loading: Pull-out failure, combined pull-out and concrete failure (bonded fasteners), concrete cone failure, blow-out failure, splitting failure, anchorage failure of supplementary reinforcement.
Failure modes under shear loading: Concrete pry-out failure, concrete edge failure.

Cracked concrete
Concrete that is likely to experience cracking during its lifetime; justification shall be provided if uncracked properties are adopted.

Crosshead
A device, driven by a connection rod, which slides on a linear motion bearing, and transmits horizontal motion to the piston without side loads.

Crosshead guide
A box-like structure, typically of cast iron, attached to the compressor frame which carries the crosshead bearing and thereby the crosshead.

Crosshead guide support
The crosshead guide support is a structural element, which provides vertical support, vertical restraint, and depending on the design some axial restraint to a cylinder and crosshead guide. It typically attaches to a crosshead guide or cylinder near the joint between crosshead guide and cylinder.

Deadweight loads
Gravity loads of constant magnitudes and fixed positions that act permanently on the structure. Such loads consist of the weight of the structural system itself and of all other material and equipment permanently attached to the structural
system.

Double spherical washer
A pair of washers mounted adjacent to a nut on an anchor bolt, with a spherical interface between them. This pair of washers provides a flat interface with the nut or bolt cap to avoid point loading. By allowing small relative angular motion between the pair of washers at the spherical interface, any lack of parallelism between the surfaces is accommodated, and pressure can be transferred with acceptable uniformity across these interfaces.

Edge distance
Distance from the edge of the concrete foundation to the centre line of the anchor bolt.

Epoxy grout
A type of grout material that consists of a resin base that is mixed with a curing agent (hardener) and usually some aggregate filler.
The aggregate allows the grout to be poured in large, thick sections because it absorbs the exothermic heat created by the resin and hardener.

Epoxy chock
Epoxy chocks are mixtures of resin and hardener and do not have aggregates.
They get much hotter during pouring and must be poured in small blocks typically around anchor bolts.
It does not include the portion of the bolt that is wrapped with tape or inside a bolt sleeve.

Embedment depth
Embedment length is defined as the length which is encapsulated by the concrete/grout.

Expansion joint
A “break” in a surface layer which allows free expansion of that layer, and acts to limit the horizontal extent over which the layer is in intimate contact with the foundation block.

Fastener
See anchor bolt.

Foot
This is a localized component integral with or bolted to a compressor or engine crankcase or frame for use in mounting. The foot presents a flat surface, facing downwards, which mates with a mounting plate facing upwards, with precision thickness shims or sometimes with an adjustable mount between the foot and the mounting plate.

Foundation
A heavy structure, typically of concrete, which supports the compressor.

Foundation block
The block of concrete which functions as the foundation.

Free bolt length
The length of the bolt which is not bonded to the concrete or grout.

Gas (stretch) load
This is the maximum net force acting on the cylinder, distance piece and frame caused by the gas forces inside the compressor cylinder and cylinder passage volumes at the head end and crank during the suction and discharge stroke.

Global loads
Vector summation from the loads of all individual cylinders.

Gravity loads
Gravity loads are the vertical forces due to the mass of the different components.

Grout
An epoxy or cement based material used to provide a uniform support and load transfer link for the installation of the machinery. This material is typical placed between the frame feet and concrete foundation or skid or between the skid and concrete foundation.

Grout box
A metal box, open from above, normally with rectangular or square cross-section as seen from above, welded to the top of a main skid beam member, with sides of 50-100 mm high. The box is filled with epoxy grout and a plate (normally milled steel) is set in the grout, with its upper surface horizontal, and typically with about 50 mm of grout under the plate. The box and plate act as a mount for the feet of a compressor and driver, so the plate and box have holes for one or two anchor bolts located to match bolt holes in the feet of the machine to be mounted at that location.

Grout expansion joint
A "break" in a surface layer which allows free expansion of that layer, and acts to limit the horizontal extent over which the layer is in intimate contact with the foundation block.

Grout head box
A box typically constructed of plywood, with rectangular cross-section when viewed from above, with typical sides of 230 to 300 mm in height, and an opening at the bottom of one long side, running the length of that side. The head box is set firmly against the side of a skid to be grouted in place, flat on the concrete surface, and filled with grout. The height of the grout in the box sets the head driving the flow across the volume between skid and concrete.

Head end support
This is a structural element, which restrains motion of the cylinder, attached near the outboard end of the cylinder, sometimes called an "outboard cylinder vibration support". For integral engine/compressors, a similar device was often referred to as a cold support. However, for high-speed separable compressors, it functions predominantly to control vibration.

Headed anchor
Steel fastener installed before placing concrete. It derives its tensile resistance at the anchor head.

Initial preload
The clamping force imposed on the machine by the anchor bolt when it is first tightened from a relaxed state.

Installation safety factors
Partial factor that accounts for the sensitivity of a fastener to installation inaccuracies on its performance.

Integral engine compressor
A combined piston compressor and motor in one single frame sharing the same crankshaft.

Jack bolt
A jack bolt consists of a thrust collar and a nut which rides on a bolt

Local loads
Forces and moments caused by each individual cylinder.

Minimum spacing
Minimum fastener spacing to allow adequate placing and compaction of concrete (cast-in fasteners) and to avoid damage to the concrete during installation (post-installed fasteners), measured centreline to centreline.,.

Minimum edge distance
Minimum distance to allow adequate placing and compacting of concrete and to avoid damage to the concrete during installation (post-installed), measured from the centreline to the outer surface of the concrete block.

Monolithic
A monolithic structure is one that behaves as a massive, seamless, uniform and rigid piece. The design objective behind a compressor installation is therefore to create a monolithic structure that clamps the series of interacting pieces together with enough size and mass so that the mat, concrete foundation, grout and machinery becomes one.

Mounting
Mounting is the location, weight support, alignment, mechanical and gas load management, and tie-down of the compressor, its driver, associated systems, and appurtenances.

Mounting plate
This component is similar to a chock on which the compressor and driver feet are mounted and which, in turn, is solidly supported by the skid or concrete block via the top grout layer. Often, the mounting plate is set in a rectangular box containing grout, and the box is welded to the skid or to a pedestal structure for mounting the engine or compressor.

Mounting system
Combination of chocks, anchor bolts, grout, and in some cases, plates whose function is to support the compressor.
Non-cracked concrete
Concrete that has been demonstrated via stress analysis to remain crack-free in the vicinity of the anchor throughout the design life under all design load considerations.

NPS
Nominal pipe size.

Package
In principle, a package is the compression system consisting of everything between the suction flange and the discharge flange, with a driver and support systems; a turnkey system which just has to be set in place, connected to compressor station gas headers, connected to fuel or power lines, started, and operated.

Packager
The Packager is the single source and point of contact for the procurement, engineering, assembly, transportation, installation, start-up, commissioning, and problem resolution for the compression system. The packager purchases and assembles the compressor, driver, coupling, vessels, coolers, controls, oil system, etc., designs a skid, mounts the components on the skid, delivers the package to the end user, installs it, starts it up, and assures its function as a system
for a finite period. When not explicitly specified by the purchaser, the packager normally decides and procures the engineering analyses, which will be employed to support the design.
Considering all industry segments they serve, packagers offer sale, lease, or contract operation.

Peak value
According to the definition of the ISO 2014-2009 [33], the peak value $\hat{U}$ of a vibration signal $u(t)$ is the maximum value during a specified time interval. The peak value of a vibration is usually taken as the maximum deviation of the vibration from its mean value. A positive peak value is the maximum positive deviation and a negative peak value is the maximum negative deviation.

Peak-to-peak value
According to the definition of the ISO 2014-2009 [33], the peak-to-peak value of a vibration signal $u(t)$ is the difference between the maximum positive and maximum negative values of a vibration during a specified interval.

Pedestal
A structure, commonly built of I-beams or wide flange beams, to provide a mounting surface at appropriate height for the compressor or its driver on the skid. An important function of the pedestal under the engine is to locate the engine's feet so the sump's lowest point is at the desired position relative to the main skid. The function of a pedestal under the compressor (if a pedestal is used here) is to elevate the compressor shaft centreline to the same level as that of the driver

Post-installed fastener
A fastener installed in hardened concrete, cement or epoxy grout.

Post tensioning
The process of applying tension to rods (anchor bolts) which pass through the concrete in order to put the concrete in the vicinity of the rod (anchor bolt) in compression.

Precision shims
Flat metal strips of uniform, and precisely known thicknesses, used to adjust height between a mounting plate and foot. Plastic shims shall not be considered. Specification of stainless steel shims will be subsequently recommended.

Pull-out failure
A failure mode in which the fastener pulls out of the concrete without development of the full concrete resistance or a failure mode in which the fastener body pulls through the expansion sleeve without development of the full concrete resistance. In case of bonded anchors this failure occurs at the interface between the bonding material and the base material (mostly concrete) or between the bonding material and the anchor element (bond failure). This failure may also contain a concrete cone at the top end and is therefore denoted as combined pull-out and concrete failure.

Pulsation analysis
An analysis of the piping system connected to a compressor to determine the acoustical and mechanical effects of pulsating flow.

Purchaser
Agency that issues the order and specification to the vendor.

Residual preload
The clamping force remaining on the machinery after external forces or conditions have affected the initial preload over time. The residual preload by definition will always be less than the initial preload.

Splitting failure
A concrete failure mode in which the concrete fractures along a plane passing through the axis of the fastener or fasteners.

Steel failure of fastener
Failure mode characterized by fracture or gross yielding of the steel fastener parts.

Supplementary reinforcement
Reinforcement tying a potential breakout body to the concrete member

Table top foundation
An elevated three-dimensional reinforcement structure that consists of large beams or a thick slab connecting the tops of the supporting columns. The mechanical equipment is supported by the large beams or the slab located at the tip of the structure.

Torque
Torque, moment or moment of force is the tendency of a force to rotate an object about an axis, or pivot. Just as a force it is a push or a pull, a torque can be thought of as a twist to an object. Mathematically, torque is defined as the cross product of the lever-arm distance and force, which tends to produce rotation.

Soft foot (or Anti Vibration Mount)
Flexible element such as a helical steel springs, a rubber blocks or pads on which the compressor is mounted.

Sole plate
A sole plate performs some similar functions to a chock or mounting plate but normally has a larger area in plain view. The sole plate is normally grouted in place on top of a concrete block providing support for a compressor or driver.
A reciprocating compressor whose drive comes from a separate machine-typically engine or motor.

Total bolt length
Embedment length + free length +chock & sole plate thickness + nut & washer thickness + number of threads above the nut to be able hydraulically preload the bolt.

Two-piece anchor bolt
A bolt used in concrete foundations with two segments (pieces). The lower segment is embedded in the concrete and held against upwards pull by a termination device (nut, washer, or disk); the lower segment does not extend above the top of the concrete block section in which it is embedded, but allows for a second, upper, segment to be attached to the lower segment by a threaded sleeve. The upper segment extends above the concrete high enough to mount whatever is to be mounted. It is typical to provide a free work gap area in the concrete around the top of the lower segment so the joint can be made too much without difficulty.

Vendor
Manufacturer or manufacturer's agent who supplies the compressor system

Support point
A point of the structure where a force is transmitted form one part to another part.

Wedge support
This is an incline plane device to hold and restrain a bottle or section of pipe. Used strictly in pairs these present flat surfaces at about 45 degrees to the vertical below and on either side of the bottle. Wedges are adjustable by means of long bolts, which pull the pair of wedges together to tighten them against the bottle. With high or variable discharge temperatures, the vertical growth of discharge nozzles requires care in the use of discharge bottle wedges.

4 Static and dynamic loads of reciprocating compressor systems

4.1 Introduction

This chapter will discuss the different static, quasi-static and dynamic loads which need to be considered in the design of the foundation and anchoring system of the compressor and driver.
Despite the fact that it is not the intention of this document to give a detailed explanation on the dynamic design of the foundation (block, piles and soil), several guidelines will be given to understand the most important issues related to this.
The loads as given in this chapter can be used in the static and dynamic design of the foundation, anchor bolt, soleplates and grout.
The different loads shall be indicated in the foundation plan as explained in the next section.

4.2 Static (dead weight or gravity) loads

According to the GMRC Technology Assessment Report TA-93-1, December 1993 [5] a major function of the foundation is to support gravity loads and the primary concern is the footprint pressure of the foundation on the soil. The second concern are the localized stresses in the concrete caused by the deadweight loads and by the preload in the anchor bolts to restrain the dynamic loads as explained later in chapter 4.3.

The significance of deadweight load is first to produce a generally downwards compressive load on the block and a distribution of compressive stress within the block. The anchor bolt preload, necessary to create a friction force to restrain the dynamic loads as summarised in chapter 4.3, will increase the compressive loads and needs to be considered in the design of the chock, soleplate, grout and concrete stress calculations. Due to the above uncertainties the local support points must be oversized due to the expected loads.

The weight of the compressor and driver will normally be a readily available piece of information from the supplier and the deadweight shall be available therefore.
The most important static loads are the weight of the compressor frame, crosshead guide, motion work, cylinders, pistons, piston rod, pulsation dampers (suction and discharge), skid, driver, coolers, separators, piping, etc.
To calculate with precision the deadweight load distribution as carried on chocks, soleplates, or a full bed grout, is however not straightforward.
The multiple support points produce a statically indeterminate system, and the loads at individual support points are a function of the relative deflections of frame and block under those loads.
The best method to calculate the deadweight loads on the support points is with a detailed finite element model of the system. However, the contribution of the deadweight to the total load is small and does not justify the costs and time involved for a detailed finite element model.
With a few exceptions, it is probably valid simply to assume uniform distribution of the compressor frame weight between support points. The crankshaft weight is reasonably distributed over the length of the compressor. The flywheel may add some local loading at one end of the compressor which must be accounted for, e.g. by adding the deadweight load to the nearest support points.

An estimation of the deadweight loads of pulsation dampers, cylinders and crosshead for all type of different compressors (e.g. horizontal, vertical, L-type, V-type and W-type) based on simple engineering rules is not easy due to the different type of cylinder and crosshead guide supports as shown in Figure 4.3Figure 4.1.

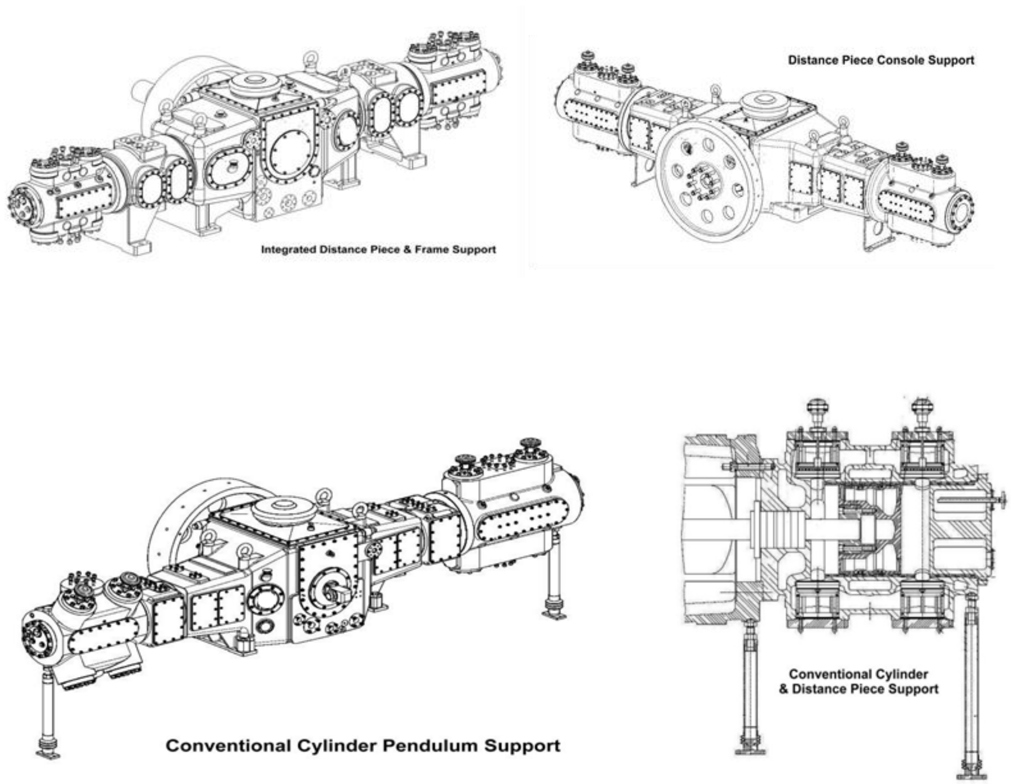


Figure 4.1 Different support configurations of cylinder crosshead of a horizontal compressor

However, nowadays most compressor manufacturers and packagers generate CAD models of the compressors system. Most CAD programs are able to calculate the deadweight loads on different locations. For that reason it is strongly recommended to use the deadweight loads as calculated with the CAD program rather than with engineering rules. The calculated deadweight loads on all support points shall be indicated on the foundation plan of which an example is shown in Figure 4.2.

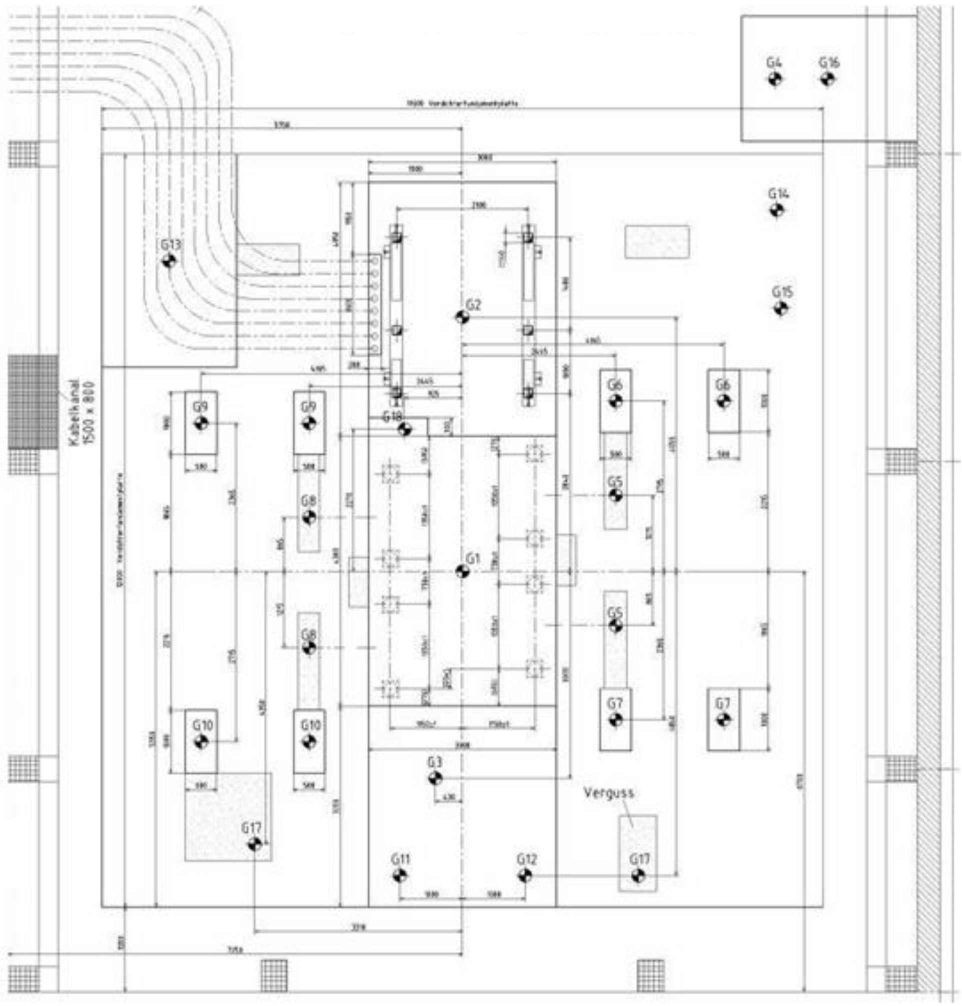


Figure 4.2 Typical foundation plan with an indication of dead weight loads (denoted as GXX)

4.3 Dynamic loads

4.3.1 Introduction

The dynamic loads as generated by the compressor or engine (diesel or gas) driver must be considered in the following cases:

1. Dynamic design of the foundation to keep the vibration levels of the complete compressor system to acceptable levels to avoid fatigue failures of the concrete and parts of the compressor system. The dynamic forces and moments in the 3 global directions shall be considered.
2. Determination of the anchor bolt preload to achieve a high enough friction force in the horizontal direction to keep the compressor tight to its foundation. The dynamic forces in the two horizontal directions shall be considered. Vertical forces are in general low in comparison with horizontal forces for horizontal compressors. However, they can be very high for vertical compressors and shall be considered for vertical machines to ensure sufficient anchor bolt preload.
3. Fatigue calculations of the anchor bolts. All dynamic loads acting in the vertical direction shall be considered. The horizontal shear forces do not contribute to shear loads on the bolt

due to the fact that the anchor bolts are designed to act only in tension. The bolt pre-tension is supposed to keep the dynamic stress on the bolt as low as possible.

In Table 4.1 a summary is given which loads shall be considered in the foundation and anchor bolt design.

Table 4.1 Loads to be considered in foundation and anchor bolt design

	Foundation design*	Anchor bolt preload**	Anchor bolt fatigue analysis**
Unbalanced loads	X	X	X
Torque fluctuations	X	X	X
Gas stretch forces	--	X	--

*Foundation shall be designed for the global loads (see chapter 4.4)
**Anchor bolts shall de designed for the local loads (see chapter 4.4)

It is noted that pulsation-induced forces acting on pulsation dampers and cylinders are also dynamic loads which shall normally be considered. However, these forces are not known during the design of the foundation and anchor bolt design.

Worst-case situations w.r.t phases of loads
In this chapter an overview will be given of different dynamic loads which act at the same time, normally with different amplitudes and different phases.
To achieve the correct load for which the bolts shall be designed, the phase relation between the different loads shall be taken into account. This can only be done in a correct way if detailed models will be generated, including all the dynamic forces. However, these detailed models are not always available in many situations and for those cases it is not so easy to take into account the correct phases between different dynamic loads. To ensure a safe and reliable operating system, the worst-case (conservative) situations shall be considered therefore. An easy way to determine the worst-case situation is simply by adding all the dynamic loads in phase which is a conservative approach.

Peak-to-peak versus zero-peak values
Dynamic loads vary as a function of time as shown in picture Figure 4.3.
According to the definition of the ISO 2014-2009 [33], the peak-to-peak value of a vibration signal $u(t)$ is the difference between the maximum positive and maximum negative value of a vibration during a specified interval. The 0-peak value of a vibration is usually taken as the maximum deviation from its mean value. A positive peak value is the maximum positive deviation and a negative peak value is the maximum negative deviation. According to Figure 4.3, the absolute maximum 0-peak value for this signal is the negative peak value.
Below a summary is given for those cases where a peak value or a peak-to-peak shall be used in the foundation design:

- Foundation block design, see chapter 5: peak-to-peak values of the summed global (definition of global is explained in chapter 4.4) dynamic forces.
- Fatigue calculations of bolts, see chapter 10: peak-to-peak values of the summed local (definition of local is explained in chapter 4.4) dynamic forces.
- Friction to hold the frame tight to the foundation, see chapter 7.3: maximum 0-peak value of the summed horizontal and vertical dynamic forces.

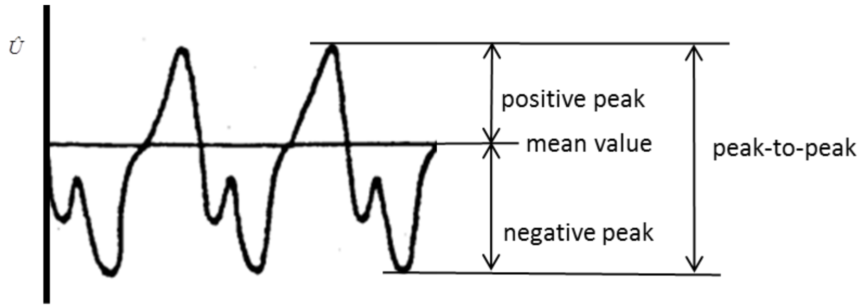


Figure 4.3 Example of a load as a function of time

4.3.2 *Cylinder gas stretching loads*

Most of the material as described in this chapter has been retrieved from the following sources:
[1] GMRC Technical Report TR-97-2 “Foundation Guidelines”, January1997
[9] ACI 351.3R-04 “Foundations for Dynamic Equipment”, May 2004
GMRC Course “Foundation Design & Repair, The Bolted Joint”, May 12-14, 2009

During the compression stroke the gas will increase in pressure inside the cylinder, The increase in pressure within the cylinder creates a reaction force both on the head end and crank end side of the cylinder which alternates as gas flows to and from each end of the cylinder. The gas forces inside the cylinder are shown in see Figure 4.4 and the total net force acting on the cylinder and piston rod is given in equation (4.1) and (4.2).
The net gas load is completely reacted within the frame, pushing on the main bearings and the cylinder which stretches and compresses the frame, distance piece and cylinder each revolution. Because of the frame flexibility, see chapter 4.4 , the crosshead guide bolts, if present, reacts to the cylinder gas loads as shown in Figure 4.5 and shall be designed for this load therefore.
The normal approach is to establish the head and crank end pressure using the maximum and minimum suction and discharge pressures. However, for design purposes, it is common to multiply equation (4.1) and (4.2) by a factor F1 to account for flow resistances of the compressor valves and pressure pulsations inside the cylinder.

Typical values for F1 are as follows:

- 1.1for compressors with good pulsation control and low valve losses
- 1.5 for a low compression ratio, high pulsations, or high valve losses
- a reasonable working value for F1 is 1.15-1.2.

For greater accuracy, the forces can be calculated more accurately with a performance analysis programme which computes the gas loads as a function of crank angle, see Figure 4.6.

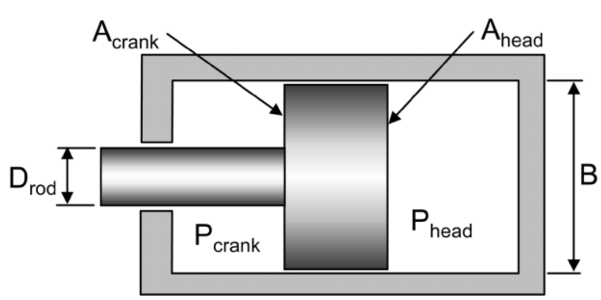


Figure 4.4 Forces in cylinder [9]

$$Frcmax = [(Pdhead)(Ahead) - (Pscrank)(Acrank)]F1 \quad (4.1)$$

$$Frtmax = [(Pdcrank)(Acrank) - (Pshead)(Ahead)]F1 \quad (4.2)$$

$$Ahead = (\pi/4)(B^2) \quad (4.3)$$

$$Acrank = (\pi/4)(B^2 - Drod^2) \quad (4.4)$$

In which:

F_{rcmax} =maximum compressive (peak) rod force (N)
F_{rtmax} =maximum tensile (peak) rod force (N)
A_{crank} =crank end area (m^2)
A_{head} =head end area (m^2)
B =cylinder bore diameter (m)
D_{rod} =rod diameter (m)
P_{head} =pressure at the head end (N/m^2)
P_{crank} =pressure at the crank end (N/m^2)
F1 =correction factor (-)

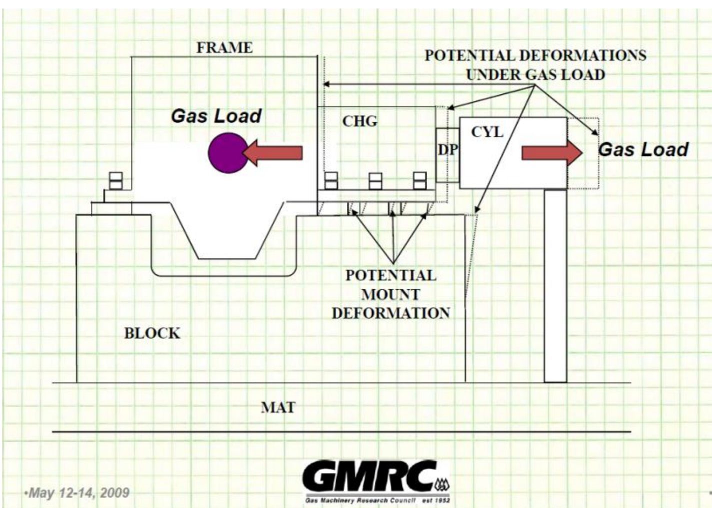


Figure 4.5 Gas load transmission and deformations [19]

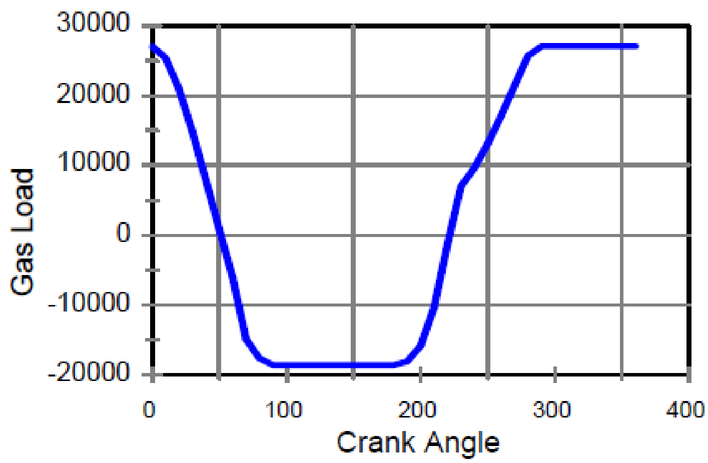


Figure 4.6 Horizontal rod gas load as a function of crank angle

4.3.3 *Unbalanced forces and moments*

Most of the material as described in this chapter has been copied or retrieved from the following sources:

[1] GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997

[9] ACI 351.3R-04 "Foundations for Dynamic Equipment", May 2004

[20] GMRC Course "Foundation Design & Repair, The Bolted Joint", May 12-14, 2009

The unbalance of a reciprocating machine comes in the form of horizontal and vertical forces and horizontal and vertical couples, see Figure 4.7. All forces and couples act about the centre of the crankshaft.

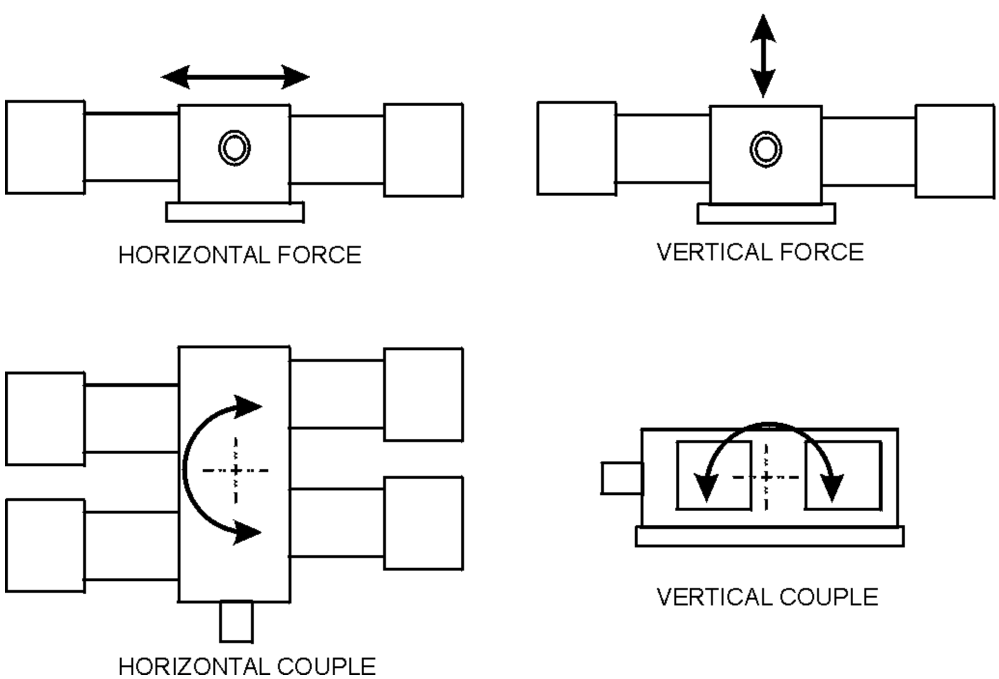


Figure 4.7 Different types of unbalanced loads in reciprocating compressors

Primary forces and couples
The primary (primary means: frequency is one times crankshaft speed) inertial forces and couples are due to:

- rotating masses of crankshaft throw weights, portion of connecting rods and crankshaft counterweights and,
- reciprocating masses such as portion of connecting rods, crossheads, crosshead balance weights, piston rod and compressor/scavenging piston assemblies.

Secondary forces and couples
The secondary (secondary means: at a frequency of two times the crankshaft speed) forces and couples are due only to the reciprocating masses of a portion of connecting rods, crossheads, crosshead balance weights and compressor piston assemblies. These forces act in the line of piston travel. There are no secondary forces and moments caused by rotating masses. The rotating masses can completely be balanced and it is assumed that this shall always be done.
Further on it shall be noted that the reciprocating mass loads cannot be balanced through counterweights: they can only be shifted in direction e.g. from vertical to horizontal.

4.3.3.1 *Theoretical back ground of unbalanced loads*

An example of a reciprocating mechanism is shown in Figure 4.8. One can derive that the inertia forces for a particular crank (can differ for each crank especially for a multi stage compressor) depending on the crank angle are as follows:

Inertia force in piston (horizontal for a horizontal compressor) direction:

$$F_x = (m_{rec} + m_{rot}) r \omega_0^{\ 2} \cos \omega_0 t + m_{rec} \frac{r^2}{L} \omega^2 \cos 2\omega_0 t \tag{4.5}$$

Inertia force perpendicular (vertical for a horizontal compressor) to piston direction:

$$Fy = m_{rot} r \omega_0^{\ 2} \sin \omega_0 t \tag{4.6}$$

In which:

F_x = load in piston direction as a function of crank angle (N)
F_y = load in perpendicular to cylinder as a function of crank angle (N)
m_{rec} =reciprocating mass* (m)
m_{rot} = rotating mass** (m)
r = stroke (m)
L = connection rod length (m)
ω_0 = circular velocity (rad/s)
t = time (sec)

*The reciprocating mass m_{rec} is usually one third of the weight of the connecting rod, plus the weight of the crosshead, piston rod, piston and weights of fasteners forming a part of various assemblies).

** The rotating mass m_{rot} is the sum of the mass of the crankshaft without the crank webs, and two thirds of the mass of the connecting rod. The centrifugal force created by these masses is the product from mass, crank radius and square of angular speed. By selecting proper counter weights and placing them on the opposite side of the crank, the rotating forces can be balanced. Therefore, the inertial forces of rotating masses produce a centrifugal force of constant magnitude that can be complete balanced by using properly sized counter weights.

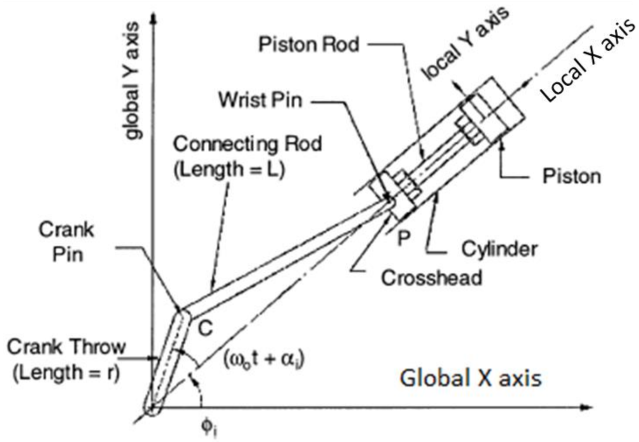


Figure 4.8 Working principle of a crank mechanism

The inertia force in the piston direction consists of two terms:

1. Primary force (one times the compressor speed):

$$F_{xp} = (m_{rec} + m_{rot}) r \omega_0^{2} \cos \omega_0 t \tag{4.7}$$

This force can be offset by the use of a counterweight that opposes the piston assembly during rotation. However, by using a counterweight to lower the horizontal inertia force, a new force is introduced when the rotation is at the midpoint of piston throw. At this stage of rotation, the counterweight is thrown into a direction perpendicular to the piston motion, and all of the counterweight's mass translates into a vertical force (vertical primary couple, or VPC) pulling the machine upwards (or downwards at the other half of the cycle).If opposed cylinder frame designs are applied, the reciprocating forces are balanced by using opposed cylinders. Since there is a much smaller counterweight in use, the vertical primary couple (VPC) is reduced to negligible levels.

2. Secondary force (two times the compressor speed):

$$F_{xs} = m_{rec} \frac{r^2}{L} \omega^2 \cos 2\omega_0 t \tag{4.8}$$

Secondary forces cannot be balanced with counterweights since they vary twice per revolution. Equal weight pistons and rods will reduce the secondary forces, however, multistage integral compressors can have different piston weights. The horizontal secondary force is much smaller than the primary force.

The vertical force does not have a secondary order component for a horizontal compressor but it has for a vertical compressor.

4.3.4 *Horizontal inertial moments*

Piston pairs are for most type of compressors not directly opposed (some OEM’s however have an opposed design) and will have a horizontally offset. The effect of that is that there is some torsional force created. These forces are called the horizontal primary couple (HPC) and horizontal secondary couple (HSC). The relative force created is determined by the offset distance "D" between the centre lines of the opposing throws, see Figure 4.9

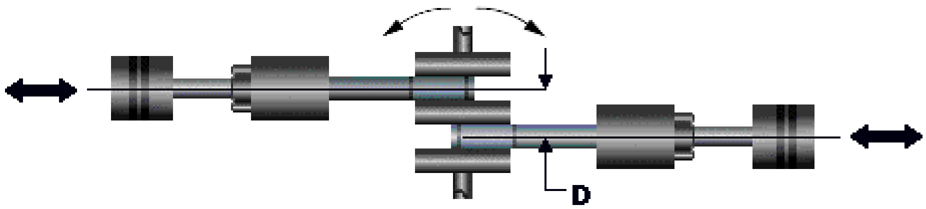


Figure 4.9 Horizontal primary and secondary couple

Most compressor manufacturers place the counterweights directly on the crank pin webs to reduce the HPC, see Figure 4.10 but this does not reduce the HSC. The counter weights only compensate the rotational forces and do not cancel out the 1st and 2nd order moments generated from the reciprocating masses.

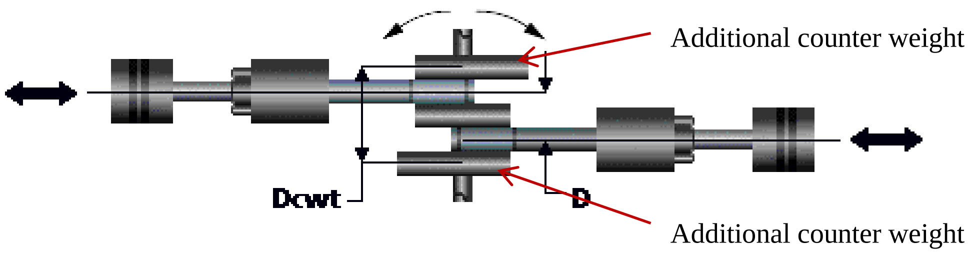


Figure 4.10 Example of additional counter weights on a crank pin web

Counterweights can be placed at the outboard of the main bearing webs, see Figure 4.11. This reduces the size of weights needed and helps reduce both HPC and HSC.

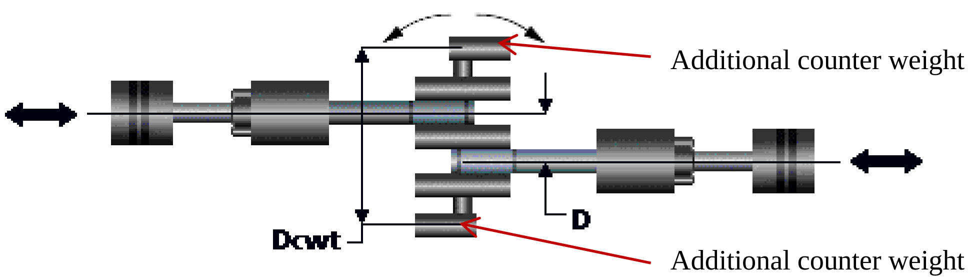


Figure 4.11 Example of additional counter weights at the outboard main bearing web

4.3.4.1 *Summed unbalanced forces and moments of all cylinders*

In a multiple cylinder/engine compressor, it is common to calculate the following eight components of unbalanced forces and moments:

- FH1, horizontal primary force
- FH2, horizontal secondary force
- FV1, vertical primary force
- FV2, vertical secondary force
- MH1, primary horizontal moment
- MH2, secondary horizontal moment
- MV1, primary vertical moment
- MV2, secondary vertical moment

Appendix A provides a comprehensive calculation method for these forces and moments in a multiple cylinder compressor/engine, with cylinders arrayed horizontally or at arbitrary angles to the horizontal. The above forces and moments result from vector summations of inertia forces from individual cylinders, accounting for phasing between crank throws.

While widely used, these summed peak-to-peak values of these global forces shall be the basis only for addressing the response of a complete foundation block upon its soil support. However, the summed (global) forces and moments cannot be used in the design of anchor bolts and the local loads shall be used for that purpose.

Managing peak-to-peak values of the global forces and moments of all cylinders summed to reduce the response of the foundation system can be done by e.g. changing phase angles between throw or by adding balance weights.
In many cases the global forces and moments can be made small in several directions but can increase on the other hand the forces and moments on bearings which are transmitted to the anchor bolts. This can overload individual tie-downs and overstress bolts and vulnerable areas in the foundations. This means that one shall be careful in managing global and local forces in a compressor foundation structure, see also chapter 4.4.
Local gas forces (0-peak value) of each individual cylinders must be considered in engineering tie-downs, in cyclic stress calculations of bolts (peak-to-peak values), and in controlling foundation block stresses (0-peak value) of tension stress. Determining local forces at individual tie-down requires the use of the individual cylinder forces as summarised in the former chapters.

4.3.5 Torque load variations

Most of the material as described in this chapter has been copied or retrieved from the following sources:
[1] GMRC Technical Report TR-97-2 “Foundation Guidelines”, January1997
[9] ACI 351.3R-04 “Foundations for Dynamic Equipment”, May 2004
[20]GMRC Course “Foundation Design & Repair, The Bolted Joint”, May 12-14, 2009

Machines such as compressors and engines require some form of drive mechanism, either integral with the machine or separate from it. When the drive mechanism is non-integral, such as a separate electric motor, reciprocating engine, and gas or steam turbine, it produces a net external drive torque on the driven machine. The torque is equal in magnitude and opposite in direction on the driver and driven machine, see left hand side picture of Figure 4.12. It shall be noted that the vertical forces as indicated in Figure 4.12 are the resultant forces caused by the deadweight and dynamic loads. For that reason they are not the same on the left and right hand side of the machine.

The torque loads must be used in the dynamic design of the foundation, determination of the anchor bolt preload (on one side of the machine the torque fluctuation causes a force in the upwards vertical direction) to achieve a high enough friction force in the horizontal direction to keep the compressor tight to its foundation and in the fatigue calculations of the anchor bolts.

The torque load causes vertical forces and if present will be transferred partly to the crosshead guide bolts and partly to the frame bolts. The crosshead guide is an integral part for may compressors and in that case the loads will be transferred to the frame bolts in the vicinity of the crosshead guide. The torque is unsteady due to the fact that the pressure in the cylinder varies with crank angle. There are two types of forces that cause torque variations at each throw: inertial and gas loads which are explained in chapter 4.3.2 and 4.3.3.
Once the inertia and gas force have been determined, they must be correctly added together for each separate throw to determine the local vertical forces which act on the crosshead guide anchor bolts. These loads are normally calculated by the compressor/engine OEM.
Without a detailed model of the compressor system it is not easy to determine which amount of the total load is transferred to respectively the frame and crosshead guide bolts.

If the results of a detailed analysis are not available a rough estimate of the vertical dynamic force on each bolt can be calculated with equation (4.9). With this approach it is assumed that the vertical dynamic load on each anchor bolt is the same for each cylinder which is not always the case, especially for a multiple stage compressor.

$$F_{b,Tw} = \frac{T_W}{n \cdot D} \qquad (4.9)$$

In which:

- F_b = vertical peak-to-peak force in each bolt (N)
- T_w = maximum amplitude of torque variation (Nm)
- n = total number of bolts (-)
- D = distance between bolts (m)

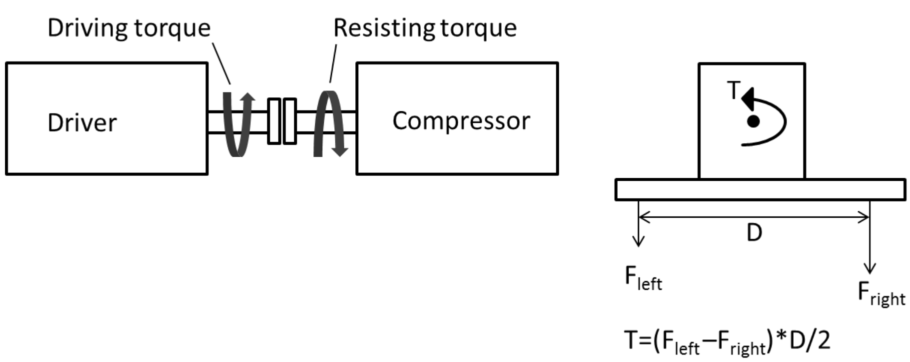


Figure 4.12 Driving and resisting torque of a respectively a driver and compressor

4.3.6 *Earthquake loads*

If a compressor is located in an earthquake area, the effect on the foundation and compressor system can be investigated by applying the earthquake loads to the foundation. This however, is a specialised analysis which shall be done by an expert in this field.

4.4 Rigid versus flexible frame

In the dynamic design of the foundation (concrete block, piles and sols), a widely accepted procedure in the past was to assume the frame of the compressor, gas/diesel engine and driver rigid, which is however not the case. With that assumption the resulting forces and moments were used by a vector summation from the loads of individual cylinders, accounting for phasing between the throws, see summary in Appendix A.

However, the loads which must be used for the individual anchor bolts must be calculated by using the local forces and moments of the individual cylinders. This was shown by previous GMRC research projects [1] which have made clear that mounting systems must sustain horizontal forces based on local forces for individual cylinders, as opposed to forces inferred from global shaking forces and moments. In general this demands higher bolt tensions than typical past practices which were based on the global forces.

Normally the compressor and driver OEM's will deliver these loads but in Appendix A an overview is given how to calculate the individual and summed forces and moments, see also [1] GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997. Since these forces are the resultant based on the assumption that the frame is rigid, this information alone is not always sufficient to design an adequate foundation system which will be explained in this chapter.

Substantial, time-varying inertia forces act on each crank throw and its bearings but not on the cylinder. This "unbalance" distinguishes inertia from gas forces. As previously discussed, the phase relationship between throws directly influences the net inertia forces and moments applied to all the bearings as a whole. However, even with summed forces and moments, small or zero, compressor frame bending flexibility ensures tie-downs and foundation near a crank throw to experience a substantial fraction of that throw's shaking forces. With an extremely rigid frame, minimizing the summed forces and moments shall also minimize the locally transmitted forces. A very flexible frame makes locally transmitted forces essentially independent of the summed forces and moments. Reality lies between the rigid and very flexible extremes.

Tests as reported in [1] "GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997 and in [5] "GMRC Technology Assessment Report TA-93-1, December 1993", have shown that there may be a gross error in the local forces at the tie-downs if the frame will be assumed infinitely stiff.

Various standard methods exist for calculating the forces transmitted to the foundation block and to each tie-down which connects the frame to the block. The major difference between these methods lies in their treatment of frame and cross head guide flexibility, and in the effort they require. Different assumptions regarding these flexibilities, which are summarized in the following subsections, can significantly influence the calculated values for transmitted forces, see also Figure 4.13.

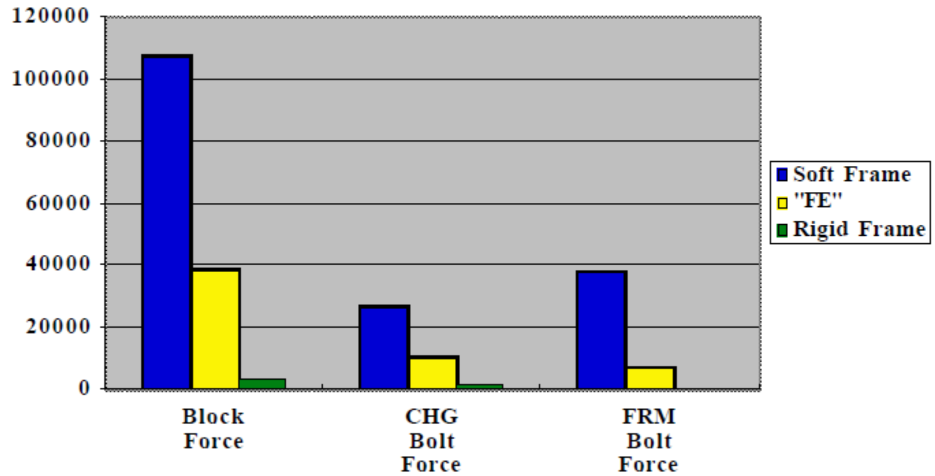


Figure 4.13 Influence of assumptions on forces to block, crosshead guide bolts and frame bolts

Non-conservative calculation method
Assume a rigid frame. This assumption allows sharing of net unbalanced forces and moments between all anchor bolts and neglects gas forces. While simple to implement, it underestimates the transmitted load and anchor forces, often by a very substantial amount, and is not recommended .

Conservative calculation method
Assume a totally flexible frame and crosshead guide. This means the tie-down and foundation strength, local to a cylinder, must carry the full maximum gas force in that cylinder, and must carry inertia forces associated with that crank throw. While relatively simple to implement, given the gas and inertia forces, this approach can overestimate forces, but is preferred to the non-conservative approach.
In [1] GMRC Technical Report TR-97-2 “Foundation Guidelines”, January1997, it is proposed to multiply the inertia and gas forces calculated for each cylinder with a frame flexibility reduction factor. However, there is not much information available on this factor and the suggested value of 0.5 from the “GMRC Technical Report TR-97-2 “Foundation Guidelines”, January1997 [1], is probably strongly dependent on the type of the compressor. For that reason the compressor manufacturer shall be contacted for this.

4.5 Summary of dynamic loads

4.5.1 Introduction

In this chapter a summary is given of the calculation method of the dynamic loads which shall be used in the design of the anchor bolts of the crosshead guide and frame. The loads shall be calculated for each individual cylinder and due to the fact that the diameter of all frame bolts are the same, the maximum value of the loads as calculated for each cylinder shall be taken for the design. The crosshead bolts are in most of the cases not the same as the frame bolts.
Further on the maximum calculated value for each cylinder shall be divided by respectively the number of crosshead bolts and the number of bolts on each side of the cylinder to get the load per bolt. As explained in chapter 4.3.1, a distinction shall be made between peak-to-peak and 0-peak value of forces for different calculations (preload and fatigue calculations of bolts, and determination of minimum required friction force).

Remarks:

1. It shall be kept in mind that the required friction force to hold the frame tight to the foundation, shall be based on the (maximum) 0-peak value instead of on the peak-to-peak value. The foundation block design as summarised in chapter 5 and the fatigue calculations of bolts as summarised in chapter 10 must be carried out with the peak-peak values of the loads.
2. Further on it shall be kept in mind that the loads which shall be used as design loads are achieved by summing all different (peak) values of the loads at a certain location.
3. It is assumed that the foundation system will not be operated at resonance conditions.
4. In different sections of this chapter it is indicated that several loads will be supported by the crosshead guide supports. However, it shall be noted that not all compressors have a separate crosshead guide support. In that case it can be assumed that the loads will be supported by the two nearest frame bolts.

4.5.2 Frame anchor bolts

4.5.2.1 In piston rod (horizontal for a horizontal compressor) direction:

The maximum (0-peak) values over a crank revolution of the inertia force of each individual cylinder (local force) in the piston rod can be calculated with equation (4.10). The maximum (0-peak) value of this force shall be taken to restrain the frame by friction at the frame tie-down bolts.

$$Fx = [(m_{rec} + m_{rot}) r \omega_0^{\,2} \cos \omega_0 t + m_{rec} \frac{r^2}{L} \omega^2 \cos 2\omega_0 t] sf \qquad (4.10)$$

In which:

F_x = load in piston direction as a function of crank angle (N)
m_{rec} = reciprocating mass* (m)
m_{rot} = rotating mass** (m)
r = stroke (m)
L = connection rod length (m)
ω_0 = circular velocity (rad/s)
t = time (sec)
sf = safe factor for frame flexibility**

*The reciprocating mass m_{rec} is usually one third of the weight of the connecting rod, plus the weight of the crosshead, piston rod, piston and weights of fasteners forming a part of various assemblies.

**There is not much information available on this factor and the suggested value of 0.5 from the "GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997 [1], is probably strongly dependent on the type of the compressor. For that reason the compressor manufacturer shall be contacted for this.

4.5.2.2 Direction perpendicular to cylinder (vertical for horizontal cylinder)

1. Preservation of bolt preload shall be calculated with the maximum upwards (peak) value of F_y which can be calculated with equation (4.11)
2. The peak-to-peak value (2 times the value as calculated with equation (4.11) F_y shall be used in the calculation of the dynamic (fatigue) stresses in the bolts.

$$Fy = (m_{rot} r \omega_0^{\ 2} \sin \omega_0 t) sf \tag{4.11}$$

In which:

- F_y = load perpendicular to cylinder as a function of crank angle (N)
- m_{rot} = rotating mass* (m)
- r = stroke (m)
- ω_0 = circular velocity (rad/s)
- t = time (sec)
- sf = safe factor for frame flexibility**

*The rotating mass m_{rot} is the sum of the mass of the crankshaft without the crank webs, and two thirds of the mass of the connecting rod. The centrifugal force created by these masses is the product from mass, crank radius and square of angular speed. By selecting proper counter weights and placing them on the opposite side of the crank, the rotating forces can be balanced. Therefore, the inertial forces of rotating masses produce a centrifugal force of constant magnitude that can be completely balanced by using properly sized counter weights.

**There is not much information available on this factor and the suggested value of 0.5 from the "GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997 [1], is probably strongly dependent on the type of the compressor.
For that reason the compressor manufacturer shall be contacted for this.

4.5.3 Crosshead guide anchor bolts (if present)

4.5.3.1 In piston rod (horizontal for a horizontal compressor) direction:

The forces to be restrained by friction at the crosshead guide bolts (if present) are the summed forces of the maximum (peak) gas load in the cylinder which can be calculated in different ways as follows, in order of preference:

a. With a performance calculation (PV chart). This excludes the pulsation effects.
b. With the maximum value of the equation (4.1) and (4.2).

4.5.3.2 Direction perpendicular to cylinder (vertical for horizontal cylinder)

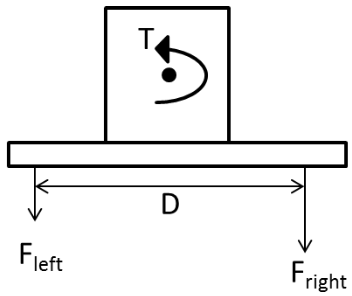
1. Preservation of bolt preload shall be calculated with the summed forces of:
   - The maximum (vertical) 0-peak value of the unbalanced forces as calculated with (4.12)
   - The maximum (vertical) 0-peak value of the torque variations as calculated with (4.13)
2. The calculation of the dynamic (fatigue) stresses in the bolts shall be carried out with the summed forces of:
   - The peak-to-peak value of the unbalanced forces as calculated with (4.12).
   - The peak-to-peak value of the torque variations as calculated with (4.13).

Inertia loads (maximum values over a crank revolution) for each cylinder:

$$Fy = (m_{rot} r \omega_0^{\ 2} \sin \omega_0 t) \mathrm{sf} \tag{4.12}$$

For an explanation of the symbols, see 4.5.2.2

Torque loads



$$F_{b,Tw} = \frac{T_W}{n \cdot D} sf \tag{4.13}$$

In which:

- F_b = vertical peak-to-peak force in each bolt (N)
- T_w = maximum peak-to-peak value of torque variation (Nm)
- n = total number of bolts (-)
- D = distance between bolts (m)
- sf = safe factor for frame flexibility* (-)

*There is not much information available on this factor and the suggested value of 0.5 from the "GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997 [1], is probably strongly dependent on the type of the compressor. For that reason the compressor manufacturer shall be contacted for this.

4.5.4 Concrete block

4.5.4.1 Horizontal and vertical forces for dynamic foundation design

The maximum of all summed global forces and moment shall be taken into account in the dynamic design of the concrete block:

– Peak-to-peak values of sum of the unbalanced forces and moments of the compressor and driver of all cylinders. These loads can be calculated with the equations as summarised in Annex A.
– Peak-to-peak values of the torque variations.

4.5.4.2 Horizontal forces on the block w.r.t concrete stresses

The 0-peak value of the horizontal force on the block at the location of the crosshead guide (if mounted on the block) acting outwards on the block from which concrete stresses shall be calculated, is the maximum tensile rod loads as summarised in the order of preference as follows:

1. With a performance calculation (PV chart). The calculated values shall be multiplied with the frame flexibility correction factor*
2. With the following equation:

$$Frtmax = [(Pdcrank)(Acrank) - (Pshead)(Ahead)]F1.\mathrm{sf} \tag{4.14}$$

In which:

F_{rcmax} = maximum compressive rod force (N)
F_{rtmax} = maximum tensile rod force (N)
A_{crank} = crank end area (m^2)
A_{head} = head end area (m^2)
B = cylinder bore diameter (m)
D_{rod} = rod diameter (m)
P_{head} = pressure at the head end (N/m^2)
P_{crank} = pressure at the crank end (N/m^2)
F1 = correction factor (-)
sf = safe factor for frame flexibility* (-)

With F1 as follows:

- 1.1for compressors with good pulsation control and low valve losses
- 1.5 for a low compression ratio, high pulsations, or high valve losses
- a reasonable working value for F1 is 1.15-1.2.

5 Foundation (Concrete Block, Mat, Piles & Soil)

5.1 Introduction

The foundation block has the role of positioning and supporting the compressor and driver system, providing a fixed reference upon which to maintain the compressor's alignment, and acting as an extension of the compressor's structure in controlling motion of the compressor under dynamic loads. Some examples of different configurations as applied for reciprocating compressors are shown in Figure 5.1.

According to the "API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 [11], a dynamic analysis for reciprocating compressors shall be carried out for machines greater than 150 kW and all table-top special purpose equipment shall be dynamically analysed. According to this standard the mass of the foundation shall be increased if a resonance is predicted.
In both resonant and non-resonant situations, the magnitude of vibration response to dynamic loads varies inversely with the vibrating mass. Thus, adding significant mass is good and a widely applied practice in the block design. The final target shall be to avoid a coincidence between the frequency of the excitation forces and the mechanical natural frequencies (MNF's) of the foundation systems. Thus for full integrity, the concrete block foundation must tolerate the applied loads.
An appropriate concrete block foundation shall have an engineering design with high strength, low and even settlement, sufficient reinforcement (size and location), energy paths and energy dissipation, adequate sole plates and grout, suitable anchor bolts.
Significant foundation material properties include the resistance to bending, shear and deflection, maximum concrete compressive strength, reinforcing steel tensile strength, and modulus of elasticity ratio.
Major concerns are the engineering design, wet mix water content, handling of the wet mix and cured concrete strength. Cold joints shall be avoided in the run of pouring the raw concrete block and construction. Rebars shall leave enough space between them to allow for sufficient concrete mass being distributed.

The vibrations of the complete foundation system shall not exceed acceptable limits caused by the dynamic loads as generated by the compressor and driver and the limits according to e.g. the EFRC Guidelines can be used for this purpose [28].
The dynamic loads which shall be taken into the dynamic design of the foundation system are the summed global unbalanced loads and the torque fluctuations of the reciprocating compressor. These loads are summarised in chapter 4 and Appendix A.
The concrete block can be assumed rigid in the dynamic design for most cases.

In case a concrete mat is part of the foundation system one shall be careful in connecting structures to the mat which are subjected to dynamic loads, e.g. pulsation dampers, pipe supports etc. Too large dynamic (vertical) forces can lead to concrete mat failures, especially when the mat is rather thin.

Despite the fact that the design of the concrete bock is not the main goal of these guidelines, several guidelines and best practices will be summarised as developed by different companies and summarised in different guidelines. Due to the fact that the soil is part of the foundation system, a short summary on the main topics of soil is given. Some background material has been given for the

mat to avoid fatigue failure caused by dynamic loads of equipment which are connected to the mat such as pulsation dampers, pipe supports, separators etc.
The sections of this chapter provides guidelines for reciprocating compressor block design. However, the final dimensions and reinforcing steel requirements can only be determined with a detailed structural static and dynamic analysis.

Sometimes it is necessary to mount a reciprocating compressor system on anti-vibration mounts (AVM's). This is e.g. required for systems which are mounted in earth quake sensitive areas, flexible soil (e.g. moor), ships or offshore platforms (e.g. to avoid structure borne noise). There are different configurations of mounting a compressor on AVM's: mounting the complete concrete block on AVM's, mounting the compressor skid to the concrete with AVM's as shown in Figure 5.2.
If a compressor system is mounted on anti-vibration mount (AVM's), the system shall be designed such that the frequencies of dominant excitation loads do not coincide or is close to the mechanical natural frequencies (MNF's) of the system.
The excitation frequencies shall be separated minimum 20% from the MNF's.
A more detailed description of the procedure how to design the system mounted on AVM's is given in section 12.8.4.

Most of the material as described in this chapter has been copied /retrieved from the following sources:

[1] GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997

[11] API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009

[20] GMRC Course "Foundation Design & Repair, The Bolted Joint", May 12-14, 2009

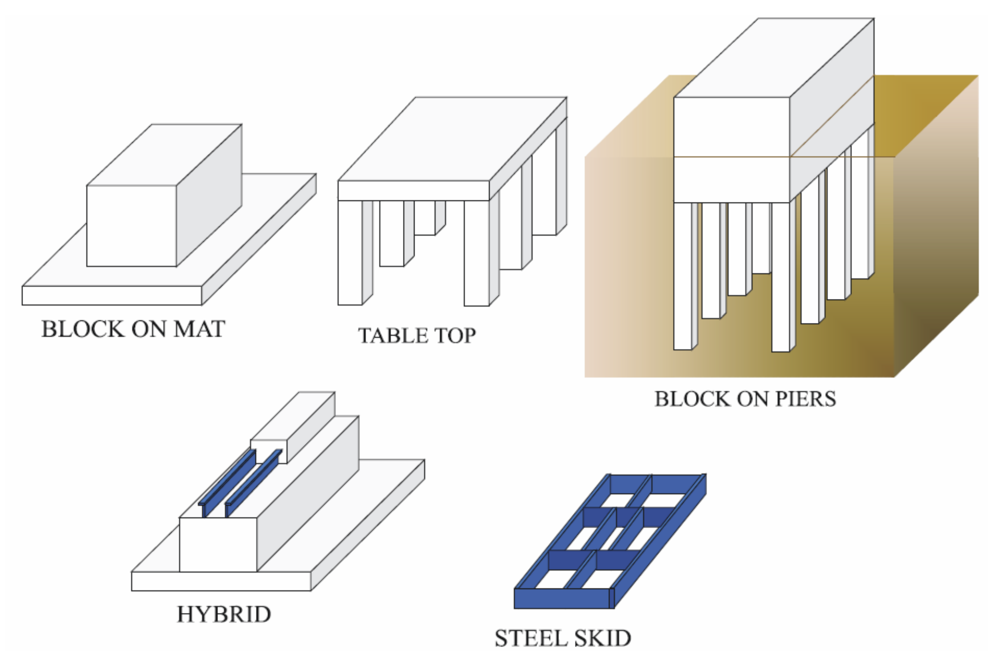


Figure 5.1 Different types of foundations [19]

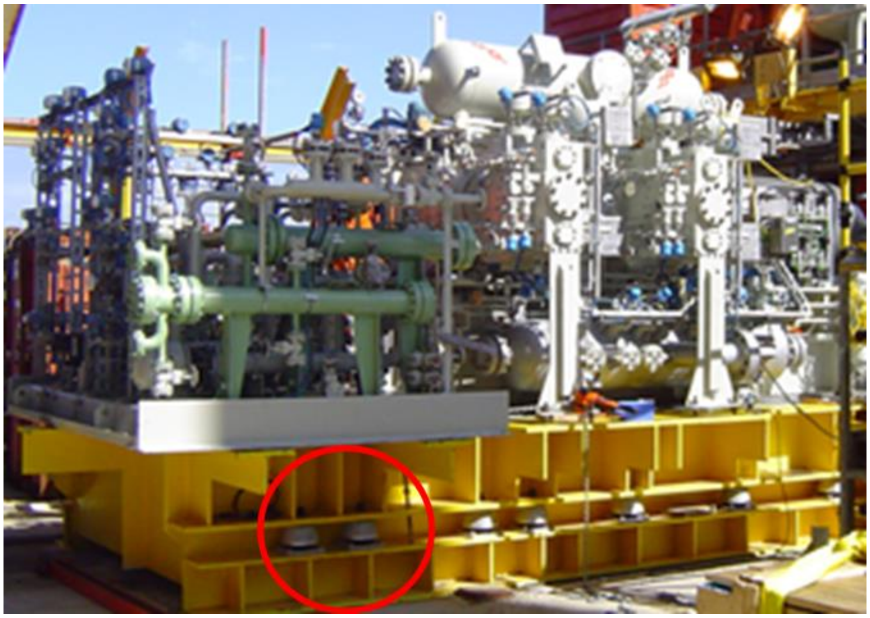


Figure 5.2 Compressor mounted on anti-vibration mounts

5.2 Dimensions & minimum weight of concrete block

Most of the guidance material for this section has been copied from:
"GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013" [7] and from "API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 " [11].

- The API Standard 686 [11] states that in addition to the static structural analysis, a complete block foundation design may require a dynamic structural analysis including consideration the soil interaction, unbalanced dynamic forces, limiting displacements and all possible modes of vibration. Besides the requirements of the API Standard 686 is also recommended to take into account, if available, the pulsation-induced forces acting on the block.
- The ratio of the weight of the block pile cap to the weight of the compressor shall be a minimum 5-10 for reciprocating compressors which is according the API Standard 686 [11]. Although the mass ratio has been a good rule of thumb for the preliminary design, only a detailed dynamic analysis will give the most accurate design. The final target of the design is to avoid resonance conditions. This can be achieved when the mechanical natural frequencies (MNF's) do not coincide with the frequency of the dominant excitation loads.
- To achieve accurate enough results, the model shall include accurate boundary conditions. Especially the soil shall be modelled accurately, especially for rotational and shear effects.
- For preliminary design of concrete block foundations, the length and width shall be 300- 600 mm longer and wider, respectively, than the equipment (if block mounted) or the skid (if skid mounted) [11]. This shall be in agreement with the minimum edge distance as discussed in chapter 9.2.4.
- Block foundations shall have a minimum of 50% of the block thickness embedded in the soil, unless otherwise specified by the equipment user [11].
- Depth shall be a minimum as follows [7]:
  - 1.2-1.5 m for drivers less than 1840 kW;
  - 1.8 m for drivers in the range of 1840-3680 kW
  - 1.8-2.5 m for drivers greater than 3680 kW

- The width of the foundation shall be at least 1.5 times the vertical distance from the base to the machine centre line, see Figure 5.3, unless analysis demonstrated that a lesser value will perform adequately [11]. The edge distance as discussed in chapter 9.2.4 shall be taken into account in the final width of the block.
- The ratio of the height of the machine crankshaft above the base to the width of the foundation block (or the pile group in the plan, if applicable) shall not be more than 0.65 [7].
- The top of the finished foundation shall be minimum 100 mm above the finished elevation of the floor slab or grade to prevent damage to the machinery from runoff or wash-down water [11].

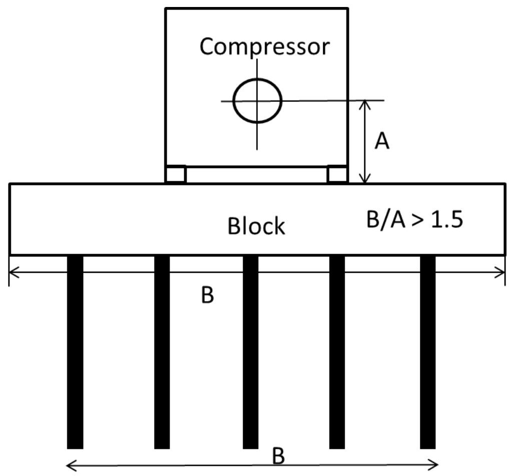


Figure 5.3 Maximum ratio of height of the machine crankshaft above base

- To minimize torsional effects, a vertical line drawn through the centroid of the machine or resultant of several machines shall pass within a distance of 5% of the plan dimensions of the base from the centroid of the contact area (or pile group), see GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013 [7], see Figure 5.4.

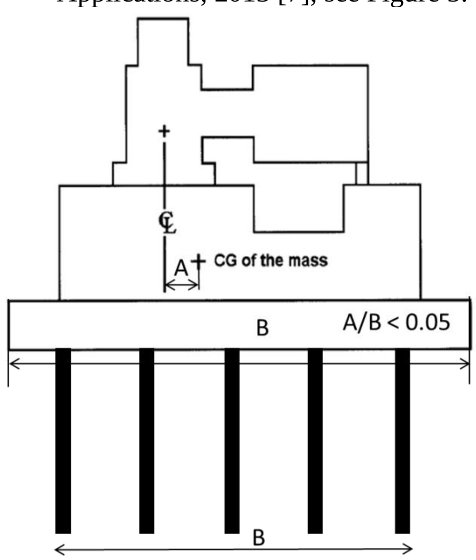


Figure 5.4 Minimum distance between foundation CG and crankshaft (extended picture from Grouting Handbook [10]

The following “rules of thumb” according [7] and [20] that have been found to be helpful for successful block and pile foundation designs are summarised below. However, as mentioned before, only a detailed static and dynamic analysis will give the optimum design. This is also mandatory according to the API RP 686 [11] for machines greater than 150 kilowatts and all table-top special purpose equipment. It also states that if the analysis predicts a mechanical resonance, the mass and/or stiffness (e.g. with piles) of the foundation shall be adjusted to avoid resonance.

1. Foundation static design parameters (ultimate base resistance, factored base resistance, shear strength) shall be reduced by 50% if reciprocating equipment is mounted. This is according to a safety factor of 1.5 as required in the API Recommended Practice 686 “Recommended Practices for Machinery Installation and Installation Design”, PIP REIE 686, Second Edition 2009 [11] to avoid overturning and sliding due to all applied dynamic forces and moments. A larger safety factor may be required depending on the type of soil.
2. The maximum dynamic load amplitude shall not exceed 1.5 times the maximum static load so that dynamic loads do not induce fatigue. Sometimes this is difficult to reach because the dynamic loads are a determined by the process conditions and by the type of compressor while the static loads are determined mainly by the deadweight.
3. A single flat top block is ideal [7].
4. Internal angles of 90 degree shall be avoided, radius and bevel are recommended, oil pan recess require special attention, see Figure 5.5.
5. Block must be mechanically isolated from surrounding structures.
6. Block shall be protected against oil intrusion with e.g. a grout cap.

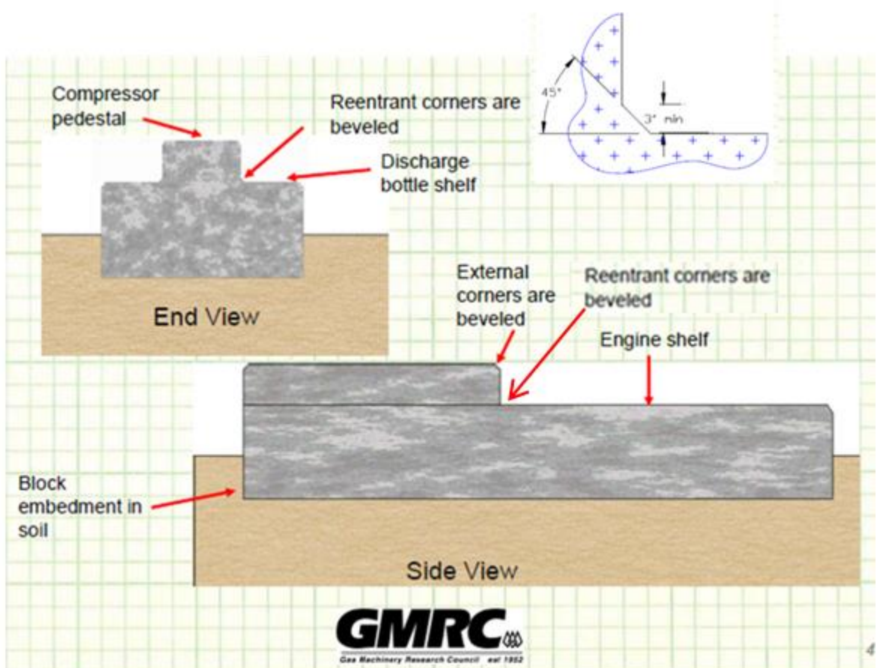


Figure 5.5 Basic Block Design [19]

5.3 Dynamic considerations of concrete mat

If present, the concrete mat including the reinforcement, shall be designed such that the vibration levels and the dynamic stresses do not exceed allowable levels.
If the dynamic stresses in the concrete and reinforcement will exceed the fatigue strength, concrete failure can occur. This is especially the case if the frequency of the excitation loads coincides or are close to a mechanical natural frequency (MNF), called mechanical resonance condition. This is especially the case for thin mats and relative weak soil and if dynamic loads are transferred to the mat via e.g. pipe supports, pulsation dampers, separators etc. Frequencies of the soil/mat configuration at frequencies lower than 10 Hz have been observed.
The soil must be included in the model in an accurate way because this will have a large influence on the dynamic behaviour and consequently on the stress ranges.

5.4 Reinforcement Designations used

5.4.1 Used designations

U.S. designations give the diameter in units of ⅛ inch, so that #8 = 8⁄8 inch = 1 inch diameter, see Table 5.1 for all dimensions.
Metric designations represent the nominal bar diameter in millimetres, rounded to the nearest 5 mm, see Table 5.1. Bars in Europe will be specified to comply with the standard EN 10080.

Table 5.1 US reinforcement designations

U.S. rebar size chart

Imperial Bar Size	"Soft" Metric Size	Mass per unit length		Nominal Diameter		Nominal Area	
		lb⁄ft	(kg/m)	(in)	(mm)	(in²)	(mm²)
#2	#6	0.167	0.249	0.250 = ¼	6.35	0.05	32
#3	#10	0.376	0.561	0.375 = ⅜	9.525	0.11	71
#4	#13	0.668	0.996	0.500 = ½	12.7	0.20	129
#5	#16	1.043	1.556	0.625 = ⅝	15.875	0.31	200
#6	#19	1.502	2.24	0.750 = ¾	19.05	0.44	284
#7	#22	2.044	3.049	0.875 = ⅞	22.225	0.60	387
#8	#25	2.670	3.982	1.000	25.4	0.79	509
#9	#29	3.400	5.071	1.128	28.65	1.00	645
#10	#32	4.303	6.418	1.270	32.26	1.27	819
#11	#36	5.313	7.924	1.410	35.81	1.56	1006
#14	#43	7.650	11.41	1.693	43	2.25	1452
#18	#57	13.60	20.284	2.257	57.3	4.00	2581
#18J		14.60	21.775	2.337	59.4	4.29	2678

Table 5.2 Metric reinforcement designations

Metric Bar Size	Mass per unit length (kg/m)	Nominal Diameter (mm)	Cross-Sectional Area (mm²)
10M	0.785	11.3	100
15M	1.570	16.0	200
20M	2.355	19.5	300
25M	3.925	25.2	500
30M	5.495	29.9	700
35M	7.850	35.7	1000
45M	11.775	43.7	1500
55M	19.625	56.4	2500

5.4.2 Reinforcement diameter

According to "API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 " [11]

- Minimum bar size: 12.7 mm (#4).
- In the event that a foundation block greater than 1.20 m thick is required for stability, rigidity, or damping, the minimum reinforcing steel may be as suggested in ACI 207.2R, with a suggested minimum reinforcement of 22.2 mm (#7) bars at 300 mm on centre.

According to "GMRC Course "Foundation Design & Repair, The Bolted Joint", May 12-14, 2009[20]:

- Minimum bar size: 25.4 mm (#8)

According to "GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013 " [7]

- Minimum bar size: 19.05 mm (#6)

According to EN 1992-2 (2005) Eurocode 2 "Design of Concrete Structures" Part 2- Concrete bridges[25]

In accordance with CEN/TS 1992 Part 4.2 NVN-CEN/TS 1992-4-2 "Design of fastenings for use in concrete- Part 4-2: Headed Fasteners"[16]

- In general, for all fasteners of a group the same diameter of reinforcement shall be provided. It shall consist of ribbed bars with a yield strength $\leq$ 500 N/mm² and a diameter not larger than 16 mm.

In Appendix D.2.3 a table has been given with the minimum required number of reinforcement bars for different bolt and reinforcement diameters for a bolt preload of 70% of the yield strength of an ASTM A 193 B7.
The values from this table are based on a based on a minimum yield strength of 414 MPa and according to the procedure according to the NVN-CEN/TS 1992-4-1 "Design of fastenings for use in concrete- Part 4-1: General[15]. An example is given in Appendix 4 of this CEN standard. The values of this table shall be adjusted if other values are used.

5.4.3 Reinforcement material

USA Definition of strength:

The grade designation is equal to the minimum yield strength of the reinforcement in ksi (1000 psi) for example grade 60 reinforcement has a minimum yield strength of 60 ksi (414 MPa). Reinforcement is typically manufactured in grades 40, 60, and 75.

According to "API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 " [11]

- Unless otherwise specified by the equipment user, all reinforcing steel shall conform to the requirements of ASTM A615, Standard Specification for Deformed and Plain Billet Steel Bars for Concrete Reinforcement, grade 60 with a minimum yield strength of 414 MPa.

According to "CEN/TS 1992 Part 4.2 NVN-CEN/TS 1992-4-2 "Design of fastenings for use in concrete- Part 4-2: Headed Fasteners"[16]:

- Historically in Europe, reinforcement comprised mild steel material with a yield strength of approximately 250 MPa. Modern reinforcement comprises high-yield steel, with a yield strength more typically 500 MPa.
- In general, for all fasteners of a group the same diameter of reinforcement shall be provided. It shall consist of ribbed bars with a yield strength $\leq$ 500 N/mm² and a diameter not larger than 16 mm.

In Appendix D.2.4 and D.2.7 tables are given with the minimum required number of reinforcement bars for different bolt and reinforcement diameters for a bolt preload of 70% of the yield strength of an ASTM A 193 B7 bolt material. These tables are based on a minimum yield strength of 414 MPa and according to the procedures of NVN-CEN/TS 1992-4-1 "Design of fastenings for use in concrete- Part 4-1: General[15]. An example is given in Appendix 4. If the requirements according the NVN-CEN/TS 1992-4-1 "Design of fastenings for use in concrete- Part 4-1: General[15]. Keep in mind that the values of this table shall be adjusted if other values are used.

5.4.4 Reinforcement spacing

Reinforcement reinforces the concrete and gives it increased tolerance to tensile stresses. A PCRC research project [1] on foundation parameters shows that the presence of reinforcement in the range of 0.2 -1% (volume) significantly reduced the extend of cracking around the anchor bolt termination point but did not eliminate it. Management of tensile stresses in the concrete and concrete's tensile strength are clearly necessary to inhibit cracking, but reinforcement has a significant role to play in the installation by its ability to control the extend of cracking once it occurs. Thus, a high density of reinforcement (as much as 1% volume or more, which is approximately 3.4% weight) appears valuable in reciprocating compressor installations. The required reinforcement spacing values found in literature are as follows:

According to
GMRC Course "Foundation Design & Repair, The Bolted Joint", May 12-14, 2009 *[20]*
Heavy reinforcement grid to gain strength and control cracking, see Figure 5.6 and Figure 5.7. The opening in the concrete block of Figure 5.7 Figure 5.7 is to accommodate an engine oil pan.
If possible such opening shall be avoided to avoid cracks at the corners and to avoid oil leakage to the concrete.

- Heavy, dense reinforcement cage in upper third of block on approximately 200 mm horizontal centres.
- Reinforcement density on approximately 400 mm centres in lower two-thirds.
- At equipment locations the reinforcement shall be on 150-300 mm.
- Extra reinforcement around anchor bolts in a 3-dimensional reinforcement cage and at oil pan trough.
- Diagonal doweling at all re-entrant angles.
- Heavy doweling into the mat.

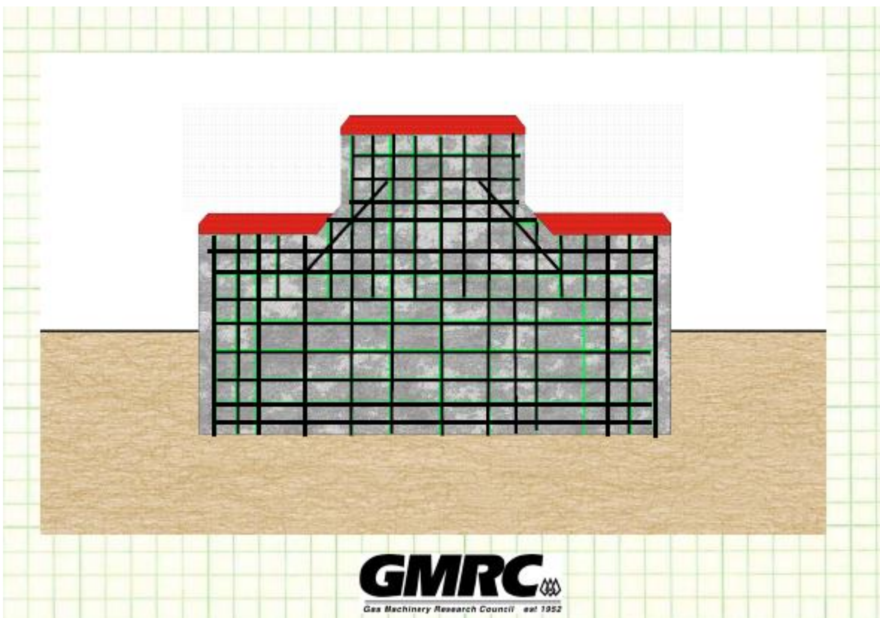


Figure 5.6 Dense reinforcement cage of modern designs [20]

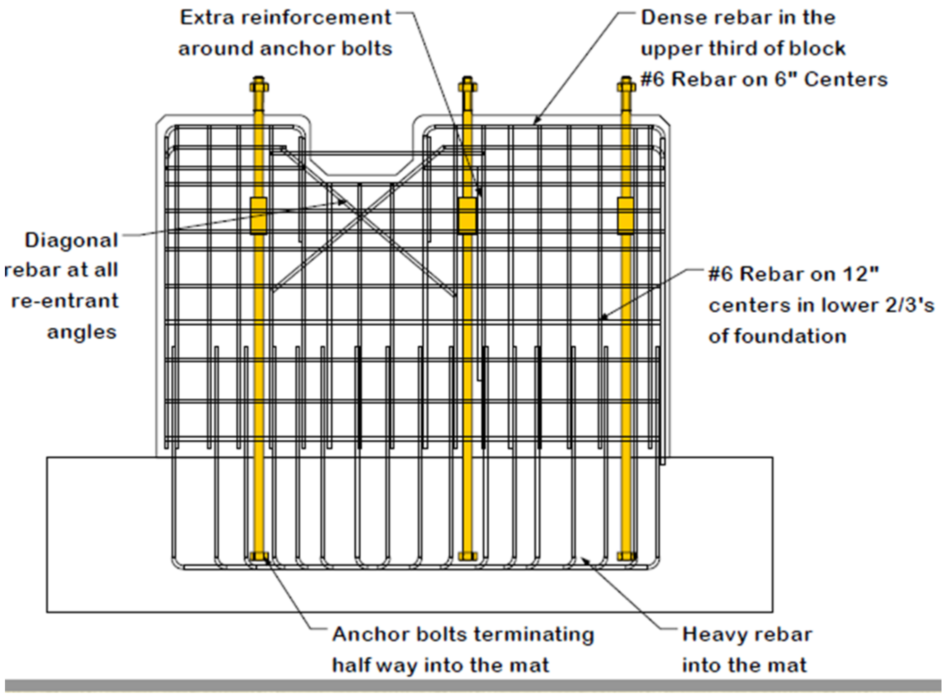


Figure 5.7 Typical modern block design for a reciprocating compressor according to [20]

According to GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013 [7]

- In equipment pedestal area: 150-300 mm horizontal centres
- The vertical distance between the reinforcement shall be approximately 150 mm near the top, 250 mm in the middle and 300 near the bottom.
- Reinforcement shall be covered with approximately 75 mm at the top and bottom and approximately 50 mm elsewhere.
- Intersecting reinforcement shall be tied rather than welded as welding requires special verification of material and special procedures for good results.

According to "API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 " [11]

- Maximum spacing is 300 mm on centre.

In Appendix D.2.4 and D.2.7 tables are given with the minimum required number of reinforcement bars for different bolt and reinforcement diameters for a bolt preload of 70% of the yield strength of an ASTM A 193 B7.
The tables from Appendix D are based on a based on a minimum yield strength of the reinforcement of 414 MPa and according to the procedures of NVN-CEN/TS 1992-4-1 "Design of fastenings for use in concrete- Part 4-1: General[15]. An example is given in Appendix 4.
According to this standard, the reinforcement bar is effective within a distance of ≤ 0.75 times the embedment length (h_{eff}). Taken a proposed embedment length of 24 times the bolt diameter, see chapter 8.8.3, means that the reinforcement distance shall be ≤ 18 times the bolt diameter.

From the calculations as given in Appendix D.2.5. it is shown that the minimum number of reinforcement bars is determined by anchorage failure of the reinforcement.
It can be shown that the proposed horizontal spacing of 150-300 mm is sufficient if the recommended minimum reinforcement diameter of 16 mm is applied.

5.5 Concrete

5.5.1 Used references on concrete material:

- ACI 301-99, Specifications for Structural Concrete, American Concrete Institute, June 2003
- Concrete Fundamentals, American Concrete Institute, 1993 [41]
- ACI Title No. 94-M49, The Influence of Aggregate on the Compressive Strength of Normal and High Strength Concrete [42]
- ACI 201.2R-01, Guide to Durable Concrete, American Concrete Institute, October 2001 [43]
- ACI Title No. 95-M24, High-Performance Concrete: Influence of Coarse Aggregates on Mechanical Properties [44]
- ACI 351.1R-99, Grouting between Foundations and Bases [45]
- for Support of Equipment and Machinery, American Concrete Institute, August 1999 [46]

5.5.2 GMRC Course "Foundation Design & Repair, The Bolted Joint", May 12-14, 2009 [20]

- Concrete is a composite material that consists of a composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate, usually a combination of fine aggregate and coarse aggregate; in Portland-cement concrete, the binder is a mixture of Portland cement and water, see "- ACI - 1998 Manual of Concrete Practice"
- Concrete is cheap.
- Portland cement derives its name because it resembled the natural limestone the Isle of Portland off the southern coast of England. Portland cement comes in different types:
  - Type I – Normal
  - Type II – Modified
  - Type III - High Early
  - Type IV - Low Heat
  - Type V - Sulphate Resistant
- Concrete hardens by an exothermal process of hydration.
- Normal concrete gains most of its strength in the first month (typically referred to as the 28-day strength).
- The hydration process continues with slow gain of strength for many years.
- Concrete strength is a function of:
  - Water content (primarily)
  - Size and type of aggregate
  - Additives.
  - Air entrainment
- Most contain "silica fume" to increase density and tensile strength. (increasing the amount of silica fume will produce a concrete likely to crack)
- Concrete is very strong in compression, but weak in tension.

5.5.3 GMRC Course "Foundation Design & Repair, The Bolted Joint", May 12-14, 2009 [20]

- Typical compressive strength is 27.6 MPa.

- Typical density is 2400 kg/m^3.
- Typical modulus of elasticity (Young's modulus) is 20.7 GPa (approximately 0.1 times that of steel).
- Coefficient of thermal expansion is similar to that of steel.
- Low tensile strength of concrete is reason for tendency to crack.
- Tensile strength is approximately 10% of the compressive strength and can be calculated according to the following equation:

$$\sigma_r = \sqrt{\sigma_c} \text{ (MPa)} \tag{5.1}$$

In which:

σ_r = tensile strength (MPa)

σ_c = compressive strength (MPa)

Specific lab tests can be performed to determine the tensile strength of concrete (beam test).

- Tensile strength must be downgraded by a factor of 2 under dynamic loads: approximate allowable tensile strength is 1.3 MPa.
- The shear strength of concrete is only about 5% of its compressive strength.
- The Young's modulus of concrete can be approximated according to the following equation:

$$E = 4700\sqrt{\sigma_c} \text{ (MPa)} \tag{5.2}$$

In which:

E = Young's modulus (MPa)

σ_c = compressive strength (MPa)

- The Young's (elasticity) modulus is a way to compare how much a material stretches or compresses under load. A "high modulus" material, such as concrete, will compress less when the anchor bolts are tightened than with a "low modulus" material such as epoxy grout which has a Young's of approximately 50% of that of concrete.

5.5.4 *Minimum design values for compressive & tensile strength*

The total loads in the vertical direction of the concrete shall not exceed the maximum allowable compressive load. The following values of the minimum compressive loads are found in the literature:

According to the API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 " [11]

- minimum compressive strength of 28 MPa

According to the
GMRC Course "Foundation Design & Repair, The Bolted Joint", May 12-14, 2009*" [20]*

- minimum compressive strength of 28 MPa shall be used

According to the GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013 " [7]

- minimum compressive strength of 28 MPa after 28 days in accordance with ACI 318 [29] shall be used

According to the DIN 4024 Part 1 Machine foundations"

- minimum compressive strength of 25 MPa (B25) according DIN 1045 shall be used.

According to the GMRC report No. TR 97-2 "Foundation Guidelines":

- concrete shall be selected with a least 28 MPa compressive strength and 2.6 MPa tensile strength.

Remarks:

1. Low tensile strength concrete mix may cause the epoxy to delaminate from the concrete surface during the cure period. For that reason the concrete must have a tensile strength of not less than 2.4 MPa to reduce the possibility of edge lifting. This will be fulfilled if a concrete is used with a minimum compressive strength of 28 MPa.
2. From EN 1993 Eurocode 3 "Design of Steel Structures" [26] it can be shown that with a conservative approach the minimum compressive strength for concrete would be at least 10 MPa which is much lower than the advised value of 28 MPa.
3. In Appendix D different tables are given where are based on a concrete compressive strength of 28 MPa and a bolt preload of 70% of the yield strength of an ASTM A193-B7 material and according to the procedures of NVN-CEN/TS 1992-4-1 "Design of fastenings for use in concrete- Part 4-1: General[15]. An example is given in Appendix D. The values of these tables shall be adjusted if materials are used with other yield strengths.
   It is the responsibility of a civil engineer to select the required number and size of reinforcing bars to comply with the all requirements for bar spacing, symmetry, concrete cover, steel failure and other criteria that may be applicable.

6 Soil & Piles

6.1 Introduction [20]

In the static and dynamic design of a compressor foundation it is important to realize the following:

- A foundation shall never be installed without a thorough characterization of the underlying soil.
- One-size-fits-all foundation designs are a recipe for trouble.
- Many locations require additional measures (excavation and backfill, pilings, etc.) for a successful installation.

Geophysical soil surveys are essential for a successful foundation design and both core samples and shear wave velocity measurements are required for an adequate design of the foundation system. The soil properties determine which type of foundation has to be used and if pilings are required. The soil properties can be determined by test borings as summarized in the next section of this report.

Key words in the design w.r.t. soil are:

- Soil stratigraphy.
- Bearing capacity.
- Effect of vibration on soil – settlement, liquefaction risk.
- Modulus of sub grade reaction (stiffness).
- Dynamic soil shear modulus, G.
- Dynamic soil-pile interaction parameters (for pile supported foundations).

6.2 Soil testing [20]

Specialized geotechnical testing is required to measure the soil dynamic properties. It is advised to select a local geotechnical consultant, since they can be expected to have specialized knowledge regarding the local soil and climatic conditions. Core-sample geotechnical testing to determine the soil profile is generally not sufficient. The critical soil properties to determine are the shear wave velocity, damping, unit weight and Poisson’s ratio.
Cross-hole seismic testing at the site is the preferred test method in most cases. With a cross-hole wave propagation test the shear modulus of soil can be determined with the following relation:

$$G = \rho v^2 \text{ (N/m}^2\text{)} \tag{6.1}$$

In which:

G = shear modulus (N/m^2)
ρ = density (kg/m^3)
v = shear wave velocity (m/s)

Many other techniques can be used, including laboratory testing. Some soil parameters are not amenable to field testing.

6.3 Soil Analysis, loading and settlement

According to the “GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013” [7]:
Clay and sand are major types of soils that exist. Wet clay can expand and contract, causing settlement and uplift. Dry sand has no cohesion and low to moderate bearing capacity. Slightly moist mixtures of clay and sand have moderate to high load bearing capacity, good stiffness, and are desirable. Rock, shale and limestone are extremely dense (hard) and form good bedrock.
Each soil layer has different stiffness and dampening properties. E.g. moisture content can have a large effect on soil properties and will vary with seasons of the year or with tides if the compressor system if installed close to the sea. Proper soil analysis is required for each foundation. Accurate soil properties are required for a dynamic analysis. A geotechnical report only offers a soil stiffness range from textbook information. Specialized geotechnical testing is required to measure the soil dynamic properties. A cross hole seismic analysis is required to obtain accurate soil stiffness values at each soil stratification. Best practice is to select a local geotechnical consultant, since they can be expected to have specialized knowledge regarding the local soil and climatic conditions.
It is important to map out the entire area that must support the foundation. Understanding the effects of layering is critical to foundation design. Soil has different layers of different compositions and for that reason the soil properties must be obtained for each layer.
The depth of the soil analysis is influenced by the type of foundation. Generally, a depth equal to 4 times the foundation equivalent radius is adequate for shallow foundations, but more depth shall be assessed to ensure the absence of an undesirable layer. Local geotechnical companies will usually be able to advise on this point. Generally the first soil layer will be backfill, which may not be the geotechnical soil. Backfill shall be engineered soil and be properly compacted.
Best practice is to make the design actual bearing capacity of the foundation soil less than 72 kPa. This is often impractical for compressor packages larger than 3680 kW, however, in no case shall the maximum actual bearing capacity exceed 96 kPa. Foundation, pier or piling areas must be designed so that the design settlement of the foundation soil does not exceed approximately 13 mm, and preferable no more than 10 mm.

6.4 Soil parameters needed for design

The following geotechnical information is minimum required for an adequate design of the foundation:

6.4.1 Soil parameters for design

- Shear Modulus (G)
- Poisson’s Ratio (ν) or Young’s Modulus (E)
- Density, ρ (shall always include water content)
- Max bearing stress, Smax.

6.4.2 Typical soil parameters are

According to: GMRC Course “Foundation Design & Repair, The Bolted Joint”, May 12-14, 2009 [20]:

Typical values for soil mass density:
- Concrete or solid rock clay: 2400 kg/m^3

- Clay: 1000-1100 kg/m^3
- Packed sand or gravel: 11600- 1900kg/m^3

Typical values for Poisson's ratio:
- Soft clay: 0.3-0.4
- Medium dens sand/gravel: 0.3-0.4
- Dense sand or gravel: 0.4-0.5
- Partially saturated clay: 0.35-0.45
- Saturated clay: 0.4-0.5

Remark: the values of the Poisson's ratio do not have a large influence on the calculations results.

6.4.3 Design parameters

The static and (global) dynamic loads as summarised in chapter 4 and Appendix A can be used in the design of the soil.

According to the "API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 " [11]:

- In the absence of known soil parameters, a qualified geotechnical consultant (soil specialist) shall establish the soil properties necessary for foundation design. This engineer shall always be used for soil foundation design for machines > 150 kW.
- The foundation shall be designed to support the applied service loading without exceeding the allowable soil bearing capacity or the limits for settlement to prevent damage to piping system configurations, internal machinery alignment, or other connecting auxiliary equipment.
- Maximum soil pressure due to static and dynamic load combinations shall not exceed 75% of the allowable soil bearing capacity.

6.5 Piles

Pilings is required when the soil is:

- too soft to support the combined deadweight of machinery and foundation so that the soil bearing capacity or the limits for settlement are exceeded;
- the soil isn't stiff enough to resist vibration forces and deflections;
- water table is too high or variable to assure consistent soil properties over time.

The stiffness of the piles is based on friction between the soil and sides of the piles and by the end-bearing pressure.
The foundation stiffness is dependent upon pile group stiffness and attachment of the piles to the block (named cap attachment). In general the block which is mounted on the piles, has a good compressive stiffness but a limited tensile and lateral stiffness. However, if the piles are tied integrally to the block it provides a good lateral stiffness.
The final pile design shall be optimized in a static and dynamic analysis of the complete foundation design, including the block (with weights of all parts of the compressor system), mat, piles and soil. The peak-to-peak values of the loads as summarized in chapter 4.5 shall be taken into account for that purpose.

The minimum requirements for piles according to "GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013" [7] are as follows:

1. Increasing the size of foundation soil contact area increases damping, everything else being equal. Therefore the plan area of the pile group shall be made as large as practical.
2. Piles to be installed below the compressor crankcase as well as under the crosshead guide supports.
3. Two piles shall be installed below each compressor cylinder head end to allow for an adequate support in the case that head end supports are required in the future.
4. The pile spacing shall be at approximately the same distance from the compressor centreline to the top of the skid or foundation block.
5. If there are multiple throws on one side of a compressor frame, the typical number of piles is equal to the number of throws plus one.

7 Grout (epoxy & cement)

7.1 Introduction

Grouting is used to completely fill the gap between a non-precise top elevation of a concrete foundation block and the machined bottom of the equipment base.
Grouting materials (either cement or epoxy based) have to withstand vertical load, while horizontal movement of a machine is restrained by the clamping force of the properly torqued anchoring system against the machinery grout. Grouting material must be able to withstand prolonged compressive loads, at equipment-operating temperatures, without creeping or allowing the base to deflect, as this will disturb the alignment of the moving parts of the machine. Grouting also provides an inert, impervious barrier between machine fluids and concrete block.

Chocks
Chocks support the frame and transmit the static and dynamic loads from the frame to the grout or sole plate on the block, see Figure 7.1.
Chocks provide for an extensive air gap, inhibiting heat transfer from frame to
block, reducing foundation thermal distortions. Chocks provide a series of positive tie down points with fixed interface conditions. Some chocks are adjustable.
The horizontal frame forces are transmitted through the chock by shear. For this transmission to take place, there must be no relative movement between the chock and the bottom of the frame and between the chock and the sole plate or grout. The chock material may be epoxy or metal.

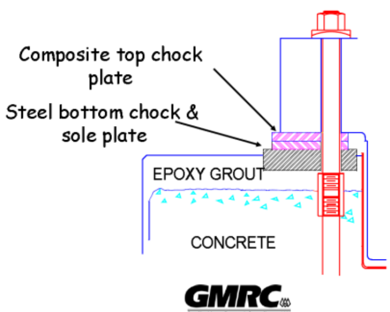


Figure 7.1 Example of a machine mounted with chocks on an epoxy grout layer on top of a concrete foundation

Epoxy grouts versus epoxy chocks
One shall be aware that epoxy grout and epoxy chocks have in general different material properties.
Epoxy grouts are mixtures of resin, hardener and aggregate. The aggregate allows the grout to be poured in large, thick sections because it absorbs the exothermic heat created by the resin and hardener.
Epoxy chocks are mixtures of resin and hardener and do not have aggregates. They get much hotter during poring and must be poured in small blocks typically around anchor bolts.

It shall be noted that the material properties of epoxy grout and epoxy chock may differ for different suppliers. For that reason the material properties shall always be provided by the supplier.

More detailed description on all aspects w.r.t. grout can be found in the following documents:

- The Grouting Handbook, a Step-by-Step Guide to Heavy Equipment Grouting, by Don Harrison, 2000 (ISBN 0-88415-887-X, Gulf Publishing Company) [10]

- GMRC Technical Report TR-97-3 “Friction Tests Typical Chock Materials and Cast Iron”, December 1997 [2]
- GMRC Technical Report TR-97-5 “Epoxy Chock Material Creep Tests”, December 1997 [3]
- SWRI “Systems Mountings Guidelines for Separable Reciprocating Compressors in Pipe Line Services”, SWRI project number 18.12083.01.401, December 2006 [6]
- GMRC Technical Report TR-97-2 “Foundation Guidelines”, January1997 [1]

7.2 Typical facts & figures of polymer modified concrete, named epoxy grout [20]

Main advantages of epoxy grout:

- Best used in limited depth applications such as grout caps from 50 – 300 mm.
- The compressive strength is much higher than that of concrete (approximately a factor 3-4 depending on the type of epoxy grout).
- Can develop a high enough compressive strength in 24 hours for supporting the machine and dry enough.
- No limitations on depth of pour or size (however: deeper epoxy grout layer means more creep and means that a longer bolt is necessary to keep enough preload).
- Very crack resistant.
- Organic grouts (develop strength by polymerization) are used almost exclusively for reciprocating machinery.
- They are much stronger in tension than cementations grouts, resist cracking, and are chemically inert once cured.
- Easy to place.
- Uniform consistency, homogeneous.
- Fast curing & development of full strength.
- Chemically inert.
- Stiff, durable and tough.
- Good adhesion to steel and concrete.
- Dimensionally stable, low shrinkage/expansion.
- Well characterized, calculable behaviour.
- Good contact with base plate.

Main disadvantages of epoxy grout:

- Epoxy grout has approximately 25% of the elasticity modulus of concrete, examples are shown in Table 7.1. Keep in mind that the values of Table 7.1 may differ for different suppliers.
- Thick grout layers will separate from the concrete over time due to interfacial shear stresses caused by differential expansion.
- Epoxy grout cures by polymerization, not by hydration like concrete.
- Epoxy grout is highly exothermic during cure.
- Large grout pours must have expansion joints, follow manufacturer’s recommendations. General applied expansion joints every 1.2-1.8 meter.
- Epoxy grout is a thermoplastic material, it is subject to low temperature creep.
- Epoxy grout is not recommended to use above a temperature of 70ºC due to the fact that the creep will increase. The 70ºC is approximately the maximum temperature at the frame footings.
- The design compressive strength of epoxy grout is much lower than the ultimate compressive strength due to the fact that creep will increase at a higher compressive load, see also chapter 7.2.2.

- Not effective with reinforcing steel.
- Much more expensive than concrete.
- Grout has a much higher creep than concrete. Most epoxy grouts will deform under compression loads to some extend when subjected to higher temperatures and higher (compressive) loads than those for which the grout was designed, see an explanation of creep in chapter 7.2.1
- Less strong than steel.
- Much higher expansion coefficient than that of steel, cast iron or concrete, see Table 7.1.Concrete has a tendency to restrain the movement of the epoxy due to the very good bond between the grout and concrete. Due to the much higher expansion of the grout, severe stresses can occur at the interface during temperature changes such start-up and shut-down of the compressor. This will finally lead to concrete failures at the interface which is particular of interest for large, thick pour layers. For that reason a maximum layer thickness of 50 mm is recommended also due to the fact that larger epoxy grout layers will result in loss of anchor bolt preload due to creep, see chapter 7.2.1.
- Thick grout layers larger than approximately 125-300 mm, shall be avoided due to the fact that creep will increase. This means loss of anchor bolt preload which can lead to misalignment. If grout layers of more than 50 mm are used, longer anchor bolts are recommended to apply. The longer the anchor bolt, the larger the bolt elongation, resulting in less creep, relaxation and loss of bolt preload and alignment.

Table 7.1 Typical comparative material properties have been retrieved from [20]

Material*	Thermal expansion coefficient (10^{-6} m/m K)	Modulus of elasticity [GPa]
Carbon steel	13	210
304 stainless steel	17.3	210
Cast iron	10.8	130- 180
Concrete	14.5	30 – 36
Epoxy grout (@	55	123—166
Cement grout	50% of epoxy grout**	200%- 400% of epoxy grout

*Keep in mind that the values of this table may differ for different suppliers.
**This values has been retrieved from [10]

7.2.1 *Effect of creep of epoxy grout*

Epoxy grout has a much higher creep than cement grout or concrete as explained in the former chapter (approximately a factor of 2-3).
Creep is the tendency of a material, when placed under a continues stress, to compress or move in a manner that relies or reduces the stress, see Figure 7.2.
The rate of creep depends upon the temperature and stress for a given epoxy formulation and creep increases as temperature rise. The creep does in general do not present a problem in the epoxy grout itself but it will lead to a loss of anchor bolt preload which can cause misalignment problems and severe vibration problems of the compressor system.
Actually creep occurs in the top of approximately 25-50 mm of an epoxy grout layer. This is because the excellent thermal insulation capability of some epoxy grouts. The temperature at the surface of the grout dramatically decreases after about 25 mm of grout thickness.
In chapter 2 of the "GMRC Technical Report TR-97-5 "Epoxy Chock Material Creep Tests", December 1997" [3] equations are given how to calculate the deflections under load of a particular

chock geometry. A summary of the creep values are given in “GMRC Technical Report TR-97-2 “Foundation Guidelines”, January1997” [1].

Typical values summarized in report is a summary of the paper of James and Winston “Predicting Creep Lifetimes for Epoxy Grouts Under Integral Gas Compressor, ASME Transaction April 1983, pp 217-222”. Data for three of the five materials tested suggest that a mount can readily be designed keeping in mind that which in 10 years a change of deflection, under 7 MPa chock (design limit) loading at 66°C, is less than 0.152 mm for a 25 mm thick chock (much less for some materials). This means that in a 760 mm long bolt, the resultant “worst case” loss in stretched length for this creep rate would be 200 micro strains, corresponding to a loss in tensile stress of about 41 MPa, which is approximately 15% for a bolt tensioned to 275 MPa. Increasing the bolt length to 1524 mm would reduce this loss in tension to 20.7 MPa (7.5%), and for a 3048 mm long bolt, the loss in tensile stress would fall to only 10.3 MPa (3.8%). Some epoxies will creep much less than 0.152 mm, so epoxy creep appears to be manageable once knowledge of the phenomenon is available and applied. In summary, understanding the creep process for epoxy grout materials and availability of creep data shall enable the mounts and anchor bolt tension to be engineered for desired applications.

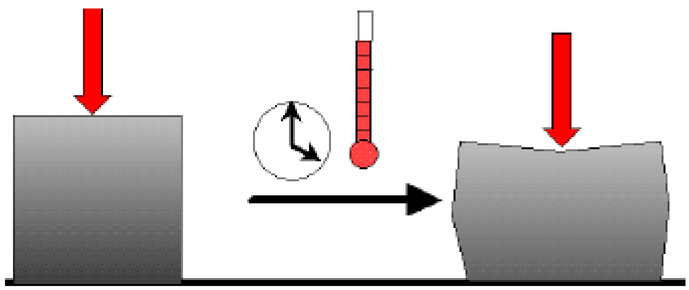


Figure 7.2 Epoxy creep effects (retrieved from [20]

To overcome the creep disadvantages (loss of bolt preload and consequently an misalignment) the following can be done:

- Keep the thickness limited (this is also beneficial to keep the stresses low due to expansion differences) to approximately 50 mm.
- If a larger thickness is required, e.g. during repairing an existing foundation, the bolt lengths shall be more than the recommended values as summarised in chapter 8.8. E.g. the recommended bolt length for an epoxy thickness of 115 mm, shall be at least 1220 mm to ensure a creep loss below 5% in a year.
- Bolt termination point far down in concrete block (this is also beneficial in separation the bolt from areas with high dynamic stresses and oil leakage)
- Keep the compressive stress in the epoxy as low as possible. For this reason the design value of the compressive strength is set much lower (approximately a factor of 10 depending on the type and manufacturer) than the maximum allowable compressive strength of the applied epoxy grout, see chapter 7.2.5.1.
- Heating the epoxy by running the engine after bolt tightening under cold conditions can induce an immediate increase in compression of the epoxy, and a loss in anchor bolt tension. The operator shall retighten the anchor bolts at operating temperature to correct for this loss in tension due to heating, see also section 8.5.4.

Remark:
It shall be noted that foundation epoxy grout layers covering the top of the concrete block can contribute more to creep loss of anchor bolt tension than epoxy chocks.

7.2.2 *Effect of temperature on the compressive strength of epoxy grout*

In The Grouting Handbook, a Step-by-Step Guide to Heavy Equipment Grouting, by Don Harrison, 2000 (ISBN 0-88415-887-X, Gulf Publishing Company) [10] a table has been shown with the different values of the compressive strength of different epoxy grouts at room temperature which varies between 79 and 125 MPa.
Published data has shown that the compressive strength of an epoxy grout (type has not been indicated) was decreased approximately a factor of 2.5- 3 for temperatures between 60- 71 ºC which is the normal temperature of a compressor frame after it has been heated up. The published values are for this grout between 52- 42.8 MPa. For a temperature of 93 ºC the reduction is even a factor of 5.3. For a normal compressor frame temperature of around 70 ºC this means that the minimum compressive strengths according
Table 7.2 would be approximately between 27- 42 MPa. Keep in mind that the values of Table 7.2 and Table 7.3 may differ for different suppliers.

Table 7.2 Compressive strength of different grouts at room temperature according ASTM C307 standard test method

Grout type*	Compressive strength (MPa)
Chock fast Red SG	125
Five star	110
Chock fast Red	105
Five Star DP	103
Ceilcote 648 CP+ Std.	96.5
Escoweld 7505E/7530	96.5
Ceilcote 648 CP+ hf	79.3

*Keep in mind that the values of this table may differ for different suppliers.

Table 7.3 Tensile strength of different grouts at room temperature according ASTM C307 standard test method

Grout type*	Tensile strength (MPa)
Chock fast Red SG	20.7
Five star	10.3
Chock fast Red	17.0
Five Star DP	11.7
Ceilcote 648 CP+ Std.	15.2
Escoweld 7505E/7530	14.5
Ceilcote 648 CP+ hf	79.3

*Keep in mind that the values of this table may differ for different suppliers.

7.2.3 *Edge lifting [14]*

The epoxy grout is the bond between the equipment and the foundation and probably the most important aspect of an installation. For epoxy grout to do its job, the concrete mix design must have

a high tensile strength because a low tensile strength may cause the epoxy to delaminate from the concrete surface during the cure period. This delamination is called edge lifting or curling. Edge lifting is often the result of weak concrete, usually caused by water added at the job site to facilitate concrete placement or insufficient surface preparation prior to grouting.
Edge lifting, or curling as it is sometimes referred to, is the phenomenon caused by the difference in the rate of thermal contraction between epoxy grout and concrete
with low tensile strength. Figure 7.3 illustrates how the different coefficients of thermal expansion/contraction react one to the other during a temperature decrease. The result of this differential contraction results in the tensile failure of the concrete just below the grout/concrete interface.

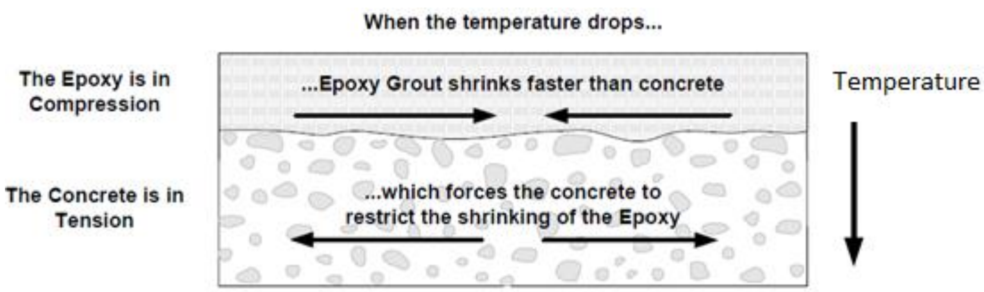


Figure 7.3 Epoxy grout and concrete expand and contract at different rates .

To avoid edge lifting the epoxy must have a minimum tensile strength of 2.4 MPa. There are several methods of preventing edge lifting such as:

1. Pin the outer edge of the foundation using 12 mm reinforcement set into a 24 mm filled with epoxy, every 300 mm along the edge of the foundation if Y <X, see Figure 7.4.
2. Round the outer edge of the concrete foundation if Y<X, see Figure 7.5.
3. Install mechanical anchors in the surface of the concrete. These are reinforcement staples or wickets that improve the bond of the concrete to the grout.

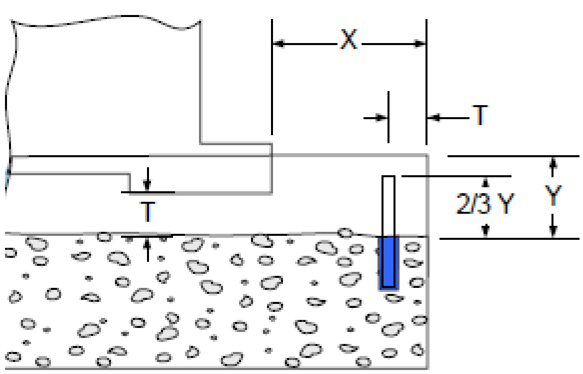


Figure 7.4 Chose pins along outer edge of concrete

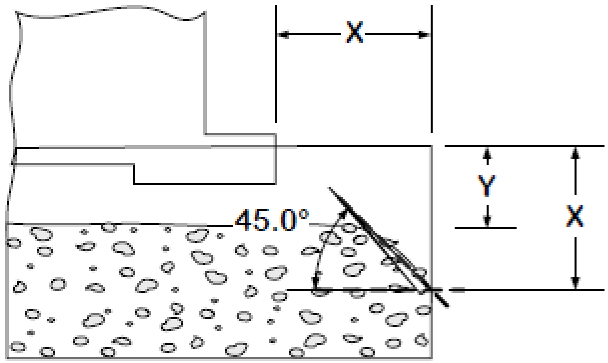


Figure 7.5 Round outer edge of concrete

7.2.4 *Expansion joints*

Expansion joints shall be incorporated into large epoxy grout pours to reduce the possibility of cracking, especially when machinery-to-grout temperature differences of 30 °C, are encountered. Expansion joints serve 2 purposes:

1. They prevent the concrete and epoxy grout from coming apart due to the difference in temperature expansion and contraction rates
2. They guide flow of grout into areas of limited size. It will ensure that the epoxy grout flows everywhere it is needed and that it will stay in place once there.

According to the [11]API Recommended Practice 686 “Recommended Practices for Machinery Installation and Installation Design”, PIP REIE 686, Second Edition 2009 [11]:

- Expansion joints shall be placed every 1.4-2.8 meter intervals in the grout foundation, see also Figure 7.6.Figure 7.6
- Expansion joints shall be made from 12-25 mm thick closed neoprene foam rubber. Polystyrene may also be used.
- Expansion joints require sealing after the grout has cured to prevent liquids to pass down to the concrete. The material shall be an elastic epoxy seam sealant (liquid rubber) or silicone rubber (room temperature vulcanizable).

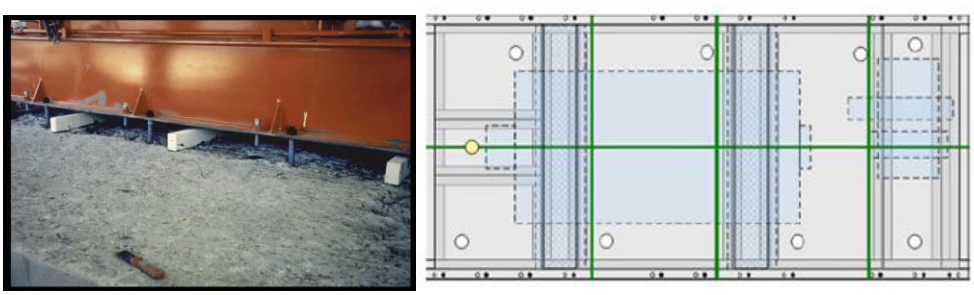


Figure 7.6 Examples of expansion joints [6] [7]

7.2.5 *Design values*

7.2.5.1 *Compressive strength in grout*

To keep the creep of the epoxy grout as low as possible, the design compressive strength is set to a much lower value than the minimum compressive strength at the compressor frame temperature of 70 ºC. In the design of the grout system the vertical static and dynamic loads as summarised in chapter 4 and Appendix A and the bolt preload as summarised in chapter 8.5 shall be used.

The design values for the compressive loads as found in literature are as follows:

GMRC Technical Report TR-97-6 "Compressor Anchor Bolt Design", December 1997 [4]

- 3.5- 6.9 MPa

Experience of an interviewed OEM

- In the marine industry a typical design value of 3.5 MPa was used for many years.

The Grouting Handbook, a Step-by-Step Guide to Heavy Equipment Grouting, by Don Harrison, 2000 (ISBN 0-88415-887-X, Gulf Publishing Company) [10]:

- 3.5 MPa for a temperature of 80 ºC and for chocks and 8.3 MPa for chocks between skids and concrete at ambient temperature.

Marine engine builder Wartsilä:

- The total surface pressure on the resin must not exceed the maximum value which depends on the type of resin and the requirements of the classification society. It is recommended to select a resin type which has a type of approval from the relevant classification society for a total surface pressure of 5 MPa.

Paper of ITW Paper James A. Kully ITW Polymer Technologies, "Best Practices in Compressor Mounting, 7th EFRC Conference Florence Italy, 2010[14]:

- 6.9 MPa to minimize creep effects.

7.2.5.2 Tensile strength

According to "The Grouting Handbook, a Step-by-Step Guide to Heavy Equipment Grouting, by Don Harrison, 2000 (ISBN 0-88415-887-X, Gulf Publishing Company) [10]:

- If epoxy grouting is used the minimum tensile strength shall be 2.4 MPa. to achieve a good bonding between the epoxy and concrete. If the tensile strength is too low delamination may occur during the cure period. This delamination is called edge lifting or curling which is often the result of weak concrete, usually caused by water added at the job site to facilitate concrete placement or insufficient surface preparation prior to grouting.
- All investigated grout materials as summarized in the grouting handbook have higher values than the required value of 2.4 MPa.

7.2.6 Cement grout versus epoxy grout [10]

Cement grout was used in the past by many companies. Nowadays cement grout is not used much because epoxy grout has many advantages over cement grouts. There are several disadvantages of cement grout and for that reason there is a tendency the last decades to use epoxy grout instead of cement grout for reciprocating compressor systems. The main advantages and disadvantages are:

Advantages of cement grout

- Much cheaper than epoxy grout.
- Less creep than epoxy grout which means lower loss of bolt preload.
- Lower expansion coefficient than that of epoxy grout which means a lower change on cracks.

Disadvantages of cement grout

- Less or almost no chemical and oil-resistance in comparison with epoxy grout. Can be solved by using a coating but the effectiveness depends on whether cracks will develop in the coating, exposing the substrate.
- Less compressive strength than epoxy grout. However, due to the fact that cement grout has less creep w.r.t epoxy grout, the design value of the compression modulus of cement is much higher than that of epoxy grout (approximately a factor of 7)
- Less pourable than epoxy grout.
- More shrinkage during curing.
- Higher downtime during curing before it reaches the maximum compressive strength:
  - Most epoxy grout reaches after 24 hours a compressive strength of approximately 55 -70 MPa while cement grout has a compressive strength of approximately 24- 27 MPa after 24 hours.
  - Most epoxy grout reaches after 7 days its ultimate compressive strength of approximately 85-100 MPa while cement grout reaches a compressive strength of approximately 35- 50 MPa after 7 days and reaches its ultimate compressive strength of approximately 55-70 MPa after 28 days.
- Has no good bond to steel.

According to a note of the API Recommended Practice 686 “Recommended Practices for Machinery Installation and Installation Design”, PIP REIE 686, Second Edition 2009 [11]:

“Cement grouts are suitable as “filler” materials in less demanding applications where vibration, dynamic loading, and temperatures extremes are not a concern.
This type of grout is typically used as “filler” inside structural steel baseplates to increase damping and reduce vibration transmission or for use on static equipment where vibration is not a concern. Cement grouts are also typically not resistant to acid and chemical attack.

A typical design value of the compressive strength of cement grout is 50 MP.

7.3 Friction force and friction coefficient

7.3.1 Introduction

Friction provides the primary mechanism for transferring dynamic horizontal forces from the base of the compressor frame to the mount. To avoid slippage under dynamic loads, the net normal force at the interface (machine footings, soleplates and grout) multiplied by the coefficient of friction must exceed the maximum horizontal dynamic (0-peak) value of the force F_e applied by the frame at the tie-down, see equation (7.1) and Figure 7.7.
It shall be noted that compressor anchor bolts are not intended to act in shear.
To assess adequacy of a compressor tie-down requires knowledge of the maximum peak value of the sum of the horizontal dynamic forces Fe the tie-down must restrain, the coefficient of friction, the tensile capacity of the anchor bolt and the tensile capacity of the anchorage of the bolt. With other words: knowledge of the friction coefficient and the maximum horizontal dynamic loads to be

restrained sets the minimum required tensile preload F_b in the bolt to assure restraining the maximum horizontal 0-peak value of the dynamic load. A summary how to calculate the maximum horizontal force Fe is given in chapter 4.5.

F_w from equation (7.1) represents the force caused by the deadweight at the support point. A conservative approach would neglect this force setting it to zero which is the normal procedure and also recommended in the GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997[1]. This is a valid and safe assumption due to the fact that the vertical distortion of frame or block may reduce the effective of deadweight force at this location. The deadweight load is in general a small part of that total compressive load if compared with the bolt preload.

The α is a design safety factor (≥1) which shall be taken into account for the friction data. This value strongly depends on several factors such as the presence of oil, tightening procedure & equipment, etc. This value shall be agreed upon by the vendor and purchaser.

$$F_f = (F_b + F_w)\frac{\mu}{\alpha} \text{ (N)} \tag{7.1}$$

In which:

- F_e = maximum value of the horizontal dynamic load (N)
- F_w = load caused by deadweight (N)
- F_b = minimum required bolt preload (N)
- F_f = minimum required friction force(N)
- μ = friction coefficient (-)
- α = design factor (-)

With the assumption that the deadweight will not be taken into account gives:

$$F_f = F_e = F_b\frac{\mu}{\alpha} \text{ (N)} \tag{7.2}$$

$$F_b \geq \frac{F_e\alpha}{\mu} \text{ (N)}$$

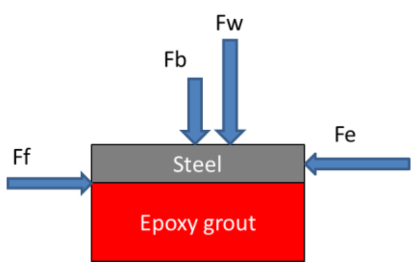


Figure 7.7 Summary of forces

Many different values for the friction factors for steel-steel, steel-epoxy, epoxy-concrete, steel cement grout exist in literature. SWRI has carried out extensive measurements on different types of grout with and without oil between the different materials, which are summarised in GMRC Technical Report TR-97-3 "Friction Tests Typical Chock Materials and Cast Iron", December 1997[2].

The Grouting Handbook, a Step-by-Step Guide to Heavy Equipment Grouting, by Don Harrison, 2000 (ISBN 0-88415-887-X, Gulf Publishing Company) [10] also give different values for different materials.
From the results of the literature it can be concluded that there is a large spread in friction factors, depending on the type of grout from different manufactures and e.g. the presence of oil.
The best way is to use the test values of the grout manufacturer. However, one shall be carefully in using the values of manufacturer because sometimes the highest measured values are given which are only valid for ideal situations which do not occur in many of the actual field situations such as ideal dry conditions, and rough (sandblasted), cleaned and degreased surfaces.

Typical values which are given in literature are as follows:

According to: GMRC Technical Report TR-97-3 "Friction Tests Typical Chock Materials and Cast Iron", December 1997[2].

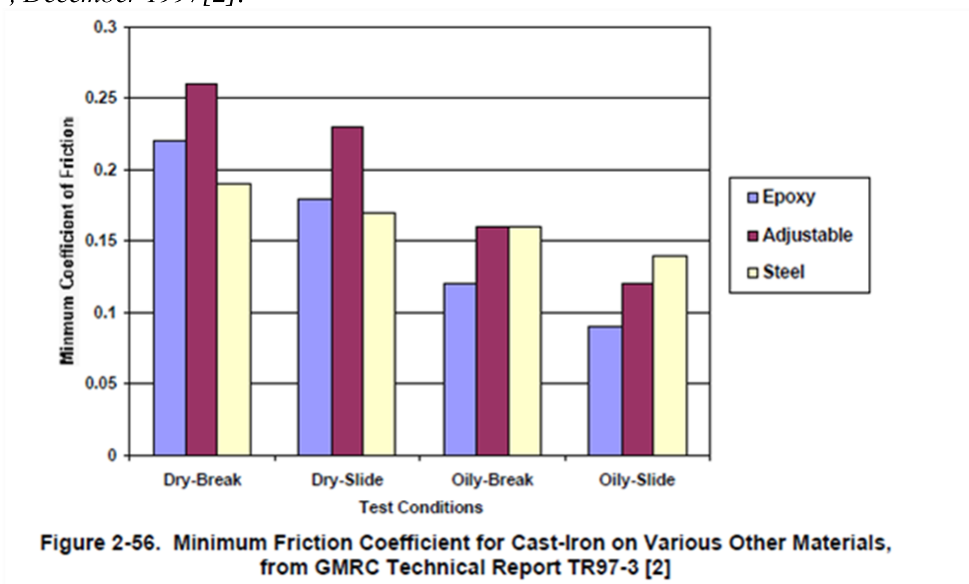


Figure 7.8 Minimum friction coefficient for cast iron on various other materials according to [2]

It is interesting to see that although the value is higher for epoxy than it is for steel chocks in dry conditions, the value for epoxy is lower than for steel for oily conditions.

According to SWRI "Systems Mountings Guidelines for Separable Reciprocating Compressors in Pipe Line Services", SWRI project number 18.12083.01.401, December 2006[6]

- In general: values can vary between 0.1-0.4 for epoxy-cast iron contact
- Dry range for steel-steel: over 0.16
- Oily range for steel-steel: about 0.12

According to" The Grouting Handbook, a Step-by-Step Guide to Heavy Equipment Grouting, by Don Harrison, 2000 (ISBN 0-88415-887-X, Gulf Publishing Company)" [10]

- Epoxy chock-cast iron: 0.7
- Steel-steel: 0.15

According to "PIP (Process Industry Practices) STE05121 "Anchor Bolt Design", October 2003[12]

PIP states that the materials used and the embedment depth of the base plate determine the friction coefficient and the given values are:

- concrete placed against as-rolled steel with the contact plane a full plate thickness below the concrete surface: 0.9
- concrete or grout placed against as-rolled steel with the contact plate coincidental with the concrete surface: 0.7
- for grouted conditions with the contact plane between grout and as-rolled steel above the concrete surface: 0.55

According to "EN 1993-1-1 (2005): Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings" [26]

- For column base steel plates mounted on sand cement mortar: 0.2

According to Paper James A. Kully ITW Polymer Technologies, "Best Practices in Compressor Mounting, 7th EFRC Conference Florence Italy, 2010" [14]

- Chock fast resins-cast iron: 0.7
- Steel-cast iron: 0.15

Remark: these values are both determined by Sulzer Brothers, Switzerland

An commonly accepted value for the friction values for new designs is 0.12. However, the design value shall be discussed and agreed upon between the vendor and purchaser.

7.4 Summary of epoxy grout

- There shall be an agreement between vendor and purchaser about the design value of the compressive strength (commonly applied value is 6.9 MPa) and the friction coefficient (commonly applied value is 0.12).
- Avoid epoxy grout layers thicker than 50 mm.
- Account for creep.
- Use expansion joints.
- Do not use cement grout but in case it cannot be avoided non-shrink grout shall be used.
- Do not use grout for equipment temperatures above approximately 70 °C.
- Use a high quality with crushed stone.
- Avoid cold joints or if this cannot be avoided glue the cold joints through epoxy injection.
- No sharp internal corners in the grouting area and volume.
- Avoid edge lifting by using an epoxy with a minimum tensile strength of 2.4 MPa, by rounding the outer edge of the concrete foundation or by pinning the outer edge of the reinforcement set into the epoxy.

8 Bolts

8.1 Introduction

To achieve high rigidly and long term integrity, the anchor bolt must apply a sufficient downwards force at the mounting interface to resist through Coulomb friction only, the highest expected horizontal loads.
GMRC research [1] has made clear that mounting systems must sustain horizontal forces based on local forces for individual cylinders as opposed to forces inferred from global shaking forces and moments. In general this demands higher bolt tensions than typical past practice.
Besides that the anchor bolt must also be designed to withstand the dynamic stresses caused by the dynamic loads in the vertical direction, see chapter 10. A summary of the loads for which the bolt must be designed is given in chapter 4.
The number, diameter, and length of the anchor bolts will depend on the shaking forces to be resisted, the strength of the material, concrete cracking considerations, and mounting chock and grout factors. The different sections of this chapter will address the following topics:

- Pre-installed versus post-installed.
- Bolt diameter.
- Bolt material.
- Bolt preload.
- Bolt types.
- Crosshead guide support bolts.
- Bolt length.
- Thread lubrication.
- Nuts.
- Termination plates.
- Washers.
- Coating.

8.2 Pre-installed versus post-installed anchor bolts

Civil engineering codes and standards typically only include non-preloaded externally loaded anchor bolts. They do not include the preloaded anchor bolts used in machine and compressor applications where friction provides the primary mechanism for transferring the dominant horizontal forces from the compressor to the foundation.
Compressor anchor bolts are not intended to act in shear and do not directly transfer shear forces via the bolt shank on the concrete. However, shear is something that shall be considered in relation to thermal expansion of the compressor and actual load will depend on bolt clearance, free bolt length and coefficient of friction. This is discussed further into detail in chapter 8.14.

The effect of preload, the compression of the clamped parts, on the tensile and compressive stresses in the concrete is generally not considered in civil engineering codes and standards. Machine foundations and their fastenings do not fall within the scope of the Eurocodes but where applicable parts can and have been used in this report for guidance. For the requirements of fastenings EN 1992 Eurocode 2 “Design of Concrete Structures” refers to Technical Specification “Design of Fastenings for Use in Concrete”. Parts from this specification that can be used for reference are CEN/TS 1992 Part 4.1 General and Part 4.2 Headed Fasteners.

Pre-installed foundation bolts
Most standards and guidelines classify headed anchors, having a nut or plate termination, as cast-in fasteners. This requires an accurate position of all bolts and sleeves prior to concrete placement. This can be achieved by using a template to aid in the placement of anchor bolts, see also picture in Figure 8.1. The bolts will be embedded in the concrete during pouring.

Figure 8.1 Example of a steel anchor bolt template plate (pre-installed)

Other type of pre-installed bolts are given in respectively Several other possibilities of pre-installed bolts are given in Figure 8.2.
In the left hand side picture of Figure 8.2. a metal sleeve is welded to the reinforcing bars. The hammer type bolt is passed through this sleeve and a stop at the bottom is achieved by means with a metal plate. Instead of a hammer type bolt, a circular plate with a nut can also be used.
In the right hand side picture of Figure 8.2 a circular hole in the concrete is kept free. The bolt is passed through this hole and at the bottom the bolt is fixed with a termination plate with nut. The plate and nut are mounted to the bolt via a hole at the outer side of the concrete. Sharp corners in the concrete shall be avoided to avoid cracks.

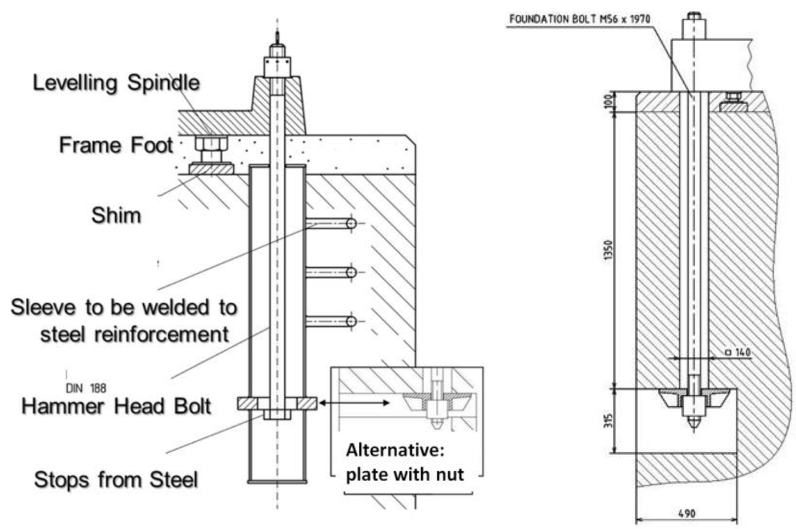


Figure 8.2 Typical examples of pre-installed bolts

Post-installed foundation bolts
To avoid a possible mismatch between the bolt location and the anchor bolt hole post-installed anchors can be used. For that reason the bolts will be mounted in a bolt pocket which will be filled later with grout, either cement or epoxy after the concrete has been poured. The creation of the pocket can be done in several ways. The first method is by drilling the cylindrical pocket after the concrete has been placed. Figure 8.3 shows examples of a cylindrical pocket hole.

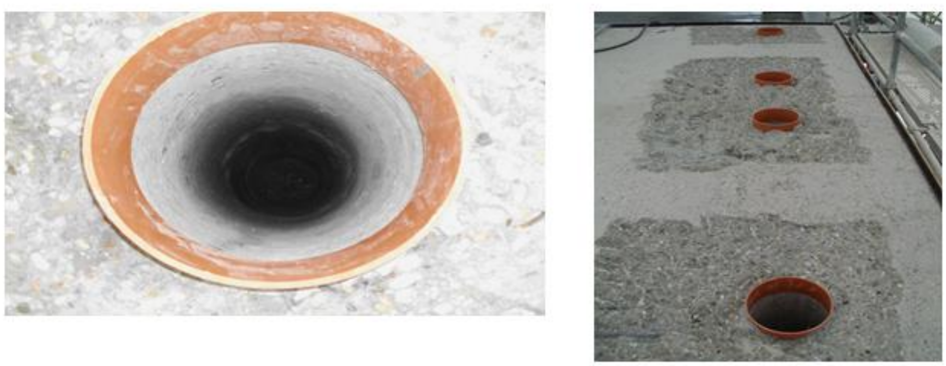


Figure 8.3 Example of circular pockets for the application of post-installed anchor bolts (Source: Apoltec)

Holes shall preferably be roughened after drilling to ensure proper bonding between the grout and concrete with steel brushes or other means. The location of the reinforcement around the anchor bolts shall be such that they will not be cut away when drilling the holes. An example of a procedure for a post-installed anchor is shown in Figure 8.4.

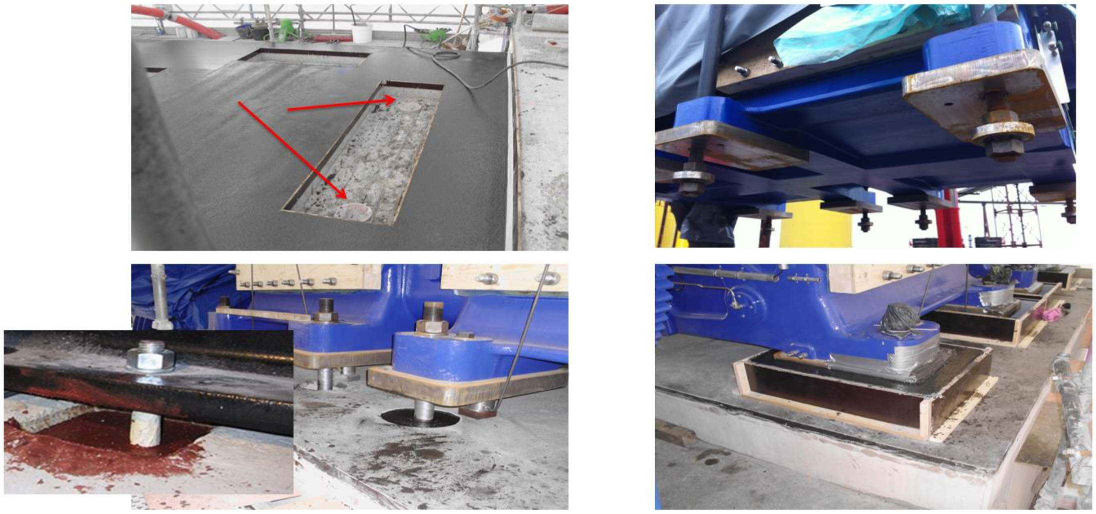


Figure 8.4 Procedure for a post-installed anchor bolt installation (Source: Apoltec)

When using cement grouts the pockets hole walls shall be wetted before grouting and this is typically done by filling the holes with water and removing the water after some period of time. This also gives an indication of the concrete quality as if cracks are present water will seep out. However, when using epoxy grout instead of cement grout the holes shall be thoroughly dried. Water shall be pumped out and pockets dried with for example compressed air, a heat gun (used for paint stripping) or other means. If the bottom of the pocket dries slowly then throwing in a few hands of dry cement will speed up the drying process.

The second method is by using temporary material (e.g. wood) which will be mounted prior to placing the concrete. A disadvantage of this second method could be that this material is sometimes difficult to remove.

The advantage is that (light) conical shapes can be used (largest area on the bottom) which will even have a better bonding after the pocket has been filled with grout. The advantages of using epoxy grout to fill the pocket is that the bond between the anchor bolt and epoxy grout and between epoxy grout and concrete block is larger than the bond between the anchor bolt and concrete.

Another advantage of using pockets filled with epoxy grout material is that it has a considerably higher compressive strength (approximately a factor of 3) than cement grout.

If the bolt is placed in the pocket one shall be sure to leave enough free length of the upper part of the bolt to be able to tension the bolt, see also chapter 8.8.4. This can be achieved by using e.g. a foam sleeve.

Sometimes, metal corrugated sleeves are used to create a pocket. The advantage is that it is not necessary or even impossible to remove this material. However, according to the experience of several operators and compressor OEM’s, these sleeves are not recommended to use due to the fact that some clearance between the outer edge of the sleeve and the concrete may occur caused by shrinking of the concrete. In that case there is a chance on pulling out the sleeve, especially for (non-conical) cylindrical sleeves. This method is not recommended therefore.

Most standards classify headed anchors, having a nut or plate termination, as cast-in fasteners instead of post-installed anchors. The anchor bolts used in most compressor applications are of the headed type but post-installed with the anchor bolt pocket filled with grout material. In several calculations, such as anchor blow out, edge distance etc., it is assumed that the bolts are cast-in e.g. the bolt pocket filled with concrete. No guidelines are available for post-installed bolts but the results be used as a guidance for post-installed bolts.

Appendix A of this report includes some calculations according CEN/TS 1992 Part 4.1 and 4.2 but only the calculation for so-called concrete blow-out failure is directly applicable. The calculations are for information only and are only made to get some idea about the limits and methods used in that specific standard.
However, the design based on the recommendations as given in this report such as the edge distance, bolt termination plate diameter and bolt preload, shall be more than adequate to prevent blow-out failure even when based on cracked concrete.

Available reports and technical articles about compressor anchor bolts as referred to in this report are:

[1] GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997
[4] GMRC Technical Report TR-97-6 "Compressor Anchor Bolt Design", December 1997
[6] SWRI "Systems Mountings Guidelines for Separable Reciprocating Compressors in Pipe Line Services", SWRI project number 18.12083.01.401, December 2006
[10] The Grouting Handbook, a Step-by-Step Guide to Heavy Equipment Grouting, by Don Harrison, 2000 (ISBN 0-88415-887-X, Gulf Publishing Company)
[11] API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009
[12] PIP (Process Industry Practices) STE05121 "Anchor Bolt Design", October 2003
[20] GMRC Course "Foundation Design & Repair, The Bolted Joint", May 12-14, 2009

8.3 Bolt diameter

The compressor frame configuration normally sets the number and diameter of anchor bolts, limiting the options available for maximizing preload capacity the choice of material, length, and thread configuration. This illustrates clearly the system aspects of compressor installation, the overlapping of responsibilities between organizations, the importance of this particular design decision for the compressor frame, and its ability to influence the integrity of the entire installation.
Thus, compressor manufacturers shall carefully review their decisions on frame holes in light of their impact on anchor bolt preload capacity and tie-down holding capacity.
The engineering process shall, therefore, involve choosing the highest readily available bolt strength (see chapter 8.5), specifying a bolt preload & tension (see chapter 8.5). This preload shall be sufficient to restrain the (dynamic) lateral forces as summarized in 4.3.

8.4 Bolt material:

Fastener Grade (US) or Class (metric) refers to the mechanical properties of the fastener material. Generally, a higher number indicates a stronger, more hardened (but also more brittle) fastener.
In ISO 898-1 [38], ISO metric fastener material property classes (grades) are defined. For example, fastener material ISO property class 5.8 means nominal (minimum) tensile ultimate strength 500 MPa and nominal (minimum) tensile yield strength 0.8 times tensile ultimate strength or 0.8x500 = 400 MPa. In a few cases, the actual tensile ultimate strength may be approximately 20 MPa higher than nominal tensile ultimate strength indicated via the nominal property class code. ISO 898-1 gives exact values.
The head often have a manufacturer stamp e.g. Grade 2, Grade 5 (US indication) , Grade 8, Class 8.8, Class 10.9 and Class 12.9 (Metric), see examples in Figure 8.5.

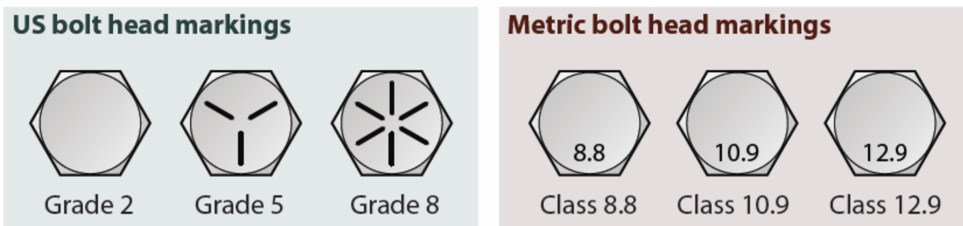


Figure 8.5 US and metric bolt head markings

According to the API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 [11]

Unless otherwise specified by the equipment user:

- ASTM F1554 Grade 36 (minimum yield strength: 248 MPa) for general purposes or Grade 105 for high strength special purpose anchor bolts (minimum yield strength: 724 MPa).

According to " GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997[1]"

- New installations: use ASTM A-193 Grade B7 (tensile strength 862 MPa < 2.5", minimum yield strength: 724 MPa)

According to the
GMRC Course "Foundation Design & Repair, The Bolted Joint", May 12-14, 2009*[20]*

- New installations and repairs shall muse high strength bolt satisfying ASTM A193, Grade B7 (tensile strength 862 MPa < 2.5", minimum yield strength: 724 MPa)

According to the PIP (Process Industry Practices) STE05121 "Anchor Bolt Design", October 2003[12]

- For low to moderate strength requirements: ASTM A307 headed bolts, ASTM A36 rods, or ASTM F1554 grade 36 rods (for minimum yield strength, 248 MPa, Table 8.1.
- For higher strength requirements use the following materials ASTM A193 grade B7, ASTM F1554 grade 55 or grade 105 or ASTM A354 grade BC or grade BD (for minimum yield strength, see Table 8.1.

Table 8.1 Properties for recommended anchor bolt according to PIP (Process Industry Practices) STE05121 “Anchor Bolt Design”, October 2003[12]

Anchor material type		F_y* (MPa)	f_{ut}** (MPa)	Ductile?
A307		Not clearly defined	414	Yes
A36 or F1554 grade 36		248	400	Yes
F1554 grade 55		380	518	Yes
F1554 grade 105		725	863	Yes
A193 grade B7 Based on bolt diameter (d_b) (used for high-temperature service)	$d_0 \leq 2.5”$	725	863	Yes
	$2.5” < d_0 \leq 4”$	656	794	Yes
	$4” < d_0 \leq 7”$	518	690	Yes
A354 grade BC		752	863	Yes
A354 grade BD		897	1035	Yes
A440 Based on bolt diameter (d_b)	$1/4” < d_0 \leq 1”$	635	828	Yes
	$1” < d_0 \leq 1.5”$	559	725	Yes
	$1.5” < d_0 \leq 3”$	400	621	Yes

*Fy= yield strength (MPa)
**f_{ut}= ultimate strength (MPa)

According to Grouting handbook [10]:

- Mild steel: ASTM A36 (minimum yield strength: 248 MPa)
- High strength: ASTM A193, Grade B7 (most commonly used in today’s high-strength anchor bolt system)

8.4.1 Large diameter bolt - low grade material versus small diameter bolt - high grade material

In general, high grade materials for bolts are used if limitations in space require smaller bolt dimensions by keeping the same pre-load.
However, different from mechanical engineering, in civil engineering there is mostly sufficient space available. For this reason and considering the aspects below, bolts with low grade material can be beneficial for compressor and motor anchor bolts. The following aspects are addressed:

1. Specific concrete load

The main advantage of using larger bolt diameters is a lower specific load of the concrete. This reduces the chance of concrete failures which are described in section 9. The reduction of specific load at most designs is caused by larger contact areas between anchor design parts and concrete entailed by using larger bolt diameters .

2. Stress corrosion cracking

Higher strength anchor bolts are more susceptible to stress corrosioncracking and higher strength materials than those mentioned above shall not be used for that reason.

3. Bolt preload

Sufficient preload of the anchor bolts can be achieved by both, large diameter bolt - low grade material and small diameter bolt - high grade material.

4. Bolt fatigue strength

Different from the preload capacity which is directly proportional to the material yield strength, the fatigue strength limit of a bolt is hardly dependent on the steel grade. This is because of the enormous stress concentration innate to every threaded connection to which high grade materials are much more sensitive than low grade materials, see VDI 2230 [21][22] (version 2003).

8.4.2 Bolt coating

- In areas exposed to corrosive chemical vapours or liquids, the anchor bolt shall be fabricated from a material resistant to chemical attack or provided with a proper chemical-resistant coating such as galvanizing.
- API RP 686 [11] states that unless otherwise specified by the equipment user, anchor bolts shall be hot dip galvanised in accordance with ASTM A153.
- PIP STE05121 [12] indicates that galvanizing is a common option for <u>low strength</u> materials such as ASTM A307, ASTM A36 and ASTM F1554 grade 36 and that stainless steel anchors are an expensive option.
- Field experience of an OEM has shown that it not always required applying galvanising compressor foundation bolts. When installations are correctly installed, grouted and maintained, there is no need for galvanising.
  Not galvanising also removes the possible difficulties with thread clearance.
- VDI 2230, 2003 [21] states that in case of hot galvanised bolts the fatigue strength is reduced by approximately 20%. So if galvanised bolts are used, the fatigue strength shall be reduced accordingly in the fatigue analysis as described in chapter 10.
- Treatment of the nut and anchor bolt section projecting above the concrete with a suitable oil/grease having rust preventative properties, thus providing corrosion protection, is always recommended.

8.4.3 Rolled threats versus cut thread

GMRC report TR-97-2 states that all new anchor bolt specifications shall use rolled (formed) threads to minimise any stress concentrations at the threads.

However, only a part of the vertical dynamic load is carried by the anchor bolt as the bolt is part of a preloaded joint. Rolled thread has a higher fatigue strength in comparison with cut thread. Rolled thread is not always a specific requirement, especially if the dynamic stress of cut threads is acceptable, see chapter 10 of the fatigue analysis.

Especially high strength materials are more susceptible to fatigue crack initiation at surface defects and for that reason thread rolling is recommended for all high strength materials (ASTM A193 B7 anchor bolts).

8.5 Bolt preload

8.5.1 Introduction

The bolt preload shall be such that the friction force is sufficient to keep the frame tight to the foundation. The maximum preload shall be such that the friction force is larger than the 0-peak value of the sum of the dynamic loads as summarised in chapter 4.5. The friction force caused by the deadweight shall not be taken into account. The bolt load shall also be larger than the maximum peak value of the sum of the dynamic loads in the vertical direction.
Further on the preload will have a positive (means lower) effect on the cyclic stress which is explained into detail in section 10 “Fatigue failure analysis of preloaded anchor bolts”. The bolt preload can be calculated with equation (8.1) as follows:

$$F_v = x \cdot S_y \cdot A_s \ (N) \qquad (8.2)$$

In which:

F_y = preload (N)
x = percentage of yield strength
S_y = minimum yield strength (N/mm^2)
A_s= smallest bolt area (mm^2)

Table 7.2 gives the results for a preload for different bolt diameters and for a stress of 70% of yield strength for two different materials.
It is noted that several standards and guidelines, e.g. the API RP 686 and the VDI 2230, summarize the bolt preload in tables. However, one shall know for which percentage of yield strength they are applicable because different standards and guidelines use different preload values which will also have a consequence for the dimensions of other parts such as pocket size, edge and anchor bolt distance, dimensions of soleplates and chocks etc., fatigue stress etc.

Table 8.2 Summary of bolt preload calculations applicable for Standard UNC thread series for bolt size up to and including 1”, above 1” series 8 UN.

								F_v (0.7 x S_y)	
	d	d_1	d_2	p	d_h	A_s***	s	Grade 5.6*	ASTM A193 B7**
Bolt size	mm	mm	mm	mm	mm	mm^2	mm	N	N
1/2 – 13	12.70	10.30	11.43	1.95	13.0	93	22.2	19477	47005
5/8 – 11	15.88	13.04	14.38	2.31	17.0	148	27.0	30996	74802
¾ - 10	19.05	15.93	17.40	2.54	21.0	218	31.8	45816	110571
1 – 8	25.40	21.50	23.34	3.18	27.0	395	41.3	82914	200099
1 ¼ - 8	31.75	27.85	29.69	3.18	34.0	650	50.8	136529	329491
1 ½ -8	38.10	34.20	36.04	3.18	40.0	969	60.3	203445	490983
1 ¾ -8	44.45	40.55	42.39	3.18	46.0	1351	69.9	283664	684573
2 – 8	50.80	46.90	48.74	3.18	54.0	1796	79.4	377182	910266
2 ½ - 8	63.50	59.60	61.44	3.18	66.0	2877	98.4	604122	1457947

*these values are based on a minimum yield strength of 300 MPa

**these values are based on a minimum yield strength of 724 MPa
***There is a small difference in screw thread stress area to be used in the calculations in accordance with the ISO and ANSI/ASME standards. The definition in accordance with the ISO is used in the calculations is:

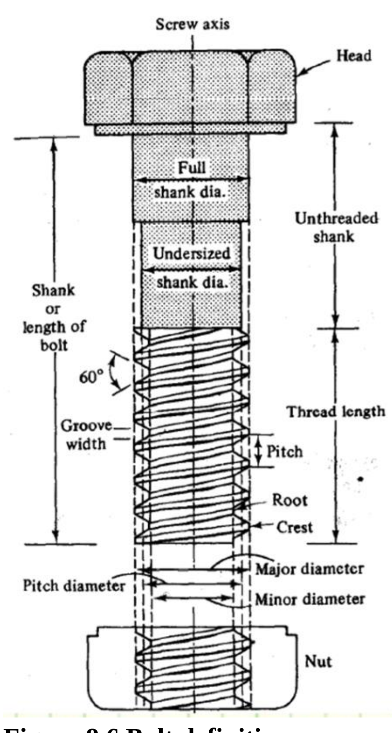
1. Stress area for metric series according ISO 898-1:

$$A_s = \frac{\pi}{4} \cdot (d - 0.938194 \cdot p)^2 = \frac{\pi}{4} \cdot \left(\frac{d_1 + d_2}{2}\right)^2 \tag{8.3}$$

2. For information, the stress area for inch series according ANSI/ASME B1.1:

$$A_s = \frac{\pi}{4} \cdot (d - 0.9743 \cdot p)^2 \tag{8.4}$$

In which:
d = nominal (major) bolt diameter (mm)
d_1 = minor diameter (mm)
d_2 = pitch diameter (mm)
p = thread pitch (mm)
d_h = bolt hole diameter of component or if applicable washer (mm)
A_s = smallest bolt stress area (mm^2)
s = width across flats of bolt or nut (mm)
F_v = bolt preload (N)



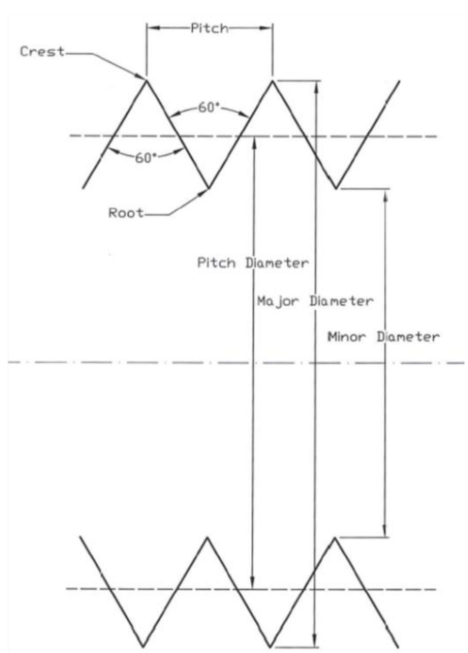


Figure 8.6 Bolt definitions

A summary of the bolt preload as given in different guidelines and standards are as follows:

According to the API RP 686 [11]

Table B.1 of Annex B of Chapter 5 of the 2nd edition of this standard gives the preload (and also the required torque) as a function of bolt diameter. This table is also given in the PIP STE05121 [12]. The values in this table are based on the following:

1. The preloads are based on an internal bolt stress of 207 MPa.
   The bolt stress of 207 MPa is based on 70% yield stress of a material with a yield strength of 300 MPa. Due to the fact that in many cases high strength steel is applied with a yield strength of 724 MPa, the value of 207 MPa for this material is much too low.
2. Values are applicable for tightening with a torque wrench. All torque values are based on anchor bolts with threads well lubricated with oil (more details on torque are given in 8.5.2.1).

According to the GMRC report 97-2 [4] and the
GMRC Course "Foundation Design & Repair, The Bolted Joint", May 12-14, 2009*" [20]*

- A preload of 70% of the minimum yield strength of the bolt material is recommended

According to the GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013 [7]

- These guidelines recommends a preload of 80%-90% of the yield stress.

According to the VDI 2230 [21][22]

- This standards gives a very detailed description how to calculate the bolt preloads. Appendix A of this standard gives tables with preloads for different bolt diameters, materials and friction factors. It is noted that the preload values are based on 90% of the yield stress of the applicable materials.

Remarks: It shall be noted that most of the calculations as made in this document, are based on a bolt preload of 70% of the minimum yield strength. It shall be noted that a higher or lower bolt preload will have an effect on the following:

- Bolt pocket size, see chapter 9
- Edge distance, see chapter 9.2.4
- Bolt spacing, see chapter 9.2.5
- Dimensions of sole plate, mounting plate and shocks, see chapter 12.7.
- Dimensions of bolt termination plates, see chapter 8.11, resulting in other edge distances etc.
- Increase of bolt elongation resulting in lower creep, relaxation and thus loss of preload, see chapter 7.2.1
- Tightening torques, see chapter 8.5.
- Cyclic (fatigue) stresses in bolts, see chapter 10.

8.5.2 Pre tensioning methods

In this chapter the different methods how to apply the preload in the bolt will be discussed. The bolts can be pre tensioned by means of:

- Torque method.
- Bolt elongation method.
- Stretch measurement method.
- Ultrasonic method.

8.5.2.1 Torque method

Applying torque to the nut is one method of stretching a bolt Five things happen when torque is applied to the nut on a bolt:

1. Stretching the bolt.
2. Friction losses in the threads
3. Friction losses between nut and washer.
4. Friction losses on the washer face if it rotates.
5. Twisting of the bolt.

Typically, only a small amount of applied torque results in elongation (preload) of the anchor bolt with this method. The amount of torque which results in elongation, also called torque efficiency, strongly depends on the lubrication of the bolt. If adequate lubrication is applied a common value of bolt efficiency is 30%.

One shall always be aware that using the torque method as a measure of tension can be ~~is~~ inaccurate if not applied in a correct way. This may cause problems such as overstressing the bolt due to the fact that the friction generates an additional torsional stress in the bolt.

However, this uncertainty can be easily covered by using a safety factor (a typical tensioning factor is 1.6).

Despite some uncertainties, the torque method is a proven method The only real drawback of the torque method is that with large bolt diameters it may be difficult to apply the required torque by regular torque wrenches.

The torque required for tension an anchor bolt as given by the following equation can be used:

$$M_a = F_v \cdot \ 0{,}001.\left\{\frac{p}{2\cdot\pi} + \frac{\mu\cdot d_2}{2\cdot\cos\frac{\gamma}{2}} + \frac{\mu}{2}\cdot\left(\frac{d_h+s}{2}\right)\right\} \text{ (Nm)} \qquad (8.5)$$

In which:

F_y= preload (N)
p = thread pitch (mm)
μ = coefficient of friction of threads and nut on washer (-)
d_2 = pitch diameter (mm)
d_h = bolt hole diameter [mm)
s = width across flats of bolt or nut (mm)
γ= thread angle (60 degrees or 55 degrees, depending on the applied thread standard)

In general an average coefficient of friction μ of 0.14 can be used for thread, bolt head and nut bearing face for a lightly oiled or greased condition. It shall be noted further that anti seize lubricants such as Molykote shall not be used.

Table 8.3 gives a summary of the required torque which is based on 70% of the yield strength and on a friction μ of 0.14.

It shall be noted that the values as given in Table 8.3 do not include any safety factor due to the the uncertainty of the amount of torque which is converted into tension. As mentioned before this uncertainty can be covered by including a tensioning safety factor and the values of Table 8.3 shall be adjusted accordingly for the applied safety factor.

Table 8.3 The results of required torque (M_a) calculations applicable for Standard UNC thread series for bolt size up to and including 1", above 1" series 8 UN. For a friction μ of 0.14.

	M_a (0.7 x S_y)	
	Grade 5.6*	**ASTM A193 B7****
Bolt size	**Nm*****	**Nm*****
1/2 – 13	48	116
5/8 – 11	95	230
¾ - 10	168	405
1 – 8	396	956
1 ¼ - 8	802	1935
1 ½ -8	1410	4802
1 ¾ -8	2265	5467
2 – 8	3437	8295
2 ½ - 8	6782	16367

*these values are based on a minimum yield strength of 300 MPa
**these values are based on a minimum yield strength of 724 MPa
***safety factors are not included

For critical applications it is recommended to use the torque method as described in VDI 2230 [21][22] because it takes into account the torsional stress caused by the friction and will not overstress the bolts. However, this method is too comprehensive to describe here into detail but can be found in the chapter "Assembly preload and tightening torque" (chapter 5.4.3.1 of Part 1 of the 2015 version). Keep in mind that the torque values as used in the VDI 2230 are applicable for a preload of 90% of the yield stress of the applicable material.
It is noted that the examples as shown in the VDI 2230 use different values for the friction. One shall be very careful in using the correct friction values for the application of interest.

Multi bolted tensioners (also named jack bolt tensioners)
These are used in lieu of a conventional nut and a picture is shown in Figure 8.7.
The systems require only hand tools to make up and break down. They reduce the amount of torque applied to the individual bolts (or also named jack bolt) to achieve the application of the ultimate torque applied to the anchor bolt. They are occasionally limited by the space required for their installation.
Multi bolted tensioners are designed as direct replacements for conventional nuts and bolts. These devices can be threaded onto a new or existing bolt, stud, threaded rod or shaft. The main thread serves to position the tensioner on the bolt or stud against the hardened washer and the load bearing surface. Once it is positioned, actual tensioning of the bolt or stud is accomplished with simple hand tools by torqueing the jack bolts which encircle the main thread. The jack bolts transfer the preload evenly into the main thread and, consequently, onto the joint. The main thread is tightened in pure tension. Jack bolts have a small friction diameter and can therefore create a high thrust force with relatively little torque input.

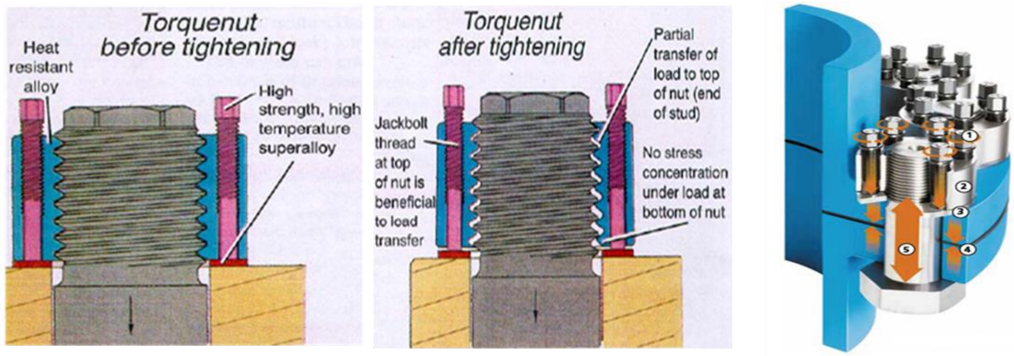


Figure 8.7 Multi bolt tensioner principle

Hydraulic torque wrench devices[10]

A hydraulic torque wrench is a tool designed to exert torque on a fastener to achieve proper tightening or loosening of a connection through the use of hydraulics. A torque wrench is applied to the nut either directly or in conjunction with an impact socket. Hydraulic torque wrenches apply a predetermined, controlled amount of torque to a properly lubricated fastener.

It does develop a somewhat uniform clamping force without the torsional effect, but you can over-stretch an anchor bolt and cause permanent bolt deformation unless you take extra care. You can know what the bolt tension is only if you apply hydraulic pressure during the tightening phase of the operation. When you transfer the load from the hydraulic jacking device to the mechanics of the nut and bolt, relaxation takes place. This load transfer relaxation is unpredictable and variable.

Figure 8.8 Example of a hydraulic torque wrench device

8.5.2.2 *Bolt elongation method with hydraulic nut*

The hydraulic nut replaces the nut normally used and stays with the stud. This is the most compact system and does not require additional stud length. The operator simply screws the nut down tight and connects the hydraulic hoses. After reaching pressure, he either screws down a collar (see Figure 8.9) or inserts shims designed for the application.

The advantage of this method that no friction will be introduced between different parts as described in section 8.5.2.1.

Figure 8.9 Working principle of a hydraulic nut

8.5.2.3 *Stretch measurement method [10][20]*

Applying torque to the nut is not the best method of pre tensioning a bolt because it is the bolt stretch that matters, not the torque on the nut.
For that reason the best method of obtaining and monitoring proper anchor bolt preload or tensioning is by its stretch. You can monitor the stretch and ultimate load or clamping force exerted by the bolt in several ways.
Stretch control eliminates the uncertainties in torque control such as coefficients of friction and bolt twist. It also eliminates the uncertainties in turn control such as the ratio of spring stiffness between bolt and joint accuracy of nut rotation measurement. Stretch control still has uncertainties due to bolt interaction with the joint such as grip length, bolt effective length, bolt material and dimensional variations and temperature differences. The longer the bolt, the less the uncertainties affect the resulting computed preload.

Some anchor bolts on the market are equipped with a permanent indicator to let the mechanic know when the correct preload is obtained. These bolts require some pre-engineering in the form of determining exactly what preload is required. The end user must tell the manufacturer what preload will be required so the indicator can be calibrated to show when the bolt reaches that point. Two basic types of load-indicating anchor bolts exist: the MagBolt® (see Figure 8.10) and bolts equipped with the Rotabolt® device (see Figure 8.11). These two systems have several characteristics in common:

- Both of these devices mechanically monitor the bolt elongation during tensioning like a micrometre or dial indicator.
- Any bolt receiving these devices must be drilled and tapped in its centre on the nut (top) end for positive anchoring of the device at a depth within the bolt to allow for accurate stretch measurement.
- Both of these devices are pre-calibrated for the ultimate load or tension required.
- During installation, it is critical that these bolts be installed at an elevation that will allow only a few threads (three to four) to protrude above the top of the nut. Each 6.25 mm of bolt projection above the nut will decrease the accuracy by approximately 5%.
- Both of these assemblies can indicate whether the bolt is over-tensioned or under-tensioned.

MagBolt®
This device does not require a torque measuring instrument to check its load.
It also uses a finger-operated indicator; however, this device can have one or several hash marks permanently stamped into the head of the bolt, see Figure 8.10. The hash mark is installed at the factory during calibration when the bolt is hydraulically stretched to the desired tension. If the pin points toward the negative symbol (-) to the left of the hash mark, the bolt's tension is lower than

design levels. If the pin points toward the positive symbol (+) to the right of the hash mark, the bolt's tension is higher than the design level.
The MagBolt® will allow the user to know how much torque above the designed preload the bolt has on it and allows for the installation of multiple has marks for different loads.

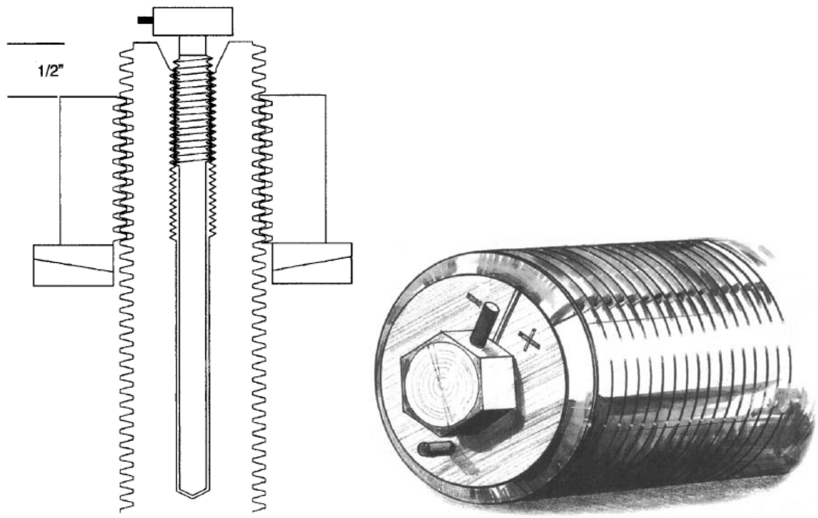


Figure 8.10 Example of the MagBold® is a device used to monitor the amounted of bolt stretch

Rotabolt®
Tensioning a bolt with this device does not require a torque measuring instrument. Check the load by simply twisting the inner or outer "control caps" with your fingers. If the outer cap turns, the bolt has exceeded its upper design limit. If the inner cap turns, the bolt has lost its minimum designed preload. This device will not tell you how much preload is above or below its design level.

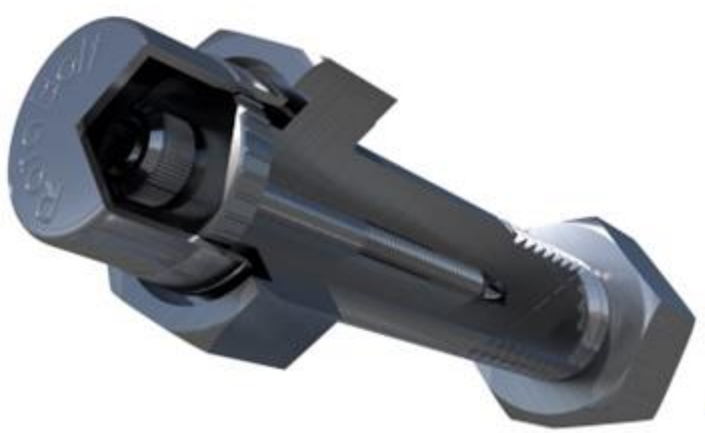


Figure 8.11 Picture of the Rotabolt®

8.5.2.4 Ultrasonic method
Ultrasonic bolt stretch measurement is the current "gold standard" for precise, reliable bolted joint make-up. It is widely used in nuclear power and process industries where high pressures, toxic substances, explosive gases are used.
Using ultrasonic technology to measure the bolt length in a relaxed state versus the bolt's elongation during and after tensioning will enable you to know the differential length. In some applications, you can compare this differential length to residual preload. To do this, you must record the bolt

measurements to provide a base reference for future measurements. These notes must contain a permanent record of the initial acoustic length of each anchor bolt that is tightened and its location. By numbering and marking each bolt, you will know the one to which you are later returning. If you have kept such a log, you can return to the bolt at any time to:

- Remeasure its current length ultrasonically.
- Compare this reading to the initial length before it was tightened.
- Calculate the stress levels in the fastener regardless of how much time has occurred since initial tightening.

If you have not used ultrasonic technology for the initial tightening of the anchor bolt, you can measure the decrease in the overall length of a few anchor bolts as they are loosened. This decrease may give you some idea of the amount of residual preload that was in the bolt before it was loosened.

8.5.3 Tightening sequence

According to the "PIP (Process Industry Practices) STE05121 "Anchor Bolt Design", October 2003" [12],

The pretensioned anchors shall be tightened in two stages:

- First stage shall apply 50% of the full pretension load to all anchors
- Second stage shall apply full pretension loads to all anchors

8.5.4 Bolt relaxation & Re-tension of bolts

Relaxation is almost always a factor in bolt and bolted joint failures. Once a bolt loses its preload, see , Figure 8.12, the assembly can slip placing bending and shear loads on the bolt. Loose bolts will increase the vibrations and will also lead to a misalignment. Tight bolts are much less susceptible to fatigue.

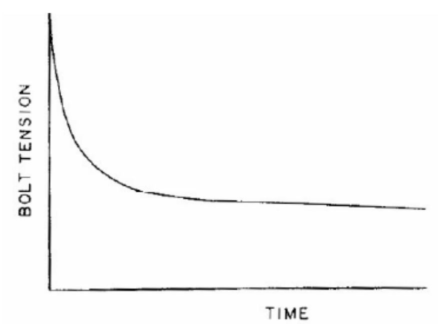


Figure 8.12 Bolt tension as a function of time [20]

Relaxation occurs in two steps [20]

1. Long term relaxation involving creep and temperature effects takes place in a matter of hours or days. Causes of long term relaxation are mainly temperature effects. Heating the epoxy by running the engine after bolt tightening under cold conditions can induce an immediate increase in compression of the epoxy and a loss in anchor bolt tension. Operators shall retighten the anchor bolts at operating temperature to correct for this loss in tension due to heating.
2. Short term relaxation usually happens in a manner of minutes. A bolt tightened at a temperature of 21 °C or below will immediately experience some loss in tension when heated up because of the temperature dependent Young's modulus of the epoxy grout.

From GMRC Technical Report TR-97-6 “Compressor Anchor Bolt Design”, December 1997[4] it is shown that for a 1200 mm long bolt with a grout layer of 114 mm and with an increase of temperature from 21 to 54 °C a loss in tension is 5%.This will be more for higher temperatures, shorter bolts and a larger grout thickness. For that reason it is strongly advised to retighten the bolts at operating temperature. Further causes of bolt relaxation are:

- Bolt twist.
- Stress relaxation during each torque pass, see Figure 8.13.
- Embedment of e.g. nut into assembly or washer.
- Plastic deformation of microscopic asperities.
- Plastic deformation of the washer.
- Poor thread engagement.
- Bending of the bolt.
- Non-perpendicular bolt heads or nut faces.
- Fillet interference with undersized hole.
- Oversized holes.
- Tightening speed & method of preloading (the slower tensioning the better).

3. According to the “PIP (Process Industry Practices) STE05121 “Anchor Bolt Design”, October 2003” [12], the value of the final bolt preload will approach 40% for short anchors to 80% for long anchors of the initial preload.

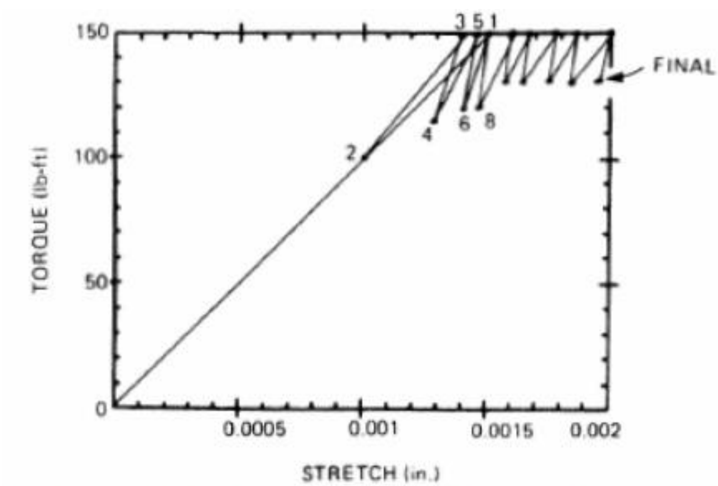


Figure 8.13 Bolt relaxation as a function of torque passes [20]

The retightening scheme according to “The Grouting Handbook, a Step-by-Step Guide to Heavy Equipment Grouting, by Don Harrison, 2000 (ISBN 0-88415-887-X, Gulf Publishing Company)” [10] is as follows:

- Tension and release the bolt two times. Perform final tensioning or preload on the third try. The amount of time between the tensioning will depend on the anchor bolt material, its elasticity, and temperature. This could range from a few minutes to many hours for the bolt to relax from the stretch imposed on it. Fight relaxation by retightening bolts after 48 hours of machinery operation.
- Check the anchor bolt for proper tension and make any necessary adjustments seven days after the equipment has been placed in service.
- Thirty days after the initial tensioning, re-check the anchor bolt for proper tension and make adjustments with the equipment at operating temperature.

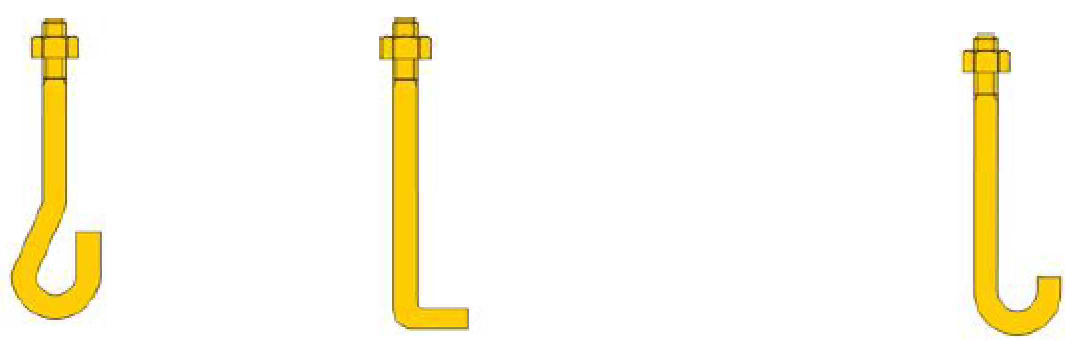
– Six months after initial tensioning, check the anchor bolts for proper tension and make adjustments.
– Check the anchor bolts for proper tension every six months thereafter and make adjustments if necessary. The anchor bolt is not loosened for this or any other tension checks unless it is grossly over-tensioned. If the bolt is over-tensioned, loosen it only enough to return it to the required or designed preload. Never completely loosen and then re-tension an anchor bolt unless it is at ambient temperature. This will ensure that the bolt will be at the deign preload at its operating temperature.

The "PIP (Process Industry Practices) STE05121 "Anchor Bolt Design", October 2003" [12], refers to the ACI 355.1R section 3.2.2 and the proposed retightening scheme is as follows:
– Retensioning the anchors about one week after initial tensioning can reduce the loss of preload. The reduction of tension can be reduced by about 30% by retensioning.

8.6 Bolt types

8.6.1 Introduction

There is a wide variety of anchor bolt designs available but only a limited number of them are applied and suitable for dynamically loaded equipment such as reciprocating compressors. Several types of anchor bolts have been used in the past such as Form A, J-type and L-type bolts as shown in Figure 8.14.
However, due to the increasing size and rating of compressors, different types and high strength materials are applied nowadays such as plate type bolts, see Figure 8.15 and 2-piece & canister bolt type supports as shown in Figure 8.16. In this chapter the different types will be discussed more into detail.



Form A bolt L-type bolt J-type bolt

Figure 8.14 "Older" A-type, L-type and J-type bolts

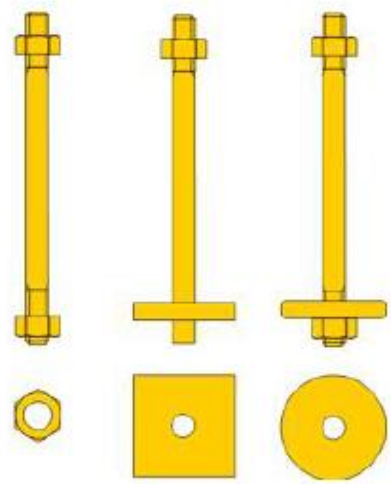


Figure 8.15 Different plate type bolts as commonly applied nowadays

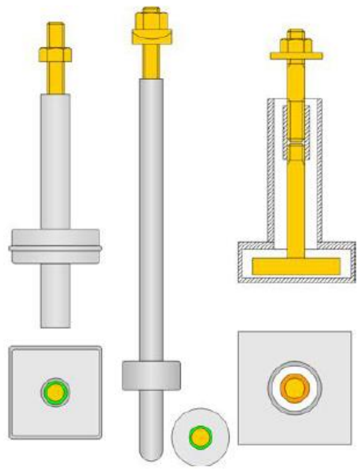


Figure 8.16 Different two piece & canister bolts

Figure 8.17 Typical hammer type bolt [47]

8.6.2 *Form A bolt (stone bolt) according to DIN 529 [37]*

The Form A (stone) bolt has been successfully applied for many decades by several compressor manufacturers. The dimensions are shown in Figure 8.18

These bolts are available in different lengths, ranging from 160-2000 mm. The most commonly applied material was according to AISI A1035 which is equivalent to C35N having mechanical properties comparable with Grade 5.6 (yield strength from 300 MPa).

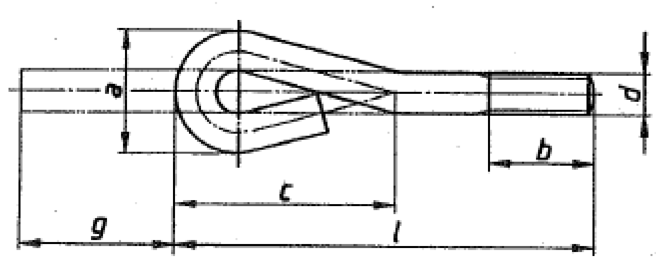
A full scale test was conducted by a compressor OEM on this type of anchor bolt in concrete in order to determine the required bolt length after requests from clients to reduce the overall length and therewith the depth of the bolt pockets. With strain gauges installed at several locations along the length of these bolts the effect of bond strength and friction was measured and the required length determined. The bolts were finally overloaded until failure. As expected and confirmed by these tests, failure occurred in the bolt thread below the nut and not at the bolt termination.

There are no specific calculation methods available in codes and standards for preloaded anchor bolts of this type. The experience from the OEM who conducted the tests, has shown that within the application limits for a preload of 50% of the materials yield strength for Grade 5.6 material, the performance of these bolts in gas engine and compressor applications has been proven.

However, the increasing size and rating of compressors requires increased preload of the compressor anchor bolts and in order to limit the required size of the bolts the bolt capacity can be easily increased by selecting a stronger material such as for example ASTM A193 B7 (724 MPa minimum yield strength) instead of Grade 5.6. The effect of an increased load on the now commonly applied bolts with DIN 529 Form A-type anchor bolt termination is however unknown and loads may already be close to the limits for the current Grade 5.6 material.

Another point to be considered is that for the creation of the Form A termination the material is heated and then formed and it may be difficult to maintain the mechanical properties in accordance with ASTM A193 B7 when anchor bolts of this material are produced by this method. For these reasons alternative anchor bolts must be applied, such as plate type bolts or a two-piece canister bolts, which allow for easy calculation and remain of simple and cost effective design.

Form A



Thread size, d	M8	M10	M12	M16	M20	M24	M30	M36	M42	M48	M56	M64	M72*6
a + / -3	24	30	36	48	60	75	95	115	135	155	180	200	240
C + / -5	45	55	65	85	105	125	155	190	220	250	290	335	370
g	30	38	45	60	75	90	115	135	155	180	210	235	260

Figure 8.18 Dimensions of A-type bolts

8.6.3 *L-type bolts and J-type bolts*

EN 1993 Eurocode 3 “Design of Steel Structures” [26] states that when bolts are provided with a hook the anchorage length shall be such as to prevent bond failure before yielding of the bolt and this type shall not be used for bolts with a yield strength higher than 300 MPa. When these anchor bolts are provided with a washer plate or other load distributing device the force shall be transferred through this device and no account shall be taken of the contribution of the bond. See sketches in Figure 8.19 according to the Eurocode 3.
These bolts are not recommended to use for reciprocating compressor systems.

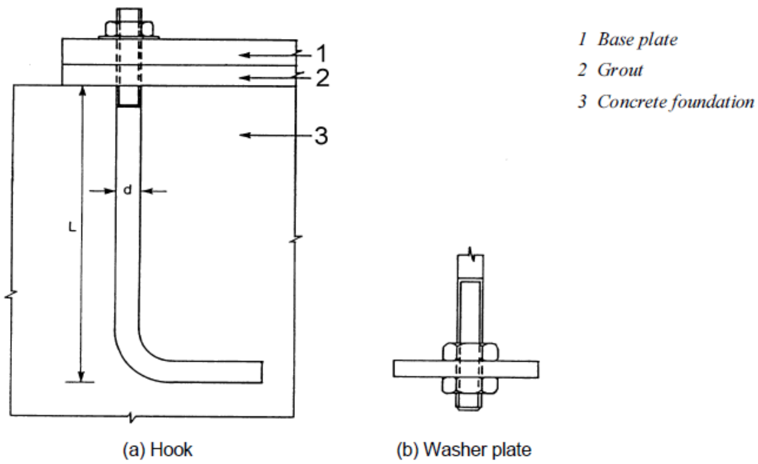


Figure 8.19 J-type bolts

8.6.4 *Plate type bolts with terminations*

A significant amount of research material and useful information on plate type bolts can be found in the following literature:

[1] GMRC Technical Report TR-97-2 “Foundation Guidelines”, January1997
[4] GMRC Technical Report TR-97-6 “Compressor Anchor Bolt Design”, December 1997
[14] Paper James A. Kully ITW Polymer Technologies, “Best Practices in Compressor Mounting, 7th EFRC Conference Florence Italy, 2010

Some examples of plate type termination bolts are shown in Figure 8.20.

The effect of the bolt termination point has been thoroughly investigated by the GMRC [4]. According to this survey anchors without terminations shall not be used. Relying on bond strength alone as proposed by some is not recommended for installations for which long term reliability is required.
Liquids used for cleaning operations, spilled liquids or oil leakage can over time affect the bond between the grout and anchor bolt and reduce the capacity of the anchor bolt to maintain its preload. Aging of the grout material, corrosion and environmental aspects are additional reasons why anchors with terminations have technical preference.

Terminations shall be symmetric and of adequate but not excessive in size in order to develop a symmetrical cone of compression in the concrete from bolt preload. Plate terminations shall be symmetrical and small. Larger terminations reduce local tensile stress in the concrete but move the location of high tensile stress further from the bolt centreline closer to the outer surface of the concrete block. The simplest design would be a nut termination and calculations have been performed for both nut and plate termination. In chapter 8.6.4.1 it will be shown that a plate termination instead of a nut meets the requirements.

A summary of the reported findings of the research project carried by the GMRC [4] is as follows:

- High tensile stress, caused by the required bolt preload, tends to induce cracking in the concrete around the bolt termination point.
- These tensile stresses in the concrete near the bolt termination attenuate rapidly with distance above the termination. They also attenuate rapidly with horizontal distance from the termination.
- A 1.5 bolt diameter thick termination plate beneficially reduces tensile stresses in the concrete for a relatively small termination diameter.
- At the same time, increasing termination plate diameter pushes the location of high tensile stresses further from the bolt centreline, potentially joining with other sources of tensile stress, and moving them closer to the outer surface of the concrete block; hence, there exists a trade off on termination plate diameter.
- Reinforcement density does not significantly influence the tendency for cracks to occur at the termination point.

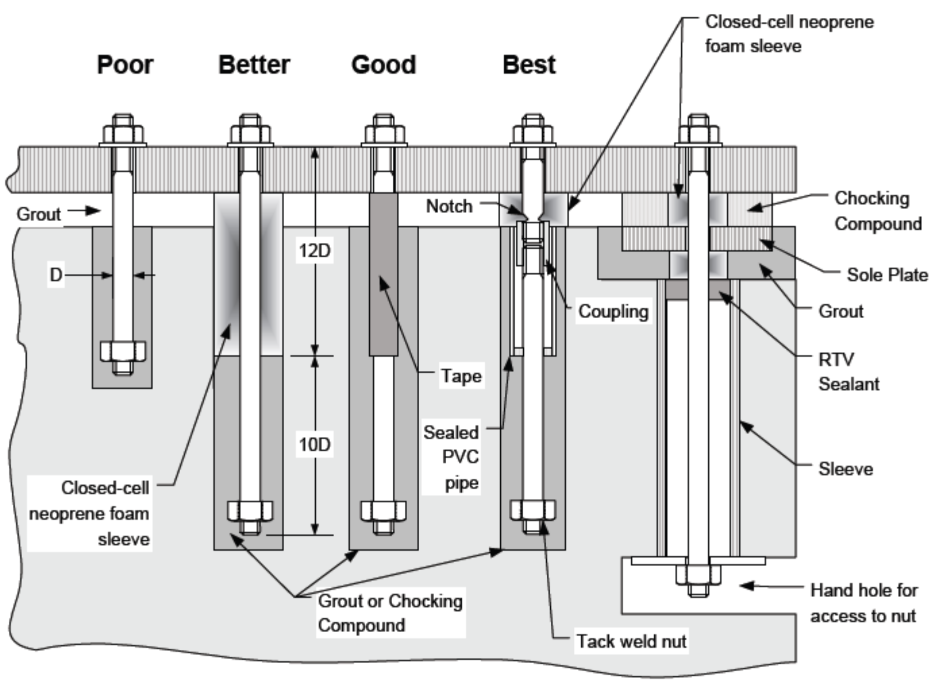


Figure 8.20 Different plate type bolts with terminations acc. to ITW Technical Bulletin #660 A

Note: It shall be noted that information supplied by grout &anchor bolt suppliers is sometimes biased towards promotion of their own products and does not always provide accurate and correct data in comparisons.

8.6.4.1 *Calculation of the termination point diameter*

In Appendix C a summary is given how to calculate the diameter of the termination point if mounted in cement grout and epoxy grout Chock fast red.

According to this calculation and the findings of the GRMC research project the following values apply:

- minimum termination diameter mounted in cement grout: 3.5 times the bolt diameter;
- minimum termination diameter mounted in chock fast red epoxy grout: 3 times the bolt diameter;
- termination point thickness: 1.3- 1.5 times the bolt diameter.

8.6.5 *Canister bolts*

The "canister bolt" as shown in Figure 5-1, has value in repair situations where the anchor bolts must be replaced, but the concrete will not be removed to the point where the bolt shall terminate. A core drilled hole, wide enough to accommodate the canister enables this configuration to be installed and epoxied in place. The bolt, attached to the canister at the bottom, uses the canister as a sleeve, and develops tension by stretching this free length between the point of connection to the canister and the compressor frame.

This configuration can serve as an anchor bolt, or as a supplementary post-tensioning bolt which can place areas of concrete, such as a cracked region in compression and add integrity. Its design enables the top of the bolt to be temporarily lowered to the top of the block.

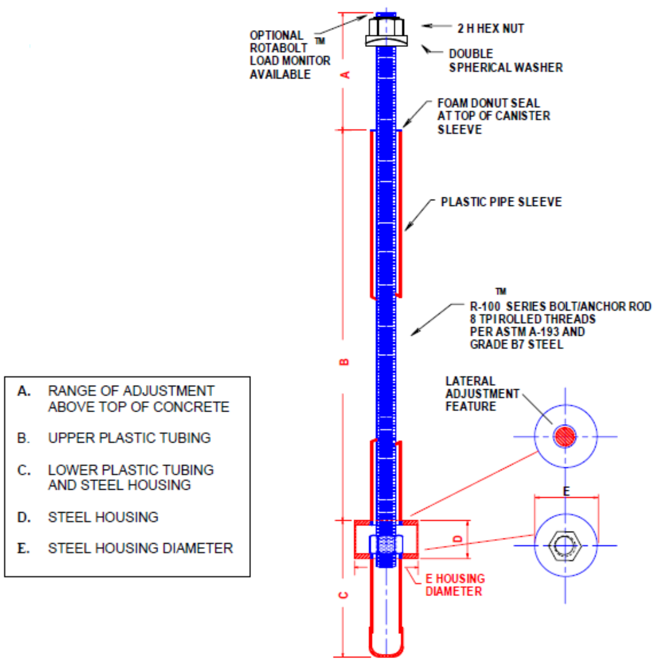


Figure 8.21 Schematic of Canister Bolt (Courtesy Robert L. Rowan)

8.6.6 *Hammer type bolts[47]*

Hammer bolt anchors, as shown in Figure 8.17, are used together with pre-installed anchor sleeves. The sleeves are held in place by the concrete but left empty (no concrete inside the sleeves). A hammer bolt anchor can finally be inserted through the slot hole of the anchor sleeve's baseplate. By turning the anchor bolt by 90°, it stays engaged in this position and preload can be applied on the bolt. The advantages of hammer bolt anchors are:

- tolerance against angular bolt misalignment
- possibility to exchange bolts later (although this is not normally required)

8.7 Crosshead guide support bolts

The cylinders and crosshead guides are cantilevered from the compressor frame.
It strongly depends on the machine type and compressor manufacturer or packager how these loads will be transferred to the supporting structure: either by outboard or inboard cylinder supports, crosshead guide (CHG) supports or by the frame.
Several compressor OEM's have a standardised crosshead guide support and this section discusses some important items w.r.t. to the bolts of these supports.
These CHG supports must themselves be appropriately mounted with direct line structural skid support to the block or, in the case of a block-mounted compressor, directly to the block. The bolts shall be engineered anchor bolts, and well-aligned mounting plates or chocks, with all metal-to-metal interfaces machined and free of rust, coating, dirt, oil, or paint shall be applied.
This area of the support structure needs to be carefully engineered and carefully installed to manage the weight and associated dynamic loads.
The stiffest crosshead guide supports are not always implemented and sometimes are not fully possible due to various reasons. In these cases, the potential that heavy pipeline cylinders and the added flexibility may lower some associated mechanical natural frequencies too close to fundamental excitation frequencies. This shall be reviewed carefully, and countermeasures planned and implemented, if necessary.
The stretching or compressive actions in response to the net cylinder forces acting inwards or outwards occur in part in the crosshead guide. With stiff, short, crosshead guide supports, this stretching motion is seen at the mounting of the crosshead guide support and most of the loads will be transferred to the CHG bolts.
If the CHG support is more flexible or not present than a part of the load or the complete load will be transferred to the frame anchor bolts.
For that reason it is important to ensure that forces and stresses set up as a result of the CHG support can be accommodated by the mounting and its support structure. Sometimes it can be decided to install a sliding CHG support for that reason.
It shall also be investigated in the concrete stress analysis if the concrete is able to carry the different loads. These CHG locations tend to be near the outer edge of the central block supporting the compressor. This may be particularly important in block-mounted applications where the crosshead guide support is mounted on concrete with a downwards vertical surface just outboard of the mount. There is a limited volume of concrete outboard of the crosshead guide support due to the fact that the width of this concrete is constrained by the point on the discharge bottles horizontally closest to the compressor.

The concrete shall withstand the loads transmitted to the concrete in the region of the anchor bolts for these mounts. This subject must be addressed in the concrete stress and strength analysis, see also discussion on minimum edge distance in chapter 9.

At this moment there is no adequate standard design procedure available for the crosshead guide anchor bolts. For fatigue, one approach could be to assume that the drive torque variation as summarised in chapter 4.3.5, are transferred via these bolts to the foundation, disregarding load sharing with the frame anchor bolts.
For static or quasi static load one could consider the thermal forces from the vertical thermal expansion of the discharge pulsation dampener and cylinder and nozzle load limits used for design.

8.8 Bolt length

8.8.1 Introduction

One very important length of the anchor bolt is the free length, which is the length of the bolt which is not bonded to the concrete or grout.
The free length is necessary to permit the proper elongation of the anchor bolt during the tightening procedure. This is necessary to decrease the cyclic stress in the bolts which is discussed in section 10. The free length will also provide clearance to reduce the bending stress that will be imposed on the bolt e.g. by expansion of the compressor frame, see also chapter 8.14. and Appendix E.
The free length is achieved by wrapping the free length of the bolt with tape or by covering it with pipe insulation foam.

Another important length is the embedment length which is defined in this document as the length which is encapsulated by the concrete/grout. The different lengths are indicated in Figure 8.22.

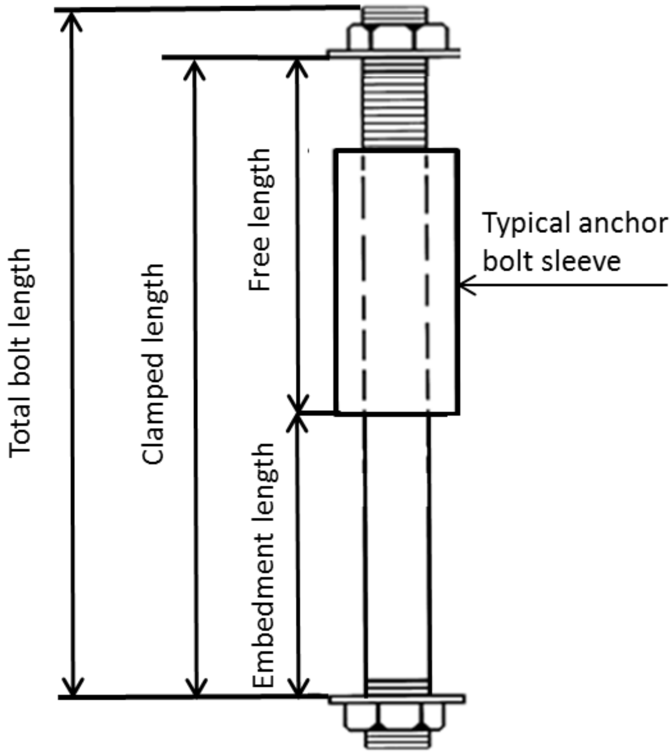


Figure 8.22 Definition of different anchor bolt length

The advantages of longer bolts have been investigated by the GMRC and have been summarised in the GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997[1] and are as follows:

1. Lengthening anchor bolts increases their tolerance to creep of any polymeric materials in the machine mounting. Even with steel chocks, current installation practice for new or repaired foundations always includes epoxy grout, so the potential for creep always exists. With creep - sensitive components (chocks, grout) localized near the top of the foundation block, doubling the anchor bolt length cuts in half the loss of bolt preload, which will occur as a result of polymer creep.
2. Lengthening the anchor bolts reduces the dynamic stresses in the concrete near the bolt termination. Horizontal and vertical dynamic loads act at the top of the foundation and cause high localized time varying stresses near the point of application. Well down in the foundation, such dynamic stresses are minimized. The anchor bolt termination can cause high tensile stress and cracking. Because cracks subject to dynamic loads tend to grow, moving the termination point far from the dynamic stress increases the chance of long term integrity.
3. Lengthening anchor bolts increases the separation of bolt termination from sources of oil. The presence of oil at any point in a crack leads to migration of oil along the crack. Oil can help grow the crack and weaken the surrounding concrete. Since cracking at the termination is hard to avoid, maximizing the separation of oil sources and the bolt termination helps ensure long term integrity of the installation.
4. Carried to the ultimate, maximizing anchor bolt length puts the termination in the mat on which the foundation is mounted, rather than in the foundation block itself. There exists a growing practice to put the anchor bolt termination on new and even repaired installations below the horizontal mid-plane of the mat. Beyond length maximization, this means that any cracks induced by tensile stresses at the termination cannot grow outwards to the side of

the block, where they are unsightly, cause concern, and may reduce integrity of the installation. In old installations penetrating the mat may encounter old reinforcement , but the overall improvements in integrity shall offset any such local loss of reinforcement. Practitioners of this approach to anchor bolt installation claim it is the easier than terminating the bolt in the poured concrete of the block itself.

5. Lengthening the bolt also beneficially reduces the ratio of chock and grout compression to anchor bolt extension for a given preload reducing this ratio reduces sensitivity to creep.
6. Decreasing Young's Modulus of the epoxy material (corresponding to increasing compliance) or thickening the foundation grout layer increases the ratio of chock and grout compression to anchor bolt extension, increases sensitivity to creep and thereby increases the desirability of a long anchor bolt.
7. Anchor bolts at least 1220 mm (48") long coupled with a grout layer of approximately 115 mm (4.5") thick or less are needed to keep creep loss in bolt tension below 5% in a year; even longer anchor bolts are desirable to minimize grout creep effects.

Some state that there is no relation between bolt diameter and required length and to some extent this is a valid remark as the bolt elongation is stress and length related and for a fixed preload stress level (70% of yield strength as recommended in this report), the elongation length shall be the same for all bolt diameters. Length is of more relevance when bond strength between bolt and grout is taken into consideration. In this case the load capability of the bolt is directly proportional with length and for the same bolt stress level the required length to diameter ratio is more or less a fixed value. For the same compliance ratio (for an explanation see chapter 10) it is often required that for larger diameter bolts the elongation length has to increase and this also suggests that a constant length to diameter ratio is a valid requirement as long as a there is also an absolute lower length limit.

Bolts must be allowed some free stretch at the top of the concrete to ensure a minimum amount of bolt elongation in order to maintain preload over time and to avoid local cracks in the grout and top of the concrete during tightening. The most commonly used anchor bolts mainly relies on bond strength with the termination providing added safety.

8.8.2 Anchor bolt sleeves

According to the API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 , [11] anchor bolt shall be installed using sleeves, unless otherwise specified by the equipment user. The use of anchor bolt sleeves is not primarily intended to permit easy bending of the bolt to aid in equipment alignment, but to allow the elongation to take place.

The inner diameter of the sleeves shall be at least twice the diameter of the anchor bolt and the length shall be the greater of 150 mm or sufficient length to permit adequate elongation of the anchor bolt during tightening. As shown in the next section the minimum recommended free length shall be 12 times the bolt diameter. The sleeve must be filled with slot mouldable material.

8.8.3 Total bolt length

There are no formal requirements available for the total bolt lengths and in many guidelines it is only mentioned that the bolt length which is embed in the grout shall be adequate to resists the equipment forces and torques. This means that bolt pull out or pull out of the grout pocket shall be avoided all the time.

Some papers and standards mention guide values ranging from a minimum of 12-17 times the bolt diameter, 20" (508 mm), 48" (1219 mm), 10 times the loaded thickness of the grout layer.

According to the AISI Steel Design Guide Series, "Column Base Plates, Third printing: October 2003[13]:

- minimum 12 times the bolt diameter for a bolt material ASTM A307, A36
- minimum 17 times the bolt diameter for a bolt material ASTM A325, A449

Remark: these lengths are adopted from the "Code Requirements for Nuclear Safety Related, Concrete Structures (ACI 349-01)" [32]

According to the GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997[1]

- anchor bolt length shall be maximised, ideally to halfway in to the mat, which is the lower part of the foundation supporting the main block.

According to the PIP (Process Industry Practices) STE05121 "Anchor Bolt Design", October 2003[12]

- The PIP refers to the ASCE Anchor bolt report which recommends a minimum length of 24 times the bolt diameter

According to Paper James A. Kully ITW Polymer Technologies, "Best Practices in Compressor Mounting, 7th EFRC Conference Florence Italy, 2010[14]

- minimum anchor bolt length of 1.2 m shall be used.

According to The Grouting Handbook, a Step-by-Step Guide to Heavy Equipment Grouting, by Don Harrison, 2000 (ISBN 0-88415-887-X, Gulf Publishing Company)[10]:

- minimum 20 times the bolt diameter .

8.8.4 Free length

According to the API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 [11]

- The greater of 150 mm or sufficient length to permit adequate elongation of the anchor bolt during tightening.

Remark:
The total anchor bolt length shall be such that they project a minimum of 2 threads above the fully engaged nuts.

According to The Grouting Handbook, a Step-by-Step Guide to Heavy Equipment Grouting, by Don Harrison, 2000 (ISBN 0-88415-887-X, Gulf Publishing Company)[10]:

- Minimum 12 times the bolt diameter.

According to Paper James A. Kully ITW Polymer Technologies, "Best Practices in Compressor Mounting, 7th EFRC Conference Florence Italy, 2010[14]

- minimum 12 times the bolt diameter or 40% to 50% of the total bolt length to free stretch

8.8.5 *Clamped length*

The clamped length is equal to the embedment length+ free length. Most of the standards and guidelines do not mention the clamped length. However, the "GMRC Technical Report TR-97-6 "Compressor Anchor Bolt Design", December 1997" [4] gives the following value:

– the research project has shown that it confirms the desirability of thin grout layers and long anchor bolts. It shows that for the specific parameters of this analysis a clamped length of at least 1219 mm (48") coupled with a grout layer no thicker than 4.5 inches are needed to keep the creep loss in bolt tension below 5 percent at 43°C.

It shall be noted that the value mentioned above of 48" is based on a grout layer of 114 mm (4.5") and 5% loss of preload per year. For much thinner grout layers, e.g. 50 mm maximum which are applied commonly nowadays for new systems, a clamped length of approximately 24 times the bolt diameter would fulfil the same criteria. The length of 1219 mm is for that reason only recommended for grout layers up to approximately 114 mm.

8.8.6 *Summary of embedment, free, clamped and total bolt length*

Nowadays a commonly praxis is to apply the lengths as summarised in GMRC Technical Report TR-97-6 "Compressor Anchor Bolt Design", December 1997[4], see also Table 8.4.

a) Clamped length:
   For epoxy grout layers of maximum 50 mm:
   - 500 mm for bolts with a diameter <1"
   - 24 times the bolt diameter for bolts with a diameter ≥ 1"

   For epoxy grout layers larger than 50 mm:
   - 500 mm for bolts with a diameter <1"
   - 24 times the bolt diameter multiplied with: grout layer/50 [mm] for bolts with a diameter ≥ 1"
b) Free length (taped or sleeved):
   For epoxy grout layers of maximum 50 mm:
   - 250 mm for bolts with a diameter <1"
   - 12 times the bolt diameter for bolts with a diameter ≥ 1"

   For epoxy grout layers larger than 50 mm:
   - 250 mm for bolts with a diameter <1"
   - 12 times the bolt diameter multiplied with: grout layer/50 [mm] for bolts with a diameter ≥ 1"
c) Total length:
   Clamped length + nut thickness + washer thickness + 2 threads above nuts

Remark: For practical use some tolerance on these limits is allowed.

Table 8.4 Minimum clamped and free bolt length for epoxy grout layers ≤50 mm and larger > 50 mm

Bolt size	d [mm]	Epoxy Grout thickness ≤ 50 mm		Epoxy Grout thickness > 50 mm	
		Clamped length [mm]	Free length [mm]	Clamped length [mm]	Free length [mm]
1/2 – 13	12.70	500	250	500	250
5/8 – 11	15.88	500	250	500	250
¾ - 10	19.05	500	250	500	250
1 – 8	25.40	610	305	610*Gt/50	305*Gt/50
1 ¼ - 8	31.75	762	381	762*Gt/50	381*Gt/50
1 ½ -8	38.10	914	457	914*Gt/50	457*Gt/50
1 ¾ -8	44.45	1068	534	1068*Gt/50	534*Gt/50
2 – 8	50.80	1220	610	1220*Gt/50	610*Gt/50
2 ½ - 8	63.50	1524	762	1524*Gt/50	762*Gt/50

*Gt= grout layer in [mm]

8.9 Thread lubrication

Threads and nut bearing faces shall be adequately oiled/greased. Anti-seize lubricants such as Molykote shall not be used unless explicitly mentioned on the applicable drawings. When for whatever reason stainless steel anchor bolts must be used make sure that a suitable thread lubricant is used in order to prevent galling during tightening.

8.10 Nuts

Hex Nuts
Conventional hex nuts are widely used in compressor installations. ASTM Specification A-194 addresses nuts for high strength bolts. They require care to achieve the needed tension through torque measurement. Investigations have shown that wide variability in tension can occur with nuts tightened to the same torque. Lubrication of the threads helps ensure uniformity. Use of one of the tension monitoring bolts on the market can also help overcome this problem. Ultrasonic bolt stretch monitoring can also provide an independent check on preload. Hydraulic tensioners can also assist.

Super Nuts
A device which helps achieve uniformity of tensioning is the Multi Jack bolt Tensioner (MJT), illustrated in Figure 8.7. Instead of a single hex nut, a series of jack bolts tightened with Allen wrenches to a relatively low and controllable torque, can provide the same tension as a much more highly torqued hex nut. This patented device is increasing in popularity. It requires careful sequencing in the processes of both tightening and loosening to avoid overload and difficulty of further adjustment.
More explanation on tension monitoring bolts, hydraulic tensioners and super nuts is given in the chapter on pretension methods, see chapter 8.5.2.

According to the API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 [11]

- Full size, heavy hex conforming ANSI B18.2.2
- When bolts are hydraulically tensioned fully machined cylindrical nuts will be required as these have negligible face run-out in comparison with standard quality heavy hex nuts.

According to the GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997*[1]*

- ASTM A-194

According to the
GMRC Course "Foundation Design & Repair, The Bolted Joint", May 12-14, 2009

- Nuts shall satisfy ASTM spec A-194, Grade B7.

According to the PIP (Process Industry Practices) STE05121 "Anchor Bolt Design", October 2003[12]

- no reference is made

According to an OEM

- ASTM A-194 2H of the hex type series according to ANSI B18.2.2.
- Fully machined special (cylindrical) nuts may be required for large diameter high strength bolts which have to preloaded by means of hydraulic jack. These nuts have a diameter equal to the "width across flats" (diagonal) of hex nuts.

According to the Grouting handbook [10]:

- Hardened nuts shall be used.

Remark:
Fully machined special "Super" nuts may be required for large diameter high strength bolts which have to preloaded by means of a hydraulic jack. These nuts have a diameter equal to the "width across flats" (diagonal) of hex nuts.

8.11 Termination plates

A termination having the following diameter meets the bearing load requirements for bolt diameters up to and including 2.5". This is according to the GMRC guidelines and also approved by calculations as shown in Appendix C as follows:

- mounted in cement grout: minimum 3.5 times the bolt diameter
- mounted in epoxy grout: 3 times the bolt diameter

The recommended termination plate thickness is as follows:

- 1.35-1.5 times the bolt diameter

Remark:
The GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013 [7], recommends a 3D reinforcement cage around the bolt termination point as shown in Figure 8.23.
However, a research project carried out by the GMRC, see GMRC Technical Report TR-97-6 “Compressor Anchor Bolt Design”, December 1997[4], has shown that reinforcement density does not significantly influence the tendency for cracks to occur at the termination point.

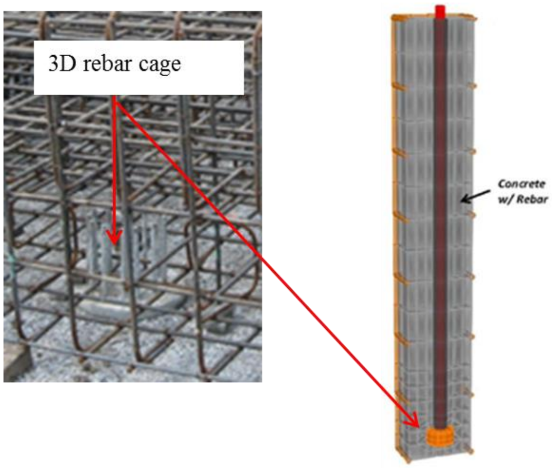


Figure 8.23 Example of a 3D reinforcement cage around the termination point location according to [4]

8.12 Washers

According to Grouting handbook [10]:

- Spherically two-piece seated washers are recommended to use, see Figure 8.24. This device compensates for misalignment of the anchor bolt up to about 7 degrees in its perpendicular direction plane and allows for full contact of the nut and washer against the bolted surface.

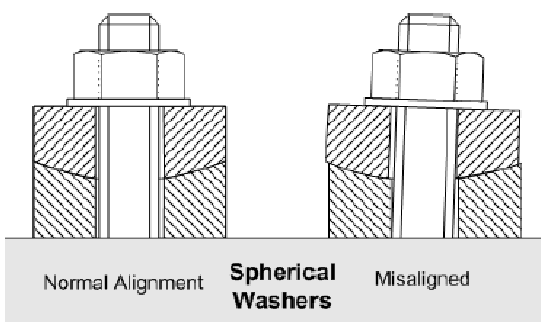


Figure 8.24 Spherical washers (ITW Kully)

According to the API Recommended Practice 686 “Recommended Practices for Machinery Installation and Installation Design”, PIP REIE 686, Second Edition 2009 [11]

- Washers shall be in accordance to ANSI B18.22.1

According to the GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997*[1]*

- Relative axial motion between frame and block during installation and operation will cause some small change in angularity between anchor bolt and frame surface. Imperfections and tolerances inevitably cause some lack of squareness. A self-aligning washer provides benefits at this location and does not appear to have any disadvantages. A common configuration involves two pieces with a spherical interface, as illustrated in Figure 8.24

According to the
GMRC Course "Foundation Design & Repair, The Bolted Joint", May 12-14, 2009*[20]*

- Hardened steel spherical washers shall be used to compensate for any
- lack of perpendicularity between the bolt and frame.

According to the PIP (Process Industry Practices) STE05121 "Anchor Bolt Design", October 2003[12]

- If anchors are pretensioned: hardened washer according to the ASTM F436.The recommended base plate hole diameter and the outside diameter is shown in
- Table 8.5.

Table 8.5 Recommended base plate hole and washer size according to PIP (Process Industry Practices) STE05121 "Anchor Bolt Design", October 2003 [12]

Anchor Bolt Dia. (Inches)	PIP-Recommended Base Plate Hole Diameter*	Outside Washer Dia. (Inches)
1/2	13/16	1-5/8
5/8	15/16	1-3/4
3/4	1-1/16	1-7/8
7/8	1-3/16	2-1/4
1	1-1/2	2 5/8
1-1/4	1-3/4	2-7/8
1-1/2	2	3-1/8
1-3/4	2-1/4	3-3/4
2	3	4-1/2
2-1/4	3-1/4	4-3/4
2-1/2	3-1/2	5
2-3/4	3-3/4	5-1/4
3-1/2	4	5-1/2

*Base plate hole size recommendations from the table are based on AISI ASD Manual, 9th edition. Hole size recommendations in the current AISI LRFD manual 3rd edition have been revised and are larger.

8.13 Coating

API RP 686 states that unless otherwise specified by the equipment user anchor bolts shall be hot dip galvanised in accordance with ASTM A153.
PIP STE05121 indicates that galvanizing is a common option for low strength materials such as ASTM A307, ASTM A36 and ASTM F1554 grade 36 and that stainless steel anchors are an expensive option.

However, OEM's experience has shown that galvanising is not required for compressor foundation bolts. When anchor bolts are correctly installed, grouted and maintained there is no need for galvanising. Not galvanising also removes the added, although small, risk of hydrogen embrittlement in case of high strength steels and possible difficulties with thread clearance.

VDI 2230 2003 states that in case of hot galvanised bolts the fatigue strength is reduced by approximately 20%.

Treatment of the nut and anchor bolt section projecting above the concrete with a suitable oil/grease having rust preventative properties, thus providing corrosion protection, is recommended.

8.14 Bending of the anchor bolts caused by thermal expansion of the compressor

Thermal expansion of compressor frames resulting from the normal operating temperature of the lube oil cannot and shall not be constrained by anchor bolts as the resulting forces and bolt stresses would become excessive. The shear force acting on a bolt depends on the diametrical bolt clearance in combination with the free bolt length and the coefficient of friction. With adequate radial clearance, defined as Δx in Figure 8.25, the maximum possible shear force is always limited by the preload times the maximum coefficient of friction at any of the interfaces of the clamped parts. In practice this coefficient of friction is unlikely to exceed a value of 0.25. The radial clearance can be calculated with the following equation which has been derived in Appendix E.

$$\Delta x = \frac{Fv \cdot l^3}{12 \cdot E \cdot J} \text{ (m)} \qquad (8.6)$$

In which:

- Δx= bolt deflection caused by the temperature (m)
- F_v= bolt preload (N)
- L = free anchor bolt length (m)
- E = bolt Young's modulus (N/m^2)
- F = friction between bolt nut and soleplate/grout/concrete

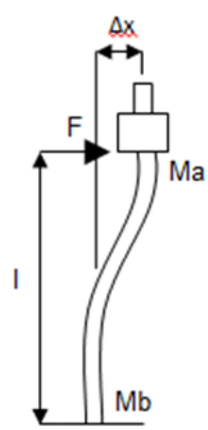


Figure 8.25 Radial clearance between bolt and concrete/grout

9 Concrete failure mechanisms

9.1 Introduction

If a bolt is loaded, both by the preload to achieve a friction force or by the dynamic loads e.g. pulsation forces, torque variations and unbalanced loads, a stress on it as well on the surrounding concrete will occur. The concrete is very sensitive to tensile stress and for that reason it is important to keep the stresses as much as possible in compression because it will crack if the tensile stress is too high.
Compressor anchor bolts are not intended to act in shear and do not directly transfer shear forces for that reason via the bolt shank on the concrete. The concrete failure mechanism caused by shear loads will not be discussed for that reason. The different failures which can occur as a result of a tension force are shown in Figure 9.1.

Civil engineering codes and standards typically only include non-preloaded externally loaded anchor bolts and not the preloaded anchor bolts used in machine and compressor applications where friction provides the primary mechanism for transferring the dominant horizontal forces from the compressor to the foundation. The effect of preload, the compression of the clamped parts, on the tensile and compressive stresses in the concrete is generally not considered in these codes and standards.
Machine foundations and their fastenings do not fall within the scope of the Eurocodes. However, where applicable, parts of these codes have been used in this report for guidance only.
For the requirements of fastenings EN 1992 Eurocode 2 “Design of Concrete Structures” [25] refers to Technical Specification “Design of Fastenings for Use in Concrete”. Parts from this specification that can be used for reference are CEN/TS 1992 Part 4.1 General and Part 4.2 Headed Fasteners [18].

Most civil engineering standards classify headed anchors, having a nut or plate termination, as cast-in fasteners instead of post-installed anchors. As discussed before, the anchor bolts used for reciprocating compressors shall be of the headed type and are in general post-installed with the anchor bolt pocket filled with epoxy grout material having a considerably higher (approximately a factor of 3) compressive strength than concrete in case of cast-in anchors. In the calculations as given in this report it is assumed that the bolts are cast-in e.g. the bolt pocket is filled with concrete, which is a worst-case consideration.
Required reinforcement near the anchor bolts are required and some guidance and recommendations are given where possible.
The different failure modes caused by tensile stresses and the requirements how to avoid them are discussed in the next sections.

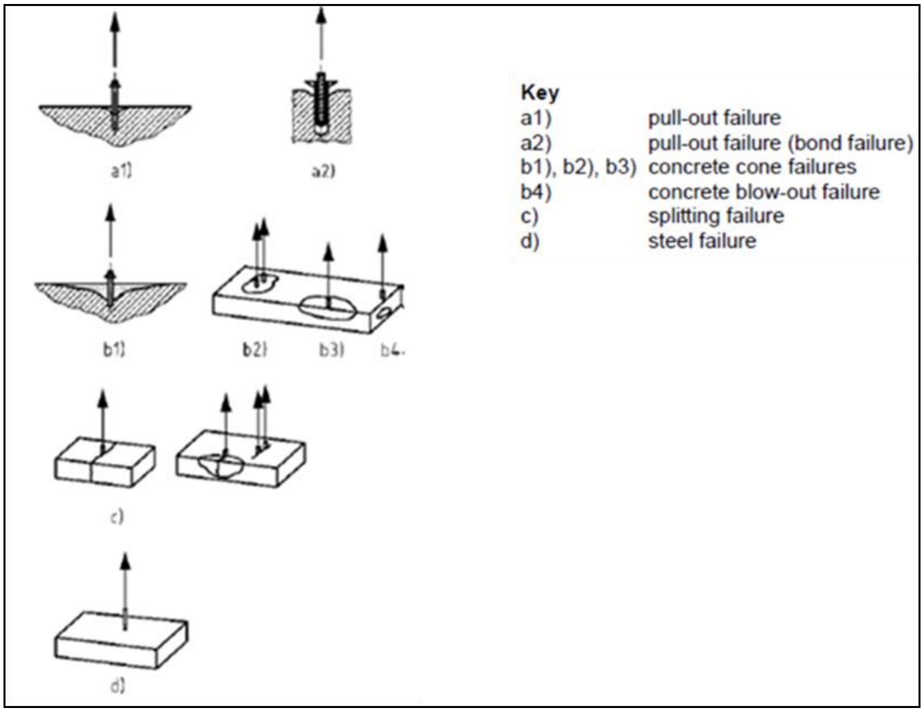


Figure 9.1 Different concrete failure modes for tension loads [NVN-CEN/TS 1992-4-1 "Design of fastenings for use in concrete- Part 4-1: General[15]

9.2 Anchor bolt pull out & bolt pocket size

9.2.1 Introduction

The bond strength between anchor bolt and grout is relatively high for epoxy grout but more important is the bond strength between the grout in the anchor bolt pocket and the surrounding concrete. In general this bond strength, depending on the load condition, exceeds either the concrete tensile strength or concrete shear strength. The tensile strength of concrete however is relatively low and for example EN 1992-1-1 Eurocode 2 [24] gives values for concrete with a compressive strength of 25 and 30 MPa and a tensile strength of respectively 1.8 and 2.0 MPa (5% fractile) up to 3.3 and 3.8 MPa (95% fractile).
For design one has to calculate with a partial safety factor for concrete of 1.5, thus further reducing these values.
The allowable shear strength in calculations is even lower than this and is in the range of 0.5 to 0.55 MPa, with an actual strength limit of around 0.8 to 0.9 MPa. There is some variation of limits in codes and standards for concrete structures but all values are low. This chapter will give rules for the calculation of the pocket size.

Anchor bolt pull out strength is the force required to pull a single bolt out of its foundation. The separation can occur between the cement or epoxy grout (left hand side picture in Figure 9.2) and the concrete foundation or it can occur between the anchor bolt and the cement or epoxy grout itself (right hand side picture of Figure 9.2). Anchor bolt pull out can also occur if the bolt is cracked.
The bond of the cement or epoxy grout to the concrete foundation is stronger than the bond of the concrete to itself. Typically, concrete will separate next to the bond line of the grout concrete. Therefore, the weakest link in the bond of the grout (cement or epoxy) to concrete is the concrete

itself. The force required to pull the concrete apart is called its shear strength and the minimum required pocket sizes, based on this bond strength, are summarized in chapter 9.2.2.1and 9.2.2.2 for respectively a square and cylindrical pocket.
It shall be noted that the calculations of the minimum required pocket sizes shall only be used as an indication. Besides that the load carrying capacity of the termination plate is not taken into account in the calculations which means that the calculations are based on the worst-case scenario.
The anchor bolt pull out, which occurs when the bond strength between bolt and grout is exceeded, is shown in the right hand picture of Figure 9.2 and is summarized in chapter 9.2.3.

Despite the fact that the several civil engineering rules and best practices, have been determined from standards which are not applicable for machine foundations (e.g. EN 1993 Eurocode 3 “Design of Steel Structures”, CEN/TS 1992 Part 4.1 General and Part 4.2 Headed fasteners), they have been applied for guidance in this chapter for the calculation of the pocket size.

The minimum required bolt pocket size to avoid pulling out the pocket together with the anchor bolt the concrete block is discussed in chapter 9.2.2.1 and 9.2.2.2 for respectively a square and cylindrical pocket.

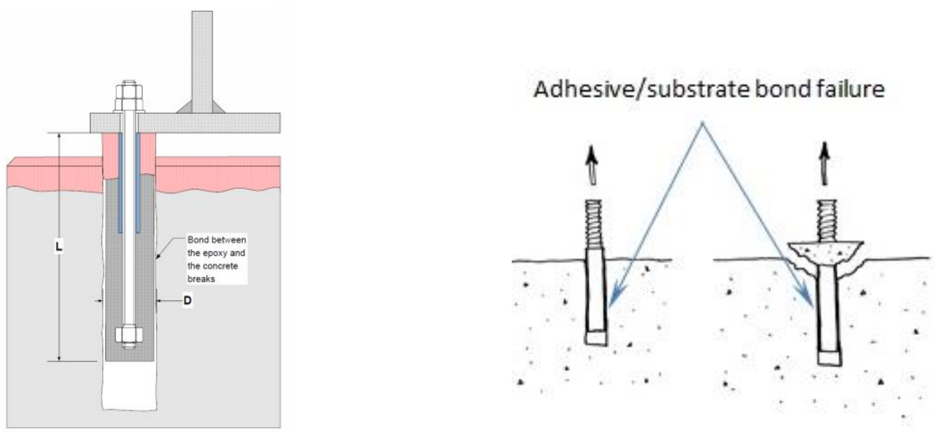


Figure 9.2 Examples of anchor bolt pull out

9.2.2 *Minimum required pocket size*

9.2.2.1 *Squared pocket*

For a square shape pocket the required length E of the sides to avoid anchor pull out can be calculated as follows:

$$F_v = 0.7 \cdot S_y \cdot A_s = 4 \cdot E \cdot L \cdot \tau_c \quad \text{(N)} \tag{9.1}$$

In which:

- F_v = preload tension (N)
- L = length of the pocket (mm)
- τ_c = the concrete shear strength (MPa)
- E = pocket size (mm)
- A_s = smallest bolt stress area (mm^2)
- S_y = bolt yield strength (MPa)

For an anchor bolt material ASTM A193 B7, the yield strength is 724 MPa. With a bolt preload of 70% of this yield strength, the embedment length and a concrete shear strength of 0.9 MPa, the minimum required pocket size is as follows:

For bolts with a diameter < 1”

$$E_{min} = \frac{0.7 \cdot S_y \cdot A_s}{4 \cdot (500) \cdot \tau_c} \text{ (mm)} \tag{9.2}$$

For bolts with a diameter ≥ 1”

$$E_{min} = \frac{0.7 \cdot 724 \cdot A_s}{4 \cdot (24 \cdot d) \cdot 0.9} \text{ (mm)} \tag{9.3}$$

In which:

d = bolt diameter (mm)

A_s = smallest bolt stress area (mm^2)

Remarks:

- If epoxy gout layers of > 50 mm are used the length L shall be multiplied with: grout layer thickness/50

Table 9.1 Minimum pocket size for a square pocket based on a preload of 70% of yield for an ASTM A193 B7 grade bolt material and a maximum grout layer thickness of 50 mm

	d	**Clamped bolt length L (rounded)**	**A_s**	**E_{min}**	**E_{min}/d**
Bolt size	**mm**	**mm**	**mm^2**	**mm**	**-**
1/2 – 13	12.70	500	93	26.2	2.06
5/8 – 11	15.88	500	148	41.7	2.63
¾ - 10	19.05	500	218	61.4	3.22
1 – 8	25.40	610	395	91.2	3.59
1 ¼ - 8	31.75	762	650	120	3.78
1 ½ -8	38.10	914	969	149.2	3.92
1 ¾ -8	44.45	1068	1351	178.2	4.01
2 – 8	50.80	1220	1796	207.4	4.08
2 ½ - 8	63.50	1524	2877	265.8	4.19

Minimum required square pocket size at the top of the pocket

The minimum required pocket size at the top of the pocket depends on the anchor bolt termination plate (for recommended values, see chapter 8.11), the required clearance for concrete tolerance, placing, filling and compacting of the grout between the pocket and termination. It is advised using square pockets which are slightly conical. A recommended value at the bottom of the pocket is E_r +25 mm.

Based on the termination plate diameter and a nominal radial clearance between the termination and pocket of 25 mm for filling and compacting of the grout and a concrete and bolt pocket position tolerance of 10 mm, the nominal pocket dimension E_r at the top shall be as follows:

A. Mounted in cement grout (termination plate diameter minimum 3.5 times the bolt diameter:
   – $3.5 \cdot d + 2 \cdot 25$ mm + 10 mm = E_r+ 25 mm (pocket size is E_r+25 mm at the bottom of pocket near termination plate)

   It follows that $E_r = 3.5 \cdot d + 35$ mm

B. Mounted in epoxy grout (termination plate diameter minimum 3 times the bolt diameter:
   – $3 \cdot d + 2 \cdot 25$ mm + 10 mm = E_r+ 25 mm (conical value)

   It follows that $E_r = 3 \cdot d + 35$ mm

The largest value of respectively equation (9.2) and A. (see above) for diameters < 1” and equation (9.3) and B. (see above) for diameters > 1”, gives the minimum required pocket value. The results are shown in Table 9.2.

Table 9.2 Required minimum pocket size at the top of the pocket for a square pocket based on a preload of 70% of yield for an ASTM A193 B7 grade bolt material

	d	**E_r** for cement grout	**E_r/d** for cement grout	**E_r** for epoxy grout	**E_r/d** for epoxy grout
Bolt size	**mm**	**mm**	**-**	**mm**	**-**
1/2 – 13	12.70	80	6.3	73	5.76
5/8 – 11	15.88	91	5.7	83	5.20
¾ - 10	19.05	102	5.4	92	4.84
1 – 8	25.40	124	4.9	111	4.38
1 ¼ - 8	31.75	146	3.5	130	4.10
1 ½ -8	38.10	169	4.6	149	3.92
1 ¾ -8	44.45	191	4.3	168	3.79
2 – 8	50.80	213	4.2	187	3.69
2 ½ - 8	63.50	257	4.0	266	3.55

*values are rounded

Remarks:

1. The use of a corrugated pipe or other forms that remain in the concrete block after concrete pouring is not recommended as it difficult to guarantee proper contact between these forms and the concrete foundation when taking into account shrinkage of concrete during concrete curing. Some companies however have used this method successfully.
2. Diamond core drilling of cylindrical pockets is also common practice. Holes shall preferably be roughened after drilling to ensure proper bonding between the grout and concrete with steel brushes or other means. The pocket must be cleaned and dried before grouting.

9.2.2.2 *Cylindrical pocket*

To avoid anchor bolt pull out for a cylindrical pocket, the minimum required pocket diameter D_p can be calculated as follows:

$$F_v = 0.7 \cdot S_y \cdot A_s = \pi \cdot Dp.L \cdot \tau_c (\mathrm{N}) \tag{9.4}$$

For bolts with a diameter < 1"

$$Dp = \frac{0.7 \cdot S_y \cdot A_s}{\pi \cdot 500 \cdot \tau_c} \ (\mathrm{mm}) \tag{9.5}$$

For bolts with a diameter ≥ 1"

$$Dp = \frac{0.7 \cdot S_y \cdot A_s}{\pi \cdot 24 \cdot d \cdot \tau_c} (\mathrm{mm}) \tag{9.6}$$

In which:

F_v = preload tension (N)
L = length of the pocket (mm)
τ_c = the concrete shear strength (MPa)
D_p = minimum required pocket diameter (mm)
A_s = smallest bolt stress area (mm^2)
S_y = bolt yield strength (MPa)
d = bolt diameter (mm)

Based on the anchor bolt termination plate (for recommended values, see chapter 8.11), the required clearance for concrete tolerance, placing, filling and compacting the grout between the pocket and termination, the minimum required pocket diameter is:

A. Mounted in cement grout (termination plate diameter minimum 3.5 times the bolt diameter :
   – $3.5 \cdot d + 2 \cdot 25$ mm + 10 mm =3.5 d+60 mm

B. Mounted in epoxy grout (termination plate diameter minimum 3 times the bolt diameter :
   – $3 \cdot d + 2 \cdot 25$ mm + 10 mm =3d+60 mm

The largest value to avoid anchor bolt pull out and the required mounting size is the largest value of the these two requirements. The minimum required diameters are summarized in Table 9.3.

Table 9.3 Minimum required pocket size diameter for a cylindrical pocket based on a preload of 70% of yield for an ASTM A193 B7 grade bolt material to avoid anchor bolt pull out and based on mounting requirements

Bolt size	Bolt diameter d	Cement grout			Epoxy grout		
		Based on bond strength	Based on mounting requirements	Advised	Based on bond strength	Based on mounting requirements	Advised
		D_p	D_p	D_p	D_p	D_p	D_p
	mm	mm	mm	mm	mm	mm	mm
1/2 – 13	12.70	26.2	105	105	26.2	98.1	98.1
5/8 – 11	15.88	41.7	116	116	41.7	107.6	108
¾ - 10	19.05	61.4	127	127	61.4	117.2	117
1 – 8	25.40	91.2	149	149	91.2	136.2	136
1 ¼ - 8	31.75	120.1	171	171	120.1	155.2	155
1 ½ -8	38.10	149.2	194	194	149.2	174.3	174
1 ¾ -8	44.45	178.3	216	216	178.3	193.4	193
2 – 8	50.80	156.0	238	238	156.0	212.4	212
2 ½ - 8	63.50	265.8	282	282	265.8	250.5	266

Remark:

- The table shall be adjusted if other values of the bolt preload, bolt material and clamped length are used.

9.2.3 *Anchor bolt pull out failure*

The anchor bolt pull out force as shown in the right hand figure of Figure 9.2 will be discussed in this chapter for a pocket with cement and epoxy grout. Two worst-case scenarios will be discussed:

- bond strength only between anchor and grout bolt termination plate only

Based on bond strength between anchor and grout

The anchor bolt pull out force based on the bond strength between steel and the cement and epoxy grout can be calculated using equation (10.7). This equation does not take into account the termination plate which is a rather worst-case scenario.

Duarte [36] has published values for the minimum and maximum bond strength of a steel bolt/epoxy and steel bolt cement grout. The values are 1.7- 3.0 MPa for cement grout and 6.3-13.4 MPa for epoxy grout.

$$P_f = \pi D L \tau_{bc} \text{ (N)} \tag{9.7}$$

In which:

P_f = bolt pull out force (N)
D = bolt outer diameter (mm)
L = length of bonded contact between bolt and grout (mm)
τ_{bc} = bond strength epoxy-steel (MPa)

In Table 9.4 the pull out forces are given for the minimum values of the bond strength for cement and epoxy grout. The calculations have been carried out only with the bolt preload to get an idea.

However, the sum of all dynamic loads (peak value), acting in the vertical direction must be added to the bolt preload. From this table the following can be concluded:

- All bolts will be pulled out for a cement grout if the highest bond strength is used without a termination plate.
- Almost all bolts will be pulled out for an epoxy grout with the lowest bond strength without a termination plate.
- None of the bolts will be pulled out if epoxy grout is used with the highest bond strength of 13.4 MPa without a termination plate.

The general conclusion is that bolts without a termination plate shall not be used.

Table 9.4 Bolt pull out forces for an epoxy grout-steel and cement grout-steel anchor bolt for an anchor based on a minimum grout bolt length as summarised in chapter 8.8.6, a maximum epoxy grout layer of 50 mm including and excluding termination plate diameters of chapter 8.6.4.1

Bolt size	Bolt diameter d	Bolt preload of 70% of yield strength ASTM A193 B7	Pull out force P_f	
			Epoxy grout*	Cement grout*
inches	mm	[KN]	[KN]	[KN]
1/2 – 13	12.70	47	62.8	17.0
5/8 – 11	15.88	74.8	78.6	21.2
¾ - 10	19.05	110.6	94.3	25.4
1 – 8	25.40	200.1	153.3	41.4
1 ¼ - 8	31.75	329.5	191.7	51.7
1 ½ -8	38.10	491	287.3	77.5
1 ¾ -8	44.45	684.6	402.1	108.5
2 – 8	50.80	910.3	613.3	165.5
2 ½ - 8	63.50	1457	957.7	258.4

Remark:
The table shall be adjusted if other values of the bolt preload, termination plate diameter and bolt material are used.

Based on termination plate diameter:

According to [18] the maximum allowable load is:

$$N_{Rk,p} = 6 \cdot A_h \cdot f_{ck,cube} \cdot \Psi_{ucr,N} \quad \text{(N)} \tag{9.8}$$

In which:
A_h = load bearing area of the head of the fastener (mm^2)
$f_{ck,cube}$ = compressive cube strength of the grout (MPa)
$\psi_{ucr,N}$ = factor taking into account the positioning of the fastening in cracked or non-cracked concrete (-)

$$A_h = \frac{\pi}{4} \cdot (d_h^2 - d^2) \; (mm^2) \tag{9.9}$$

In which:

d_h =diameter of termination plate diameter (mm) (3 bolt diameter for epoxy grout and 3.5 bolt diameter for cement grout)

d = diameter of anchor bolt (mm)

$\psi_{ucr,N}$ = 1.0 for fasteners in cracked concrete (1.4 for non-cracked concrete)

$f_{ck,cube}$ = cube design bearing load (MPa)

In accordance with Appendix C, the termination plate has a minimum diameter d_h of 3 times the bolt diameter d for epoxy grout and 3.5 for cement grout.
The design bearing load $f_{ck,cube}$ of cement grout is 40 MPa (50 MPa minimum compressive strength of the cement grout divided by a design factor C_1 =1.25).
For a conservative approach, assuming cracked concrete, the allowable design bearing load would be as given in Table 9.5.
From the table it can be concluded that for cement grout the bolt will not be pulled out if a termination plate is used in cement grout. This also confirms what is concluded in Appendix C: a simple nut termination would not be sufficient in most cases and a plate termination is always required!
It shall be noted that in the calculations only the bolt preload has been considered. However, there is enough safety margin for the sum of the amplitudes of the dynamic loads.

Table 9.5 Bolt pull out forces based on termination plate diameter only for cement gout based on cracked concrete

Bolt size	**Bolt diameter d**	**Bolt preload of 70% of yield strength ASTM A193 B7**	**Pull out force P_f for cement grout**
inches	**mm**	**[KN]**	**[KN]**
1/2 – 13	12.70	47	342
5/8 – 11	15.88	74.8	543
¾ - 10	19.05	110.6	769
1 – 8	25.40	200.1	1368
1 ¼ - 8	31.75	329.5	2138
1 ½ -8	38.10	491	3078
1 ¾ -8	44.45	684.6	4189
2 – 8	50.80	910.3	5473
2 ½ - 8	63.50	1457	8550

*values are rounded

9.2.4 *Edge distance & concrete blow-out failure*

9.2.4.1 *Introduction*

If a bolt is preloaded, a stress on it as well on the surrounding concrete will occur. If the stress is too high the concrete can crack, especially if the bolt is too close to the edge of the foundation. The different failures which can occur as a result of a tension force are shown in Figure 9.3. In Figure 9.4 a more detailed indication of the crack is shown for different failures modes.

The minimum edge distance which is required to avoid concrete blow out will be discussed in this chapter. The failure associated with this involves the development of a conical failure surface between the anchor and the edge of the concrete similar to the pull-out of a cone of concrete due to the direct tension.

Most civil engineering standards classify headed anchors, having a nut or plate termination, as cast-in fasteners instead of post-installed anchors.
In the calculations as given in this report it is assumed that the bolts are cast-in which is a worst-case consideration.

Appendix D of this report includes several detailed calculations according CEN/TS 1992 Part 4.1 and 4.2 but only the calculation for so-called concrete blow-out failure which is applicable for reciprocating compressor foundations.
The calculations according to this standard in the appendix are for information only and are only made to get some idea about the limits and methods used in this specific CEN standard.

In chapter D.2.8 of this Appendix the minimum required edge distance is calculated. According to these calculations, the proposed edge distances, termination plate diameters and bolt preload as summarised as given in this report, shall be more than adequate to prevent blow-out failure even when based on cracked concrete.

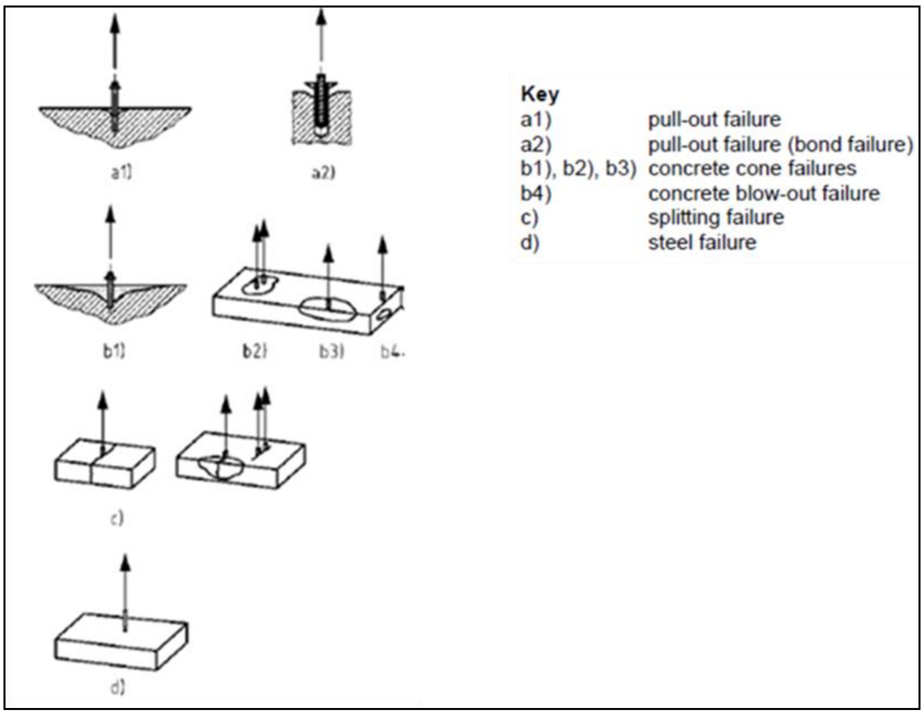
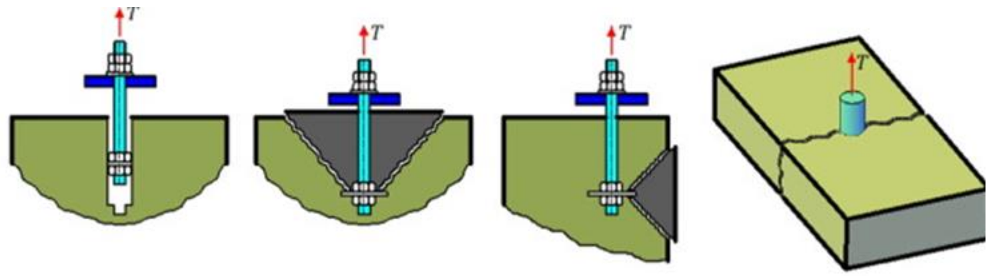


Figure 9.3 Different concrete failure modes for tension loads [NVN-CEN/TS 1992-4-1 "Design of fastenings for use in concrete- Part 4-1: General[15]



Pull out failure Cone failure Blow out failure Splitting failure

Figure 9.4 More detailed indication of different concrete failure modes as described in "NVN-CEN/TS 1992-4-1 "Design of fastenings for use in concrete- Part 4-1: General" [15]

9.2.4.2 Summary of recommended values in different guidelines, standards etc.

According to API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 [11]

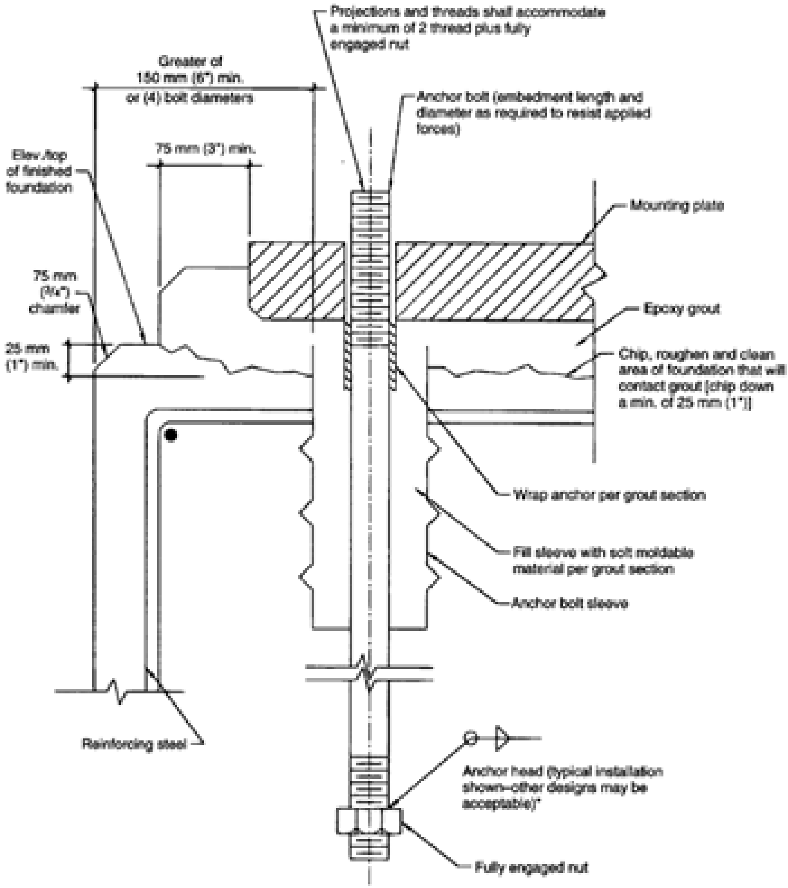
- the greater of 150 mm or 4d, see Figure 9.5 and Figure 9.6

Remark:
It shall be noted that the edge distance as defined in the API 686 differs from those as used in most other civil engineering standards & guidelines.
In the API 686 the edge distance is defined as the distance from the outer edge of the concrete foundation to the outer edge of the sleeve.
In most other civil engineering standards & guidelines the edge distance is defined as the distance from the centre of an anchor bolt shaft to the edge of concrete. This definition has been used in this document.
That means that if the used API RP 686 definition is transferred into the definition as used in this document, the edge distance is as follows:

- the greater of 150 +0.5d_s or 4d+0.5d_s (d_s is sleeve diameter).

According to API 686, see chapter 8.8.2, the sleeve diameter shall be minimum 2 times the bolt diameter. This mean that the edge distance is as follows:

- the greater of 150 +1d or 5d (mm)



Note: ACI 349 may be a possible design reference for anchor head.

Figure 9.5 Figure B-3 from the API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 [11]

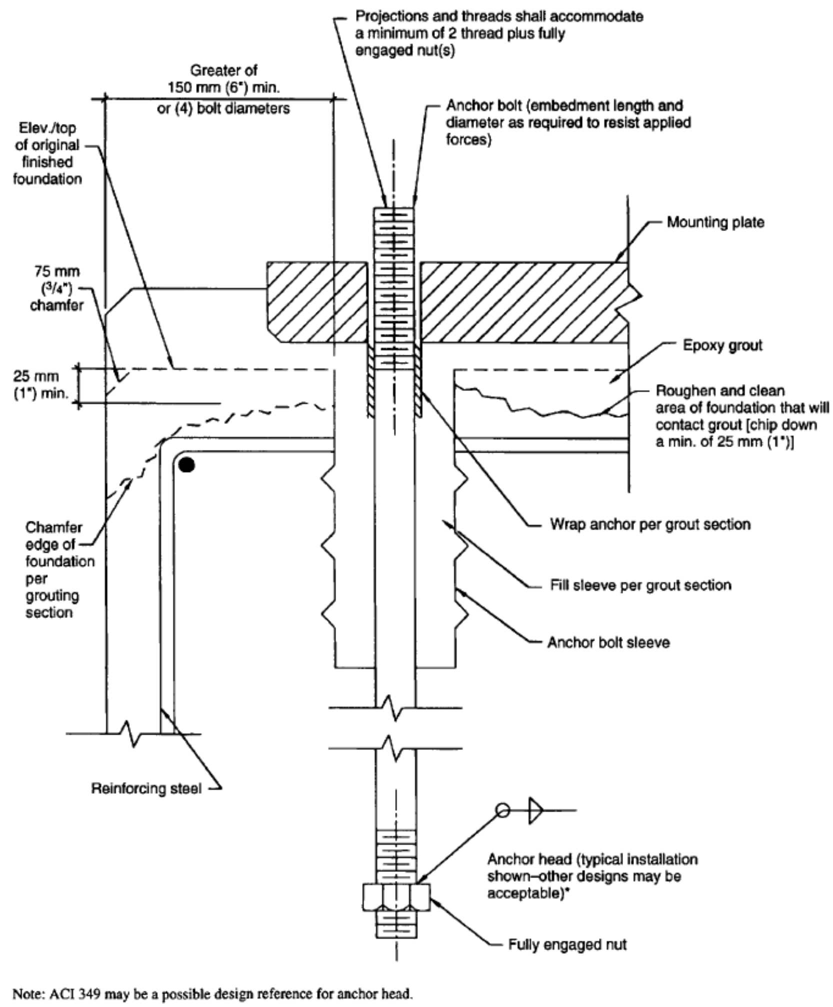


Figure A-4—Typical Anchor Bolt Detail—
Option 2, Grout Pour to Edge of Foundation

Figure 9.6 Figure B-4 from the API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 [11]

According to GMRC TR 97-6 [4]:

- 4.5-6 bolt diameter (concrete block tests done with 2" bolt with 6" termination)

According to GMRC TR 97-2[1]:

- recess anchor bolts: 305 mm from any vertical plane.

According to AISI steel design guide series 1 "Column Base Plates" [13]

- edge distance adopted from ACI 349: see Table 9.6

Table 9.6 Minimum embedded length and minimum edge distance for different bolt materials according to ACI 349

Bolt type, material	Minimum embedment edge distance
A307, A36	5d > 4”
A325, A449	7d> 4”

According to PIP STE05121 “Anchor Bolt Design Guide”[12]:

- It refers to PIP REIE686 (identical to API 686), ACI 318 and an ASCE report “Anchor bolt report” (report number is unknown).
- The ASCE report recommends a minimum edge distance of 4 bolt diameter for ASTM A307 or ASTM A36 bolts or their equivalent and 6d for high strength bolts.

  It is further stated that if a plate is used at the bottom of the anchor the edge distance shall be increased by half of the plate diameter minus half of the width of the nut (chapter 5.6.4 of the PIP SE0512).
  If sleeves are used, the edge distance shall be increased by an amount to half the sleeve diameter minus half the anchor diameter: $0.5(d_s-d_o)$, with d_s being the sleeve diameter and d_o the bolt outer diameter.

  The width across flats of standard nuts depends on the bolt diameter and ranges from approximately 1.75 times the bolt diameter for smaller bolts to approximately 1.55 times the bolt diameter for larger bolts. Width across corners is $2/\sqrt{3}$ times the width across flats and will therefore vary between 2.0 times the bolt diameter for smaller bolts and 1.8 times the bolts diameter for larger bolts.
  With a chosen plate diameter of minimum 3 times the bolt diameter for epoxy grout, the minimum edge distance for high strength bolts will therefore be between 6.5 and 6.6 times the bolt diameter.

Minimum edge distance may also be determined by the following requirement:

- minimum concrete cover between the surface of concrete reinforcement and the outer concrete surface (edge of the foundation),
- minimum diameter of the reinforcement
- minimum concrete cover between the reinforcement and anchor bolt pocket

According to API 686 [11]:

- minimum of 76 mm of concrete covering the reinforcing steel

According to EN 1992 Eurocode 2 [24]:

- distance between the outer edge of the bolt pocket and the reinforcement steel: minimum reinforcement diameter+10 mm.
- for the cover on the outside, between the reinforcement steel and the outer surface of the concrete: 45 mm + 10 mm allowance which is less than the values as recommended by the API RP 686 of 76 mm.

The minimum total distance between the bolt centreline to the outer surface of the concrete taken into account the bolt pocket size as summarised in 9.2.2 for a square pocket and in chapter 9.2.2.2 for a cylindrical pocket, tensile plus transverse reinforcement steel, tolerances and concrete cover based on EN 1992-2 and CEN/TS 1992 for a recommended reinforcement diameter of 16 mm is as follows:

For a square pocket:

$$ED_c = [(E+25)/2] + C_o + C_p + 2 \cdot D_r \text{ (mm)} \quad (9.10)$$

For a cylindrical pocket:

$$ED_c = E + C_o + C_p + 2 \cdot D_r \text{ (mm)} \quad (9.11)$$

In which:

ED_c	= edge distance based on minimum cover (mm)
E	= pocket size at the top of pocket (mm)
E_p	= minimum (cylindrical or square) bolt pocket size (mm)
C_o	= outside cover (mm)
C_p	= pocket size cover (mm)
T	= installation tolerance (mm)
D_r	= reinforcement diameter (mm)

It is recommended to take the following values:

- Pocket side cover according to EN-1992: 26 (16 reinforcement +10 tolerance)
- Outside cover according to EN-1992: 56 mm (10 tolerance +46 cover):
- Reinforcement diameter : 16 mm

This will give the following values:

Square bolt pocket:

$$ED_c = [(E+25)/2] + 114 \text{ (mm)}$$

Cylindrical bolt pocket:

$$ED_c = (E/2) + 114 \text{ (mm)}$$

The minimum edge distances for a square pocket according different standards and guidelines and a value based on minimum bolt pocket size and concrete cover (ED) are summarised in Table 9.7.

Table 9.7 Minimum edge distances for a square pocket according different standards and guidelines and a value based on minimum bolt pocket size and concrete cover (ED) and a preload of 70% of yield for an ASTM A193 B7 grade bolt material

	d	API 686 (150+1d)	6.5d (GMRC & PIP)	Minimum cover & pocket* size cement grout	Minimum cover & pocket* size epoxy grout	Edge distance (ED) cement grout	Edge distance (ED) epoxy grout	ED/d cement grout	ED/d epoxy grout
Bolt size	**mm**	**mm**	**mm**	**mm**	**mm**	**mm**	**mm**	**-**	**-**
1/2 – 13	12.70	162.7	83	166.5	163	166.5	163	13.1	12.8
5/8 – 11	15.88	165.88	103	172	168	172	168	10.9	10.6
¾ - 10	19.05	169.05	124	177.5	172.5	177.5	172.5	9.3	9.1
1 – 8	25.40	175.4	165	188.5	182	188.5	182	7.42	7.2
1 ¼ - 8	31.75	181.75	206	199.5	191.5	206	206	6.5	6.5
1 ½ -8	38.10	188.1	248	211	201	248	248	6.5	6.5
1 ¾ -8	44.45	194.5	289	222	210.5	289	289	6.5	6.5
2 – 8	50.80	200.8	330	233	220	330	330	6.5	6.5
2 ½ - 8	63.50	213.5	413	255	239.5	413	413	6.5	6.5

Remarks:

- Small deviations from the above values are allowed.
- The values are identical for a cylindrical and a square pocket size due to the fact that the values of the pocket size are determined by mounting restrictions.
- The table shall be adjusted if other values of the reinforcement diameter, bolt preload and bolt material are used.

9.2.5 *Bolt spacing*

A minimum anchor bolt spacing is required to preclude overlap of the cones of compression or tension above and below the anchor bolt termination, see Figure 9.7. Overlap of the cones of compression lead to compressive failure and spalling of concrete from sides of concrete foundation. Overlap of the cones of tension lead to concrete cracking. To avoid spalling at the outer edge of the concrete, the edge distance shall be large enough as discussed in the former section.

Appendix D of this report includes several detailed calculations according CEN/TS 1992 Part 4.1 and 4.2. The calculations according to this standard are for information only and are only made to get some idea about the limits and methods used in this specific CEN standard.
In accordance with the calculation method, even for worst-case assumptions, which does not seem correct and suitable for finding the minimum spacing required, the spacing between bolts can be made very, and unrealistically, small.
For that reason the spacing required for placing, concrete compacting and other requirements determine the actual spacing and will be discussed in this chapter.

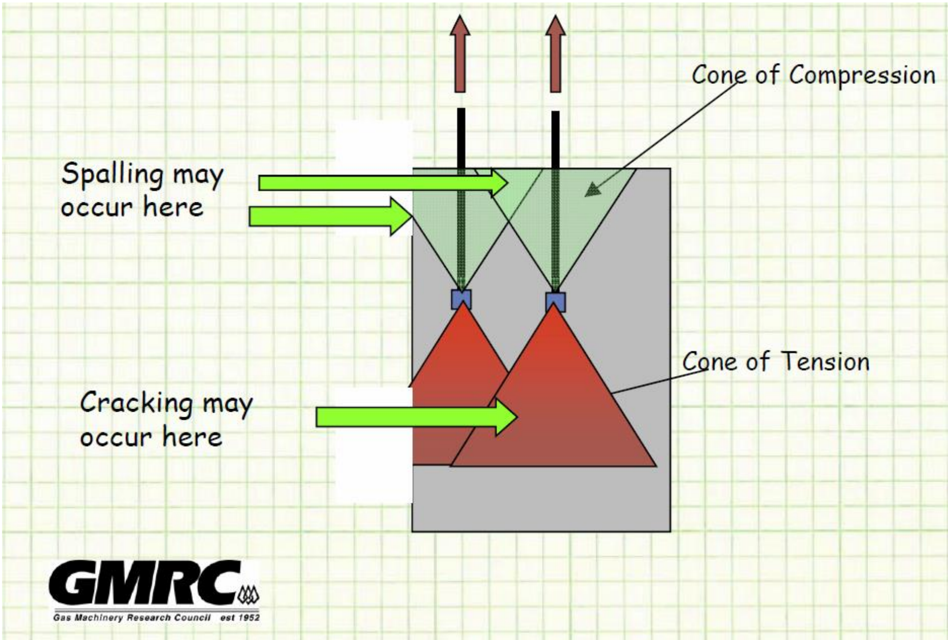


Figure 9.7 Cones of compression and tension caused by an external load [20]

For bolt spacing a more or less similar approach as used for the edge spacing can be used. The minimum spacing between bolts located at the edge of the concrete, taking into account tensile plus transverse reinforcement and concrete cover, is as follows:

For a square pocket:

$$S = (E + 25) + 2 \cdot C_p + 2 \cdot D_r \text{ (mm)} \tag{9.12}$$

For a cylindrical pocket:

$$S = E + 2 \cdot C_p + 2 \cdot D_r \text{ (mm)} \tag{9.13}$$

In which:

S = bolt spacing distance based on minimum cover (mm)
E = pocket size at the top of pocket (mm)
E_p = minimum (cylindrical or square) bolt pocket size (mm)
C_p = pocket size cover (mm)
T = installation tolerance (mm)
D_r = reinforcement diameter (mm)

It is recommended to take the following values:

- Pocket side cover according to EN-1992: 26 (16 mm reinforcement +10 mm tolerance)
- Reinforcement diameter: 16 mm

This will give the following values:

Square bolt pocket:

$$S = E + 109 \text{ (mm)}$$

Cylindrical bolt pocket:
$S = E + 84$ (mm)

In other words the distance is governed by the bolt pocket size and required minimum thickness of concrete between two pockets.

A practical choice is to use 120 mm. Based on the available information, standards and reports a general recommendation for minimum spacing for high strength anchor bolts would be the maximum value of:

- 7.5d From PIP STE05121* for bolt with termination plate
- E + 109 mm For square pocket, see above
- E + 84 mm For cylindrical pocket, see above

*PIP STE05121: 6D for torqued cast-in anchors plus the plate width if the termination plate is used at the bottom of the anchor bolt

In Table 9.8 a summary is given for the minimum advised anchor spacing. Due to the fact that the values are rounded (multiple of 5) and that for several bolt diameters the values according to the PIP are governing, the values of a square and cylindrical pocket are the same.

Table 9.8 Recommended minimum bolt spacing for a square pocket according different standards and guidelines based on a preload of 70% of yield for an ASTM A193 B7 grade bolt material.

	d	**7.5d (PIP)**	**Minimum spacing for a cement grout pocket**	**Minimum spacing for an epoxy grout pocket**	**Advised spacing for a cement grout pocket***	**Advised spacing for an epoxy grout pocket***	**S/d for a cement grout pocket**	**S/d for an epoxy grout pocket**
Bolt size	**mm**	**mm**	**mm**	**mm**	**mm**	**mm**	**-**	
1/2 – 13	12.70	88.9	189	182	190	185	15.0	14.6
5/8 – 11	15.88	111.2	200	192	200	195	12.6	12.3
¾ - 10	19.05	133.4	211	201	215	205	11.3	10.8
1 – 8	25.40	177.8	233	220	235	220	9.3	8.7
1 ¼ - 8	31.75	222.3	255	239	255	240	8.0	7.6
1 ½ -8	38.10	266.7	278	258	280	270	7.3	7.1
1 ¾ -8	44.45	311.2	300	277	315	315	7.1	7.1
2 – 8	50.80	355.6	322	296	360	360	7.1	7.1
2 ½ - 8	63.50	444.5	366	375	445	445	7.0	7.0

*Values are rounded to a multiple of 5

Remarks:

- The table shall be adjusted if other values of the reinforcement diameter, bolt preload and bolt material are used.
- Small deviations from the above values are allowed.

– The values are identical for a cylindrical and a square pocket size due to the fact that the values of the pocket size are determined by mounting restrictions

9.3 Concrete cone failure

This is a failure mode which normally cannot occur by the bolt preload. Only the sum of the dynamic loads in vertical direction can cause a concrete cone failure.
Calculations have been carried out according to CEN/TS 1992 Part 4.2 [18] to get an idea if cone failure can occur. These calculations are summarised in In Appendix D, section D.2.3 of this of this EFRC document.
From the results it can be concluded that the maximum sum of the amplitudes of the dynamic forces (pulsation forces, unbalanced forces and torque variation forces) are not allowed to exceed the values as shown in
Table **9.9**. The values are based on a plate termination diameter as summarised in chapter 8.11 and a clamped length as summarised in chapter 8.8.
In general the dynamic loads are much smaller than the allowable values as given in the table so it is not expected that concrete cone failure will occur.

Table 9.9 Allowable dynamic loads (sum of the amplitudes) to avoid concrete cone failure

	d	**$N_{Rd,c}$**
Bolt size	**mm**	**N**
1/2 – 13	12.70	34578
5/8 – 11	15.88	48347
¾ - 10	19.05	63524
1 – 8	25.40	97801
1 ¼ - 8	31.75	136681
1 ½ -8	38.10	179672
1 ¾ -8	44.45	226413
2 – 8	50.80	276623
2 ½ - 8	63.50	386593

9.4 Steel failure (bolt and reinforcement, anchorage of reinforcement)

In Appendix D.2.3 a table has been given with the minimum required number of reinforcement bars to avoid failure of the rebars. This table is applicable for different bolt and reinforcement diameters for a bolt preload of 70% of the yield strength of an ASTM A 193 B7.

9.5 Concrete splitting failure (due to installation and loading)

9.5.1 Installation

Splitting failure due to installation is not considered as the proposed anchors with plate termination do not rely on deformation during preloading or have so-called wedge type terminations.
Additionally no European Technical Specification is available that includes the minimum values for edge distance, spacing and member thickness for this anchor type.

9.5.2 *Splitting failure due to loading*

Having established the requirement for supplementary reinforcement as summarised in Appendix D.2.3 in order to prevent concrete cone failure for the proposed edge distance, longitudinal (transverse, or horizontal direction) splitting reinforcement is also required at the edge of the concrete block.
In Appendix D.2.3 a table has been given with the minimum required number of reinforcement bars for different bolt and reinforcement diameters for a bolt preload of 70% of the yield strength of an ASTM A 193 B7.
In chapter 5.4 a summary has been given with the minimum required reinforcement density.

10 Fatigue failure analysis of preloaded anchor bolts

10.1 Introduction

This section is intended to provide a brief understanding of fatigue analysis of compressor anchor bolts caused by the vertical dynamic loads (anchor bolts do act in shear), presenting hand calculation methods for optimizing the life of anchor bolt interface.
The areas of fatigue and fracture mechanics are very much inter-related. The differences between fatigue and fracture mechanics analyses are in their basic philosophies; fatigue estimates the life to failure of an untracked item while fracture mechanics calculates whether or not a crack of a given size will propagate in a catastrophic manner under cyclic loading. In many cases, the relevant analysis tasks are complementary but usually a fracture critical item is designed to only one of these methods. This section will consider only the fatigue analysis method.
Fatigue occurs in a material under the cumulative effect of a number of cycles of alternating, repeated or varying stresses of a level lower than the maximum static failure (or yield) stress. Such failure occurs due to progressive extension of a micro crack initiating at the point of highest stress in a local stress field.
Fatigue analysis is required on anchor bolts when designing the compressor interface due to the fact that such an interface is highly likely to experience alternating loading which may lead to crack propagation. If a compressor interface is designed poorly without considering the fatigue life of its anchor bolts, there is a potential for the ultimate failure of the joint.
It is therefore recommended that a fatigue analysis shall be performed on anchor bolts in order to underwrite their structural integrity over the duration of their life time.

10.2 Fatigue mechanisms

There are two main fatigue mechanisms which can result in the extension of a crack within an anchor bolt. The failure propagation will accelerate if the concrete is contaminated with oil or water.

- **Cyclic Loading –** If there is an alternating loading environment applied to the anchor bolt (see also section 4.3), there will be a resulting alternating stress within the anchor bolt leading to crack growth.
- **Thermal fatigue –** If within the anchor bolt assembly there is a mix of materials with differences in coefficient of thermal expansion which in term is subjected to a cycling thermal environment, there will be a resulting alternating stress within the anchor bolt leading to crack growth.
  Due to the fact that the thermal environment of anchor bolts within compressor interfaces are generally benign, thermal fatigue will not be considered further within this document. However, there are other aspects of a compressor design where thermal fatigue may be a failure mode and therefore shall carefully considered. This is especially the case for compressor systems which are started and stopped several times a day e.g. for underground gas storage systems.

In areas exposed to corrosive chemical vapours or liquids, the anchor bolt shall be fabricated from a material resistant to chemical attack or provided with a proper chemical-resistant coating such as galvanizing. However, it not always required to galvanise compressor foundation bolts when correctly installed, grouted and maintained. Not galvanising also removes the added, although small, risk of hydrogen embrittlement in case of high strength steels and possible difficulties with thread clearance. VDI 2230, 2003 [21] even states that in case of hot galvanised bolts the fatigue strength is reduced by approximately 20%. So if galvanised bolts are used, the fatigue strength shall be reduced accordingly in the fatigue analysis.

10.3 The mechanics of fatigue in bolts [40]

The target of designing compressor anchor bolts is to have infinite endurance life against a defined alternating loading environment. This will simplify compressor maintenance required during the life of the compressor. Before this can be achieved, the fundamental principle of a bolt interface shall be understood.

10.3.1 Bolted joint fundamental

Figure 10.1 provides an overview of a typical anchor bolt configuration. When a torque load is applied to an anchor bolt, a combination of compression of the clamped region and bolt extension occurs which ultimately leads to the generation of preload within the interface.

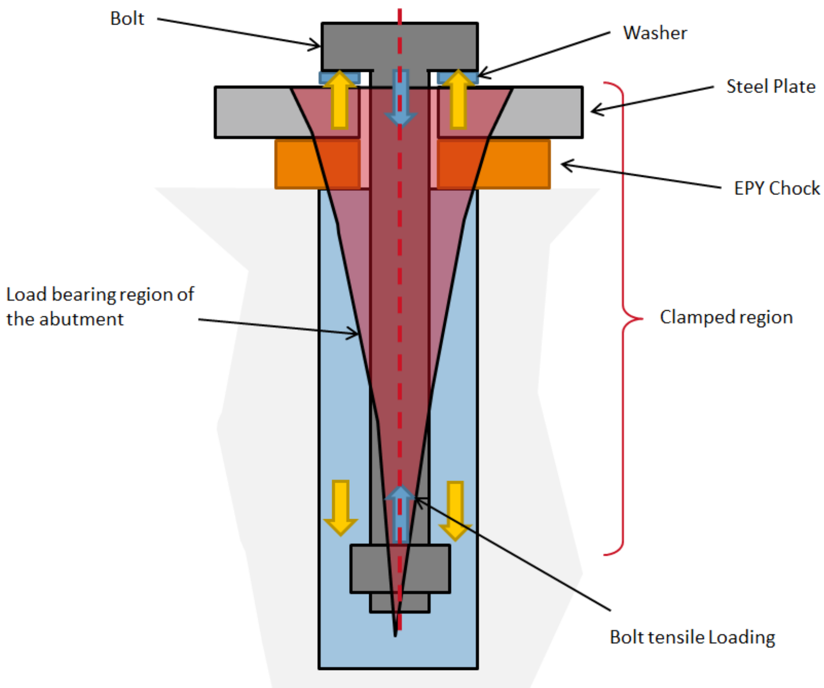


Figure 10.1 A typical anchor bolt configuration.

The bolt extension and compression of the clamped region is dependent on the torque applied as well as the ratio of stiffness values known as the compliance ratio, also named bolt load factor. Figure 10.2 summaries the relationship between bolt extension and compression of the clamped region.

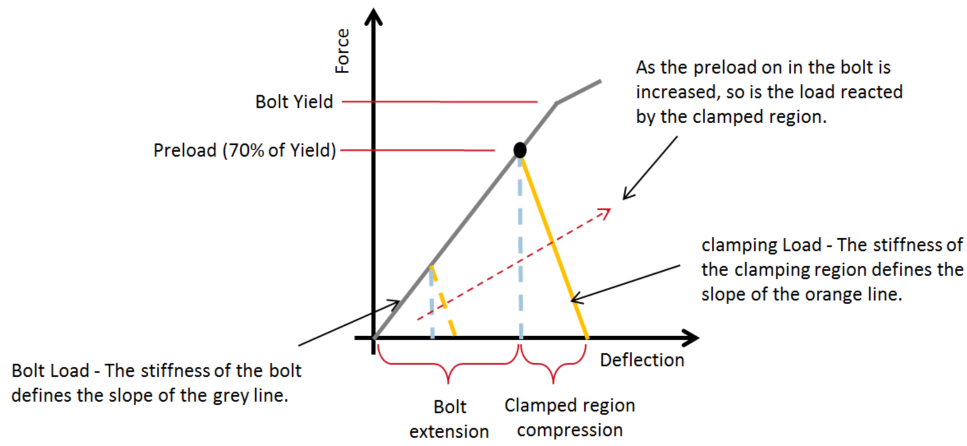


Figure 10.2 Joint stiffness diagram

The variance of the under-head and thread friction of an anchor bolt has a signification impact on the resulting preload being generated by torqueing (see also section 8.5.2). If friction is high, then less preload will be generated by a particular torque value. Figure 10.3 demonstrates the impact of friction variance on the preload of an anchor bolt. This affect shall always be considered when performing a bolt analysis and the most conservative preload shall be used depending on the failure mode under investigation. For example strength related failure modes such as fatigue shall consider the maximum preload and stability related failure modes such as sliding shall consider the minimum preload.

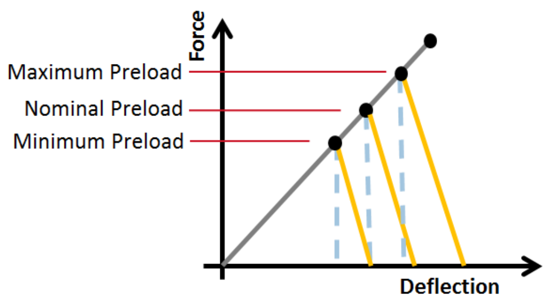


Figure 10.3 Joint stiffness diagram with effect of friction variance

When an external tensile load is applied to an anchor bolt, the preload on the clamped region is relieved, hence there is a reduction in compression load and the tensile load on the bolt is simultaneously increased.

There is a critical point where the external applied load extends well beyond the preload leading to gapping, see Figure 10.4. This is a highly undesirable situation for not only the fatigue life of the anchor bolt but also for the stability of the overall compressor interface.

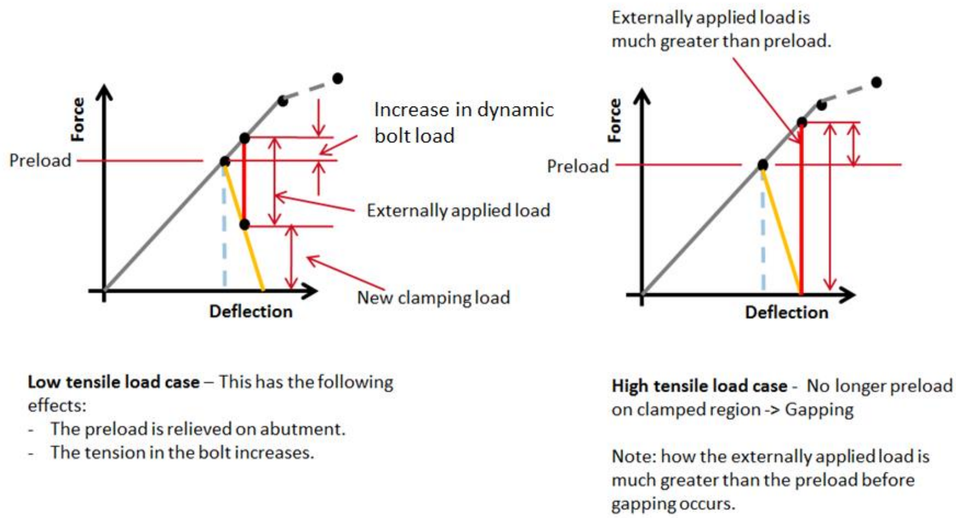


Figure 10.4 Joint stiffness diagram with a static external load and gapping

In an alternating load environment, the compression of the clamped region is relieved and the bolt tensile load is increased in a similar fashion to that of the static load environment previously described. However under an alternating loading there is continuous variation in the bolt load. Preload is critical in reducing the effect of alternating loading on the endurance life of an anchor bolt. From Figure 10.4 it can be shown that the increase in dynamic bolt load is only a small part of the externally applied dynamic load. This will prolong the fatigue life of an anchor bolt.
It shall be noted that with a loss in preload, the applied externally alternating load will directly lead to an increase of the dynamic load on the bolt. This demonstrates the criticality of locking anchor bolts after torqueing or regularly checking bolt preload during compressor maintenance.

The ratio of the clamped region compression relief and bolt tensile load increase is a function of the anchor bolt compliance ratio. For this reason, it is possible to further optimize the endurance life of anchor bolt by tailoring the compliance ratio which further reduces the resulting alternating tensile loading in the anchor bolt.
Figure 10.5 summaries the effects on the bolt alternating tensile load with both a high and low stiffness of the abutment.

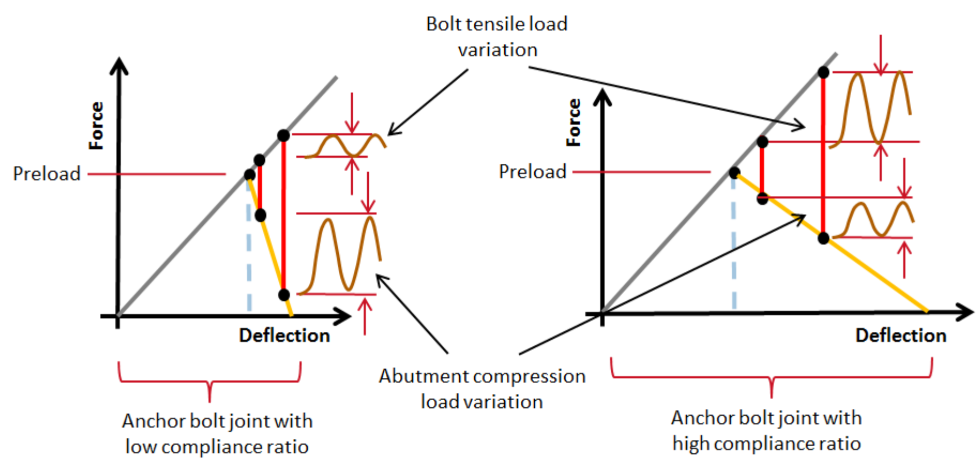


Figure 10.5 Joint stiffness diagram with a low/high compression ratio

If the clamped region stiffness is infinite, then for alternating loads where maximum load is less than the anchor bolt preload then there be no resultant variation in the tensile load of the bolt. The anchor bolt would therefore have an infinite endurance life, independent of its material properties.
In many cases, it is not possible to design the clamped region of an anchor bolt to ensure that its stiffness tends towards infinite. An alternative approach, which is commonly adopted by industry, is to increase the length of the anchor bolt such that its stiffness is greatly reduced in comparison to the clamped region stiffness. An example of this can be seen in Figure 10.6.

Figure 10.6 Bolt length extensions

10.3.2 *Compliance ratio*

The compliance ratio (also named bolt load factor) of anchor bolt is the ratio between the bolt and clamped region stiffness values. It indicates which ratio of the externally applied dynamic load acts on the bolt. E.g. a compliance ratio of 0.2 means that only 20% of the total dynamic load acts on the anchor bolt.
Based on the method defined in the VDI 2230 [21] [22] (version 1986), the compliance ratio can be calculated as follows:

$$\Phi = \frac{\delta_p}{\delta_p + \delta_s} = \frac{\frac{l_k}{A_{repl} \cdot E_{clamped}}}{\frac{l_k}{A_{repl} \cdot E_{clamped}} + \frac{l_k}{A_{bolt} \cdot E_{bolt}}} \tag{10.1}$$

With:

$$x = \sqrt[3]{\frac{l_k \cdot d_w}{D_A^2}} \tag{10.2}$$

$$A_{repl} = \frac{\pi}{4} \cdot (d_w^2 - d^2) + \frac{\pi}{8} \cdot d_w \cdot (D_A - d_w) \cdot [(x+1)^2 - 1] \tag{10.3}$$

In which:

Φ	= compliance ratio
l_k	= clamped length
d_w	= diameter of the termination

D_A	= outer diameter of the clamped parts (twice times the edge distance)
A_{repl}	= replacement area
d	= nominal bolt diameter
δ_s	= bolt stiffness
δ_p	= abutment stiffness
$E_{clamped}$	= clamped parts modulus of elasticity
A_{bolt}	= bolt cross-sectional area
E_{bolt}	= bolt modulus of elasticity

Assumptions are:

- The modulus of elasticity of the clamped parts varies between a lowest value of approximately 13790 MPa for epoxy grout (Chock fast Red) and a value ≥ 27000 MPa for cement grout and concrete.

For an anchor bolt fatigue analysis, the compliance ratio defines how the alternating load may be divided between the bolt and the clamped region. So a smaller compliance ratio will lead to a smaller cyclic stress in the bolt.

10.3.3 Material Fatigue Life Allowable

The initial speed of extension of the crack is dependent on the crack properties of the material and the applied cycle. Eventually a point of rapid and unstable crack growth occurs resulting in ultimate failure of the anchor bolt.

The number of cycles to failure decreases as the range of alternating stress increases. For some materials an indefinitely long crack free life may be expected provided that the range of alternating stress is sufficiently low. However, some materials (such as aluminium alloy) have no fatigue limit, although the slope at high values of N becomes very low. A typical alternating stress verses number of cycles to failure (S-N) curve is shown in Figure 10.7.

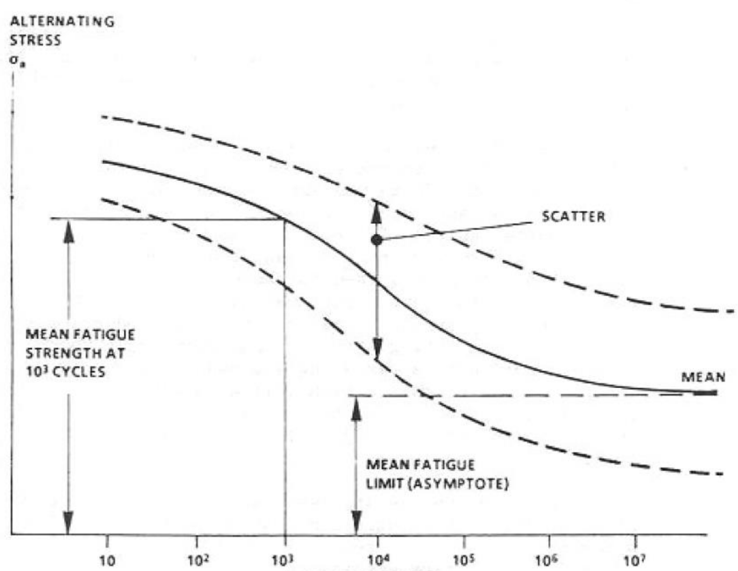


Figure 10.7 Typical S-N curve for a material.

It is possible to conduct a quick look analysis to determine whether an anchor bolt has an infinite life in a particular alternating environment.

For bolts rolled before heat treatment, VDI 2230 [21][22] (version 2003) states that the allowable unintensified dynamic stress range (peak-peak) is equal to:

$$\sigma_{a,allowable} = 0.85 \cdot \left(\frac{150}{d} + 45\right) \tag{10.4}$$

In which::

$\sigma_{a,allowable}$= allowable stress amplitude (0-peak) for infinite life (N/mm^2)
d = nominal bolt diameter (mm)

Assumptions:

- Applicable for 8.8, 10.9 and 12.9 bolts (as defined in VDI 2230, version 1986)
- The allowable stress amplitude shall be reduced with 20% for galvanized/stainless steel bolts
- Applicable to bolts with standard thread pitches
- 1% probability of failure
- Independent of bolt preload.
- Effects of corrosion not considered.
- Includes the notching effect of the thread.
- The factor of 0.85 is the lower limit of scatter range.

For compressor anchor bolts a 1% probability of failure may be considered to be optimistic as the cost of replacing broken bolts in service is extremely expensive.
For that reason it is recommended that the user specifies a lower probability of failure and assuming a standard deviation will give a lower allowable stress amplitude.
Further on it shall be noted that the fatigue limit of fine thread decreases with increasing strength and the degree of fineness of the threads. For example, in joints having the strength grade 12.9, it may be up to 30% lower than I standards threads.

10.3.4 Fatigue Analysis

Quick look Analysis

It is recommended that a quick look analysis shall be performed on the most highly loaded anchor bolt in an array to determine the sensitivity of the anchor bolt to the applied alternating load environment. The quick look analysis flow is stated in Figure 10.8.
The last block of the flow chart is the determination of the safety margin. The VDI 2230 [21][22] (version 2003) refers to a guideline [39] which recommends to apply a minimum safety margin of 1.2. However, the safety margin shall be established by the user. If there is insufficient margin, it is recommended that either design changes are made to the anchor bolt design or a more detailed/representative analysis shall be performed. The process for conducting a more detailed/representative fatigue analysis on anchor bolts is rather complicated and not covered by this guideline and a specialist shall be consulted for this.

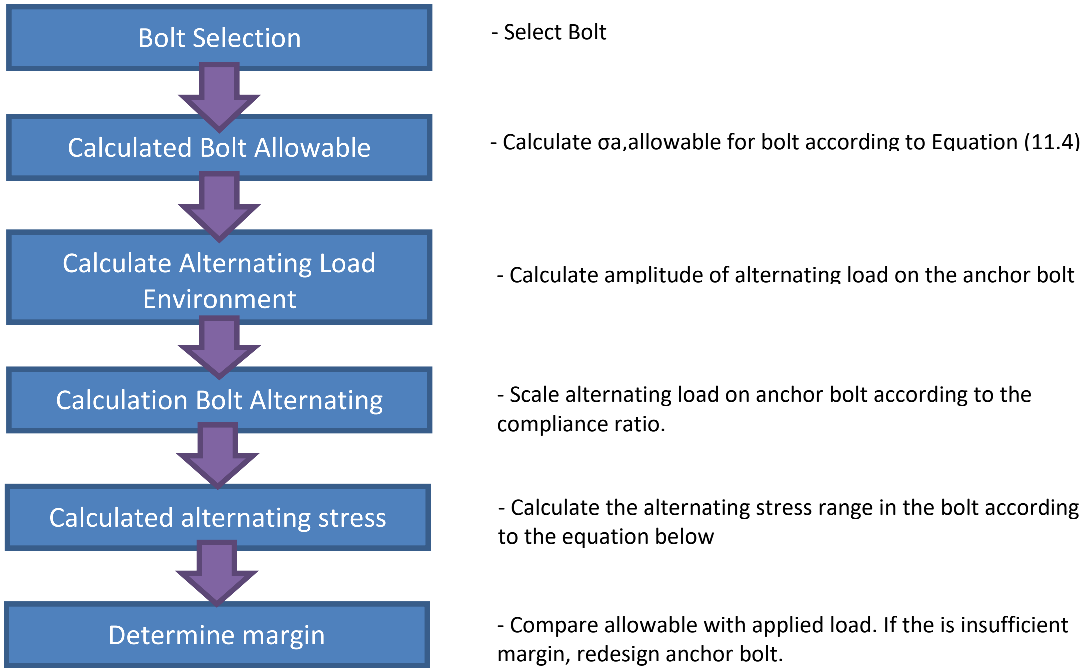


Figure 10.8 Quick look fatigue analysis flow.

Quick look Analysis Example

<u>Step 1 Bolt Selection</u>
Assume a 1” bolt diameter (25.4 mm)

<u>Step 1 Calculate Bolt allowable</u>

$$\sigma_{a,allowable} = 0.85 \cdot \left(\frac{150}{d} + 45\right) = 0.85 \cdot \left(\frac{150}{25.4} + 45\right) = 43.3 \text{ MPa (peak-to-peak)}$$

<u>Step 3 Calculate Alternating Load Environment</u>
Calculate the sum of the peak-to-peak value of the vertical alternating load as described in chapter 4.5 for the highest loaded bolt. Assume a maximum alternating load of 30 kN (peak-to-peak).

<u>Step 4 Scale Alternating Load Environment</u>
Assuming :

- Minimum edge distance of 6.5 x d
- Outer diameter D_A of the clamped parts is at least 13 x d (twice the edge distance)
- The diameter of the termination d_w is at least 3 x d.
- The clamped length l_k is at least 24 x d.

The replacement area of the clamped parts can be calculated as follows:

$$x = \sqrt[3]{\frac{l_k \cdot d_w}{D_A^3}} = \sqrt[3]{\frac{24d \cdot 3d}{(13d)^2}} = 0.6527$$

$$A_{repl} = \frac{\pi}{4} \cdot (d_w^2 - d^2) + \frac{\pi}{8} \cdot d_w \cdot (D_A - d_w) \cdot [(x+1)^2 - 1]$$

$$A_{repl} = \frac{\pi}{4} \cdot ((3d)^2 - d^2) + \frac{\pi}{8} \cdot 3d \cdot (13d - 3d) \cdot [(0.6527+1)^2 - 1] = 26.68 \cdot d^2$$

The compliance ratio can be calculated assuming:

- A modulus of elasticity of the steel bolt (E_{bolt}) equal to 206000 MPa.
- The modulus of elasticity (Ep) of the clamped parts varies between a lowest value of approximately 13790 MPa for epoxy grout (Chock fast Red) and a value ≥ 27000 MPa for cement grout and concrete.

The maximum compliance ratio will give the maximum cyclic stress range in the bolt and can be calculated as follows:

$$\Phi = \frac{\delta_p}{\delta_p + \delta_s} = \frac{\frac{l_k}{A_{repl} \cdot E_{clamped}}}{\frac{l_k}{A_{repl} \cdot E_{clamped}} + \frac{l_k}{A_{bolt} \cdot E_{bolt}}} = \frac{\frac{1}{26.68 \cdot d^2 \cdot 13790}}{\frac{1}{26.68 \cdot d^2 \cdot 13790} + \frac{1}{\frac{\pi}{4} \cdot d^2 \cdot 206000}} = 0.322$$

Therefore the anchor bolt alternating load is as follows:

F_a = 30 kN x 0.322 = 9.66 kN (pp)

In which:
F_a = bolt alternating load (kN) (peak-to-peak)

<u>Step 5 Calculate bolt alternating stress range:</u>

Stress area for metric series according ISO 898-1:

$$A_s = \frac{\pi}{4} \cdot (d - 0.938194 \cdot p)^2 = \frac{\pi}{4} \cdot \left(\frac{d_1 + d_2}{2}\right)^2$$

$$A_s = \frac{\pi}{4} \cdot (25.4 - 0.938194 \cdot 1.5)^2 = 452 \text{ mm}^2$$

In which:
A_s =stress area of a bolt (mm^2)
d = nominal bolt diameter (mm)
p = thread pitch (mm)

Stress in anchor bolt due to alternating load:

$$\sigma_a = \frac{F_a}{A_s} = \frac{9660}{452} = 21.4 \text{ (MPa)}$$

Where:
σ_a = anchor bolt alternating stress range (MPa)

<u>Step 6 Anchor bolt fatigue safety margin:</u>

$$\text{Fatigue safety margin} = \frac{\sigma_{a,allowable}}{\sigma_a} = \frac{75.4}{21.4} = 3.52$$

11 Skid mounted compressors

11.1 Introduction

First of all it shall be mentioned that most of the material as used in this chapter is copied from the "GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013", [7] which is the work that has been carried out by different companies from the USA. The most important references as used in [7] are as follows:

1. Gas Machinery Research Council, Guideline for Assembly and Maintenance of Bolted Joints in High Vibration Environments (2011).
2. Gas Machinery Research Council, Research Guideline: Mounting Separable Reciprocating Compressors in Pipeline Service (2006).
3. Beta Machinery Analysis: Foundation Analysis and Design For Reciprocating and Rotating Equipment (2006).
4. Gas Machinery Research Council, Reciprocating Compressor Foundations: Loading, Design Analysis, Monitoring & Repair, December 1993.
5. Gas Machinery Research Council, Parameter Studies for Enhancing Integrity of Reciprocating Compressors, September 1994 GMRC).
6. Geotechnical Considerations for Design and Construction of Foundations, Oct 1999, Gas Machinery Conference, Larry Lanz, P.E., El Paso Energy.

Compared to classic, slow-speed API 618 compressors, high-speed reciprocating compressors are much more likely to be installed on a steel skid for compressors with a power up to approximately 3700 kW. The goal of the foundation and skid design is to ensure that the compressor, driver and other equipment has a stable base for safe, long term operation.

Some skid mount advantages:
Unifies and streamlines compressor/driver installation.

- Takes advantage of established, efficient, competitive packager business.
- Minimizes lead time.
- Likely minimizes first cost.
- Provides single point of contact for compression system.
- Makes attachment of components more straightforward.
- Normally simplifies geometry of the foundation block.
- Spreads the footprint and base and enhances sharing of dynamic loads to the anchor bolts; this shall help reduce tensile stresses in the concrete.
- Simplifies any needed structural changes after installation.

Some skid mount disadvantages

- Transportation limits exist for large single packages.
- Skid may be less rigid than block for force management.
- The extra height at which crank forces act aggravates response.
- Can require unproductive travel for major components.
- If most components are shipped direct to site, the skid may be seen as providing an unnecessary extra interface.

– If all components needed for a high horsepower installation must be on the skid, it will tend to be crowded.

Some block mount advantages

– Shall be more rigid than a skid (if properly engineered).
– Provides a solid reference for alignment.
– Lower shipping costs.
– Eliminates the need to install skid as an intermediate component.
– The required installation at site opens up freedom to mount ancillary equipment off skid or even outside the building from the main compressor installation.
– The block automatically minimizes the height of the compressor CG.
– The compressor feet and crosshead guide support feet can be mounted at the same level on the same flat concrete surface, ensuring very stiff crosshead guide supports.
– Any differences that exist between the driver and compressor in the height above their mounting feet and their shaft centreline can be accommodated with a difference in height of the concrete surfaces on which driver and compressor are mounted.

Some block mount disadvantages

– More complex and time-consuming engineering and installation required (if block is engineered to enjoy all potential advantages).
– Overall project team will likely need new skills and interfaces and management of the team will be more complex.
– Block mounting may cost more than skid mount.
– Block mounting must be carefully engineered for particular installation site and local geophysical considerations, as well as thermal expansion.
– Protection of the concrete from oil will be more critical.
– Higher local forces will have to be restrained by concrete; higher concrete tensile stresses may result.
– Requires careful integration of high strength anchor bolts with concrete.
– May involve sales, packaging, and warranty outside normal channels.

The skid requires analysis to evaluate the design for lifting, transportation and other environmental loads as well as dynamic loads that occur during operation. The foundation must also be evaluated to ensure that it is suitable to carry the static and dynamic loads from the compressor package.
The skid is the fabricated steel structure that supports the compressor and driver and often the vessels, piping and other equipment required for the compressor operation. Figure 11.1 shows a typical arrangement of a skid mounted compressor package. The skid is sometimes composed of two main structures, one being a pedestal and the other being the main skid. The pedestal, sometimes called a pony skid, is the structure that supports the driver (engine or motor, typically) and compressor. The main skid is a structure that supports the pedestal as well as supporting the other components of the compressor package. The pedestal may be part of, or integral to, the main skid in some cases.
The foundation is the structure that supports the skid. The foundation for compressor packages covered by these best practices is often a concrete block or slab (shallow foundation). However, in some applications, it can be a pile design (deep foundation).
Skids shall be designed for compatibility with their foundations. For example, a skid on a concrete block foundation will require a different design than a skid on a pile foundation. In general, the more flexible the foundation, the stiffer the compressor skid must be.

This chapter provides recommendations for skid mounted compressors for use in the specification and design of foundations and skids for large, high-speed reciprocating compressors and their drivers.

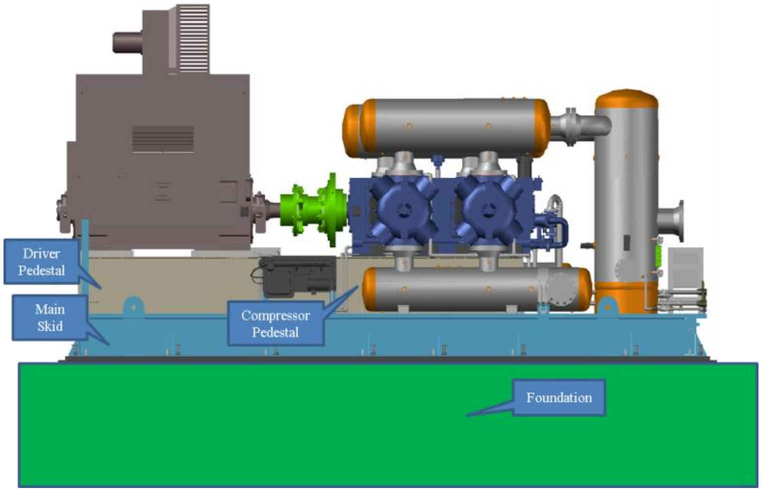


Figure 11.1 Typical foundation-mounted skidded compressor package [7]

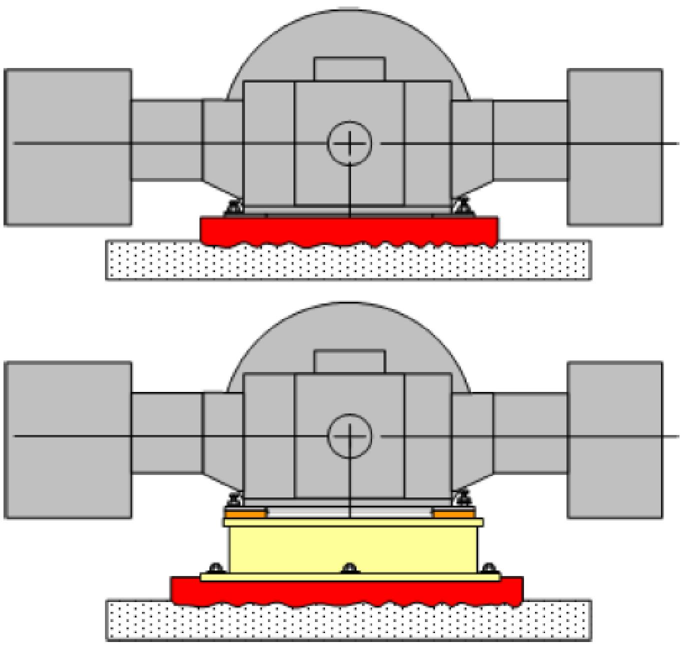


Figure 11.2 Straight versus skid mounted compressors [14]

11.2 Skid design

For engine and compressor frames over 3680 kW, a block mounted foundation is recommended. For units up to and including 3680 kW, guidelines in this section are best practices for skid design. Figure 11.4 and Figure 11.5 show the preferred skid design that has resulted in best practice for this class of equipment.

11.2.1 Skid beams

The skid shall have four full-length main runner beams parallel to the crankshaft (item 1 in Figure 11.5) with additional width in the engine area for auxiliaries and maintenance platforms. Two runner beams shall be located below the compressor feet and two runner beams located below the crosshead guide support. Full depth transverse beams are typically installed near the crosshead guide support anchor bolts and compressor frame anchor bolts, see example in figure

All beams are full depth. All beams shall have full coped connections; keyed connections with webs cut out under the flanges are not acceptable. The beam flanges shall have full penetration welds and the beam webs shall have fillet welds all around.

The height of the skid beams must be designed to minimize the height of the compressor above the foundation, while still allowing for the proper discharge bottle size to be installed. Mounting the discharge pulsation bottles directly on the foundation, off the skid as shown in Figure 11.4, usually reduces the required beam height.

11.2.2 Pedestal

The compressor sits on a pedestal (item 2 in Figure 11.5) that shall be extended out under the crosshead supports. The pedestal beams shall match the main skid beams with the beam webs aligned vertically. Compressor frame anchor bolts extend through the pedestal and main skid beams. Crosshead guide support anchor bolts must be located as close to the web of the skid beam as possible, leaving enough space for accessing anchor bolt nuts for tightening.

Access holes may be required in the skid top plate to check grouting and tightening the internal anchor bolts. These require removable covers, as open holes pose a trip and fall hazard.

It is important to note, that unlike the majority of high-speed compressor skids, the coolers for large pipeline and gas storage applications, if required, are mounted off the main skid. Scrubbers may also be mounted off the skid, and this practice often permits more rigid and less vibration prone mounting.

11.2.3 Top plate

The pedestal and skid shall be covered with a 38 mm thick steel top plate that adds rotational stability to the pedestal and skid.

All components and their mountings shall be welded to the skis structural members, NOT to the deck plates.

11.2.4 Grout boxes and soleplates

The compressor frame and crosshead supports shall be levelled and supported with grout boxes and soleplates (item 3 in Figure 11.5) on top of the compressor pedestal. The engine is supported by a deep engine pedestal with external gussets for horizontal stiffness (item 4 in Figure 11.5). The engine is supported and levelled with screw or incline plain adjustable devices on top of 1 inch thick support plates.

11.2.5 Anchor bolts

Perimeter anchor bolts shall be placed at the end of main skid beams, under the engine and compressor feet, at all skid corners and at the end of internal main runners (item 5 in Figure 11.5).

11.2.6 Skid gussets

Two full depth skid gussets shall be welded on both sides of each anchor bolt of the compressor and auxiliary equipment, see examples in Figure 11.3.
Gussets must be a minimum distance from the anchor bolt, but leaving enough space for accessing nuts for tightening.

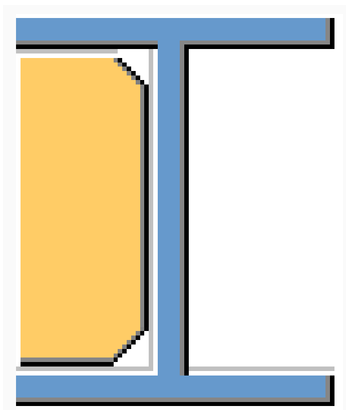


Figure 11.3 Examples of vertical stiffener plates

11.2.7 Scrubbers and secondary bottles

Scrubbers and/or secondary volume vessels are mounted off-skid and welded to 50 mm, grouted, foundation plates (item 6 in Figure 11.5). This normally insures flexibility for the suction bottle inlet flange to enter horizontally into the vessel head. Vertical suction vessels shall be located as close to the main skid as practical.

11.2.8 Pulsation dampers

Discharge pulsation dampers can be mounted either on the skid and off the skid.
Disadvantages of discharge dampers mounted on the skid:

- Compressor must be mounted higher on a sub-skid or pedestal, resulting in a lower stiffness and a higher change on vibrations.
- Higher cg's for prime mover and compressor.
- Larger moments.

Advantages of discharge dampers off the skid (hanging over the side):

- Compressor mounted lower.
- Smaller moments.
- Higher stiffness resulting in lower vibrations.
- Separate pads and clamps must be provided for bottles.
- Design not as "clean".

Discharge bottles are overhung off the skid to achieve low pedestal heights and low centres of gravity. The discharge bottles are supported with bottle wedges in-line with each compressor nozzle and wedges with straps for extended bottle overhangs. The distance between the bottom of the discharge bottle and the bottom of the wedges shall be around 150 to 200 mm. The wedge supports shall be mounted directly on grouted, foundation sole plates or skid beam outriggers that are grouted (item 7 in Figure 11.5).

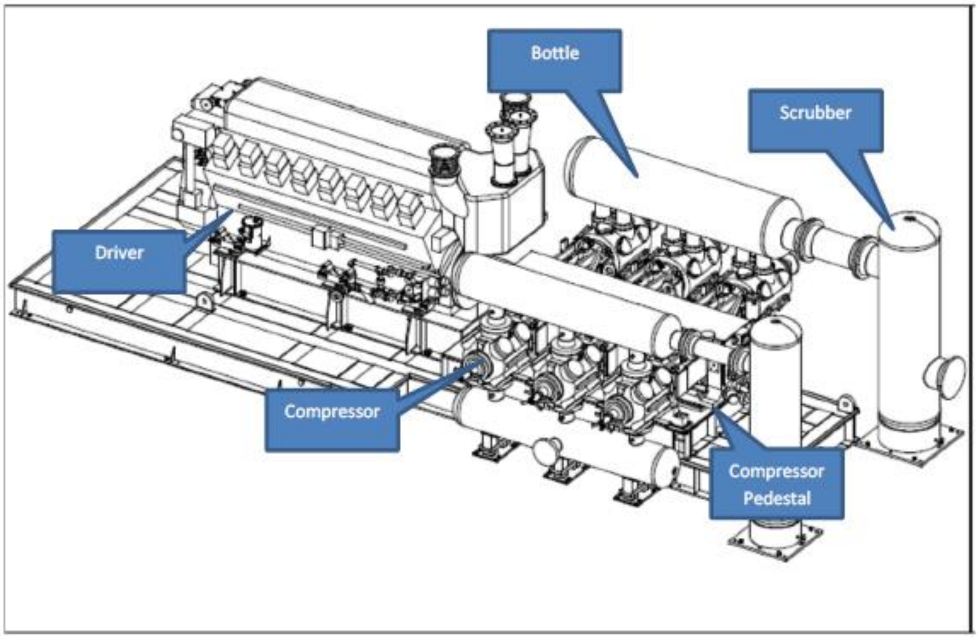


Figure 11.4 Preferred Large power high speed compressor skid construction [7]

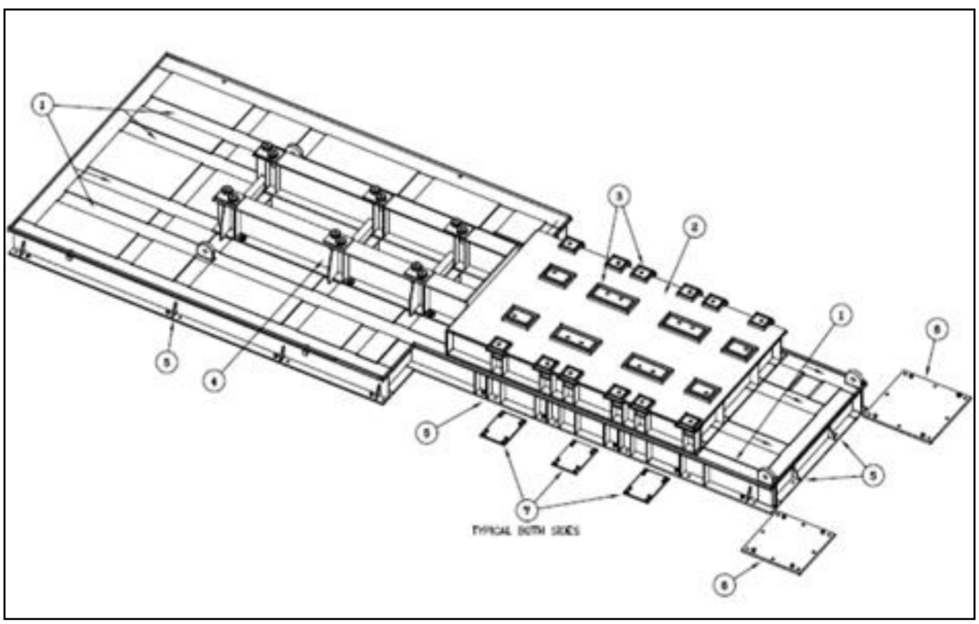


Figure 11.5 Detailed view of preferred large power high speed compressor skid construction [7]

11.3 Skid static design requirements

The skid must be designed to withstand static loads that occur during fabrication, transport, installation and operation of the equipment. The skid and package are usually lifted by cranes in the packager's facility as well as on-site when being installed. Deflection of the skid during the lift can cause distortion of the skid which must be prevented. Small skid packages are often loaded and unloaded by pulling the skid off a tail board truck, which can cause high loads on the structural elements. Some jurisdictions require analysis of the loads on the skid and the anchoring system (tie-downs) that occur during transportation of the skid from the packager facility to the operating location.

Once installed and operating, static skid loading includes major equipment weight, auxiliary component weight and anchor bolt forces. In addition, wind loads, seismic loads or other environmental loads experienced during operation are typically analysed as static loads. The skid design must be designed so that it can manage these static loads.

11.4 Skid Dynamic Design Requirements

The skid will also experience significant dynamic loads from the compressor and driver that must be evaluated. Dynamic loading includes driver dynamic (roll) torque, crankshaft inertia unbalance forces and moments, vertical crosshead forces, and time domain gas and inertia forces at each compressor throw. Dynamic loads can cause vibration of the skid or components mounted on the skid if the skid design is insufficient. Vibration analysis of skids and foundations is discussed in more detail in Chapter 7 of the GMRC Guidelines", [7], however a few additional best practices are worthy of note in this section.

Only proven, industry accepted software shall be used for modelling and analysis. The entire energy path must be included in appropriate detail, including the mounted equipment, skids, soleplates, grout, anchor bolts and foundation. The concrete and reinforcement shall be modelled as individual members (see Figure 6.17). Dynamic loads to be applied to the model include driver dynamic (roll) torque, crankshaft inertia unbalance forces and moments, vertical crosshead forces, and time domain gas and inertia forces at each compressor throw. It is not necessary to include pulsation forces in the piping when doing a dynamic foundation analysis.

The dynamic analysis is often done for only the compressor package when the package is mounted on a concrete foundation. This approach assumes the concrete foundation will not be resonant and will be much stiffer than the compressor skid. This assumption must be supported by dynamic analysis of the foundation and soil. Experience has shown that a concrete block foundation can be flexible and resonant if the soil restraint is insufficient or the block foundation is not stiff enough.

Highest stress levels in a properly designed foundation occur at anchor bolt disks due to preload. Anchor bolt disks must be in 3D reinforcement cages. The second highest stress levels are the top of equipment pedestals due to equipment weight and anchor bolt forces. Pedestal loads are spread out with the use of soleplates, chocks and grout. Stresses due to dynamic loads are small relative to the stresses resulting from static loads.

When the compressor package will be mounted directly on piles, the dynamic analysis must also include the pile foundation.

Damping

Damping reduces vibration. Concrete reinforced with reinforcement has a test range of 7 to 10% damping. A value of 7.5% is recommended for calculations.

Steel skids with equipment have a lab test range of 2 to 4%. A value of 2.5% is recommended.

11.5 Concrete fill

Adding concrete to the skid is generally beneficial in reducing vibration on the skid as well as components on the skid. Concrete has the benefit of adding stiffness as well as adding damping. Concrete is recommended in the skid below the compressor crankcase, crosshead guides and coupling area between the compressor and driver. Concrete is often recommended for the area below the driver particularly for high power units. If scrubbers are mounted on the skid, the area under them shall also be filled with concrete. Best practice, however, is to mount the scrubbers off-skid. If the skid design includes a pedestal or pony skid as shown in Figure 11.6, the concrete shall be filled in the pedestal in the same areas as the main skid, see Figure 11.7. If the pedestal is not filled with concrete, provisions must be made to allow for concrete to be added on-site, if required.

Concrete has a low bond strength with steel, and concrete fill can have a tendency to powder at edges and break loose from steel. A mechanical connection between the concrete and steel using Nelson studs of which an example is shown in Figure 11.8 or reinforcement welded to the beams is recommended. Note that welding reinforcement can be problematic, as the material properties of reinforcement can be highly variable (e.g., inclusions of chrome from recycled material).

Some concrete shrinks significantly as it cures and shall not be used. Additives can be used to prevent shrinkage or even cause the concrete to expand as it cures.

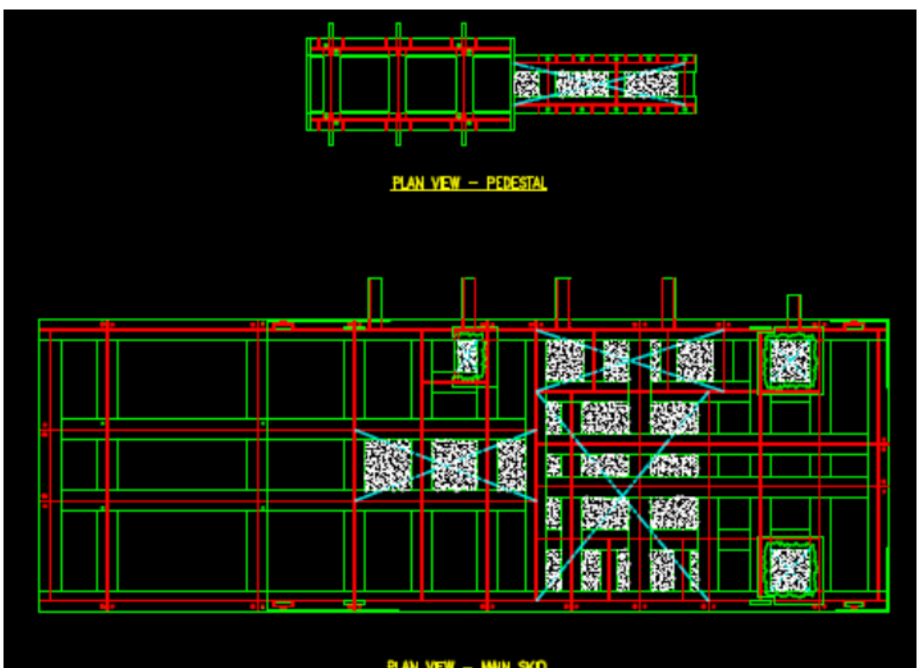


Figure 11.9 Typical skid showing concrete fill locations [7]

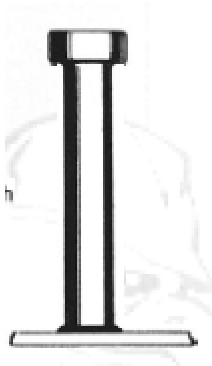


Figure 11.10 Example of a welded Nelson stud

11.6 Anchor bolt locations

Anchor bolts are recommended on the perimeter of the main skid as well as key locations on the interior of the skid. The locations are normally at the perimeter of the load-transmitting skid beams.

11.6.1 Exterior bolt locations

As a minimum, skid anchor bolts shall be located at the following perimeter locations, as shown as blue dots in Figure 11.11 as follows:

- Corner of main skid, scrubber outrigger boxes and pipe support outriggers.
- Ends of main transverse beams under compressor and driver feet.
- End of main transverse beams under scrubber support plates.
- Ends of main transverse beams under skid-mounted coolers.
- End of main transverse beams under crosshead guide supports.
- Ends of main longitudinal beams at both ends of the skid.

11.6.2 Interior bolt locations

Interior anchor bolts are typically recommended near the crosshead guide supports, all compressor and driver anchor bolt locations as shown in red dots in Figure 11.11.

11.6.3 Auxiliary equipment

It is recommended to mount scrubbers and/or secondary volume vessels off-skid and welded to 50 mm, grouted, foundation plates (item 6 in Figure 11.5).
This normally insures flexibility for the suction bottle inlet flange to enter horizontally into the vessel head. Vertical suction vessels shall be located as close to the main skid as practical. Discharge bottles are overhung off the skid.

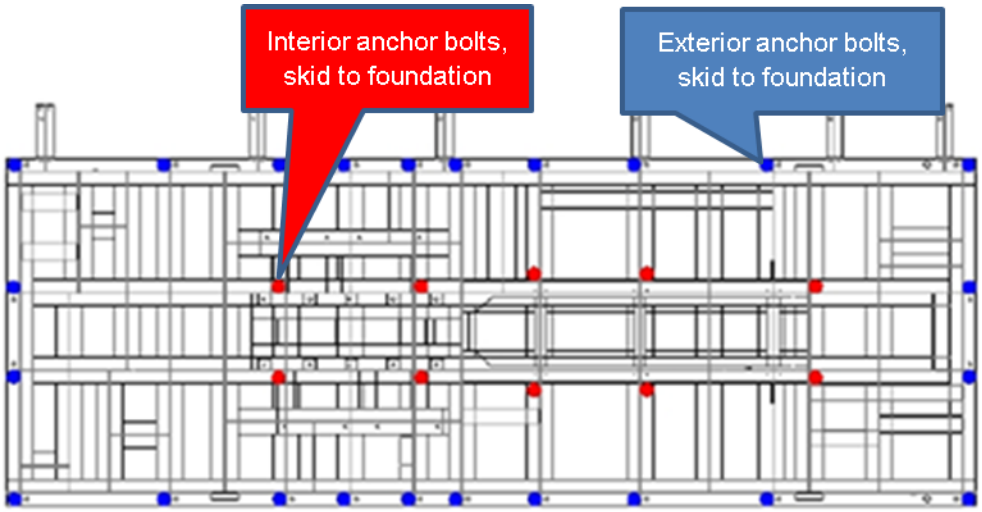


Figure 11.11 Skid bolt locations [7]

11.7 Anchor bolt length

Anchor bolts must have a free bolt length of at least 12 bolt diameters, see also chapter 8.8.4. The free bolt length is necessary to allow the bolt to stretch in the tension direction and to allow movement of the frame caused by thermal expansion.
Extended length of crosshead guide and compressor anchor bolts can be achieved by applying extension tubes as shown in Figure 11.12 through Figure 11.14

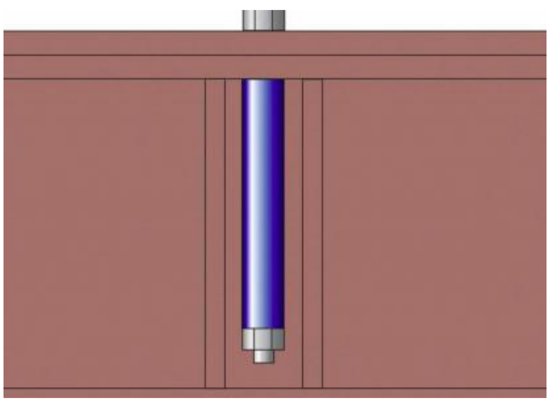


Figure 11.12 Extension tube used to lengthen the bolt

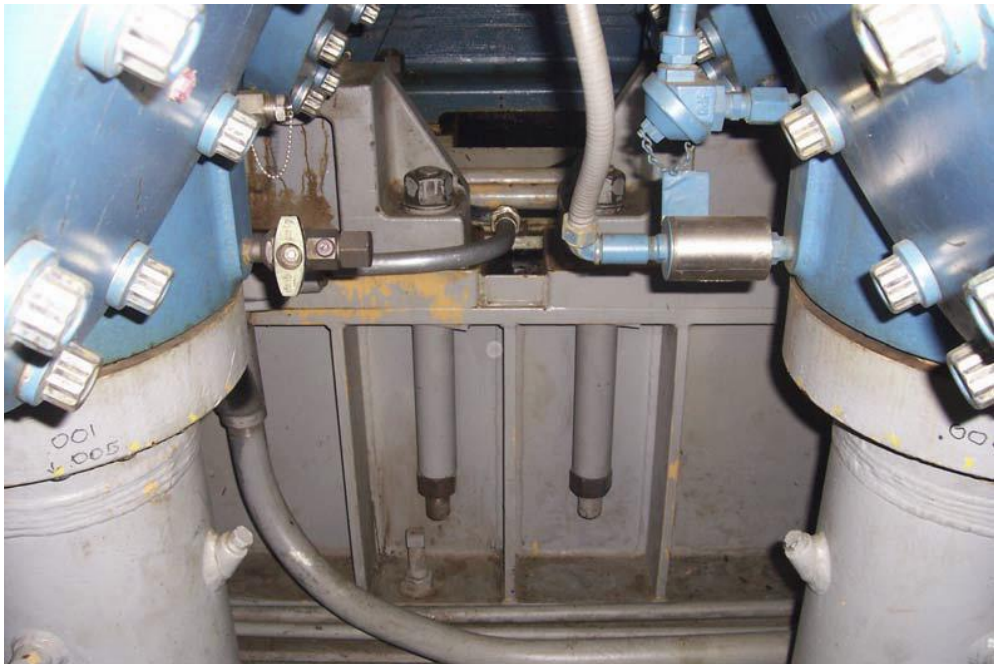


Figure 11.13 Example of achieving extended length of crosshead guide anchor bolts [6]

Figure 11.14 Example of achieving extended length of crosshead guide anchor bolts with reinforcing horizontal plate [6]

Figure 11.15 Example of achieving extended length of crosshead guide anchor bolts, including horizontal reinforcing plate [6]

11.8 Loads to be considered

The static and dynamic loads which act on the anchor and crosshead guide support bolts are summarised in chapter 4.
The static and dynamic loads which act on the bolts, which connect the skid to grout/concrete, are more difficult to determine due to the fact that the loads acting on the compressor anchor bolts and crosshead guide support bolts will be distributed over all skid anchor bolts. If a detailed model is not available, the most easiest way is to assume that the loads will act on the nearest bolts.
This means that different skid bolts could have different diameters. However, it is advised to use the same diameter for all skid bolts.

11.9 Anchor bolt diameter and material

As indicated before, the compressor frame configuration normally sets the number and diameter of anchor bolts, limiting the options available for maximizing preload capacity to choice of material, length, and thread configuration. This means that the maximum possible bolt diameter shall be chosen. A summary of the bolt sizes is given in Table 8.2. This table gives the results for a preload for different bolt diameters and for a stress of 70% of yield strength for two different materials.
It is noted that several standards and guidelines, e.g. the API RP 686 and the VDI 2230, summarize the bolt preload in tables. However, one shall know for which percentage of yield strength they are applicable because different standards and guidelines use different preload values which will also have a consequence for the dimensions of other parts such as pocket size, edge and anchor bolt distance, soleplates, chocks etc., fatigue stress etc.

According to GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013[7]

- The bolt diameter shall be minimum 28.6 mm (1.125") for equipment and skids. Where equipment permits use of larger diameters than 28.6 mm (1.125"), use the largest size that is compatible with the mounting holes in the frame.
- Further on it is advised to use a skid bolt clearance of 1.6 mm (3.2 mm diametral clearance) on all sides.

11.10 Bolt nuts and washers

The bolt material, nuts, washers etc. as recommended in chapter 8 can also be applied for skid mounted compressors.

11.11 Bolt preload

The bolt preload as recommended in chapter 8 can be applied also for skid mounted compressors.

11.12 Interior anchor bolts

According to the CompressorTech2 article [31], it is advised to apply the following:

- For internal anchorage of the interior or longitudinal wide flange skid beams supporting the compressor and the driver, a coupled canister-type anchor bolt design allows the top anchor rod/stud, which typically terminates at the top flange, to be removed during the skid package placement, see Figure 11.16.

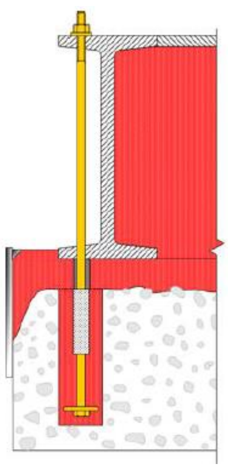


Figure 11.16 Example of canister type bolt for mounting the skid to the concrete

12 Mounting systems, base plates (sole plates) and chocks

12.1 Introduction [7]

This chapter discusses the different ways how to connect the compressor, driver and equipment to the skid and concrete.
Mounting compressors directly to a foundation block without a skid is generally preferred for units greater than 3680 kW.
In general compressors, skids and/or equipment shall not be mounted on foundations with isolators or isolation pads, also called anti-vibration mounts (AVM's). However, mounting a driver or compressor with isolation pads may be required if structure born noise (in e.g. living quarters of offshore platforms) or vibrations may become an issue. In that case a detailed dynamic analysis is required of the complete skid, including all the mounted equipment, isolation pads and the structure on which the isolation pads are mounted. A general requirement for those systems is that the structure above and below the isolation pads shall be sufficient stiff. These system shall be analysed for all possible dynamic loads to achieve an optimum design with acceptable vibration levels.
When installing equipment to the skid or block, it's important to ensure that all mounting points are flat and parallel to the equipment feet to avoid angular and parallel soft foot. Properly implemented mounts provide a robust, stable support while eliminating soft foot". Soft foot is defined as gapping between the mounting foot and the foundation surface as shown in Figure 12.1.
The classic example is a parallel gap, simply the variation between mounting points, which is to be expected in a fabricated structure. Also possible is an angular error between the two surfaces. Note that this shall not be addressed by stacking partial or "step" shims under one side of the mounting foot as they provide point contact only, and they may extrude from the joint over time. Angular soft foot shall be remedied by identifying the source and applying a fix there.
Checking for soft foot is most commonly done using a dial indicator indexed to the top of the mounting foot. With the mounts fully torqued in place, the indicator shall be zeroed. The mounting bolt torque is then released, revealing on the dial indicator what linear error exists. Final soft foot checks shall be done with the engine and compressor fully warmed up, enough so that the temperature of the mounting foot reaches a constant (or near constant) value. Be certain that jack bolts have been backed out before making this check.
In the next chapters a short explanation is given of the different mounting methods.

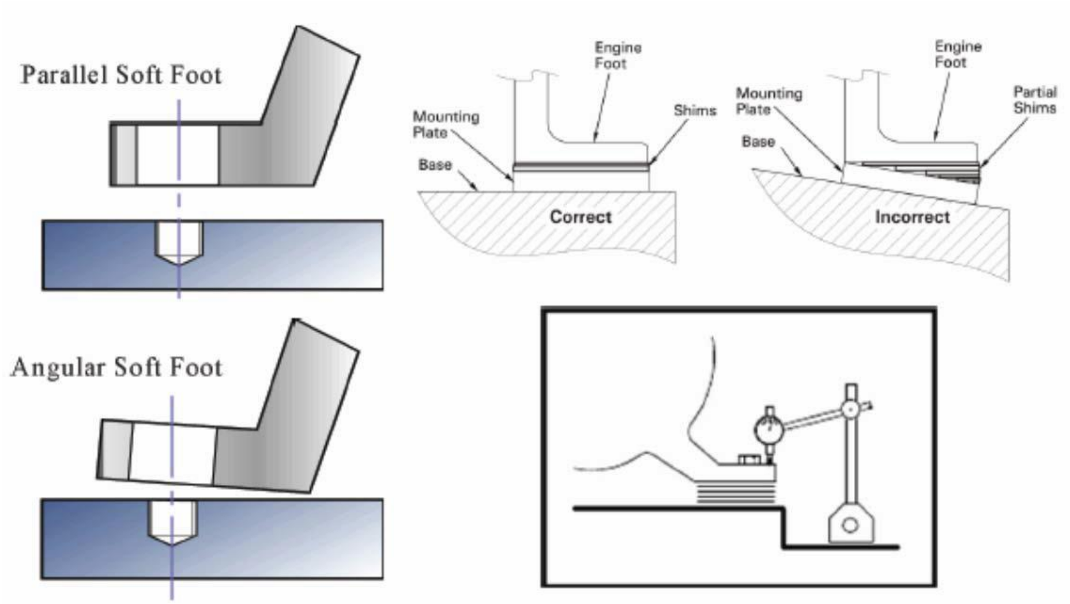


Figure 12.1 Soft foot is defined as gapping between the bottom of the mounting foot and the foundation surface. It can be verified by movement when the mounting bolts are loosened [7]

12.2 Compressor connection to skid

Mounting compressors directly to a foundation block without a skid is generally preferred for units greater than 3680 kW.
Epoxy grout chocks (see 12.7.2), metal chocks (see 12.7.3), soleplates (see 12.6) and stainless steel shim packs are often considered best practice for mounting the compressor and driver to the skid. Shim packs must not be more than approximately 6 mm thick. It is also important that no more than 3 shims are used in a pack, as more shims lead to spongy (soft) pads. Adjustable chocks in which the load is principally carried by a threaded member are not recommended under compressors or crosshead guides. Some examples are shown in Figure 12.2 and Figure 12.3.

Figure 12.2 Welded steel chokes shall be machined after welding [7]

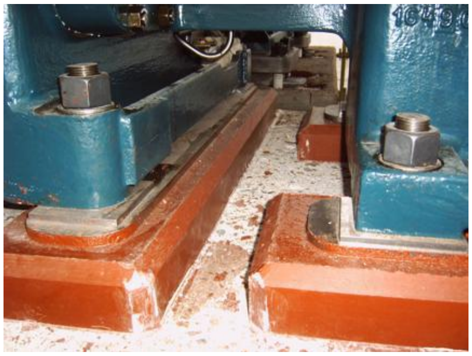
Figure 12.3 Well-designed crosshead guide supports provide high axial (parallel to the crankshaft) and vertical stiffness that usually eliminates the need for head end cylinder supports [7]

12.3 Mounting system of compressor to concrete block

Available block mounting methods include steel rail mounting, soleplates, chocks (metal or epoxy) and shims. Figure 12.4 and Figure 12.5 shows different ways how to connect the compressor to the concrete block. More details, advantages and disadvantages of soleplates and chocks are discussed in chapter 12.6 and 12.7.

Full bed grouted systems always requires soleplates and shims. New installations are mounted on chocks nowadays due to the advantages of chocks.

If soleplates and chocks are used, the upper part of the concrete block shall have a liquid tight coating to avoid that liquid will intrude into the concrete block leading to an increase of cracks.



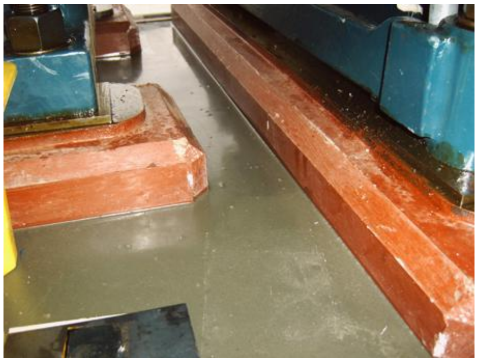


Figure 12.4 Examples of compressor mounted with shims, sole (mounting) plates and grout chocks to concrete [14]

Figure 12.5 Example of compressor mounted with grouted sole plates and grouted chocks to concrete [14]

12.4 Crosshead guide support (CHS)

The crosshead guide support must be supported on the mounting system, either the skid or the concrete block. The crosshead guide support and the part on which it is mounted shall be stiff due to the fact that large dynamic forces shall be restrained at these locations. Stiff supports also increase the mechanical natural frequencies.

12.5 Mounting systems of skid to concrete block

In general the skid can be mounted to the concrete block in two different ways, see also

1. With shims and metal or epoxy chocks mounted to the concrete, see middle and right hand picture of Figure 12.6 and Figure 12.7 . With this configuration there will be a gap between the bottom of the skid and the concrete/grout. Due to the fact that the skid does not make contact over the entire area, the skid will be more flexible which means a higher chance on unacceptable vibrations. This configurations requires a vibration analysis to ensure that the vibrations will be acceptable.
2. With a full bed grout. This means that the bottom of the skid is fully embedded in the grout. There is no gap between the bottom of the skid and the grout, see left hand side picture of Figure 12.6, Figure 12.8 and Figure 12.9. This is very stiff construction which means a low chance on unallowable vibrations and is for that reason the preferred solution and is most commonly applied nowadays.

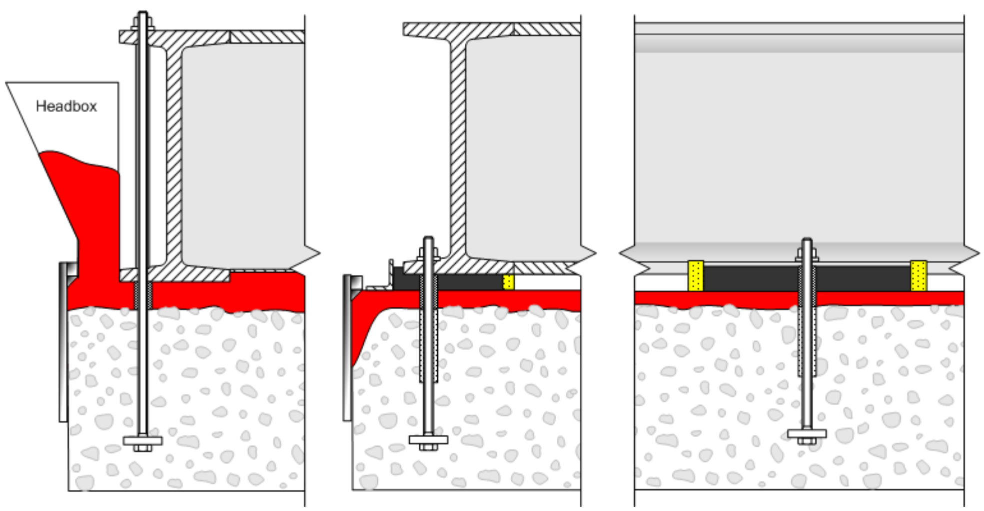


Figure 12.6 Two general applied methods of mounting the skid to the concrete

Figure 12.7 Example of a skid mounted with shims and epoxy chocks direct to concrete block [14]

Figure 12.8 Example of a full bed grouted skid [14]

Figure 12.9 Example of a full bed grouted skid [14]

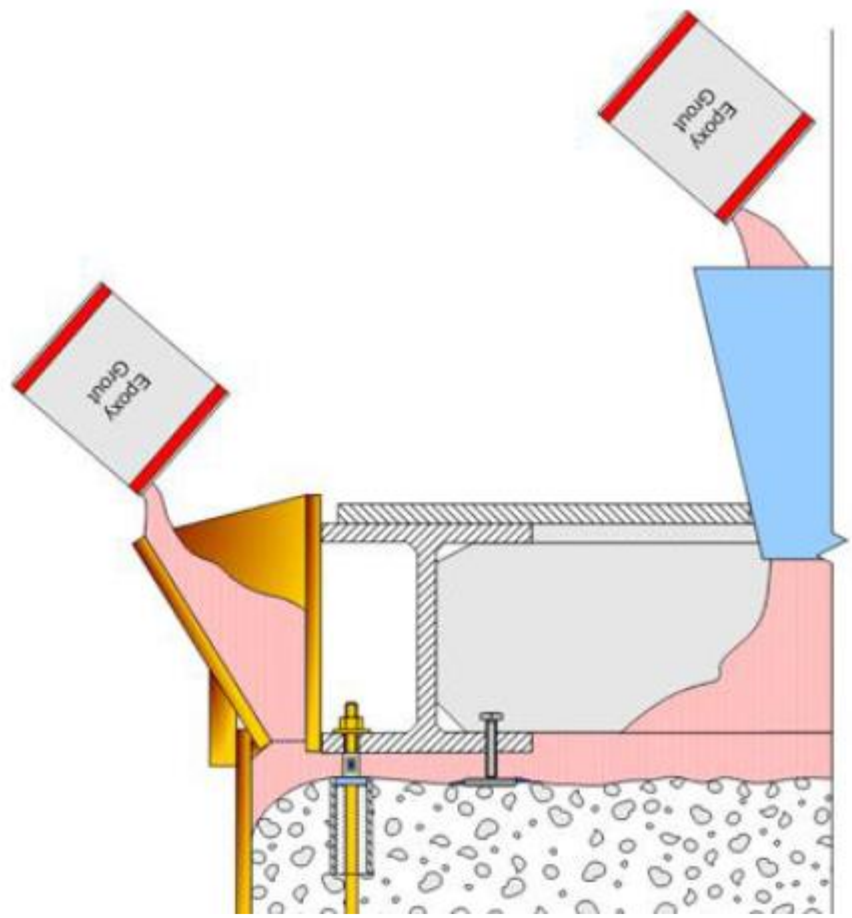


Figure 12.10 Example of a full bed grout skid [14]

12.6 Mounting (sole) plate design

According to the API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009 [11]:

- Unless otherwise specified by the user, all equipment shall be installed on mounting plates.
- All mounting plates outside corners shall have a minimum of 50 mm radius to prevent cracking of the foundation plate due to stress concentration at the corners.
- All mounting plates anchor bolts holes shall have a minimum 3 mm diametral clearance with the anchor bolt to allow for field alignment of mounting plates.
- Mounting plate machined surfaces shall extend at least 25 mm beyond the outer tree sides of equipment feet as installed (necessary area for levelling)
- Mounting plates shall be provided with vertical levelling screws, as opposed to shims or wedges. Shims and wedges (under the mounting plate) are not be used because if they are left in place after grouting, may cause "hard spots" that interfere with the grout's ability to provide uniform base support. They also allow moisture penetration and the resultant corrosion and grout spalling.
- Elevation adjustment screws are not permitted under the mounting plate that will be grouted in and become a permanent part of the foundation. This allows the mounting pate to be supported by the grout, not by the levelling devices.

If the mounting plates will be mounted in the grout, the dimensions of the mounting plates can be calculated with equation (12.1).
It is assumed that the load of the equipment will be distributed equally over the mounting plate.
Some examples of mounting plates are shown in Figure 12.4 and Figure 12.11.

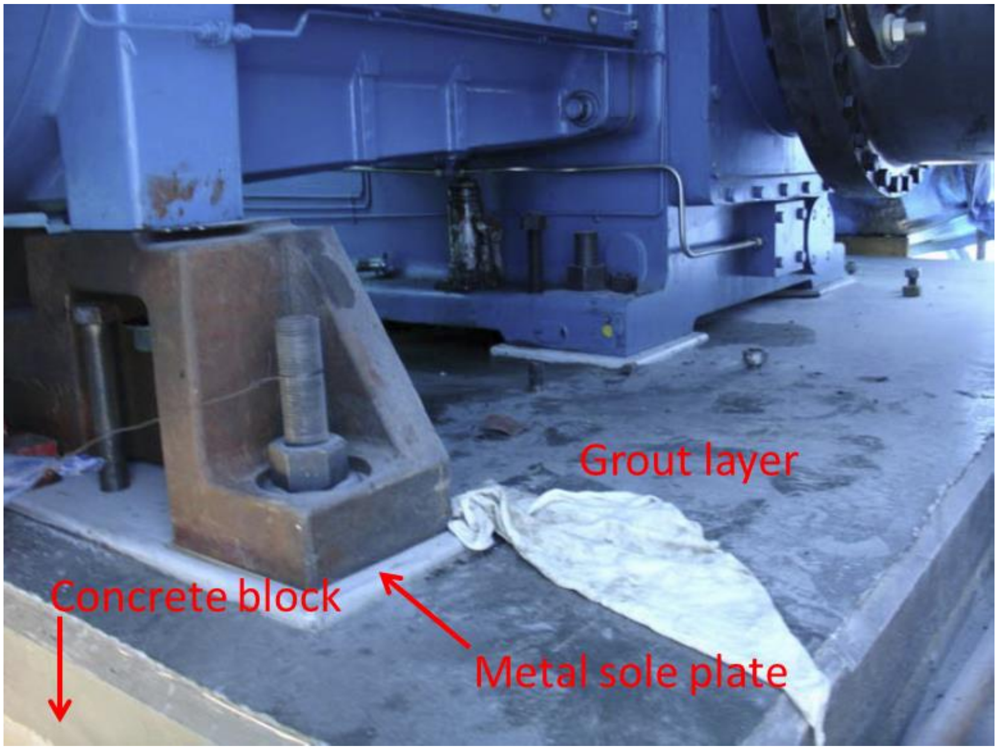


Figure 12.11 This example shows the foot for a block-mounted JGV6 medium speed compressor. The compressor foot is held against a metal sole plate by an anchor bolt. The anchor bolt is set into the. The sole plate is grouted into the concrete [6]

12.7 Chocks

12.7.1 Introduction

Chocks (metal or epoxy grout) provide for an extensive air gap, inhibiting heat transfer from frame to block, reducing foundation thermal distortions. Chocks provide a series of positive tie down points with fixed, computable, interface conditions.

Chocks support the frame and transmit the static and dynamic loads from the frame to the grout or sole plate on the block. The horizontal frame forces are transmitted through the chock by shear. For this transmission to take place, there must be no relative movement between the chock and the bottom of the frame and between the chock and the sole plate or grout. The only thing to keep the chock from slipping is friction which has been thoroughly explained in chapter 7.3.

The vertical static and dynamic loads as summarised in chapter 4 and Appendix A and the bolt preload as summarised in chapter 8.5 shall be used as design loads to determine the chock loading area.

Chocks and chock materials are available from a number of commercial sources. Several specialized designs have been developed to meet specific needs and requirements. The best chock for a particular application depends on a number of factors and the main chock selection factors are as follows:

- Height needed.
- Thermal isolation requirements.
- Adjustability and ease of adjustability.
- Coefficient of friction with frame and sole plate/grout.
- Pourability.
- Durability, stability, and chemical resistance.
- Young’s modulus.
- Compressive and shear strength.
- Creep properties (for epoxies).
- Cost (first and life-cycle).

The most applied materials for chocks are epoxy grout and steel of which the advantages and disadvantages are summarized below.

Advantages of steel chocks:

- Stronger than alternatives.
- Stiffer than alternatives.
- Does not creep.
- Adjustable using shims.
- Smaller chock bearing area required because of higher compressive strength.

Disadvantages of steel chocks:

- High thermal conductivity.
- Cannot be poured in place.
- Not self-levelling.
- Require precision machining and shims to achieve required support height.
- Subject to fretting and wear damage if anchor bolts become loose.
- Typical steel chocks touches the sole plate on a limited number of points, which can lead to fretting.

Advantages of epoxy chocks:

- Pourable, self-levelling.
- Lower thermal conductivity than steel. This means that the heat build-up in concrete foundations will be reduced reducing the possibility of thermal distortion. They also reduce frame distortion commonly, most typical for large systems with full bed grout.
- Less damaged by fretting and wear if anchor bolts become loose.
- If cast in place, they fit perfectly with 100% contact.
- Epoxy chocks have less creep than foundation grout layers, resulting in less bolt pre tension.

Disadvantages of epoxy chocks:

- Less stiff than steel.
- Susceptible to low temperature creep.
- Weaker than steel in compression and shear requiring larger bearing areas than steel.
- Some formulations are brittle.
- Higher coefficient of thermal expansion than steel, cast iron, or concrete.

12.7.2 Epoxy chocks

One shall be aware that in general the material properties of epoxy grout and epoxy chocks differ. The manufacturer shall always be contacted for a correct application and material properties of the chock. It shall be noted that foundation epoxy grout <u>layers</u> can contribute more to creep loss of anchor bolt tension than epoxy <u>chocks</u>. However, to stay on the safe side the design value of the compressive strength of epoxy grout of 6.9 MPa, see chapter 7.2.5.1. can be used for the epoxy chock.

The machine weight, the dynamic vertical downwards (peak value) loads, and the applied anchor bolt tension must be considered when sizing the chock area. The minimum required load bearing area can be calculated with the following equation:

$$A_{lb} = \frac{F_v}{\sigma_b} \text{ (mm}^2\text{)} \tag{12.1}$$

In which:

> F_v[1] = summed maximum design load (N)
> A_{lb} = load bearing area (mm^2)
> σ_b = design value of epoxy grout compressive strength (MPa)
>
> [1]Fv shall be the sum of maximum (static) deadweight as summarised in chapter 4.2 and the sum of the dynamic (peak) loads in the downwards direction as summarised in chapter 4.3.

If the required anchor bolt loading results in excessive chock stress, the options are:

- increase chock surface area.
- change chock material to one with higher capacity.
- reduce anchor bolt tension (not recommended).

The grout box can be cast-in-place with a metal welded grout box, see Figure 12.12 and Figure 12.13 or without a grout box, see Figure 12.14.

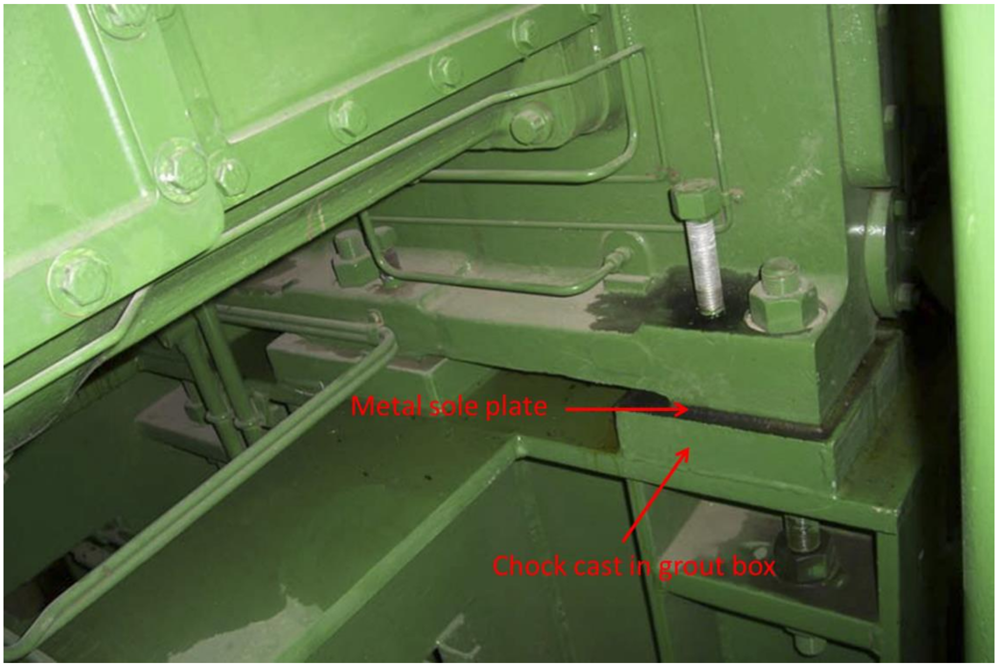


Figure 12.12 Compressor Foot of JGD4 Driven by Cat G3616, Mounted on Chock Set in Grout Box [6]

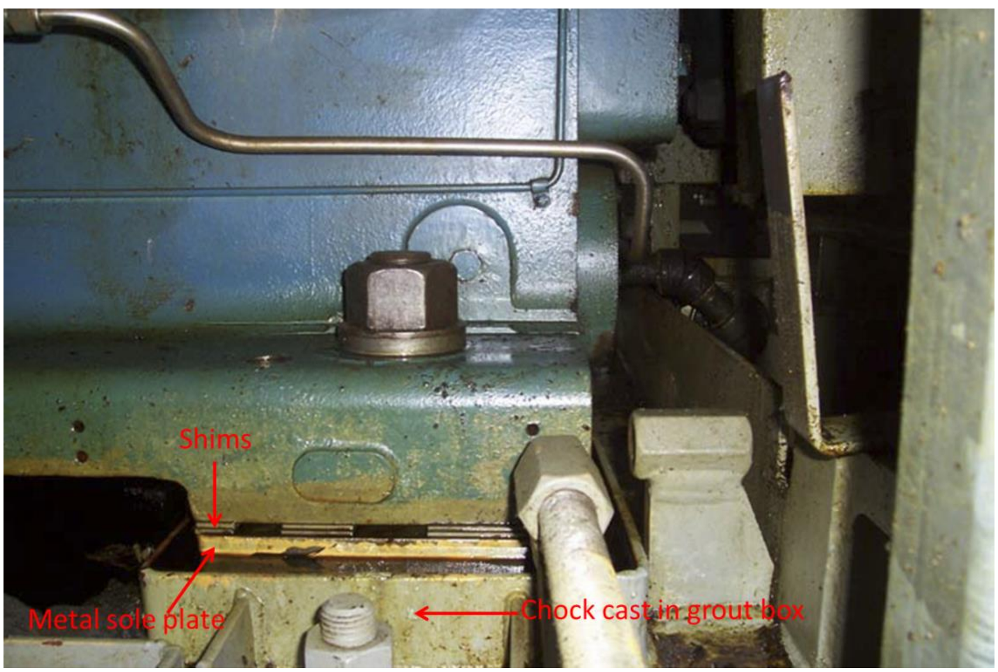


Figure 12.13 Foot is anchored to skid and supported by shims on chock, which is set in grout box. Jacking screws for horizontal adjustment can be seen [6]

Figure 12.14 Example of a poured in place chocks [20]

12.7.3 Welded metal chocks(material from [7])

Note that flatness and parallelism can be difficult to achieve with the use of welded steel chocks of the type shown in Figure 12.15. The mounting method depends heavily on the packager's ability to duplicate skid flatness at installation. It is recommended that steel chocks be machined after welding to avoid angular soft foot.

Figure 12.15 Welded steel chock (shall be machined after welding) [7]

12.7.4 Adjustable chocks

Adjustable chocks in which the load is principally carried by a threaded member are not recommended under compressors or crosshead guides. However, they have been used successfully for engine mounting, which requires any more mounting points and more tedious adjustments during the alignment process, see chapter 13.3.

12.8 Alignment tools [14]

12.8.1 Introduction

Some sort of jacking device must be used to position the compressor and driver. There are many different types of jacking devices and all (except nuts on anchor bolts under the mounting plate) are acceptable if they are removed completely from the grout.

Jacks, wedges, shims, and blocks of any shape or size must never be left inside the grout, otherwise cracks are guaranteed.

For large weight units (approximately >60.000 kg), jacking screws cannot be used anymore. For those cases the soleplates shall be aligned and mounted into the grout before mounting the unit on the soleplates.

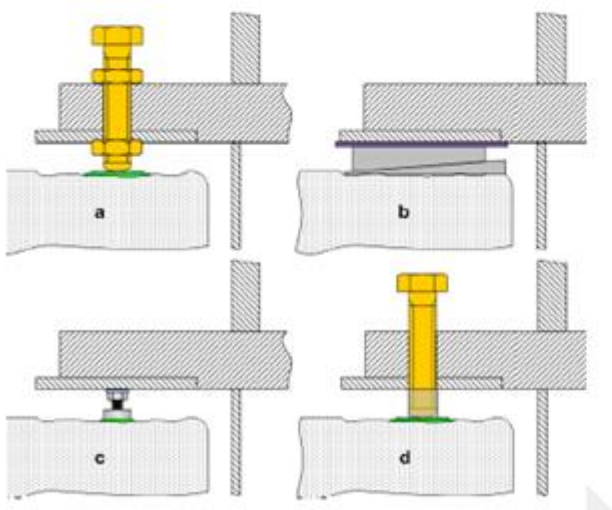


Figure 12.16 Examples of different jacking devices [14]

12.8.2 Jacking screws

- The best practice here is to use jacking screws, see (d) from Figure 12.16 and back out the screw completely after the grout has cured. Left in place, the jacking screws can be crack initiation sites. This can be done if the threads of the jacking screws are coated with non-melt grease. Jacking devices that are isolated and grouted around must have a second pour to fill in the space where the jacking screw was located. This is costly and unnecessary. The best practice is to use jacking screws with non-melt grease on their threads. This is more cost effective as it allows the entire area to be grouted at one time.
- The vertical jacking screws shall be mounted adjacent to each anchor bolt.
- Jackscrews shall be engineered to carry full weight of skid, concrete fill, and mounted equipment under all conditions expected during skid levelling.

  Minimum 3 jacking screws are advised to use per side.

12.8.3 Jackscrew landing pads

- A best practice is to have the jacking screw touch-down on a relative thin, round, landing plate with rounded edges, according the API Standard 686 [11], see Figure 12.17 .
- Do never use square levelling pads.
- Radius pads on the edges to reduce stress concentrations in the grout.
- The levelling pad shall be stainless steel, it shall be free of dirt, oil, scale or burrs.
- The 10 mm drill points as indicated in Figure 12.18 is only required when the levelling pads are NOT to be grouted in position.

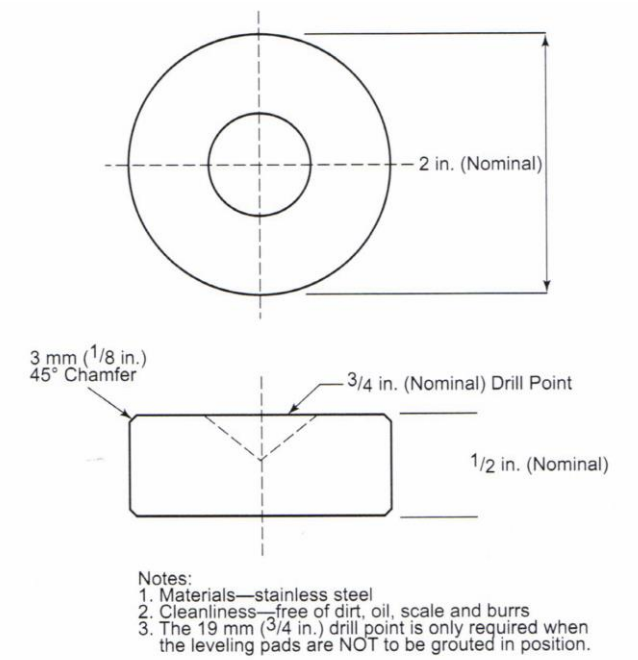


Figure 12.17 Typical mounting plate levelling pad according to the API Standard 686 [11].

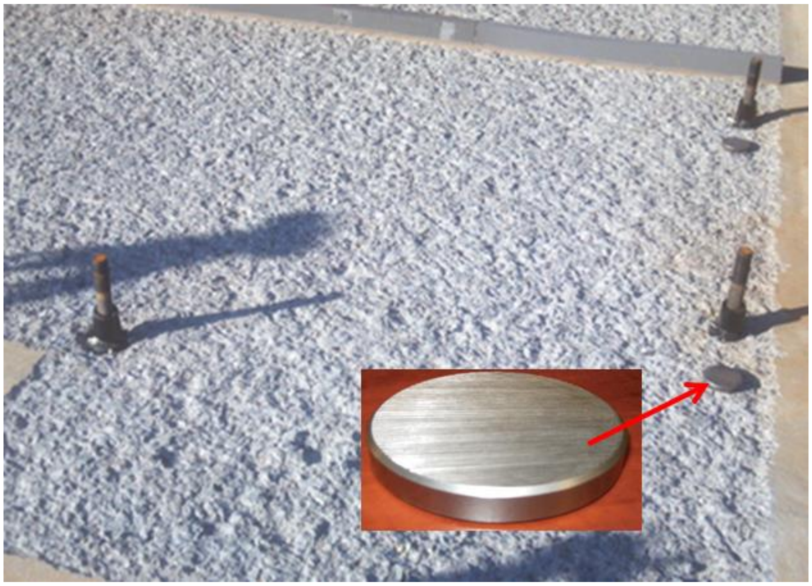


Figure 12.18 Picture of a jackscrew landing pad

12.8.4 Anti-Vibration Mounts (AVM's)

Purpose

Elastic mounts are used in order to isolate the compressor system from the supporting structure (in general the concrete foundation or earth), to avoid that the dynamic loads introduced by the machine will have a negative influence on the dynamic behaviour on the surrounding structures, e.g. structure borne noise transfer for offshore platforms, vibration transfer to other equipment via weak soil, etc. The elastic elements (springs) are usually located below the machine skid and occasionally (if necessary) even below the complete foundation block

Elastic mounts are not used to achieve lower vibrations of the machine itself. On the contrary, depending on the available mass of the system above the spring elements, higher vibrations of the compressor system can be expected compared to rigid mounts. The system shall be designed such that the vibrations of the system above the elastic elements are acceptable to operate safe and reliable for the long term. The cyclic stress in the attached pipe system shall also be within the fatigue limits.

Design

The vibration isolation of elastic mounts shall be accomplished by locating the mechanical natural frequencies (MNF's) with dominant loads of the system far below the lowest rotational speed frequency. As a rule this separation shall be minimum 20%. Such system is termed "low tuned" as opposed to "high tuned" with rigid mounts.

Sometimes only the vertical movement is considered in the design of AVM systems. This can be done in a very easy way even by hand calculations. However, it shall be noted that any rotational movement or forces in the horizontal direction, which is usually also present or even dominant (and is often just forgotten to be considered) may be even more critical and needs particular attention. Examples are: two throw vertical compressor which may introduce large moments and a V-type compressor which has an unbalanced horizontal force and a horizontal boxer compressors which have unbalanced forces acting on the foundation blocks and which have their centre of gravity far below the machine centre line etc.

A typical design sequence is the following:

1. Spring element selection
   Select the number and size of the spring elements capable to carry the full static (weight) of all equipment. Keep in mind that it is sometimes necessary to use different spring stiffness on different locations to keep the system in a horizontal plan as a result of the static loads. Manufacturers of elastic elements provide guidance for the initial element selection. Considering just the vertical vibration mode, the static weight load capacity of the elements and their vertical stiffness, a mechanical natural frequency can be calculated.

2. Set up of calculation model.
   The most comprehensive calculation model is the use of a full finite element analysis (FEA) model. However, as a first estimate, the supported system can be considered stiff compared to the spring elements. In this case it is sufficient to lump all system components in terms of their translation mass and moments of inertia . An example of such a model is shown in Figure 12.20 of an existing system as shown in Figure 12.19.

3. Calculation of mechanical natural frequencies (MNF's)
   Calculate and check if the MNF's of the dominant loads (in most cases one and two times compressor speed) are below the lowest possible crank shaft speed.

4. Calculate response
   Excite the model with unbalanced forces and compare the isolation efficiency and dynamic loads which are acting on the spring elements and the vibrations of the compressor system and compare them with the acceptable limits.

   The isolation efficiency η is defined as follows:

$$\eta = 1 - \frac{Fs}{Fex} \qquad (12.1)$$

   In which:
   Fs = spring load [N]
   Fex = excitation load [N]

   In the ideal (best) case, the spring load is zero which means that no load (read vibrations) is transferred into the ground. In that case the isolation efficiency is one.
   The isolation efficiency limit is usually given by the purchaser, the static load capacity limits by the spring element supplier and the allowable compressor vibrations by the compressor manufacturer.

5. Modifications of the original design
   In case of exceedings of the limits modifications are required. Possible solutions are:
   a. Add mass to the system (fill skid with concrete, add other mass elements, locate spring elements below the foundation to utilize the foundation mass)
   b. Arrange two or more spring elements if required respectively in series in order to make them softer by keeping their static load capacity.
   c. Use viscous damper elements if low tuning is not feasible. One shall be aware that the damping force of the viscous dampers will act on the structure below these dampers. It depends on the application if the forces will not introduce structure born noise problems.

Further on it shall be kept in mind that the separation of the compressor system with the underlying structure is most optimal if the stiffness above and below the springs is much larger than the spring stiffness. For an accurate and detailed optimized design, all relevant flexible parts above (e.g. compressor skid) and below the springs shall be included in a finite element analysis.

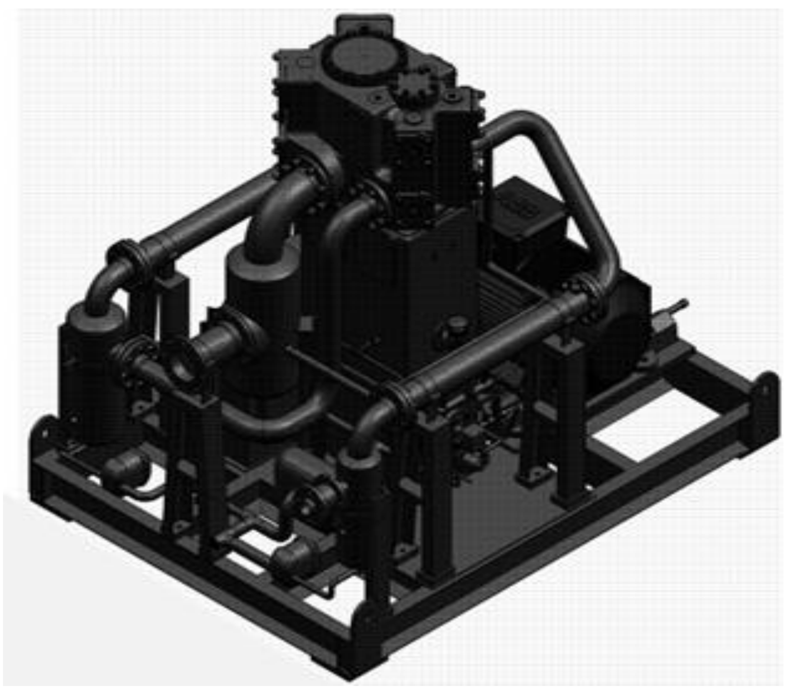


Figure 12.19 As built system

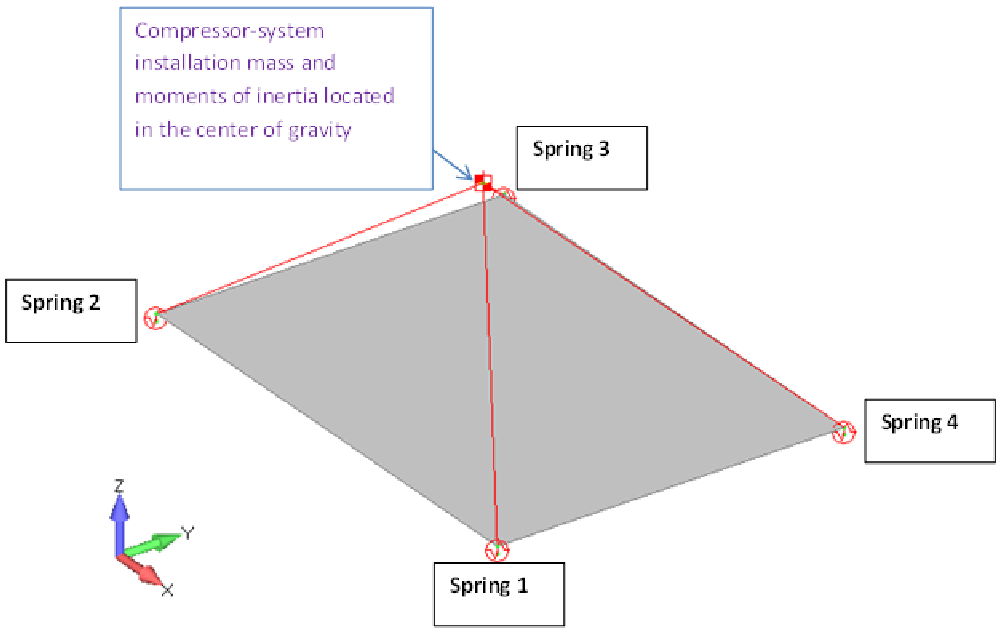


Figure 12.20 Lumped mass system

Spring element stiffness numbers must be given in all 3 translational degrees of freedom (DOF). The lumped mass element is located in the system centre of gravity and rigidly connected to the spring elements. Next to its translation mass property it provides also the moments of inertia. The centre of gravity as well as the translation mass and moments of inertia properties can be taken from the CAD system.

External forces , and if required also the torque moment fluctuations, are to be applied at their respective points of action, connected by rigid elements to the lumped mass point. External moments can be applied at the lumped mass directly. External forces and moments are the inertial dynamic foundation loads provided by the compressor manufacturer. The forced response calculation is typically run in the frequency domain.

Calculation results are 6 mechanical natural frequencies with their respective modes as well as vibration levels or transfer functions as shown in Figure 12.21.

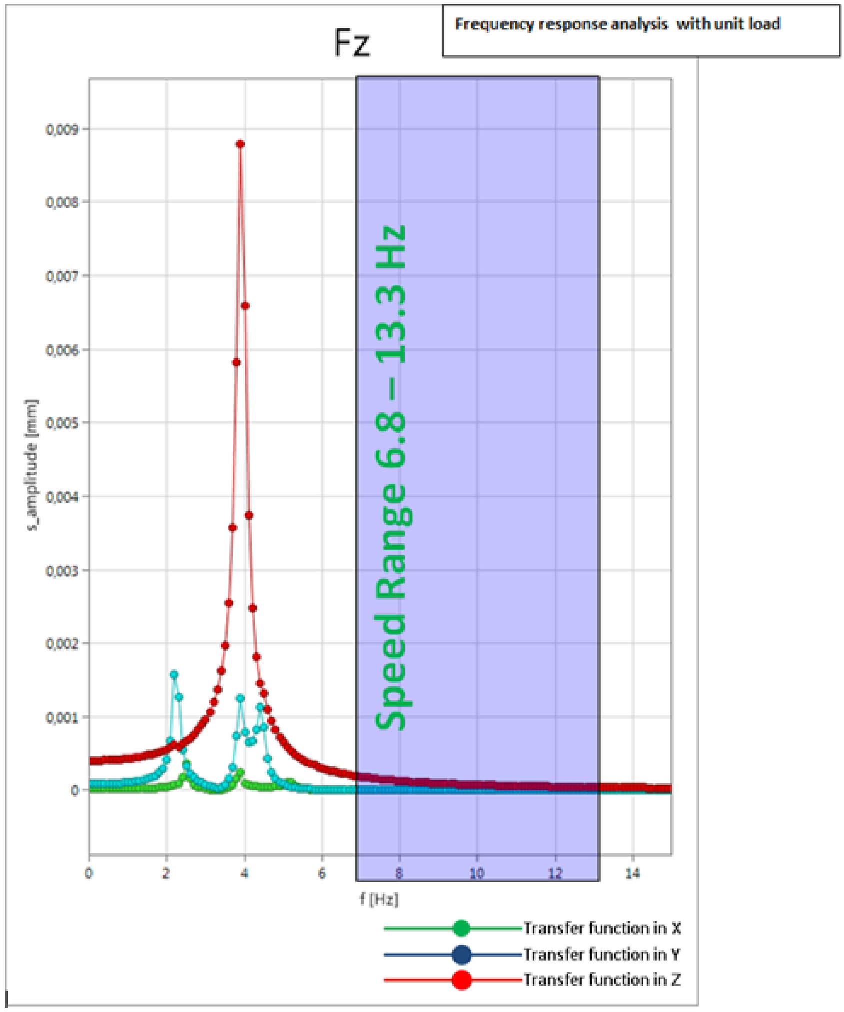


Figure 12.21 Transfer functions for a unit load (example is for a vertical (Fz) force excitation)

13 Driver mounting

13.1 Mounting on skid

Experience with threaded adjustable chocks under drivers is mixed. Best practice is a grouted sole plate design with stainless steel shims mounting system of compressor to skid. Adjustable chocks are often used under engines, which have more hold-down bolts and lower vibratory forces that need to be restrained.

Figure 13.1 Note engine foot mounted via shims on chock set in "red" grout box. Grout box is welded to skid. Note heavy gusseting of skid [6]

13.2 Mounting on concrete

Figure 13.2 Mounting examples of an electric motor with shims and soleplates in grout bed [14]

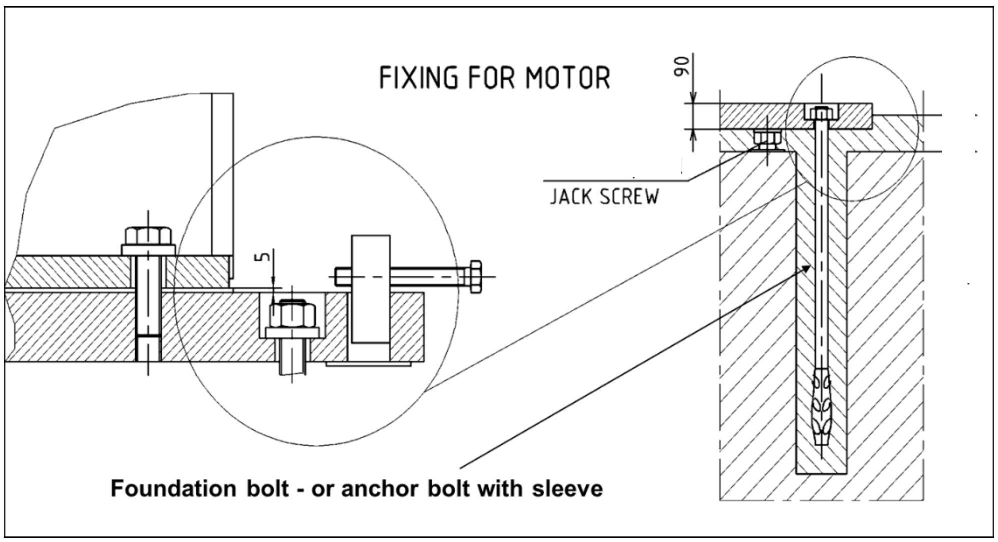


Figure 13.3 Typical fixation of E-motor

13.3 Adjustable mounts (material from [7])

Adjustable chocks in which the load is principally carried by a threaded member are not recommended under compressors or crosshead guides. However, they have been used successfully for engine mounting, which requires any more mounting points and more tedious adjustments during the alignment process. Some examples are shown in Figure 13.4 through Figure 13.6.
Adjustable engine mounts must be designed for the environment in which the unit will operate. That requires that they be appropriately lubricated as shown in Figure 13.6 and protected from corrosion and dirt contamination prior to the initial installation and perpetually through the life of the equipment. They must provide solid, stable support over years of operation in potentially hot, high vibration conditions, even subject to the prevailing weather.

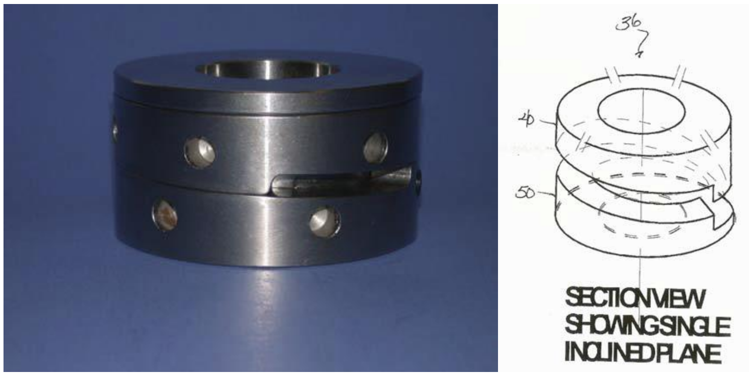


Figure 13.4 Schematic of Alternative Adjustable Mount – Patent Pending (Courtesy Robert L. Rowan and Associates) [6]

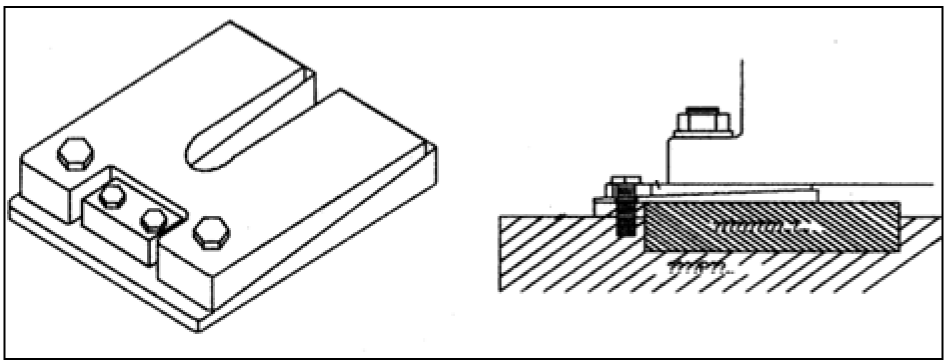


Figure 13.5 Example of an adjustable steel lock-chock (Courtesy Robert L. Rowan and Associates) [6]

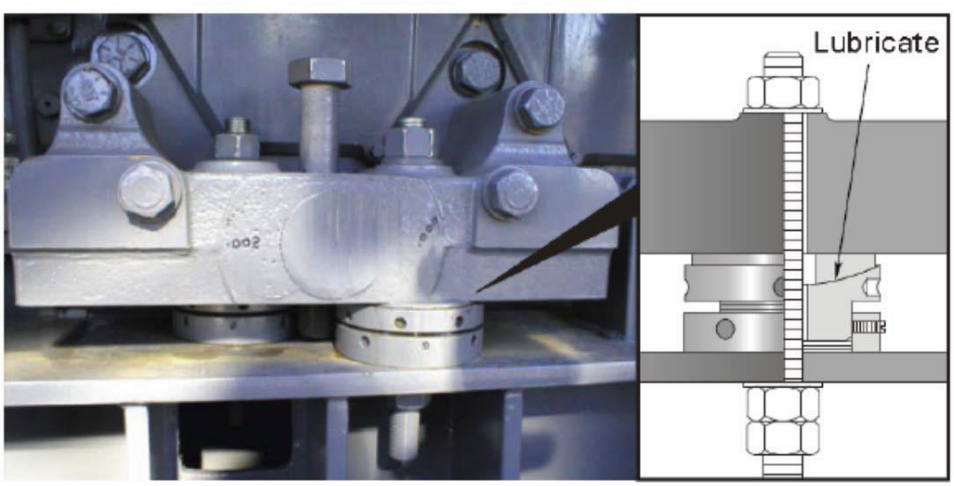


Figure 13.6 Example of adjustable engine mounts [7]

14 References

[1] GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997

[2] GMRC Technical Report TR-97-3 "Friction Tests Typical Chock Materials and Cast Iron", December 1997

[3] GMRC Technical Report TR-97-5 "Epoxy Chock Material Creep Tests", December 1997

[4] GMRC Technical Report TR-97-6 "Compressor Anchor Bolt Design", December 1997

[5] GMRC Technology Assessment Report TA-93-1, December 1993

[6] SWRI "Systems Mountings Guidelines for Separable Reciprocating Compressors in Pipe Line Services", SWRI project number 18.12083.01.401, December 2006

[7] GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013

[8] SWRI Advanced Reciprocating Compression Technology (ARCT), December 2005

[9] ACI 351.3R-04 "Foundations for Dynamic Equipment", May 2004

[10] The Grouting Handbook, a Step-by-Step Guide to Heavy Equipment Grouting, by Don Harrison, 2000 (ISBN 0-88415-887-X, Gulf Publishing Company)

[11] API Recommended Practice 686 "Recommended Practices for Machinery Installation and Installation Design", PIP REIE 686, Second Edition 2009

[12] PIP (Process Industry Practices) STE05121 "Anchor Bolt Design", October 2003

[13] AISI Steel Design Guide Series, "Column Base Plates, Third printing: October 2003

[14] Paper James A. Kully ITW Polymer Technologies, "Best Practices in Compressor Mounting, 7th EFRC Conference Florence Italy, 2010

[15] NVN-CEN/TS 1992-4-1 "Design of fastenings for use in concrete- Part 4-1: General

[16] NVN-CEN/TS 1992-4-2 "Design of fastenings for use in concrete- Part 4-2: Headed Fasteners

[17] NVN-CEN/TS 1992-4-4 "Design of fastenings for use in concrete- Part 4-4: Post installed fasteners- Mechanical systems

[18] NVN-CEN/TS 1992-4-5 "Design of fastenings for use in concrete- Part 4-5: Post installed fasteners- Chemical systems

[19] EN-1992-4 "Design of Fastenings for use in Concrete",

[20] GMRC Course "Foundation Design & Repair, The Bolted Joint", May 12-14, 2009

[21] VDI-2230 Part 1, “Systematic Calculation of high duty bolted joints, Joints with one cylindrical bolt, November 2015

[22] VDI-2230 Part 2, “Systematic Calculation of high duty bolted joints-Mehrschraubenverbindungen”, December 2014

[23] EN-1992-1-3 Eurocode 3:

[24] EN 1992-1-1 (2005) Eurocode 2 “Design of Concrete Structures” Part 1-1 General rules and rules for buildings

[25] EN 1992-2 (2005) Eurocode 2 “Design of Concrete Structures” Part 2- Concrete bridges

[26] EN 1993-1-1 (2005): Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings

[27] API Standard 618, 5th edition 2007

[28] EFRC Guidelines for vibrations in reciprocating compressor systems, 4th edition, May 2012

[29] ACI 318 “Building Code Requirements for Structural Concrete”

[30] Schwarzkopf, M. Fatigue design of tack-welded mesh reinforcing bars, Structural Engineering International 5 (1995) 102-106

[31] Compressor Tech2 article, October 2013 of G. Anderson (Tech Transfer Inc, B. Rowan from Rowan & Associates and J. Butler from Eagle Compression LLC)

[32] Code Requirements for Nuclear Safety Related, Concrete Structures (ACI 349-01)

[33] ISO 2014-2009 Mechanical vibration, shock and condition monitoring - Vocabulary (ISO 2041:2009,IDT)

[34] “Compressor Foundation Analysis Tool (COFANTO)”, A. Eijk, TNO Fluid Dynamics, S. Lentzen, F. Galanti, B. Coelho, TNO Structural Dynamics, 8th Conference of the EFRC, September 27th / 28th, 2012, Düsseldorf

[35] ITW Bulletin 691B “Calculation of anchor bolt pull out”

[36] D. V. Faria, V. G. Lucio, A. P. Ramos, 3rd fib International Congress 2012, “Bond behaviour of prestress steel strands bonded with an epoxy adhesive and a cement grout for flat slab strengthening purposes- experimental study”

[37] DIN 529 Masonry and foundation bolts, published 09/01/2010 by Deutsches Institut Fur Normung E.V. (German National Standard)

[38] ISO 898-1:1999 “Mechanical properties of fasteners made of carbon steel and alloy steel -- Part 1: Bolts, screws and studs”

[39] TGL 38 512, Entwurf 11/89: Maschinenbauteile – Stahlschraubenverbindungen–Berechnung

[40] ECSS-E-HB-32-23A – Thread-Fastners_Handbook-4-16-10

[41] ACI 301-99, Specifications for Structural Concrete, American Concrete Institute, June 2003

[42] Concrete Fundamentals, American Concrete Institute, 1993

[43] ACI Title No. 94-M49, The Influence of Aggregate on the Compressive Strength of Normal and High Strength Concrete

[44] ACI 201.2R-01, Guide to Durable Concrete, American Concrete Institute, October 2001

[45] ACI Title No. 95-M24, High-Performance Concrete: Influence of Coarse Aggregates on Mechanical Properties

[46] ACI 351.1R-99, Grouting between Foundations and Bases for Support of Equipment and Machinery, American Concrete Institute, August 1999

[47] DIN 188, February 2011, T-Head Bolts With Double Nip

ANNEX

A Summed unbalanced loads of multiple cylinder machines according to "GMRC Technical Report TR-97-2 "Foundation Guidelines", January1997" [1]

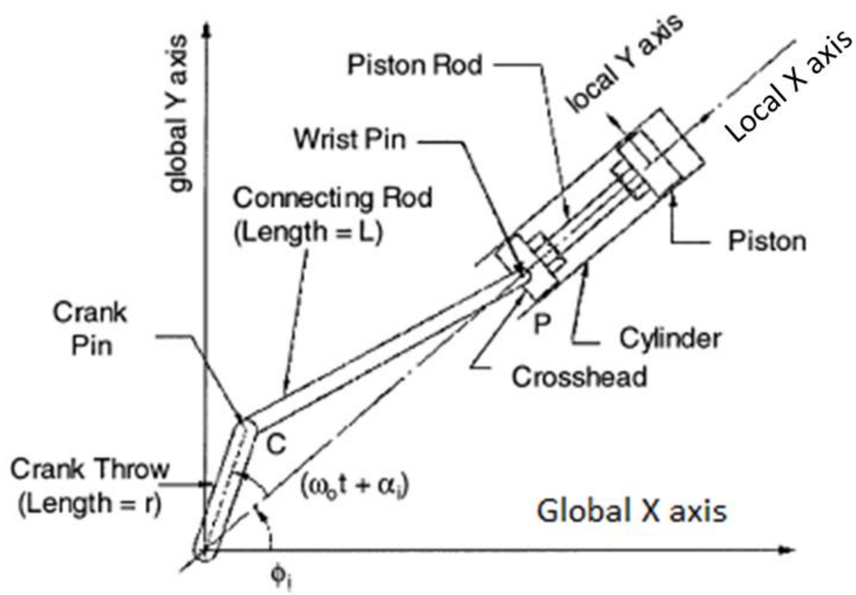


Figure A1 Crank-rod configuration with indicating the global and local axis definition

A1. Unbalanced forces

<u>Inertia force in piston (z) (horizontal for a horizontal compressor) direction:</u>

$$F_x = (m_{rec} + m_{rot}) r \omega_0^{\ 2} \cos \omega_0 t + m_{rec} \frac{r^2}{L} \omega^2 \cos 2\omega_0 t \tag{A 1}$$

<u>Inertia force perpendicular (y) (vertical for a horizontal compressor) to piston direction:</u>

$$F_y = m_{rot} r \omega_0^{\ 2} \sin \omega_0 t \tag{A 2}$$

In which:

F_x = force in piston direction as a function of crank angle (N)
F_y = force perpendicular to piston as function of crank angle (N)

m_{rec} = reciprocating mass* (m)
m_{rot} = rotating mass** (m)
r = stroke (m)
L = connection rod length (m)
ω_0 = circular velocity (rad/s)
t = time (sec)

*The reciprocating mass m_{rec} is usually one third of the weight of the connecting rod, plus the weight of the crosshead, piston rod, piston and weights of fasteners forming a part of various assemblies)

** The rotating mass m_{rot} is the sum of the mass of the crankshaft without the crank webs, and two thirds of the mass of the connecting rod. The centrifugal force created by these masses is the product from mass, crank radius and square of angular speed. By selecting proper counter weights and placing them on the opposite side of the crank, the rotating forces can be balanced. Therefore, the inertial forces of rotating masses produce a centrifugal force of constant magnitude that can be complete balanced by using properly sized counter weights.

For a multiple cylinder machine, with n number of cylinders, the unbalanced forces for the i-th cylinder can be written as follows:

$$F_{xi} = (m_{reci} + m_{roti})r_i\omega_0^{\;2}\cos(\omega_0 t + \alpha_i) + m_{reci}\frac{r_i^{\;2}}{L}\omega^2\cos 2(\omega_0 t + \alpha_i) \qquad \text{(A 3)}$$

and

$$F_{yi} = m_{roti}r_i\omega_0^{\;2}\sin(\omega_0 t + \alpha_i) \qquad \text{(A 4)}$$

Where α is the phase angle for the crack radius of the i-th cylinder. Noting that the above equations have force components at one and two times (secondary) the crankshaft driving frequency, they can be written as follows:

$$F_{xi} = F_{xi}^1 + F_{xi}^2 \qquad \text{(A 5)}$$

$$F_{yi} = F_{yi}^1 \qquad \text{(A 6)}$$

With:

$$F_{xi}^1 = (m_{reci} + m_{roti})r_i\omega_0^{\;2}\cos(\omega_0 t + \alpha_i) \qquad \text{(A 7)}$$

$$F_{xi}^2 m_{reci}\frac{r_i^{\;2}}{L}\omega^2\cos 2(\omega_0 t + \alpha_i) \qquad \text{(A 8)}$$

$$F_{yi}^1 = m_{roti}r_i\omega_0^{\;2}\sin(\omega_0 t + \alpha_i) \qquad \text{(A 9)}$$

In the above equations, F_{xi} and F_{yi} are respectively, the horizontal primary and the vertical primary components, and $F_{xi}^{\;2}$ is the horizontal secondary component of the unbalanced loads. The resultant forces F_x and F_y transmitted to the foundation by n number of cylinders are given by:

$$Fx = \sum_{i=1}^{n}[F_{xi}^{1} + F_{xi}^{2}] \tag{A 10}$$

$$F_y = \sum_{i=1}^{n} F_{yi}^{1} \tag{A 11}$$

If all cylinders have identical geometry and component weight, for is not true in most case of multi-stage machines, the last two equations can be simplified to:

$$F_x = r\omega_0{}^2[(m_{rec} + m_{rot})\sum_{i}^{n} \cos(\omega_0 t + \alpha_i) + m_{rec}\frac{r}{L}\sum_{i}^{n} \cos 2(\omega_0 t + \alpha_i)] \tag{A 12}$$

$$F_y = m_{rot} r_i \omega_0{}^2 \sum_{i}^{n} \sin(\omega_0 t + \alpha_i) \tag{A 13}$$

In which:

$$m_{rot} = \sum_{i}^{n} m_{roti} \text{ and } m_{rec} = \sum_{i}^{n} m_{reci}$$

A2. Unbalanced (global) moments

Referring to figure A.2, the horizontal and vertical moments due to the above unbalanced forces are given by:

$$M_x = \sum_{i=1}^{n} F_{yi} Z_i \tag{A 14}$$

$$M_y = \sum_{i=1}^{n} F_{xi} Z_i \tag{A 15}$$

The above equations assume that all cylinder axes are located in the XZ plane as shown in figure A.2. The quantities F_{xi} and F_{yi} are given by equations (A16) and (A 17). If the cylinders are opposed or inclined to the global X-axis (e.g. vertical, L-type, W-type, or V-type compressors), with orientation angles Φ_i , then equations (A 3) and (A 4) can be considered as forces in local axes with global components F_{xi}^{G} and F_{yi}^{G} given by:

$$F_{xi}^{G} = F_{xi} \cos\phi_i - F_{yi} \sin\phi_i \tag{A 16}$$

$$F_{yi}^{G} = F_{xi} \sin\phi_i - F_{yi} \cos\phi_i \tag{A 17}$$

The resultant forces and moments due to n cylinders in global coordinates can be calculated in the same manner as described earlier. They are given by:

$$F_x^{GP} = \sum_{i=1}^{n} [F_{xi}^{1} \cos\phi_i - F_{yi}^{1} \sin\phi_i] \tag{A 18}$$

$$F_x^{GS} = \sum_{i=1}^{n} F_{xi}^2 \cos\phi_i \quad \text{(A 19)}$$

$$F_y^{GP} = \sum_{i=1}^{n} [F_{xi}^1 \sin\phi_i - F_{yi}^1 \cos\phi_i] \quad \text{(A 20)}$$

$$F_y^{GS} = \sum_{i=1}^{n} F_{xi}^2 \sin\phi_i \quad \text{(A 21)}$$

$$M_x^{GP} = \sum_{i=1}^{n} [F_{xi}^1 \sin\phi_i - F_{yi}^1 \cos\phi_i] Z_i \quad \text{(A 22)}$$

$$M_x^{GS} = \sum_{i=1}^{n} [F_{xi}^2 \sin\phi_i] Z_i \quad \text{(A 23)}$$

$$M_y^{GP} = \sum_{i=1}^{n} [F_{xi}^1 \cos\phi_i - F_{yi}^1 \sin\phi_i] Z_i \quad \text{(A 24)}$$

$$M_y^{GS} = \sum_{i=1}^{n} [F_{xi}^2 \cos\phi_i] Z_i \quad \text{(A 25)}$$

In which:

F_x^{GP} = horizontal primary force

F_x^{GS} = horizontal secondary force

F_y^{GP} = vertical primary force

F_y^{GS} = vertical secondary force

M_x^{GP} = horizontal primary moment (about x-axis)

M_x^{GS} = horizontal secondary moment (about x-axis)

M_y^{GP} = vertical primary moment (about y-axis)

M_y^{GS} = vertical secondary moment (about y-axis)

When counterweights on the crankshaft are used to reduce the resulting unbalanced forces or moments, their effect can be included by using Equations (A-5) through (A-9) and using $m_{rec} = 0$ and m_{rot} to represent the actual weight of the counterweight. Then, these forces can be included into Equation (A-18) through (A-25) to calculate the resultant unbalanced forces and moments. Note that the rotating counterweight results only in primary forces and couples.

The terms m_{reci} and m_{roti} in Equations (A-3) and (A-4) include component weights as defined below:

Reciprocating Weights (m_{rec}):

- Piston
- Piston Rod
- Crosshead
- Crosshead Pin

- Crosshead Nut
- Cover Plates
- Connecting Rod Small End
- Tie Bolts, Nuts, Washers, Etc.

Rotating Weights (m_{rot}):

- Connecting Rod Big End
- Crank Pin
- Washers
- Counterweights
- Unbalanced Part Crank Web

Generally, the crankshafts are forged and machined to check complete balance. Crank webs are symmetrical relative to the shaft axis and with accurate weight balance for each web. However, if this not the case, and if the unbalanced equivalent weight at the crank pin location can be computed, then it can be included in the rotating weight, $m_{roti.}$

Equations (A 18) through (A 25) provide instantaneous values of the various force and moment components for a given value of ωt.

The maximum values of the instantaneous (0-peak) values are achieved by computing the primary forces and moment for ωt = 0 and 90 degrees and computing secondary forces and moments at ωt = 0 and 45 degrees.

It can be shown that the <u>amplitudes</u> of the various force and moment components are given by the equations of below.

<u>For dynamic design purposes of the foundation block the peak-to-peak values shall be taken which are 2 times the values of the loads as given below:</u>

$$FH1 = F_x^{GP} = SQRT\left[\left(F_{x0}^P\right)^2 + \left(F_{x90}^P\right)^2\right] \quad \text{(A 26)}$$

$$FV1 = F_y^{GP} = SQRT\left[\left(F_{y0}^P\right)^2 + \left(F_{y90}^P\right)^2\right] \quad \text{(A 27)}$$

$$FH2 = F_x^{GS} = SQRT\left[\left(F_{x0}^S\right)^2 + \left(F_{x45}^S\right)^2\right] \quad \text{(A 28)}$$

$$FV2 = F_y^{GS} = SQRT\left[\left(F_{y0}^S\right)^2 + \left(F_{y45}^S\right)^2\right] \quad \text{(A 29)}$$

$$MH1 = M_x^{GP} = SQRT\left[\left(M_{x0}^P\right)^2 + \left(M_{x90}^P\right)^2\right] \quad \text{(A 30)}$$

$$MV1 = M_y^{GP} = SQRT\left[\left(M_{y0}^P\right)^2 + \left(M_{y90}^P\right)^2\right] \quad \text{(A 31)}$$

$$MH2 = M_x^{GS} = SQRT\left[\left(M_{x0}^S\right)^2 + \left(M_{x45}^S\right)^2\right] \quad \text{(A 32)}$$

$$MV2 = M_y^{GS} = SQRT\left[\left(M_{y0}^S\right)^2 + \left(M_{y45}^S\right)^2\right] \quad \text{(A 33)}$$

F_{x0}^{P}, F_{x90}^{P} =horizontal primary forces for ωt = 0, 90 degrees
F_{y0}^{P}, F_{y90}^{P} = vertical primary forces for ωt = 0, 90 degrees
F_{x0}^{S}, F_{x45}^{S} = horizontal secondary forces for ωt = 0, 45 degrees
F_{y0}^{S}, F_{y45}^{S} = vertical secondary forces for ωt = 0, 45 degrees
M_{x0}^{P}, F_{x90}^{P} = primary moments about x-axis for ωt = 0, 90 degrees
M_{y0}^{P}, F_{y90}^{P} = primary moments about y-axis for ωt = 0, 90 degrees
M_{x0}^{S}, F_{x45}^{S} =secondary moments about x-axis for ωt = 0, 45 degrees
M_{y0}^{S}, F_{y45}^{S} = secondary moments about y-axis for ωt = 0, 45 degrees

When calculating shaking forces, the gas loads are generally assumed to cancel each other and as such are excluded from the calculation of unbalanced loads. However, this assumption may not be valid if the main frame has significant flexibility and the unbalanced loads are to be used for sizing the anchor bolts that tie down the frame to the skid.
The unbalanced forces and moments generated due to inertial loading in a compressor can be computed by hand using the procedure and the equations given so far. If such computations are needed routinely on several different units, it will be easy to prepare a spreadsheet to input the necessary data for each machine, and to let the program compute the necessary components of primary and secondary forces and moments. Such spreadsheets can be prepared on a personal computer by using any spreadsheet program that the user prefers.

A3. Analysis for counterweights
Counterweights are often added to the crankshaft as a means of offsetting unbalance, and as a means of controlling the summed forces and moments. Since counterweights rotate at shaft speed and do not reciprocate, they can only contribute to forces acting at first order of rotational speed ω.
The individual points of attachment for counterweights are normally the webs of each throw, whose axial location differs a small amount from the centre of the adjacent throw. A comprehensive analysis of the contributions of counterweights to the summed forces and moments would consider each counterweight (j) have the following attributes:

$(m_w.r_w)_j$ = unbalance times radius of unbalance vector (kgm).
Ψ_{wj} = angle of unbalance vector from reference throw.
Z_{wj} = axial location of counterweight line of action, usually referred tounit mid-point.
N_w = total number of counterweights to be considered.

Adapting equations (A-7) and (A-9) will give:

$$F_{xwj} = (m_w r_w)\omega^2 \cos(\omega_0 t + \Psi_{wj}) \qquad \text{(A 34)}$$

$$F_{ywj} = (m_w r_w)\omega^2 \sin(\omega_0 t + \Psi_{wj}) \qquad \text{(A 35)}$$

$$F_{xw} = \sum_{j=1}^{Nw} F_{xwj} \qquad \text{(A 36)}$$

$$F_{yw} = \sum_{j=1}^{Nw} F_{ywj} \qquad \text{(A 37)}$$

$$M_{xw} = \sum_{j=1}^{Nw} F_{ywj} Z_j \quad \text{(A 38)}$$

$$M_{yx} = \sum_{j=1}^{Nw} F_{xwj} Z_j \quad \text{(A 39)}$$

In which:

F_{xwj}, F_{ywj} = individual counterweight unbalance forces in X and Y directions
F_{xw}, F_{yw} = summed counterweight forces in X, Y directions
M_{xu}, My = summed counterweight moments about point Z = 0

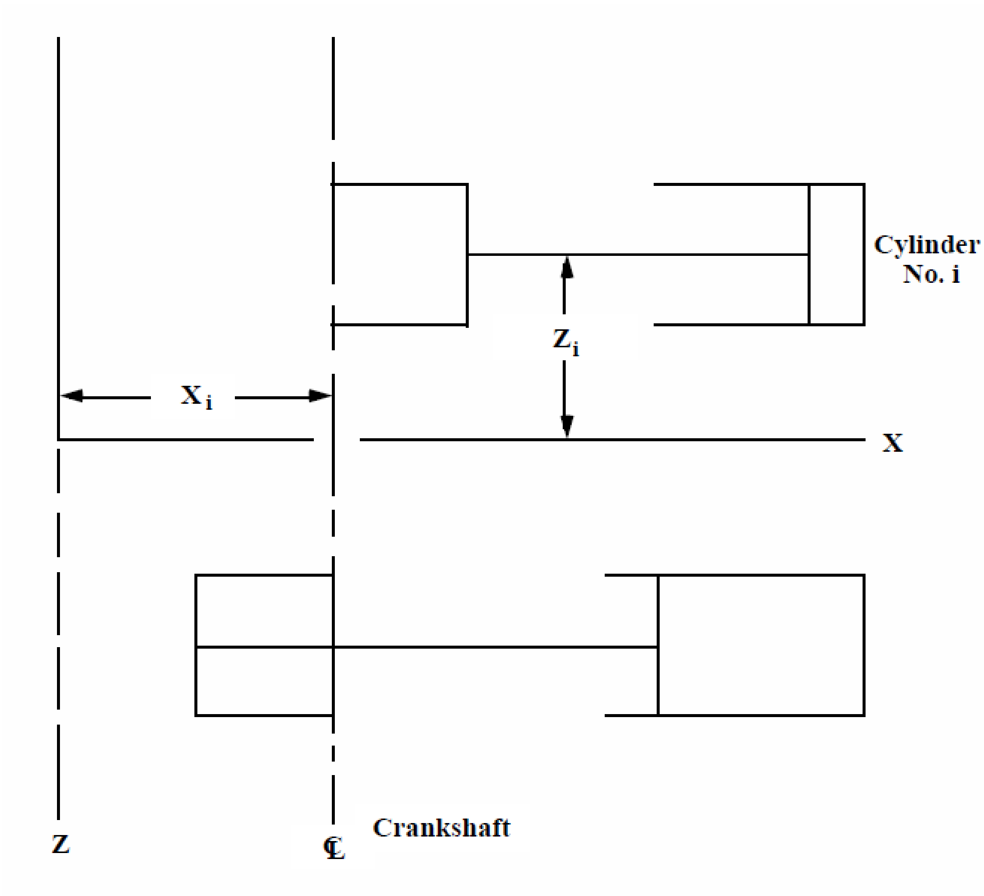


Figure A.2 Cylinder configuration

B Calculation according EN 1993- Eurocode 3 for the minimum compressive strength of concrete and grouting

EN 1993 Eurocode 3 “Design of Steel Structures” with its underlying and referenced standards can be used to determine practical safe limits for the compressive load on the concrete at frame footings and soleplates. Machine foundations and their fastenings do not fall within the scope of the Eurocodes but where applicable parts can and have been used in this report for guidance.

For column base plates on concrete for example the design bearing strength is f_{jd}, with:

$$f_{jd} = \beta_j \cdot \frac{F_{Rdu}}{(b_{eff} \cdot l_{eff})} \quad \text{(MPa)} \qquad \text{(B1)}$$

In which:

- β_j = 2/3 (foundation joint material coefficient) (-)
- F_{Rdu} is the concentrated design resistance force (N)
  given in EN 1992 Eurocode 2 “Design of Concrete Structures”,
  where the loaded area $A_{c0} = b_{eff} \cdot l_{eff}$ (m^2)
  b_{eff} and l_{eff} are the effective width and length of the load bearing area (m)

$$F_{Rdu} = A_{c0} \cdot f_{cd} \cdot \sqrt{\frac{A_{c1}}{A_{c0}}} \leq 3 \cdot f_{cd} \cdot A_{c0} \qquad \text{(N)} \qquad \text{(B2)}$$

In which:

- A_{c1} is the maximum design distribution area with a similar shape to A_{c0} (m^2) and shall correspond to the following conditions:
  - The height for the load distribution in the load direction shall correspond to the conditions in the figure below.
  - The centre of the design distribution area A_{c1} shall be on the line of action passing through the centre of the load area A_{c0}.
  - If there is more than one compression force acting on the concrete cross section, the designed distributed areas shall not overlap.
- f_{cd} is the design value of concrete compressive strength (MPa)

Remark: the value of F_{Rdu} shall be reduced if the load is not uniformly distributed on the area A_{c0} or if high shear forces exist.

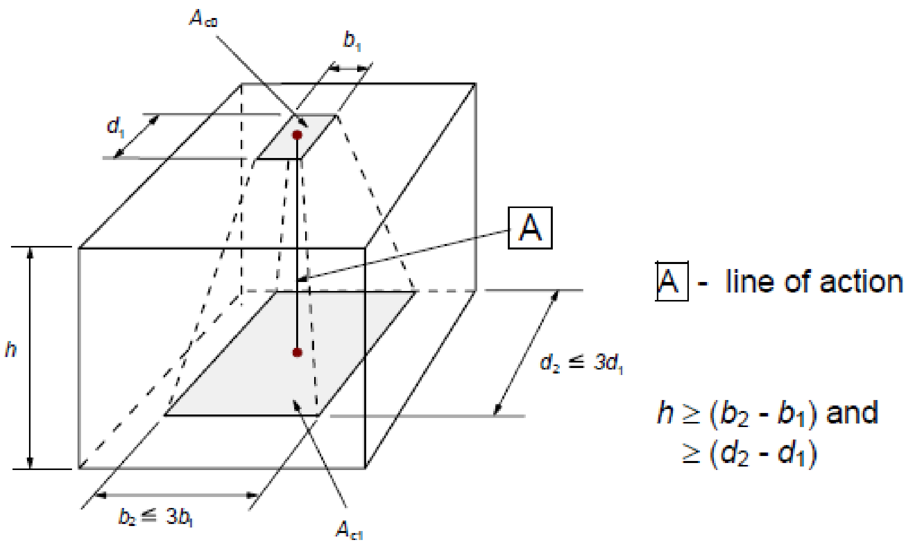


Figure B.1 Load bearing area

In order to find a conservative allowable bearing strength we can simplify this by assuming $A_{c1} = A_{c0}$, which represents a worst case approach. The design bearing strength f_{jd} becomes:

$$f_{jd} = \frac{2}{3} \cdot f_{cd} \text{ (MPa)} \qquad \text{(B4)}$$

With:

$$f_{cd} = \alpha_{cc} \cdot \frac{f_{ck}}{\gamma_c} \text{ (MPa)} \qquad \text{(B5)}$$

In which:

- α_{cc} is the coefficient taking account of long term effects on the compressive strength and unfavourable effect from the way the load is applied. It shall be between 0.8 and 1.0 with 1.0 being the recommended value (-)
- γ_c = 1.5 is the partial safety factor for concrete (-)
- f_{ck} is the characteristic compressive cylinder strength of concrete (MPa)

Remark:
It shall be noted that many older standards use the cube strength $f_{ck,cube}$ instead of the cylinder strength ($f_{ck,cube} > f_{ck}$)

Again using the lowest value of 0.8 for α_{cc}, the design bearing strength is as follows:

$$f_{jd} = \frac{2}{3} \cdot 0.8 \cdot \frac{f_{ck}}{1{,}5} = \frac{16}{45} \cdot f_{ck} \text{ (MPa)}$$

The API 618 5th edition [27] refers to the API RP 686 [11] which recommends a minimum concrete compressive strength of 28 MPa. Based on the foregoing simplifications the design bearing strength for concrete would be at least 10.0 MPa ((16/45)x 28). If a higher compressive strength is used the design bearing strength shall be multiplied with the ratio of the higher to the minimum advised value of 28 MPa.

Based on the foregoing it can be concluded that the limits imposed by marine classification societies for diesel propulsion engines are overly conservative for typical low temperature compressor applications. Marine engine and compressor applications do however share the requirement to maintain precise alignment and 6.9 MPa can therefore be considered a practical design limit for epoxy chocks. For the underlying concrete and grout materials on cement basis slightly higher values up to 10 MPa could be allowed but because epoxy grout is most commonly used a standard design limit of 6.9 MPa is recommended.

C Calculation of the termination point diameter

The load bearing area $A_{b,nut}$ of a nut termination:

$$A_{b,nut} = \frac{s^2 \cdot \sqrt{3}}{2} - \frac{\pi}{4} \cdot d^2 \text{ (mm}^2\text{)} \tag{C1}$$

In which:

d= nominal bolt outer diameter (mm)

s= width across flats of bolt or nut (mm)

The compressive bearing load $\sigma_{o,nut}$ on the nut termination is as follows:

$$\sigma_{o,nut} = \frac{F_v}{A_{b,nut}} \text{ (MPa)} \tag{C2}$$

In which:

Fv = preload (N)

$A_{b,nut}$ = load bearing area (mm^2)

The results of the calculations based on the bolt preload for ASTM A-193, B7 material are presented in the following table:

Table C.1 Compressive bearing load on nut termination based on 70% of yield strength of

				F_v (0.7 x S_y)	
	d	**s**	**$A_{b,nut}$**	**ASTM A193 B7**	**$\sigma_{o,nut}$**
Bolt size	**mm**	**mm**	**mm^2**	**N**	**MPa**
1/2 – 13	12.70	22.2	301	47005	157
5/8 – 11	15.88	27.0	433	74802	172
¾ - 10	19.05	31.8	588	110571	188
1 – 8	25.40	41.3	969	200099	207
1 ¼ - 8	31.75	50.8	1443	329491	228
1 ½ -8	38.10	60.3	2011	490983	244
1 ¾ -8	44.45	69.9	2674	684573	256
2 – 8	50.80	79.4	3429	910266	266
2 ½ - 8	63.50	98.4	5223	1457947	279

It shall be emphasized that this assumption is based on the fact that the nut termination will carry all the load. This means that there is no bond between the bolt and grout, which is the worst-case situation.

The allowable compressive strength of epoxy grout is approximately 80-125 MPa depending on the grout, see

Table **7.2**, and approximately 50 MPa for cement grout. For all bolt diameters this value is exceeded for a simple nut termination.
Based on these calculation results it can be concluded that a nut termination does not meet the requirements and the required diameter of a plate termination can be determined.

The required plate area as given below is based on the minimum required compressive strength $\sigma_{c,min}$ of 50 MPa for cement grout and a design factor C_1 of 1.25 for additional safety to take into account for possible variations in preload, dynamic loads etc.
It shall be noted that epoxy grout materials typically have a higher compressive strength when compared with grout materials on cement basis. Compressive strength of epoxy grout is generally greater than 70 MPa and in most cases more than 100 MPa.

The required plate termination area is calculated as follows:

$$A_{plate,req} = \frac{F_v \cdot C_1}{\sigma_{c,min}} \quad (mm^2) \qquad (C3)$$

In which:

$A_{plate,\,req}$ = required plate termination area (mm^2)
F_v = preload (N)
$\sigma_{c,min}$= maximum allowable compressive strength (MPa)

The required plate diameter:

$$d_{plate,req} \geq \sqrt{A_{plate,req} \cdot \frac{4}{\pi} + d^2} \quad (mm^2) \qquad (C4)$$

In which:

$A_{plate,\,req}$ = required plate termination area (mm^2)
$d_{plate,req}$ = required termination plate diameter (mm)
d = bolt outer diameter [mm]

The ratio of the plate to bolt diameter:

$$R_{dpb} = \frac{d_{plate,req}}{d} \quad (-) \qquad (C5)$$

The results of the calculations based on the bolt preload for ASTM-B7 material for a cement grout with a maximum compressive strength of 50 MPa are presented in the following table:

Table C.2 Table with required bolt termination diameter for a ASTM-B7 material mounted to cement grout

	d	F_v (0.7 x S_y) ASTM A-193 B7	$A_{plate.req}$	$d_{plate.req}$	R_{dpb}
Bolt size	**mm**	**N**	**mm²**	**mm**	**-**
1/2 – 13	12.70	47005	1175	40.7	3.2
5/8 – 11	15.88	74802	1870	51.3	3.2
¾ - 10	19.05	110571	2764	62.3	3.3
1 – 8	25.40	200099	5002	83.75	3.3
1 ¼ - 8	31.75	329491	8238	107.2	3.4
1 ½ -8	38.10	490983	12275	130.7	3.4
1 ¾ -8	44.45	684573	17115	154	3.5
2 – 8	50.80	910266	22757	177.6	3.5
2 ½ - 8	63.50	1457947	36449	224.6	3.5

The results of the calculations based on the bolt preload for ASTM-B7 material for an epoxy grout with a maximum compressive strength of 82 MPa are presented in the following table:

Table C.3 Table with required bolt termination diameter for a ASTM-B7 material mounted to epoxy grout

	d	F_v (0.7 x S_y) ASTM A-193 B7	$A_{plate.req}$	$d_{plate.req}$	R_{dpb}
Bolt size	**mm**	**N**	**mm²**	**mm**	**-**
1/2 – 13	12.70	47005	716	32.8	2.6
5/8 – 11	15.88	74802	1140	41.3	2.6
¾ - 10	19.05	110571	1685	50.1	2.6
1 – 8	25.40	200099	3050	67.3	2.6
1 ¼ - 8	31.75	329491	5023	86.0	2.7
1 ½ -8	38.10	490983	7485	104.8	2.8
1 ¾ -8	44.45	684573	10436	123.5	2.8
2 – 8	50.80	910266	13876	142.3	2.8
2 ½ - 8	63.50	1457947	22225	179.8	2.8

A termination having a diameter the following diameter or more meets the bearing load requirements for all bolt diameters as follows:

- mounted on cement grout: minimum 3.5 times the bolt diameter
- mounted on epoxy grout: 3 times the bolt diameter

A similar recommendation is given in GMRC SWRI Report No. TR 97-6 [4] which recommends a termination plate diameter of three to four bolt diameters if mounted to epoxy grout.

The GMRC report also includes investigation of the effect of termination thickness, although only investigated for a thickness of 0.75 and 1.5 times the bolt diameter, with the thicker plate reducing local tensile stress in the concrete. Based on the concrete compressive and tensile stress data in the GMRC report and allowing some tolerance (10%) for selection of commercially available plate material and manufacturing tolerances, the recommended termination thickness is 1.35 to 1.5 times the bolt diameter.

D Calculations according to EN 1992 Eurocode 2 “Design of Steel Structures”, CEN/TS 1992 Part 4.1 General and Part 4.2 Headed fasteners

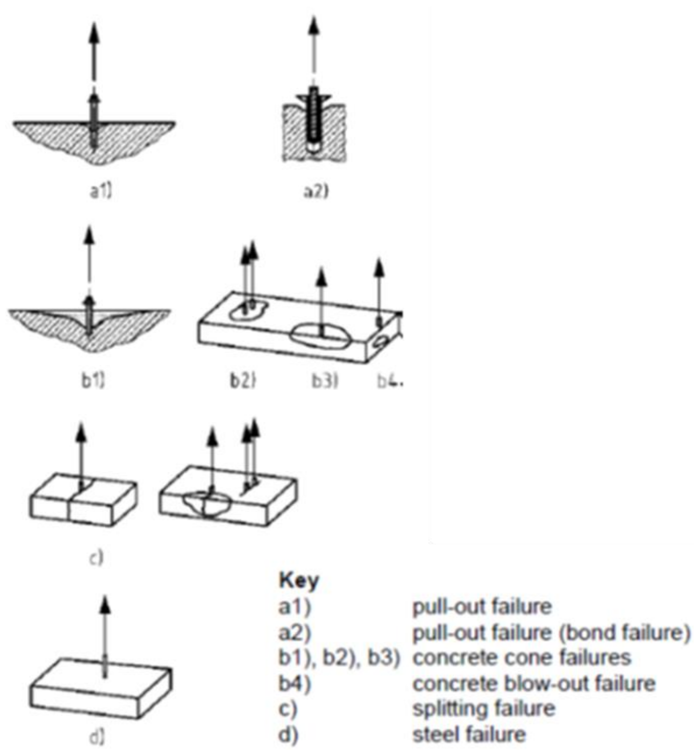
D.1 Introduction

The following calculations and design guides are for information and reference only. Calculation methods and procedures vary between standards such as CEN/TS 1992 Part 4.1 and 4.2 (Headed Fasteners) , ACI 318, etc.,

The following shall be noted:

- All calculations have been carried out with an anchor preload of 70% of the minimum yield strength. The values as calculated in all the examples of this appendix will also change for other bolt preloads.
- Despite the fact that the several civil engineering rules and best practices, have been determined from standards which are not applicable for machine foundations (e.g. EN 1993 Eurocode 3 “Design of Steel Structures”, CEN/TS 1992 Part 4.1 General and Part 4.2 Headed fasteners), they have been applied for guidance in this report.

D.2 Tension load



D.2.1 *Steel failure of fastener*

$$N_{Ed} \leq N_{Rd,s} = \frac{N_{Rk,s}}{\gamma_{Ms}} \quad \text{(D1)}$$

In which:

N_{Ed} = design value of the fastener (N)
$N_{Rd,s}$ = design value of resistance (N)
$N_{Rk,s}$ = characteristic value of resistance (N)
γ_{Ms} = partial factor for steel (-)

$$\gamma_{Ms} = 1.2 \cdot \frac{f_{uk}}{f_{yk}} \geq 1.4 \quad \text{(D2)}$$

In which:

f_{uk} = characteristic steel ultimate tensile strength (MPa)
f_{yk} =characteristic steel yield strength (MPa)

$$N_{Rk,s} = A_s \cdot f_{uk} \quad \text{(D3)}$$

In which:

A_s = stress area according ISO 898 (mm^2), see Table 8.2 of this report

For an ASTM A193 B7 bolt material with an ultimate tensile strength of 862 MPa and a yield strength of 724 MPa the value of $\gamma_{Ms} = 1.43$
This means that the stress level for the design value of resistance is the tensile strength divided by the partial factor and thus 603 MPa which is 83% of the yield strength. As the bolt preload and thus the design value is limited to 70% of the yield strength, the design margin against steel failure will be more than adequate even if a design factor C_1 of 1.25 for additional safety is included to take into account possible variations in preload, dynamic loads etc.

D.2.2 *Pull-out failure of fastener*

$$N_{Ed} \leq N_{Rd,p} = \frac{N_{Rk,p}}{\gamma_{Mp}} \quad \text{(D4)}$$

In which:

N_{Ed} =design value of the fastener (N)
$N_{Rd,p}$ =design value of resistance (N)
$N_{Rk,p}$ =characteristic value of resistance (N)
γ_{Mp} =partial factor for pull-out failure (-)

$$\gamma_{Mp} = \gamma_{Mc} = \gamma_c \cdot \gamma_{inst} \quad \text{(D5)}$$

In which:

γ_{Mc} = partial factor for concrete break-out failure modes (-)
γ_{Mc} = partial factor for concrete under compression (-)
γ_{inst} =partial factor taking into account installation safety (-)

With values of γ_c = 1.5 and γ_{inst} = 1 for systems with high installation safety

$\gamma_{Mp} = \gamma_{Mc} = 1.5$

$$N_{Rk,p} = 6 \cdot A_h \cdot f_{ck,cube} \cdot \Psi_{ucr,N} \quad \text{(D6)}$$

In which:

A_h = load bearing area of the head of the fastener (mm^2)
$f_{ck,cube}$= compressive cube strength of concrete (MPa)
$\psi_{ucr,N}$ = factor taking into account the positioning of the fastening in cracked or non-cracked concrete

$$A_h = \frac{\pi}{4} \cdot (d_h^2 - d^2) \text{ (mm}^2\text{)} \quad \text{(D7)}$$

In which:

d_h =diameter of anchor head or termination plate diameter (mm)
d =diameter of anchor bolt (mm)

$\psi_{ucr,N}$ = 1.0 for fasteners in cracked concrete (1.4 for non-cracked concrete)

The API 618 5th edition refers to the API RP 686 which recommends a minimum concrete compressive strength of 28 MPa. This means a value $f_{ck,cube}$ = 28 MPa.
For a conservative approach, assuming cracked concrete, the allowable design bearing load according equation (D6) is 112 MPa and 157 MPa for non-cracked concrete.

This confirms what is concluded in chapter Appendix C that a simple nut termination would not be sufficient in most cases and a plate termination is required therefore.
In accordance with Appendix C, the termination has a minimum diameter d_h of 3 times the bolt diameter d for epoxy grout (3.5 for cement grout), and a design bearing load of 40 MPa (50 MPa minimum compressive strength of the grout divided by a design factor C_1 =1.25). This bearing load is far below the limit of 157 MPa for pull-out failure of the fastener in non-cracked concrete and 112 MPa for cracked concrete.

D.2.3 Concrete cone failure

This is a failure mode which normally cannot occur with preloaded compressor anchor bolts that aren’t loaded with external vertical tension working loads of relevant magnitude in comparison with preload.

The following calculations are for fasteners without the use of supplementary reinforcement and for information only.

$$N_{Ed} \leq N_{Rd,c} = \frac{N_{Rk,c}}{\gamma_{Mc}} \quad \text{(D8)}$$

In which:

N_{Ed} = design value of the fastener (N)
$N_{Rd,c}$ = design value of resistance (N)
$N_{Rk,c}$ = characteristic value of resistance (N)
γ_{Mc} = partial factor for concrete break-out failure modes (-)

$\gamma_{Mc} = 1.5$

$$N_{Rk,c} = N^o_{Rk,c} \cdot \frac{A_{c,N}}{A^o_{c,N}} \cdot \Psi_{s,N} \cdot \Psi_{re,N} \cdot \Psi_{ec,N} \tag{D9}$$

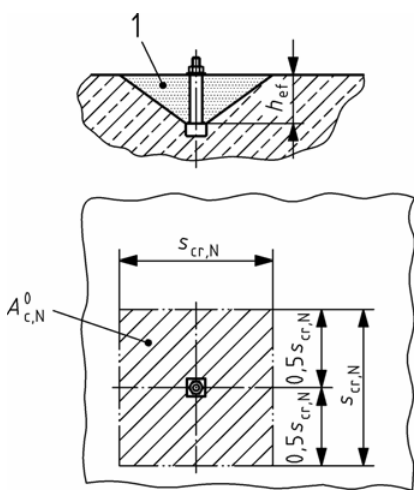
In which:

- $A^o_{c,N}$ = reference projected area (mm^2)
- $A_{c,N}$ = actual projected area, limited by overlapping cones of adjacent fasteners $s \leq s_{cr,N}$ as well as edges $c \leq c_{cr,N}$
- $s_{cr,N}$ = characteristic spacing of fasteners
- $c_{cr,N}$ = characteristic edge distance of fastener
- $\psi_{s,N}$ = factor taking into account disturbance of concrete stresses due to edges
- $\psi_{re,N}$ = factor taking into account the effect of a dense reinforcement for embedment depth $h_{eff} < 100$ mm
- $\psi_{ec,N}$ = factor taking into account the eccentricity of the load in a group of fasteners

$$N^o_{Rk,c} = k_{ucr} \cdot \sqrt{f_{ck,cube}} \cdot h^{1.5}_{ef} \tag{D10}$$

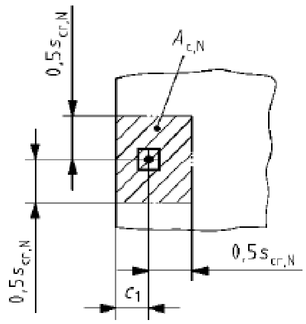
In which:

- $N^o_{Rk,c}$ = characteristic resistance of a fastener not influenced by adjacent fasteners or edges (N)
- k_{ucr} = factor to take into account the influence of load transfer mechanisms (-) for cracked concrete use k_{cr} instead of k_{ucr}
- h_{eff} = effective embedment depth (mm)



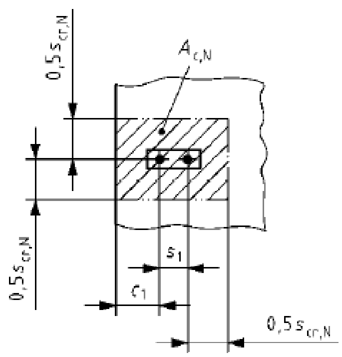
$$A^o_{c,N} = s_{cr,N} \cdot s_{cr,N} \tag{D11}$$

$$s_{cr,N} = 2 \cdot c_{cr,N} = 3 \cdot h_{eff} \tag{D12}$$

a) 

$A_{c,N} = (c_1 + 0,5\,s_{cr,N}) \cdot s_{cr,N}$

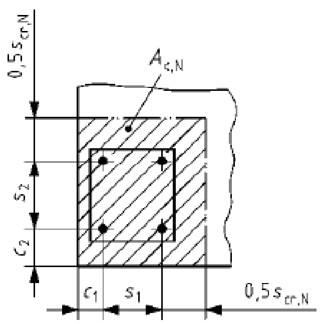
if: $c_1 \leq c_{cr,N}$

b) 

$A_{c,N} = (c_1 + s_1 + 0,5\,s_{cr,N}) \cdot s_{cr,N}$

if: $c_1 \leq c_{cr,N}$

$s_1 \leq s_{cr,N}$

c) 

$A_{c,N} = (c_1 + s_1 + 0,5\,s_{cr,N}) \cdot (c_2 + s_2 + 0,5\,s_{cr,N})$

if: $c_1; c_2 \leq c_{cr,N}$

$s_1 ; s_2 \leq s_{cr,N}$

Key

a) Individual fastener at the edge of a concrete member

b) Group of two fasteners at the edge of a concrete member

c) Group of four fasteners at a corner of a concrete member

$$\Psi_{s,N} = 0.7 + 0.3 \cdot \frac{c}{c_{cr,N}} \leq 1 \quad \text{(D13)}$$

In which:

c = smallest edge distance (mm)

$$\Psi_{re,N} = 0.5 + \frac{h_{eff}}{200\ \text{mm}} \leq 1 \quad \text{(D14)}$$

$$\Psi_{ec,N} = \frac{1}{1+2\cdot\frac{e_N}{s_{cr,N}}} \leq 1 \quad \text{(D15)}$$

In which:

e_N = eccentricity of the resulting tensile load (mm)
h_{eff} = effective bolt embedment length (mm)

The calculations will be based on the following data:
k_{ucr} = 11.9 (k_{cr} = 8.5 for cracked concrete)
$f_{ck,cube}$ = 28 MPa (minimum compressive concrete strength)
h_{eff} ≈ 20d (clamped length ≈ 24d minus (height soleplate+ grout thickness) see also chapter □)

For a conservative approach, assuming cracked concrete, the value of $N^o_{Rk,c}$ is as follows:

$$N^o_{Rk,c} = 4023 \cdot d^{1.5}$$

With:
$s_{cr,N}$ = 72xd (3 x h_{eff} = 3 x 24 x d)
$c_{cr,N}$ = 36xd (1.5x h_{eff} = 1.5 x 24 x d)

$$A^o_{c,N} = s_{cr,N} \cdot s_{cr,N} = 72 \cdot d \cdot 72 \cdot d = 5184 \cdot d^2$$

For a corner bolt c = c_1 = c_2 = 6.5 x d (based on PIP STE05121) in a long and wide foundation block $A_{c,N}$ becomes:

$$A_{c,N} = (c_1 + 0.5 \cdot s_{cr,N}) \cdot (c_2 + 0.5 \cdot s_{cr,N}) = 1806 \cdot d^2$$

$$\Psi_{s,N} = 0.7 + 0.3 \cdot \frac{6.5 \cdot \mathrm{d}}{36 \cdot \mathrm{d}} = 0.7542$$

Because h_{eff} is always > 100 mm $\psi_{re,N}$ = 1. For a single fastener the eccentricity is zero and $\psi_{ec,N}$ = 1 it follows that:

$$N_{Rd,c} = \frac{N_{Rk,c}}{\gamma_{Mc}} = \frac{N^o_{Rk,c} \cdot \frac{A_{c,N}}{A^o_{c,N}} \cdot \Psi_{s,N} \cdot \Psi_{re,N} \cdot \Psi_{ec,N}}{\gamma_{Mc}} = 1307.6 \cdot d^{1.5}$$

The results for different bolt diameters for a bolt with material ASTM A193 Grade B7 based on a preload of 70% of the yield strength are presented in the table D.1

Table D.1 Design value of resistance to avoid concrete cone failure based on worst-case assumption

	d	F_v (0.7 x S_y) ASTM A193 Grade B7	$N_{Rd,c}$
Bolt size	**mm**	**N**	**N**
1/2 – 13	12.70	47005	59180
5/8 – 11	15.88	74802	82747
¾ - 10	19.05	110571	108721
1 – 8	25.40	200099	167388
1 ¼ - 8	31.75	329491	233932
1 ½ -8	38.10	490983	307512
1 ¾ -8	44.45	684573	387509
2 – 8	50.80	910266	473446
2 ½ - 8	63.50	1457947	661661

The conclusion is that $N_{Rd,c} < F_v$ for diameters ≥ ¾ - 10

For a narrow member column with three or more edge distances less than $c_{cr,N}$ the previous calculation method is too conservative and more precise results can be obtained as follows:

$$h'_{ef} = \frac{c_{max}}{c_{cr,N}} \cdot h_{eff} \qquad \text{(D16)}$$

In which:
c_{max} = maximum distance from centre of faster to the edge of the concrete member ≤ $c_{cr,N}$

$$s'_{cr,N} = s_{cr,N} \cdot \frac{h'_{ef}}{h_{ef}} \qquad \text{(D17)}$$

$$c'_{cr,N} = c_{cr,N} \cdot \frac{h'_{ef}}{h_{ef}} \qquad \text{(D18)}$$

With a minimum edge distance c = $c_1 = c_2 = c_{max}$ = 6.5d (based on PIP STE05121) the minimum column width equals 2 times 6.5 d = 13d

$$h'_{ef} = \frac{6.5 \cdot d}{36 \cdot d} \cdot 24 \cdot d = 4.33 \cdot d \qquad \text{(D19)}$$

$$s'_{cr,N} = 72 \cdot d \cdot \frac{4.33 \cdot d}{24 \cdot d} = 13 \cdot d \qquad \text{(D20)}$$

$$c'_{cr,N} = 36 \cdot d \cdot \frac{4.33 \cdot d}{24 \cdot d} = 6.5 \cdot d \qquad \text{(D21)}$$

$$N^o_{Rk,c} = k_{cr} \cdot \sqrt{f_{ck,cube}} \cdot h'^{1.5}_{ef} = 406 \cdot d^{1.5} \qquad \text{(D22)}$$

$$A^o_{c,N} = s'_{cr,N} \cdot s'_{cr,N} = 169 \cdot d^2 \qquad \text{(D23)}$$

$$A_{c,N} = (c_1 + 0.5 \cdot s'_{cr,N}) \cdot (c_2 + c_2) = 169 \cdot d^2 \qquad \text{(D24)}$$

$$\Psi_{s,N} = 0.7 + 0.3 \cdot \frac{c}{c'_{cr,N}} = 1 \qquad \text{(D25)}$$

Because for some bolt diameters (< 1") the value of h'_{eff} < 100 mm:

$$\Psi_{re,N} = 0.5 + \frac{4.33 \cdot d}{200\ \mathrm{mm}} \leq 1$$

For a single fastener the eccentricity is zero and $\psi_{ec,N} = 1$.

$$N_{Rd,c} = \frac{N_{Rk,c}}{\gamma_{Mc}} = \frac{N^0_{Rk,c} \cdot \frac{A_{c,N}}{A^0_{c,N}} \cdot \Psi_{s,N} \cdot \Psi_{re,N} \cdot \Psi_{ec,N}}{\gamma_{Mc}} = 270.7 \cdot d^{1.5} \cdot min\left(0.5 + \frac{4.33 \cdot d}{200\ \mathrm{mm}}; 1\right) \qquad \text{(D26)}$$

The results for different bolt diameters are presented in the table D.2

Table D.2 Design value of resistance to avoid concrete cone failure

	d	F_v (0.7 x S_y) ASTM A193 Grade B7	$N_{Rd,c}$
Bolt size	**mm**	**N**	**N**
1/2 – 13	12.70	47005	9493
5/8 – 11	15.88	74802	14453
¾ - 10	19.05	110571	20534
1 – 8	25.40	200099	36649
1 ¼ - 8	31.75	329491	48423
1 ½ -8	38.10	490983	63653
1 ¾ -8	44.45	684573	80213
2 – 8	50.80	910266	98001
2 ½ - 8	63.50	1457947	136961

Conclusions:
The conclusion is that $N_{Rd,c} < F_v$ for all bolt diameters. Both tables with calculation results for cracked concrete show that without supplementary reinforcement, the requirement for concrete cone failure cannot be met for bolts located at corners and in narrow members when bolt preload is assumed to act as an external tension load (which as we know is not a correct assumption).
For non-cracked concrete the characteristic resistance of the fastener would be somewhat higher by a factor 11.9 / 8.5 = 1.4 but without supplementary reinforcement minimum edge distance would have to be increased significantly in all cases.
When spacing between bolts is less than the characteristic spacing $s < s_{cr,N}$ the tabulated values are reduced even further. It shall be noted that calculations are performed for a minimum edge distance of 6.5 times the bolt diameter but this distance is larger than 6.5d for bolts ≤ 1" based on the table with earlier derived data for a general recommendation for minimum edge distance.

In accordance with the Technical Specification CEN/TS 1992 Part 4.2 the design tension forces $N_{Ed,re}$ in the supplementary reinforcement shall be calculated using the (total) design load on the fastener.

Remarks:
It shall be mentioned once again that this is a failure mode which normally cannot occur with preloaded compressor anchor bolts that aren't loaded with external vertical tension working loads of relevant magnitude in comparison with preload.
For that reason the values $N_{Rd,c}$ shall be compared with the sum of the amplitude of all dynamic forces in the vertical direction (pulsation forces, unbalanced forces and torque variation forces) instead of the bolt preload values.
It shall be noted that the sum of all dynamic loads (which is a worst-case assumption) is normally much lower than the anchor preloads.

D.2.4 Steel failure of the supplementary reinforcement

Having established the requirement for supplementary reinforcement in order to prevent concrete cone failure for the proposed edge distance in the previous calculation, the following requirement must be fulfilled.

$$N_{Ed,re} \leq N_{Rd,re} = \frac{N_{Rk,re}}{\gamma_{Ms,re}} \qquad \text{(D27)}$$

In which:
- $N_{Ed,re}$= design value of the reinforcement (N)
- $N_{Rd,re}$ = design value of resistance (N)
- $N_{Rk,re}$ = characteristic value of resistance (N)
- $\gamma_{Ms,re}$ = partial factor for concrete break-out failure modes (-)

$N_{Ed,re}$ = N_{Ed} (design load reinforcement = design load of fastener)

$\gamma_{Ms,re}$ = 1.15

$$N_{Rk,re} = n \cdot A_s \cdot f_{yk} \qquad \text{(D28)}$$

In which:
- $N_{Rk,re}$= characteristic resistance of the supplementary reinforcement of one reinforcement (N)
- A = is cross section of one leg of the supplementary reinforcement (mm^2)
- N = number of legs of the supplementary reinforcement effective for one fastener
- f_{yk} = nominal yield strength of the supplementary reinforcement (MPa) ≤ 500 MPa

API RP 686 recommends a minimum yield strength of the reinforcement of 414 MPa and procedures as per EN 1992 Eurocode 2 "Design of Concrete Structures" are valid for a yield strength in the range of 400 to 600 MPa. The recommended diameter of the reinforcement of 16 mm has been taken in the calculations, see also chapter 5.4.2.
According to the EN 1992-4-2, bars within a distance ≤ 0.75 x h_{eff}, from the fastener are assumed as being effective which is 18 times the bolt diameter.

The design load N_{Ed} = $N_{Ed,re}$ is equal to the bolt preload which is based on 70% of the yield strength of the bolt material. For calculation of the minimum cross section of the reinforcement the following method can be used:

$$N_{E,d} = N_{Rd,re} = A_{sb} \cdot \frac{f_{ykb}}{2} = \frac{n \cdot A_s \cdot f_{yk}}{\gamma_{Ms,re}} \quad \text{(D29)}$$

In which:

A_{sb}= stress area according ISO 898 (mm^2), see Table 0.4 of this report
f_{ykb} = characteristic steel yield strength of the bolt material (MPa)

Using f_{ykb} = 724 MPa, and f_{yk}= 414 MPa, it follows:

$$n \geq 1.408 \frac{A_{sb}}{A_s}$$

The results for different bolt and reinforcement diameters for a bolt preload of 70% of the yield strength of an ASTM A 193 B7 bolt are presented in the following table D.3

Table D.3 Minimum number of bars to avoid Steel failure of the supplementary reinforcement

	d	**A_{sb}**	**n x A_s**	**n*$_{16\ mm\ bars}$**	**n*$_{19.5\ mm\ bars}$**	**n*$_{25.2\ mm\ bars}$**
Bolt size	**mm**	**mm^2**	**mm^2**	**-**	**-**	**-**
1/2 – 13	12.70	93	94	1	1	1
5/8 – 11	15.88	148	149	1	1	1
¾ - 10	19.05	218	219	2	2	1
1 – 8	25.40	395	397	3	2	2
1 ¼ - 8	31.75	650	654	5	4	2
1 ½ -8	38.10	969	975	7	5	3
1 ¾ -8	44.45	1351	1359	10	7	4
2 – 8	50.80	1796	1807	13	9	6
2 ½ - 8	63.50	2877	2894	20	14	9

* The actual number or bar size will be based on other additional requirements such as symmetry around the fastener, etc.

Note:
The responsible civil engineer can select the required number and size of reinforcing bars to comply with the above requirements and requirements for bar spacing, symmetry, concrete cover, anchorage of reinforcement and other criteria that may be applicable. The recommendations for the reinforcement spacing as given in 5.4.4 may be overruled.

D.2.5 Anchorage failure of reinforcement

$$N_{Ed,re} \leq N_{Rd,a} \quad \text{(D30)}$$

In which:

$N_{Ed,re}$= design value of the reinforcement (N)
$N_{Rd,a}$ = design value of resistance (N)

$$N_{Rd,a} = \sum_n \frac{l_1 \cdot \pi \cdot d_s \cdot f_{bd}}{a} \quad \text{(D31)}$$

In which:

l_1 = anchorage length of the supplementary reinforcement in the assumed failure cone (mm)

$\geq$ $l_{b,min}$ = 4 d_s for anchorage with bens, hooks or loops

$\geq$ $10d_s$ for anchorage with straight bars with or without welded transverse bars

$l_{b,min}$ = minimum anchorage length (mm)

d_s = diameter of the reinforcement bar (mm)

f_{bd} = design bond strength for ribbed bars according EN 1992-1-1

α = influencing factor according EN 1992-1-1, 0.7 for hooked bars

n number of legs of the supplementary reinforcement effective for one fastener

$$f_{bd} = 2.25 \cdot \eta_1 \cdot \eta_2 \cdot f_{ctd} \text{ (MPa)} \qquad \text{(D32)}$$

In which:

f_{ctd} = design value of concrete tensile strength (MPa)

η_1 = coefficient related to the quality of the bond condition and the position of the bar during concreting

η_1 =1when good conditions are obtained

η_1 = 0.7 for all other cases

η_2 =coefficient related to bar diameter

η_2 = 1 for a bar diameter $\leq$ 32 mm

η_2 = (132-d_s)/100 for a bar diameter > 32 mm

For a supplementary reinforcement with $d_s \leq$ 16 mm, η_2 = 1

$$f_{ctd} = \alpha_{ct} \cdot \frac{f_{ctk,0.05}}{\gamma_c} \qquad \text{(D33)}$$

In which:

$f_{ctk,0.05}$=5% fractile of characteristic tensile strength (MPa)

α_{ct} = coefficient taking into account long term effects on the tensile strength and unfavourable effects resulting from the way the load is applied. The recommended value is 1.

γ_c = partial safety factor for concrete

For a minimum recommended compressive strength of 28 MPa, see chapter 5.5.4, a value of 1.9 MPa can be used for $f_{ctk,0.05}$. With γ_c = 1.5 it follows:

$$f_{bd} = 2.25 \cdot \eta_1 \cdot \eta_2 \cdot \alpha_{ct} \cdot \frac{f_{ctk,0.05}}{\gamma_c} = 2.85 \text{ (MPa)}$$

Because it is recommended to use anchor bolts with effective clamped length (called embedment depth in EN 1992) of approximately 20-24 times the bolt diameter d and any supplementary reinforcement is positioned close to the anchor bolt, simply because of the limited edge distance, the minimum anchorage in the assumed failure cone will be the largest value of $10d_s$ and at least 10 times the bolt diameter.

A very conservative approach is to use α = 1 for straight bars with minimum concrete cover and confinement instead of α = 0.7 for hooked bars.

The design load $N_{Ed} = N_{Rd,a}$ is equal to the bolt preload which is based on 70% of the yield strength of the bolt material. For calculation of the minimum cross section of the reinforcement the following equation can be used:

$$N_{E,d} = N_{Rd,a} = A_{sb} \cdot 0.7. f_{ykb} = \sum_{n} \frac{l_1 \cdot \pi \cdot d_{s \cdot} \cdot f_{bd}}{a}$$

In which:

A_{sb} = area according ISO 898 (mm²), see Table 0.5 of this report

f_{ykb} = characteristic steel yield strength of the bolt material (MPa)

For an ASTM A 193 B7 anchor bolt material with f_{ykb} = 724 MPa, it follows:

$$n \geq \frac{A_{sb} \cdot 0.7. f_{ykb} \cdot a}{\pi \cdot f_{bd} .n \cdot l_1. d_s} = \frac{A_{sb} \cdot 56.603}{l_1. d_s}$$

$$n \quad \geq \frac{5.6603 \cdot A_{sb}}{\max(d_s; d) \cdot d_s}$$

The results for different bolt and reinforcement diameters for a bolt preload of 70% of the yield strength of an ASTM A 193 B7 bolt are presented in the table D.4

Table D.4 Minimum number of bars to avoid anchorage failure of reinforcement

	d	**A_{sb}**	**n*16 mm bars**	**n*19.5 mm bars**	**n* 25.2 mm bars**
Bolt size	**mm**	**mm²**	-	-	-
1/2 – 13	12.70	93	3	2	1
5/8 – 11	15.88	148	4	3	2
¾ - 10	19.05	218	5	4	2
1 – 8	25.40	395	6	5	4
1 ¼ - 8	31.75	650	8	6	5
1 ½ -8	38.10	969	9	8	6
1 ¾ -8	44.45	1351	11	9	7
2 – 8	50.80	1796	13	11	8
2 ½ - 8	63.50	2877	16	14	11

* The actual number or bar size will be based on other additional requirements such as symmetry around the fastener, etc.

Note:
The responsible civil engineer can select the required number and size of reinforcing bars to comply with the above requirements and requirements for bar spacing, symmetry, concrete cover, steel failure and other criteria that may be applicable.

The table with the number of required reinforcement bars for "Steel failure of the supplementary reinforcement" and the table for "Anchorage failure of reinforcement" are for information only and added to provide some practical information to determine if reinforcement can be achieved within realistic design constraints for number and diameter of reinforcing bars. The recommendations for the reinforcement spacing as given in 5.4.4 may be overruled if necessary.

D.2.6 *Splitting failure due to installation*

Splitting failure due to installation is not considered as the proposed anchors with plate termination do not rely on deformation during preloading or have so-called wedge type terminations. Additionally no European Technical Specification is available that includes the minimum values for edge distance, spacing and member thickness for this anchor type.

D.2.7 *Splitting failure due to loading*

Having established the requirement for supplementary reinforcement in order to prevent concrete cone failure for the proposed edge distance in the previous calculations, longitudinal (transverse, or horizontal direction) splitting reinforcement is also required at the edge of the member and the following requirement for cross section A_s of transverse splitting reinforcement must be fulfilled:

$$A_s = 0.5 \cdot \frac{N_{Ed}}{\frac{f_{yk}}{\gamma_{Ms,re}}} \text{ (mm}^2\text{)} \qquad \text{(D34)}$$

In which:
- N_{Ed} = design load of fastener (MPa)
- f_{yk} = nominal yield strength of the supplementary reinforcement (MPa) $\leq$ 500 MPa
- $\gamma_{Ms,re}$ = partial factor for concrete break-out failure modes (-)

API RP 686 recommends a minimum yield strength of 414 MPa and procedures as per EN 1992 Eurocode 2 “Design of Concrete Structures” are valid for a yield strength in the range of 400 to 600 MPa.

$$N_{E,d} = A_{sb} \cdot 0.7.f_{ykb} \text{ (MPa)} \qquad \text{(D35)}$$

In which:
- A_{sb} = stress area according ISO 898 (mm^2), see Table 8.2 of this report
- f_{ykb} = characteristic steel yield strength of the bolt material (MPa)

With f_{yk}= 414 MPa, $\gamma_{Ms,re}$ = 1.15 and the design load N_{Ed} which is equal to the bolt preload being 70% of the yield strength (f_{ykb} = 724 MPa) of the bolt material it follows:

$$A_s = 0.5 \cdot \frac{A_{sb} \cdot 0.7.f_{ykb}}{\frac{f_{yk}}{\gamma_{Ms,re}}} \text{ (mm}^2\text{)} \quad \text{and} \quad n \geq \frac{0.8962.A_{sb}}{{d_s}^2} \text{ (-)}$$

The results for different bolt and reinforcement diameters for a bolt preload of 70% of the yield strength of an ASTM A 193 B7 bolt are presented in the table D.5.

Table D.5 Minimum number of bars to avoid splitting failure due to loading

	D	A_{sb}	$n^*_{16\ mm}$ bars	$n^*_{19.5\ mm}$ bars	$n^*_{25.2\ mm}$ bars
Bolt size	**mm**	**mm²**	**-**	**-**	**-**
1/2 – 13	12.70	93	1	1	1
5/8 – 11	15.88	148	1	1	1
¾ - 10	19.05	218	1	1	1
1 – 8	25.40	395	2	1	1
1 ¼ - 8	31.75	650	3	2	1
1 ½ -8	38.10	969	4	3	2
1 ¾ -8	44.45	1351	5	4	2
2 – 8	50.80	1796	7	5	3
2 ½ - 8	63.50	2877	11	7	5

D.2.8 Blow-out failure of concrete & minimum required edge distance

The following calculations are for fasteners <u>without</u> the use of supplementary reinforcement and are for information only.

$$N_{Ed} \leq N_{Rd,cb} = \frac{N_{Rk,cb}}{\gamma_{Mc}} \quad \text{(D36)}$$

In which:

N_{Ed} = design value of the fastener (N)
$N_{Rd,cb}$ = design value of resistance (N)
$N_{Rk,cb}$ = characteristic value of resistance (N)
γ_{Mc} = partial factor for concrete break-out failure modes (-)

$\gamma_{Mc} = 1.5$

$$N_{Rk,cb} = N^{o}_{Rk,cb} \cdot \frac{A_{c,Nb}}{A^{o}_{c,Nb}} \cdot \Psi_{s,Nb} \cdot \Psi_{g,Nb} \cdot \Psi_{ec,Nb} \cdot \Psi_{ucr,N} \quad \text{(D37)}$$

In which:

$N^{o}_{Rk,cb}$ = characteristic resistance of a fastener not influenced by adjacent fasteners or edges placed in cracked concrete (N)
$A^{o}_{c,Nb}$ = reference projected area (mm²)
$A_{c,Nb}$ = actual projected area, limited by overlapping break-out bodies of adjacent fasteners $s \leq 4c_1$ as well as by the edges of the concrete member $c_2 \leq 2c_1$ or the member depth
$\psi_{s,Nb}$ = factor taking into account disturbance of concrete stresses due to a corner. For fastenings with several edge distances (e.g. in a corner) the smallest edge distance c_2 shall be inserted
$\psi_{g,Nb}$ = factor taking into account the bearing areas of individual fasteners in a group
$\psi_{ec,Nb}$ = factor taking into account the eccentricity of the load

$\psi_{ucr,N}$ = factor taking into account the effect of position of the fastening in cracked or non-cracked concrete

$$N^o_{Rk,cb} = 8 \cdot c_1 \cdot \sqrt{A_h} \cdot \sqrt{f_{ck,cube}} \tag{D38}$$

In which:

- c_1 = edge distance (mm)
- A_h = load bearing area of the head of the fastener (mm^2)
- $f_{ck,cube}$ = compressive cube strength of concrete (MPa)

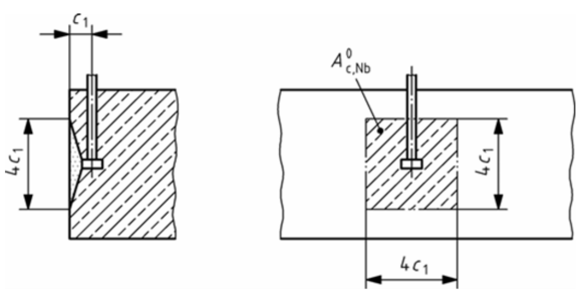
With:

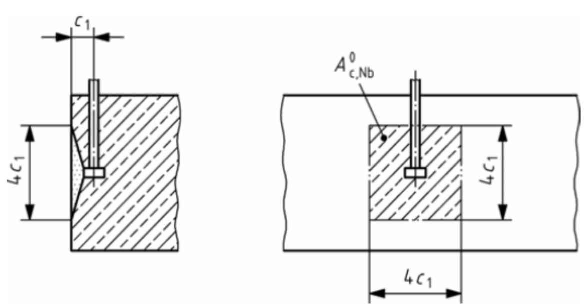
$$A_h = \frac{\pi}{4} \cdot (d_h^2 - d^2) \tag{D39}$$

In which:

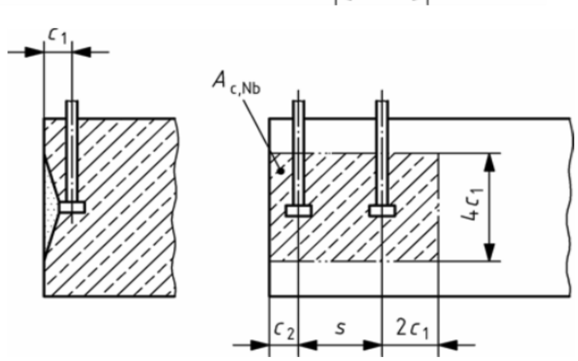
- d_h = diameter of anchor head (mm)
- d = diameter of fastener (mm)

$$A^o_{c,Nb} = (4 \cdot c_1)^2 \tag{D40}$$





$A_{c,Nb} = 4\,c_1\,(c_2 + s + 2\,c_1)$
$c_2 \leq 2\,c_1$
$s \leq 4\,c_1$



$A_{c,Nb} = (2\,c_1 + f)(4\,c_1 + s)$
$f \leq 2\,c_1$
$s \leq 4\,c_1$

$$\Psi_{s,Nb} = 0.7 + 0.3 \cdot \frac{c_2}{c_1} \leq 1 \quad \text{(D41)}$$

$$\Psi_{g,Nb} = \sqrt{n} + \left(1 - \sqrt{n}\right) \cdot \frac{s_1}{4 \cdot c_1} \geq 1 \quad \text{(D42)}$$

In which:

N= number of tensioned fasteners in a row parallel to the edge $s_1 \leq 4 \times c_1$

$$\Psi_{ec,Nb} = \frac{1}{1+2 \cdot \frac{e_N}{4 \cdot c_1}} \leq 1 \quad \text{(D43)}$$

In which:

e_N = eccentricity of the resulting tensile load

$\psi_{ucr,N}$= 1.0 for fastenings in <u>cracked</u> concrete, 1.4 for fastenings in <u>non-cracked</u> concrete

The calculations will be based on the following data:

- For a corner bolt $c = c_1 = c_2 = 6.5$ d (based on PIP STE05121).
- Termination plate diameter d_h of minimum 3d.
- Recommended minimum concrete compressive strength according chapter 5.4.3 is 28 MPa, so $f_{ck,cube} = 28$ MPa

It follows:

$$N^o_{Rk,cb} = 8 \cdot c_1 \cdot \sqrt{A_h} \cdot \sqrt{f_{ck,cube}} = 690 \cdot d^2$$

$$A^o_{c,Nb} = (4 \cdot c_1)^2 = (4 \cdot 6.5 \cdot d)^2 = 676 \cdot d^2$$

For a single corner bolt ($c_1 = c_2 = 6.5 \times d$ in a long member):

$$A_{c,Nb} = 4 \cdot c_1 \cdot (c_2 + 2 \cdot c_1) = 507 \cdot d^2$$

$$\Psi_{s,Nb} = 0.7 + 0.3 \cdot \frac{6.5 \cdot d}{6.5 \cdot d} = 1$$

With:

- $\Psi_{g,Nb} = 1$ for a single corner bolt:
- $\psi_{ec,Nb} = 1$ for a single fastener with eccentricity zero
- $\psi_{ucr,N} = 1$ assuming cracked concrete for a conservative approach

It follows:

$$N_{Rd,cb} = \frac{N^o_{Rk,cb} \cdot \frac{A_{c,Nb}}{A^o_{c,Nb}} \cdot \Psi_{s,Nb} \cdot \Psi_{g,Nb} \cdot \Psi_{ec,Nb} \cdot \Psi_{ucr,N}}{\gamma_{Mc}} = 345 \cdot d^2$$

The results of $\mathbf{N_{Rd,cb}}$ for different bolt diameters are presented in table D.6.

Table D.6 Design value of resistance to avoid blow-out failure of concrete

	d	F_v (0.7 x S_y) ASTM A193 Grade B7	$N_{Rd,cb}$
Bolt size	**mm**	**N**	**N**
1/2 – 13	12.70	47005	55645
5/8 – 11	15.88	74802	87000
¾ - 10	19.05	110571	125201
1 – 8	25.40	200099	222580
1 ¼ - 8	31.75	329491	347782
1 ½ -8	38.10	490983	500805
1 ¾ -8	44.45	684573	681652
2 – 8	50.80	910266	890321
2 ½ - 8	63.50	1457947	1391126

Conclusions:

From the table it can be concluded that the allowable tension forces $N_{Rd,cb}$ to avoid blow out is larger than the bolt preload F_v for bolts diameters ≤1.5" for a single anchor with a corner edge distance of minimum 6.5 times the bolt diameter.

It is also apparent from the calculation of $N^o_{Rk,cb}$ that the termination plate diameter shall not be made too small.

For non-cracked concrete the tabulated values increase by a factor 1.4. which means that the allowable levels of $N_{Rd,cb}$ are a factor of 1.4 higher and for that case the edge distance of minimum 6.5 times is more than sufficient.

Besides that it shall be noted that the calculations are performed for a minimum edge distance of 6.5 times the bolt diameter but that this distance is bigger than 6.5d for bolts ≤ 1" based on the table with earlier derived data for a general minimum edge distance recommendation.

However, the sum of the amplitude of the dynamic loads in vertical direction shall be added to the anchor bolt preload in the calculations.

Due to the fact that the dynamics loads in vertical direction are in general much lower than the anchor bolt preload, especially for horizontal compressors, it is expected that the minimum edge distance of 6.5 the bolt diameter is sufficient.

However, one shall be aware that the dynamic loads for vertical compressors are much larger than those of horizontal compressors.

Remark:

When spacing between bolts (see chapter 9.2.5) is less than 4 times the edge distance c_1 ($s< 4 \times c_1$) the design value of resistance for each fastener is reduced.

Minimum required edge distance

The method described above can also be used to determine the required edge distance for each bolt diameter and if necessary, may overrule the recommendation as given in chapter 9. However, it shall be kept in mind that all calculations are based on worst-case situations.

For $c_1 = c_2 = y.d$: (D44)

$$N^{o}_{Rk,cb} = 8 \cdot c_1 \cdot \sqrt{A_h} \cdot \sqrt{f_{ck,cube}} = 106 \cdot d^2$$

$$A^{o}_{c,Nb} = (4 \cdot c_1)^2 = (4 \cdot y \cdot d)^2 = 16 \cdot y^2 \cdot d^2$$

For a single corner bolt ($c_1 = c_2 = y.d$ in a long member), it follows:

$$A_{c,Nb} = 4 \cdot c_1 \cdot (c_2 + 2 \cdot c_1) = 12 \cdot y^2 \cdot d^2$$

$$\Psi_{s,Nb} = 0.7 + 0.3 \cdot \frac{y \cdot d}{y \cdot d} = 1$$

With:

- $\Psi_{g,Nb} = 1$ for a single corner bolt
- $\psi_{ec,Nb} = 1$ for a single fastener with eccentricity zero
- $\psi_{ucr,N} = 1$ assuming cracked concrete for a conservative approach

$$N_{Rd,cb} = \frac{N^{o}_{Rk,cb} \cdot \frac{A_{c,Nb}}{A^{o}_{c,Nb}} \cdot \Psi_{s,Nb} \cdot \Psi_{g,Nb} \cdot \Psi_{ec,Nb} \cdot \Psi_{ucr,N}}{\gamma_{Mc}} = 53 \cdot y . d^2$$

It follows that: $y \geq \frac{N_{Rd,cb}}{53 \cdot d^2}$ (-)

In which:

$N_{Rd,cb}$ = bolt preload plus the sum of the amplitudes of the dynamic forces in vertical direction

To give an idea for the minimum edge distance for different bolt diameters and for cracked concrete and non-cracked concrete, the values are given in table D.7 based on a bolt preload of 70% of yield strength for ASTM A193 Grade B7 anchor bolts. As mentioned before the $N_{Rd,cb}$ shall be the bolt preload plus the sum of the 0-peak of the dynamic forces in vertical direction.
Reinforcement will be applied all the time. This means that the minimum required edge distances of 6.5d as proposed in chapter 9.2.4 is sufficient for all bolts.
Due to the fact that the dynamic loads are in general much lower than the bolt preload and due to the fact that worst-case assumptions have been made, it is expected that the proposed minimum edge distance of 6.5 the bolt diameter is sufficient.

Table D.7 Minimum required edge distance to avoid blow-out failure of concrete

	d	F_v (0.7 x S_y) ASTM B7	Y Cracked concrete	Y Non-cracked concrete
Bolt size	**mm**	**N**	-	-
1/2 – 13	12.70	47005	5.46	3.9
5/8 – 11	15.88	74802	5.60	4.0
¾ - 10	19.05	110571	5.74	4.1
1 – 8	25.40	200099	5.88	4.2
1 ¼ - 8	31.75	329491	6.16	4.4
1 ½ -8	38.10	490983	6.44	4.6
1 ¾ -8	44.45	684573	6.58	4.7
2 – 8	50.80	910266	6.72	4.8
2 ½ - 8	63.50	1457947	6.86	4.9

D.2.9 Minimum required bolt spacing distance

The minimum required bolt spacing s for a long member containing one corner bolt with an edge distance $c_1 = c_2 = 6.5d$ and a second bolt with spacing can be calculated as follows:

$$N^o_{Rk,cb} = 690 \cdot d^2$$

$$A^o_{c,Nb} = 676 \cdot d^2$$

$$A_{c,Nb} = 4 \cdot c_1 \cdot (c_2 + s + 2 \cdot c_1) = 507 \cdot d^2 + 26 \cdot d \cdot s$$

$$\Psi_{s,Nb} = 1$$

For the two bolts:

$$\Psi_{g,Nb} = \sqrt{n} + (1 - \sqrt{n}) \cdot \frac{s_1}{4 \cdot c_1} = \sqrt{2} - 0.01593 \cdot \frac{s}{d} \quad \text{(D45)}$$

Note:
One can already see that the calculation method is flawed as if one would theoretically install two bolts at the same location and thus s = 0, $\psi_{g,Nb}$ becomes √2 instead of 1 and all other parameters stay the same. This means that the concrete load capacity for this location is √2 times higher when two bolts are installed instead of one at the same location. In practice this is not possible but bolts could be spaced very close in accordance with this calculation method.

Assuming the eccentricity is zero and $\psi_{ec,Nb} = 1$.

For a conservative approach, assuming cracked concrete $\psi_{ucr,N} = 1$ the design resistance for a group of fasteners (in this case a group of two bolts):

$$N^{g}_{Rd,cb} = \frac{690 \cdot d^2 \cdot \frac{507 \cdot d^2 + 26 \cdot d \cdot s}{676 \cdot d^2} \cdot 1 \cdot \left(\sqrt{2} - 0.01593 \cdot \frac{s}{d}\right) \cdot 1 \cdot 1}{1.5}$$

For x = s / d and a group design resistance $N^{g}_{Rd,cb}$ equal to the total preload F_v of the two bolts in the group and $y = \frac{N^{g}_{Rd,cb}}{d^2} = \frac{2 \cdot F_v}{d^2}$ the equation can be written as follows:

$$N^{g}_{Rd,cb} = \frac{690 \cdot d^2 \cdot \frac{507 \cdot d^2 + 26 \cdot d^2 \cdot x}{676 \cdot d^2} \cdot 1 \cdot (\sqrt{2} - 0.01593 \cdot x) \cdot 1 \cdot 1}{1.5} = y \cdot d^2$$

With:

$$\frac{690 \cdot \frac{507 + 26 \cdot x}{676} \cdot 1 \cdot (\sqrt{2} - 0.01593 \cdot x) \cdot 1 \cdot 1}{1.5} = y$$

Solving for x gives:

$$x = \frac{19.52 - \sqrt{19.52^2 - 4 \cdot 0.2818 \cdot (y - 487.9)}}{2 \cdot 0.2818}$$

Table D.8 Minimum required bolt spacing distance to avoid blow-out failure of concrete

	d	**F_v (0.7 x S_y) ASTM A193 Grade B7**	**y = 2F_v / d^2**	**x = s/d**
Bolt size	**mm**	**N**	-	-
1/2 – 13	12.70	47005	582	0
5/8 – 11	15.88	74802	594	0
¾ - 10	19.05	110571	609	0
1 – 8	25.40	200099	620	0
1 ¼ - 8	31.75	329491	654	0
1 ½ -8	38.10	490983	676	0.3
1 ¾ -8	44.45	684573	693	0.4
2 – 8	50.80	910266	706	0.8
2 ½ - 8	63.50	1457947	724	1.5

In accordance with the calculation method, even for worst-case assumptions, which does not seem correct and suitable for finding the minimum spacing required, the spacing between bolts can be made very, and unrealistically, small.
The spacing required for placing, concrete compacting and other requirements determine the actual spacing. A spacing of 7 times the bolt diameter based on PIP STE05121 [12] is more than sufficient.

E Bolt stresses caused by thermal expansion of the frame

A compressor frame will expand as shown in Figure E.1. Thermal expansion of compressor frames resulting from the normal operating temperature of the lube oil cannot and shall not be constrained by anchor bolts as the resulting forces and bolt stresses would become excessive.

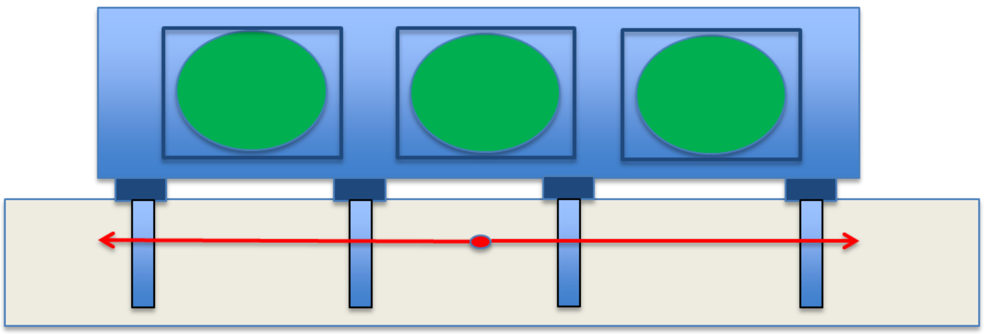


Figure E.1 Thermal expansion of compressor frame

The shear force acting on a bolt depends on the diametrical bolt clearance in combination with the free bolt length and the coefficient of friction. With adequate clearance the maximum possible shear force is always limited by the preload times the maximum coefficient of friction at any of the interfaces of the clamped parts. In practice this coefficient of friction is unlikely to exceed a value of 0.25.

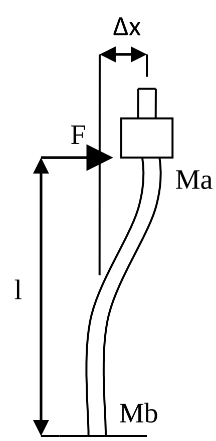


Figure E.2 Deformation of the anchor bolt caused by thermal expansion of the frame

The thermal expansion Δx (see figure E.2) can be based on the maximum allowable compressor sump temperature of 70°C according API 618 and an ambient or concrete temperature of 20°C during installation/grouting. The coefficient of thermal expansion α for most cast irons is approximately 11 x 10^{-6} /°C. The length l_{exp} over which expansion of the compressor frame takes place depends on the compressor frame type and size and if we for example would perform a calculation for a distance of 4000 mm between the frame geometrical centre and most outer corner frame anchor, the expansion is:

$$\Delta x = l_{exp} \cdot \alpha \cdot \Delta t = 0.00221\ m \qquad \text{(E1)}$$

If we assume that sufficient diametrical bolt clearance is present and the free bolt length l is such that the maximum possible shear force is generated than the following can be derived for this 2½"-8 UN B7 bolt preloaded F_v at 70% of the yield strength with a maximum assumed friction coefficient (steel-steel contact):

$$F = F_v \cdot \mu = 364487 \text{ (N)} \qquad \text{(E2)}$$

$$F = \Delta x \cdot \frac{12 \cdot E \cdot J}{l^3} \text{ (N)} \qquad \text{(E3)}$$

In which:

E = the modulus of elasticity of the bolt material (Pa)

J = area moment of inertia of the bolt (m^4), with

$$J = \frac{\pi}{64} \cdot d_s^4 \qquad \text{(E4)}$$

In which:

d_s = stress diameter of the bolt (m)

$$d_s = \sqrt{\frac{4}{\pi} \cdot A_s} = d - 0.938194 \cdot p = \frac{d_1 + d_2}{2} \qquad \text{(E5)}$$

With a bolt diameter d = 0.0635 (m) and a pitch p of 0.0254/8 = 0.003175 (m) it follows:

$$d_s = 0.0635 - 0.938194 \cdot 0.003175 = 0.0605 \text{ (m)}$$

$$l = \sqrt[3]{\frac{\Delta x \cdot 12 \cdot E \cdot \frac{\pi}{64} \cdot d_1^4}{F}} = 0.2449\ [m]$$

If the actual free length over which the bolt can move freely in radial direction is more than 245 mm than the shear bolt load will be less than the maximum possible value.

The maximum bending moment in the bolt for this maximum shear force condition is:

$$M_a = M_b = \frac{1}{2} \cdot F \cdot l = 44631 \text{ (Nm)} \qquad \text{(E6)}$$

And the maximum bending stress:

$$\sigma_b = \frac{M_b}{W_b} = \frac{M_b}{\frac{\pi}{32} \cdot d_s^3} = \frac{41861}{\frac{\pi}{32} \cdot 0.0605^3} = 2052 \cdot 10^6 \text{ (Pa)} \qquad \text{(E7)}$$

This 2052 MPa bending stress far exceeds the bolt materials yield strength so we can conclude that the actual free length shall be significantly more than 245 mm.
If we assume a free length equal to 12 bolt diameters, see chapter 8.8.4, than the following is calculated for the largest bolt diameter of 63.5 mm:

$l = 12 \cdot d = 0.762$ (m)

$F = \Delta x \cdot \frac{12 \cdot E \cdot J}{l^3} = \Delta x \cdot \frac{12 \cdot E \cdot \frac{\pi}{64} \cdot d_s^4}{l^3} = 9719$ (N)

$M_a = M_b = \frac{1}{2} \cdot F \cdot l = 3703$ (Nm)

$\sigma_b = \frac{M_b}{W_b} = \frac{M_b}{\frac{\pi}{32} \cdot d_s^3} = \frac{3259}{\frac{\pi}{32} \cdot 0.0605^3} = 170 \cdot 10^6$ (Pa)

The shear stress from F:

$\tau_F = \frac{F}{A_s} = \frac{F}{\frac{\pi}{4} \cdot d_s^2} = 3.15 \cdot 10^6$ (Pa) (E8)

$\sigma_t = 0.70 \cdot \sigma_y = 0.70 \cdot 724 \cdot 10^6 = 507 \cdot 10^6$ (Pa)

When the bolt is preloaded by a torque wrench the additional shear stress from this method of tightening is equal to:

$\tau_T = \sigma_t \cdot \frac{4 \cdot \left(\frac{P}{\pi \cdot d_2} + \frac{\mu}{\cos \frac{\gamma}{2}} \right)}{1 + \frac{d_1}{d_2}}$ (Pa) (E9)

With a thread angle γ of 60 degrees, a coefficient of friction of 0.14 and a minor diameter d_1 = 0.0590604 m and a pitch diameter d_2 = 0.061438 m gives a torsional stress of 183 MPa.

The maximum "worst case" total combined tension, shear, bending and torsional stress is:

$\sigma_{id} = \sqrt{(\sigma_t + \sigma_b)^2 + 3 \cdot (\tau_F + \tau_T)^2}$ =732 (Pa) (E10)

The calculated value of 732 MPa is 101 % of the minimum yield strength of 724 MPa and just exceed the allowable level.
This means that the free bolt length of 12 times the bolt diameter is just a bit too short. Either a larger free bolt length (13 times the diameter for this example) or a smaller preload (69% in this example) is required for this example.
This approach clearly shows that adequate clearance and free length are required but more importantly that bolt preload shall not be too high or the free length not too short.
The above equations can be simplified by assuming d = d_s for the calculation of the free length and use a ratio of shear stress to direct tensile stress from bolt torque of 0.437 based on a 1"-8 UNC bolt. Normally 1" is the smallest bolt size used for compressor anchor bolts and for smaller bolts this ratio is somewhat higher than for large bolts and therefore represents a worst-case approach.

With a nominal preload stress of 70% of the yield stress the shear stress from bolt torque is 0.7 times a value of 0.437 which is 0.306 times the yield strength.

$$\sigma_{id} = \sqrt{\left[\left(0.7 \cdot \sigma_y\right) + \left(\frac{\Delta x \cdot 3 \cdot E}{100 \cdot d_s}\right)\right]^2 + 3 \cdot \left[\left(0.306 \cdot \sigma_y\right) + \left(\frac{\Delta x \cdot 3 \cdot E}{4000 \cdot d_s}\right)\right]^2} \text{ (Pa)} \qquad \text{(E11)}$$

With this equation it is possible to calculate the necessary clearance between bolt and grout/concrete for different bolt materials and different preloads.

Thermal expansion is a low cycle phenomena and the calculated bending and shear stresses in the example are unintensified peak-to-peak values. A more detailed calculation shall be performed, including applicable stress concentration factors for fatigue, but one has to consider that the allowable dynamic stresses are very high for the low number of cycles involved.
For one start per week over a period of twenty years the number of cycles is only 1040 and even this may be overestimating the number of cycles for typical compressors in refining applications.
It shall be noted that for Underground Gas storage Systems (UGS systems) the number of cycles is much more than 1040. Examples are known where the compressor is started twice a day and the allowable stress range for this number of cycles is approximately reduced with a factor of 3.
Another point to consider is that even for systems with some but perhaps insufficient diametrical bolt clearance and free bolt length, and in which the yield strength is possibly exceeded during the initial load cycles, the stress amplitudes in subsequent load cycles may be reduced as some load induced clearance can be formed between the bolt and grout in the anchor bolt pocket. This means that the joint becomes compliant due to embedding and relaxation. It is however better no to rely on these phenomena but to design for some thermal expansion with adequate clearance and free length.

For crosshead guides no calculation is made as this calculation shall somehow include the flexibility of the crosshead guide support to obtain usable results for the shear forces and thermal displacement.

The lateral bolt deformation and thus the required clearance Δx from the start of the free length in the bolt pocket y = 0 up to the top of the concrete y = l = 12 x d can be calculated with the following equation:

$$\Delta x = \frac{Fv \cdot l^3}{12 \cdot E \cdot J} \cdot \left[3 \cdot \left(\frac{y}{l}\right)^2 - 2 \cdot \left(\frac{y}{l}\right)^3\right] \text{ (m)} \qquad \text{(E12)}$$

The equations shows that the clearance does not have to be the same over the total free length. The closer to the top of the concrete the more clearance shall be included in the design. However, for practical reasons it is easier to use one value, being the value at the top of the concrete, y=l. This gives the following equation:

$$\Delta x = \frac{Fv \cdot l^3}{12 \cdot E \cdot J} \text{ (m)}$$

The final conclusion is that it has been proven that the free length of 12 times the bolt diameter is minimum required to avoid that the bolt will be broken due to thermal expansion of the compressor. Besides that enough clearance must be present between the bolt and bolt pocket over the free length of the bolt.

Bolt free taped or sleeved length shall be at least 12 times the bolt diameter as summarised in chapter 8.8.4. The material for taping/sleeving that allows adequate free radial movement shall be selected by the engineering department. Material for example closed cell neoprene.