# LIMIT STATE DESIGN: FASTENING TO CONCRETE

Paper presented at Concrete 99
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This paper reviews the various limit states which determine the performance of fastenings in concrete with reference to principle types of cast-in and post-installed fasteners including undercut, expansion and adhesive (grouted and chemical anchors). Design methods consistent with current Australian limit state standards are presented with appropriate capacity reduction factors for strength and serviceability limit states according to the anchor types.

Keywords: concrete, fasteners (anchors), limit state design, structural design, cast-in, post-installed, tension, shear.

**INTRODUCTION**

Innovations in structural design and in the properties of construction materials has progressed rapidly in recent years. New structures incorporating these improvements demand new methods of fastening between the structural elements to provide improved performance and minimise risk.
By their very nature, fastenings are located at places within structures where load concentrations occur and as a result, the performance of the fastenings under load can influence the overall performance of the structure. Unfortunately there is a general lack of awareness amongst designers about the performance differences between various types of fastenings to concrete.

Current concrete design standards e.g. Australian Standard AS3600 (1), provide little guidance for designers and focus only on strength limit states, written around the design of (steel) fixings cast into the concrete. There is no distinction between cast-in and post-installed fastenings nor anchors which use materials other than concrete and steel e.g. adhesive anchors "chemical anchors".
The behaviour of commonly used, post-installed fastenings can be very different to that of cast-in fixings.

There is a clear need for standards to provide requirements for fastenings using limit state design principles describing strength and serviceability limit states consistent with current design practice.

**TRADITIONAL DESIGN APPROACH**

Concrete fastenings have been designed by comparing the applied load with a "safe working load" calculated for the anchor. This safe working load was derived by factoring down (with a "factor of safety" - usually four) the ultimate failure load obtained from static laboratory tests using dense, uncracked concrete and ideal installation conditions. Only the maximum load achieved in the test was recorded without regard to what actually failed or how it failed. It is self-evident that these methods were deficient because the same factor was specified irrespective of anchor type, behaviour prior to failure or possible serviceability constraints. Designs based on this approach can be either conservative or very unconservative depending upon the type of anchor and the circumstances in which it is used.

The first Australian Standard to recognise performance limitations was AS3850:1990 (2), a standard developed for precast concrete and tilt-up construction, which limited the use of different types of post-installed fastenings according to their behaviour under load. Accident investigations showed that fastenings specified on the basis of ultimate strengths had failed in service by other mechanisms. AS3850 was not a limit state design standard but it restricted the use of certain types of anchors in order to avoid failures.
Research published in Europe and the USA has provided a better understanding of the behaviour and performance of various types of anchorages. ACI committee 355 (3) highlighted the value of the performance approach in the design of fastenings and the need to specify by considering factors other than the ultimate load. New ACI codes will include specific sections covering anchorage to concrete.

**LIMIT STATE DESIGN**

The following equation must be satisfied for every limit state applicable to the design (1,4) :

$S^* \leq \phi R_u$

where

**$S^*$** = design action effect (i.e. design shear load and / or design tension load) on the anchor

**$R_u$** = nominal capacity (ultimate strength) of the anchor

$\phi$ = capacity reduction factor

The design action effect $S^*$ is calculated from the factored limit state load in AS 1170-1989 (5)

**FASTENING LIMIT STATES**

In examining limit states it is useful to classify concrete fastenings by their method of anchorage:

| | |
|---|---|
| CONCRETE INTERLOCK | (Cast-In and Undercut Anchors) |
| FRICTION | (Expansion Anchors) |
| ADHESION | (Grouted and Chemical Anchors) |

**Material Strength Limit States**

| | | |
|---|---|---|
| Fastening (bolt) material, Concrete | - | all anchors |
| Bond | - | adhesive anchors only |

**Serviceability Limit States**

| | | |
|---|---|---|
| Preload dependent: | | |
| clamping force | - | all anchors if required |
| fatigue, | - | all anchors if required |
| slip | - | expansion anchors |
| Adhesive variability | - | adhesion anchors |
| Heat | - | adhesion and plastic anchors |
| Corrosion | - | all anchors |

**MATERIAL STRENGTH**

**Steel failure - all fastenings**

The characteristic ultimate strength of the anchor steel for tension and shear.

For standard materials reference may be made to published standards e.g. according to ISO bolt strength class: ISO 8.8 = 800MPa tension, 496MPa shear.

Appropriate equations for steel fastenings to concrete are as follows:

Steel bolt in tension $N_{tf}^* \leq \phi_s N_{tf}$ refer AS4100 Cl. 3.4 (d), AS3600 Cl. 2.3 (d)

where $N_{tf}$ = Nominal strength of the anchor as controlled by ultimate steel strength

Steel bolt in shear $V_f^* \leq \phi_s V_f$

$V_f = 0.62 f_{uf}$ for single plane shear refer AS4100

The capacity reduction factor for steel $\phi_s = 0.8$ refer AS4100 table 3.4.

**Concrete failure - all fastenings**

$N_{tc}^* \leq \phi_c \phi_{cr} N_{tc}$

$N_{tc}$ = Nominal strength of the anchor as controlled by concrete cone failure

$\phi_c$ = 0.6 strength reduction factor for concrete: refer AS3600 table 2.3 (j)

$\phi_{crN}$ = strength reduction factor for cracked concrete in tension

***"Cone" failure developed by a fastening in concrete***

Where the load transmitted through the fastening exceeds the tensile strength of the concrete, a cone or truncated cone of concrete is pulled out by the anchor. The capacity of the concrete is a function of:

- tensile strength of the concrete (related to $f'_c$)
- embedment depth of the anchor
- proximity of the anchor to any free edge or other anchor
- existence of cracks or possible development of cracks in the vicinity of the anchor

This behaviour is well researched. The ultimate strength of an anchor may be expressed by equations for tension and shear using the concrete capacity design method (CCD), developed at Stuttgart University, reported in (6,7,8) which has now been adopted in Europe and endorsed by ACI for future code revisions. These equations provide a simple, consistent approach to the design for tension and shear where concrete cone failure can be expected to occur, which is in the majority of applications.
In certain circumstances other failure modes can occur: side blow-out failures (deep embedments, high loads and close edge distances) and concrete splitting (very close to one or more edges, low strength concrete, small concrete members compared to embedded anchor length) are not predicted by these equations. In general, however, such failures can be avoided where edge distance $\geq 1.5h_e$, spacings between anchors $\geq 3h_e$ and concrete member thickness $\geq 2h_e$ with $f'_c \geq 20$MPa (8) .

*Effect of cracks*
Reinforced concrete is designed to crack in tension zones. Where cracks occur in the vicinity of fastenings, performance is degraded according to the type of fastening, the nature of the cracks and the loading regime. Concrete cracks in the vicinity of anchors reduce the cone failure strength of the concrete and may lead to other types of failure depending upon the type of fastening. Consideration for the effects of cracks is especially important in the tension zones of concrete members where cracks open up during service.

**Anchors loaded in tension:**
The ultimate strength of the concrete for cone failure for anchors installed in
*un-cracked concrete well away from edges* is predicted by the following CCD equation (6,8):

$$\mathbf{N_{tc0} = k_{nc} * h_{ef}^{1.5} * \sqrt{f'_c}}$$

**$N_{tc0}$** = Nominal tensile strength as controlled by concrete strength for a single anchor
located well away from edges and therefore unaffected by edge effects
**$h_{ef}$** = embedment depth
**$f'c$** = concrete compressive strength
**$k_{nc}$** = 15.5 for cast-in, headed fasteners
= 13.5 for post-installed fasteners

*and in cracked concrete*
The following k factors (7) for anchors suitable for use in cracked concrete have been used to modify the results from the above equation using a capacity reduction factor $\phi_{crN}$ rather than change k factors.

**$k_{nc}$** = 11.5 for cast-in headed anchors $\phi_{crN}$ = 0.75
= 10 for undercut anchors $\phi_{crN}$ = 0.75
= 9 for heavy shield, load controlled expansion anchors $\phi_{crN}$ = 0.65

The following types of fastenings are *not suitable* for tension loads in cracked concrete:

- Grouted and adhesive anchors, deformation controlled and low-load slip expansion anchors: $\phi_{crN} = 0$

These fastenings exhibit strong sensitivity to cracks, suffering large displacements at small crack widths, significantly reduced failure loads (as low as 20% for adhesive anchors in 0.4mm cracks) concrete displacements in the anchoring zone, with a high degree of scatter between results (3,7,8).

*edge effects and anchor groups*
The CCD method uses the "$\psi$ method" (3,6,8) to calculate appropriate reduction factors for fastenings placed near edges and in anchor groups. A complete explanation for the derivation of the method is beyond the scope of this paper however the method provides the following expressions:

$N_{tc} = (A_{Ntc} / A_{Ntc0})\ \psi_1\ \psi_2\ N_{tc0}$
$A_{Ntc} / A_{Ntc0}$ = ratio of actual projected area $A_{Ntc}$ of the at the concrete surface compared to the projected area of a theoretical cone concrete cone (simplified as a rectangular pyramid with sides = $3h_e$) generated by an anchor group.
$\psi_1$ = load eccentricity factor = $1 / (1 + 2e_{Ntc}/(3h_{ef})) \leq 1$
$\psi_2$ = "tuning factor" for edges = $0.7 + 0.3(c_1/1.5h_{ef})$ for $c_1 \leq 1.5h_{ef}$

$e_{Ntc}$ = distanced between the resultant tensile force of a group of fasteners and the centroid of the fasteners.
$c_1$ = distance of a fastener to a free edge

**Anchors loaded in shear:**
For anchors loaded in shear toward a free edge in uncracked concrete:

$\mathbf{V_c^* \leq \phi_c \, \phi_{crv} \, V_{c0}}$

$\phi_{crV} = 0.7$ strength reduction factor for cracked concrete in shear
A strength reduction of approximately 30% occurs in concrete with cracks of 0.4mm width and is almost independent of the type of anchor (8).

$V_{c0} = (h_e / d)^{0.2} \sqrt{d} \sqrt{f'_c} \, c_1^{1.5}$
d = outside diameter of the fastening
For anchors where $h_e \approx 4$ this simplifies (8) to:
$V_{c0} = 1.4 \sqrt{d} \sqrt{f'_c} \, c_1^{1.5}$

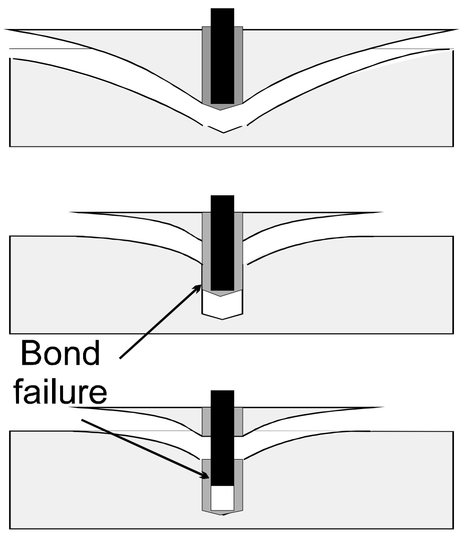
and for anchor groups and close edge distances:
$V_c = (A_{Vc} / A_{Vc0}) \, \psi_4 \, \psi_5 \, V_{c0}$
$A_{Vc} / A_{Vc0}$ = ratio of actual projected area $A_{Vc}$ of the concrete at the edge surface compared to the projected area of a theoretical cone (simplified as a rectangular pyramid with sides $1.5c_1$ and $3c_1$) generated by an anchor group.
$\psi_4$ = load eccentricity factor = $1 / (1 + 2e_{Vc}/(3c_1)) \leq 1$
$\psi_5$ = "tuning factor" for a corner = $0.7 + 0.3(c_2/1.5c_1)$ for $c_2 \leq 1.5c_1$
$c_1$ = edge distance in the loading direction
$c_2$ = edge distance perpendicular to the loading direction

**Adhesion failure: - grouted & adhesive fastenings**
The characteristic ultimate bond strength developed between adhesive & fastening and adhesive & concrete. This limit state governs the performance of fastenings which are "glued" into concrete.
These comprise a threaded rod set into a drilled hole with a cementitious grout or a plastic resin adhesive (structural glue). In general the adhesives and grouts are two-component mixtures which when mixed together in strictly defined proportions undergo chemical reactions causing the grout/adhesive to harden. Provided anchors are carefully installed, bond failure for deeply embedded anchors is normally preceded by concrete cone failure. The limit state for bond failure is given by the following equation (9):
$N_b^* \leq \phi_b \, \phi_{heat} \, N_b$

| | | |
|---|---|---|
| $N_b^*$ | = | Nominal strength of the anchor as controlled by bond strength |
| $\phi_b$ | = | Capacity reduction factor for bond. |
| $\phi_{heat}$ | = | Capacity reduction for heat |
| $N_b$ | = | $\tau_{fc} \, \pi \, d h_{ef}$ |
| $\tau_{fc}$ | = | design bond stress at the anchor/adhesive interface |
| d | = | outside diameter of the anchor |

The bond strength of chemical anchors is variable and depends on (8):
- the type of adhesive (polyester, epoxy etc),
- the percentage, size and type of filler materials in the mortar,
- the method of drilling the hole which affects the surface roughness (percussion or diamond core),
- the cleanliness of the hole walls, the amount of dust left in the hole (which mixes with the mortar as a filler and reduces strength),
- the degree of mixing,
- the number and size of air voids,
- presence of moisture,

**CONCRETE FAILURE**




**BOND & CONCRETE FAILURE (common)**

Figure 1. Grouted & chemical anchors

- the curing time and temperature

## SERVICEABILITY

### Limit states dependent upon preload

*Preload*

Fastenings are preloaded during installation to induce a clamping force between the base material and the fixture. AS4100 provides requirements for the installation of standard structural bolts. Preload and its effects on anchor performance are discussed in ACI and CEB State of the Art Reports (3,8). Preload is normally applied by setting fastenings at a nominated tightening torque. Whilst there is no direct relationship between torque and induced preload (principally due to uncontrollable variations in friction), tests have shown that when bolts are tightened within the elastic load range, sufficient preload may be achieved for given bolt types at nominated installation torques. In critical applications the preload should be applied with a calibrated loading jack.

*Retained preload*

After installation some of the initial preload is lost. The highly stressed concrete in the vicinity of the anchoring region (especially with expansion anchors) creeps and allows the stress in the anchor bolt to relax. The degree of relaxation varies according to the type, design and materials of the anchor.

The serviceability limit states affected by the retained anchor preload are defined as follows:

$N_{ti}^* \leq \phi_{cf} N_{ti}$

$N_{ti}^* \leq \phi_{slip} N_{ti}$

$N_{ti}^* \leq \phi_{fatigue} N_{ti}$

$N_{ti}$ = tension induced in the bolt during installation.

$\phi_{cf}$ = clamping force capacity reduction factor.

$\phi_{slip}$ = expansion anchor slip capacity reduction factor.

$\phi_{fatigue}$ = fatigue capacity reduction factor.

**Clamping force** $\phi_{cf} =$ **0.8**

The clamping force exerted between the fixture and the base material is lost when bolt preload drops to zero and the applied load acts directly upon the anchoring mechanism.
In some designs a clamping force must be maintained e.g. to limit deflections.

In other cases more restrictive capacity reduction factors are required:

$\phi_{cf} = \mathbf{0.7}$

refer: AS 4100 Cl. 3.5.5

i.e. in applications where it is critical to maintain set levels of preload to ensure that the fastenings do not move e.g. anchors subject to vibrating and shock loads, friction grip joints, etc.

Where the integrity of the anchoring mechanism is itself load dependent, e.g. expansion anchors, then the slip limit state governs: see below.

**Expansion anchor slip**

Well embedded expansion anchors slip prior to developing their ultimate failure load. This movement limits the use of expansion anchors. The security of these fastenings is directly proportional to the friction force exerted by the expansion mechanism on the concrete.

*Slip* (permanent anchor displacement) occurs when the applied load exceeds the friction resistance developed between the fastening and the concrete. Depending upon the design, materials and manufacture of the anchor, the movement of the expansion wedge against the shield may (or may not) be recoverable when the load is relaxed. Some movement is never recoverable which results in permanent slip. The load at which *first slip* occurs and the amount of slip prior failure to is highly variable and depends upon anchor design and installation method.

When anchors slip, a gap may develop between the fixture and the base material and repeated load cycles are then magnified by impact, leading to creep pullout failure (3,10,11) .
"If the applied sustained or cyclic load exceeds the load at first slip in short term tests, creep pullout of the bolt will occur" (11) .

***Deformation controlled anchors*** $\phi_{slip}$ = 0 (variable & unreliable)

e.g. Drop-ins, Self drilling anchors, Spring coil anchors
Frictional resistance is developed in a *once-only* maximum expansion during setting . There is *no follow up,* the anchors pull out after first slip. The load in a bolt screwed into this type of fastening does not affect these anchors because their performance is only dependent upon the initial (compressive) preload developed between the expansion wedge/shield and concrete during setting (see fig. 2). Slip occurs when the applied load exceeds the setting force and there being no further resistance, the entire anchor slips from the hole by *case-slip*. Anchor performance depends upon the dimensional accuracy of the drilled hole (8) and it is not possible to measure the expansion preload without failing the anchor.

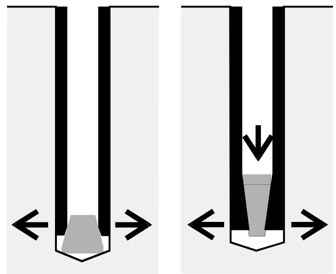


Figure 2. Deformation control

Whilst the expansion force developed by these fastenings (when carefully installed) can be higher than other types of expansion anchors (8), their design makes them highly sensitive to installation methods and hole diameters resulting in variable expansion (30-70% expansion achieved in tests (7) and severely affected by cracks. They are therefore unreliable and failure is unpredictable and cannot be recommended for structural applications.
The unsuitability of these fixings for structural applications was recognised by AS3850.

***Load controlled expansion anchors***

These fastenings have a bottom wedge which is drawn into a surrounding expansion shield to exert a friction force on the walls of the hole. The friction force increases with load *provided that the wedge is free to move against the shield*. After first slip, the expansion force continues to increase with applied load as the wedge is drawn into the shield *(follow up)*, accompanied by further slip. The shape and thickness of the shields and their freedom to slide under load determines the *expansion reserve*.

*High-load slip, load controlled, expansion anchors* $\phi_{slip}$ = 0.6

Heavy duty load controlled (sometimes referred to as torque controlled) expansion anchors.
These have thick expansion shields (see fig.3) capable of efficiently transmitting high expansion forces to the concrete generating high friction forces and resistance to slip. They have good expansion reserve and are suitable for structural anchoring in cracked concrete in tension zones.
These anchors can be expected to reliably retain 60% of the initial preload (10,12,13). The initial loss of preload is quick - in the first few hours after installation. In critical applications it is beneficial to re-apply the preload after 7-14 days. Long term tests (14) in excess of 8 years with some types of heavy duty expansion anchors have shown them to be capable of maintaining in excess of 70% of their initial preload

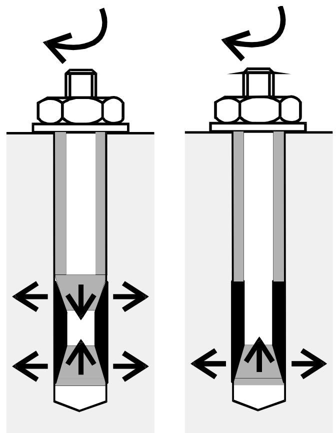


Figure 3. High-load

*Low-load slip, load controlled expansion anchors* $\phi_{slip}$ = 0.25

Sleeve anchors and Wedge (Stud) anchors
These are general purpose fastenings which should only be considered for non-critical applications, where cracks are not expected. These relatively have thin and/or small expansion shields with very limited expansion reserve and follow-up. They do not reliably retain more than 20-30% of the initial preload and slip at low loads, and fail by progressively *pulling out* of the hole or *pull-through* of the internal wedge past the expansion shield.

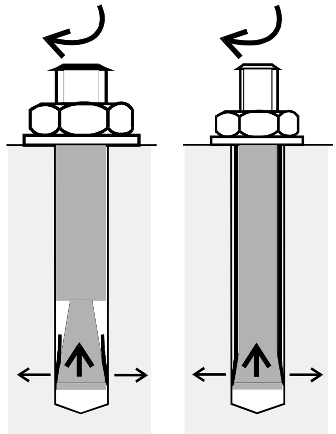


Figure 4. Low-load

The thin shields (refer fig. 4) deform under the point loads developed between the wedge and concrete. This results in inefficient load transfer, jamming of the wedge and loss of follow-up, which in turn causes failure by “case-slip”. Many cases of slippage have been noted in the field. These fastenings perform poorly in cracks because the shields are too thin to compensate for movement (3, 7).

**Fatigue** $\phi_{fatigue} = 0.6$

When fastenings are subject to vibrating loads and/or load reversals, the maintenance of a clamping force can be critical to avoid fatigue failure of the fastening components.
AS4100 section 11 contains provisions for the fatigue design of bolts.

**Adhesive Bond:** $\phi_b = 0.6$ $\tau_{fc} =$ 8MPa

*Grouted & adhesive anchors*

Adhesive anchors (commonly referred to *as chemical anchors*) have progressively replaced cementitious grouted anchors. They are faster to install, generally considered to be stronger, more flexible, easier to use and more reliable in the majority of applications at ambient temperatures.
A capacity reduction factor of (0.85) for bond was proposed by Cook et al. (9) for chemical anchors of known bond strength. This is not considered to be sufficiently conservative for a general design capacity factor given the number of variables and the extent by which bond can be affected by material variations, errors of installation and environmental factors.
A capacity reduction factor of 0.6 as used for concrete (which also accounts for variability) is more appropriate for chemical anchors and a design bond stress of 8MPa has been proposed (8).

Adhesive mortars are mixtures of a polymer base and an inert, filler material (usually synthetic silica).
Commonly used polymer systems are:

- Polyester (polymerised styrene)
- Vinylester (a modified polyester sometimes referred to as epoxy acrylate)
- Epoxy

A number of factors lead to variations in the bond strength of adhesive and grouted anchors.
Properties of the finally hardened material are very dependent on the type of adhesive and filler, the condition of the components prior to mixing and the mix proportions. Cement mortars can be affected by exposure to moisture in storage whilst chemical adhesive mortars are degraded by exposure to heat and/or light and moisture and generally have a limited shelf life.
Adhesive anchors are very sensitive to hole cleanliness with reductions of 30%-80% having been reported in tests undertaken in different studies (8). If the drilled holes are not scrupulously cleaned, a dust film may separate the surface of the concrete from the adhesive surface. Mixing of dust from the hole dilutes the chemical mortar which weakens it and reduces bond strength (8).

There are two types of adhesive systems in general use:
*Post-mix:* (mix in the hole). This is the original “chemical anchor” system where the adhesive components are contained within a glass (sometimes plastic) capsule which is placed into the bottom of the hole and mixed directly by penetration with the stud and vigorous rotation. The mixture flows back over the stud and fully fills the cavities. The vigorous movement of the stud during mixing, together with the presence of fractured glass, helps to scour the hole walls and remove adhering dust which is taken up into the moving adhesive mixture. The performance of capsule anchors is highly dependent upon the quality of mixing.
A variant has a glass capsule which is designed for mixing by hammering in the stud.
*Pre-mix:* The mixed adhesive is placed or injected into the bottom of the hole and the stud introduced with limited rotation. The mixture flows back past the stud to fill the hole.
Pre-mix systems (and also hammer-in systems) are potentially more sensitive to hole cleanliness and installation errors than the original post-mix systems. With pre-mix systems there is a danger that the mixture “skins over” with a dry dust film which prevents the adhesive mixture from fully wetting and bonding to the surfaces of the hole. These systems are also prone to another serious installation error: if (as often happens) the mixture is placed at the top of the hole rather than into the bottom, when the stud

is introduced the mixture oozes back out rather than filling the hole, leaving little actually in contact. Neither of these problems can be revealed by inspection of the finished fastening.
Tests have shown that the bond strength of injection anchors are typically 20% lower than equivalent conventional capsule post-mix systems. Bond strength is affected by heat (see fig. 6 below).

**Heat**
Materials exhibit plastic extension (creep) when subjected to loads over long periods. Heat increases the rate at which creep occurs. Creep is not normally a limitation for concrete and steel (except in the high temperatures generated by fires).
All polymer resins and therefore adhesive anchors are sensitive to heat and dependent upon the types and formulations of adhesives (8,9). Results vary widely, refer to the following graph in fig.6 below.
Plastic materials and adhesives used for fixings begin to decline in strength above about 50ºC and show significant reductions above 100ºC.

In view of the variability of these materials, a capacity reduction factor appropriate for design is:

$\phi_{heat,\ 0\text{-}50^{o}C} = 1$ $\qquad \phi_{heat,\ 50\text{-}100^{o}C} = 0.6$ $\qquad \phi_{heat,\ >100^{o}C} = 0$

Where heat is a design consideration the reduction factor would be applied to the bond strength in the case of chemical anchors or material strength for plastic fasteners as an additional capacity reduction.

$$N_b^* \leq \phi_b\ \phi_{heat,\ 50\text{-}100^{o}C}\ N_b$$

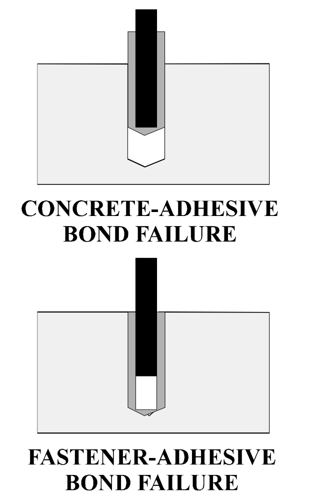



Figure 5 Bond failures

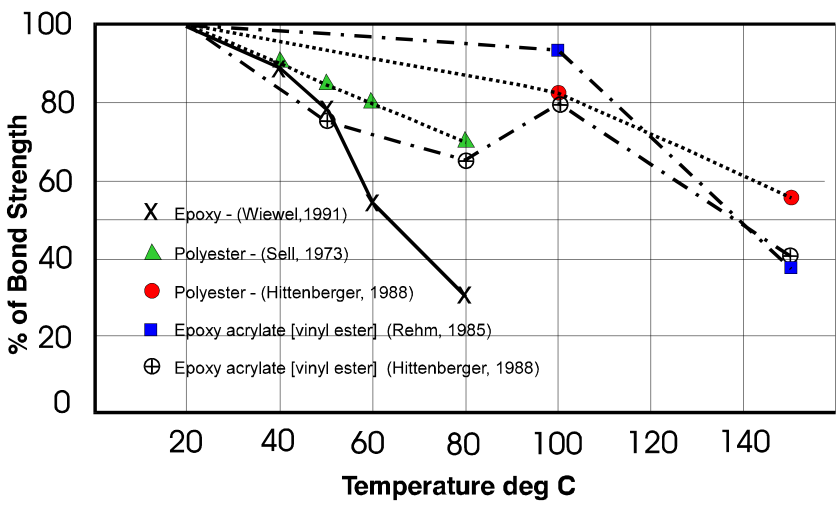



Figure 6Effect of heat on chemical anchors (8)

NB: In many parts of Australia the surface temperatures of exposed steelwork can be in excess of 50ºC in summer.

Low temperatures can also affect plastic materials - particularly during installation. Adhesive anchors are not suitable for installation at temperatures below -5ºC and the embrittling effect of low temperatures on plastic anchors limits their installation to temperatures greater than 0ºC (8).

**Corrosion**
It is rarely possible or practical to ascribe a simple capacity reduction factor (e.g. based on general corrosion loss of area) because of the number of variables at work.
The rate and type of corrosion (general, pitting, crevice, galvanic, stress corrosion) depend upon materials, joint morphology and exposure conditions.
Design for corrosion is therefore a selection process for materials and joint designs which resist deterioration in strength or serviceability according to the nature of the corrosivity of their environment.

Corrosion of the expansion mechanisms in load controlled anchors causes lock-up and without the ability to follow up, these anchors may fail in case-slip. This is of particular concern when these anchors are used in applications where cracks may occur (which themselves assist in the corrosion process by enabling admission of corrodents to the expansion mechanism).

## SUMMARY OF FASTENING TYPES & FEATURES

### CONCRETE INTERLOCK (Cast-In and Undercut Anchors):

Suitable for all situations in cracked and uncracked concrete, anchoring mechanism unaffected by preload.

**Cast-in anchors**

Very reliable but subject to positioning errors, fouling, damage.

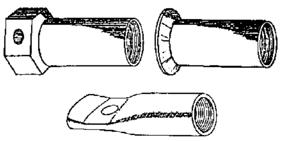


**Figure 7 Cast-in inserts**

**Undercut Anchors**

Similar performance to cast-in with drilled-in convenience & flexibility.

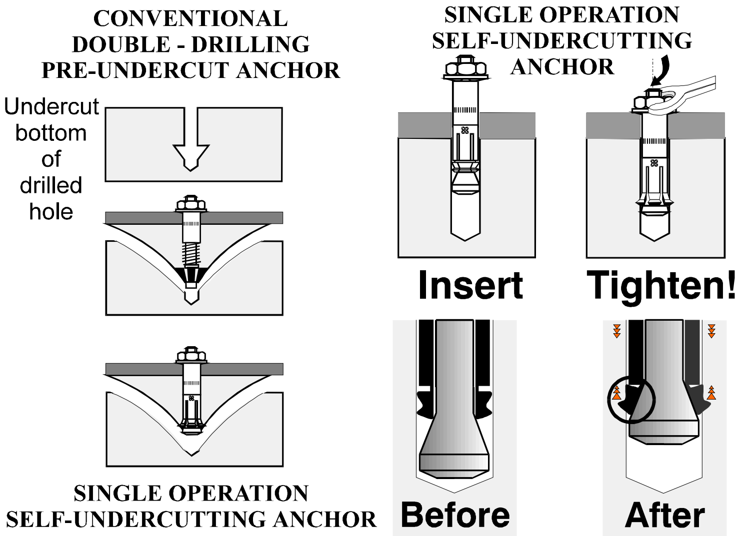



**Figure 8 Undercut anchors**

*Pre-undercut*
Generate no expansive forces, can be used close to edges and applications with high loads and severe vibration. A disadvantage is the two-stage drilling operation.
*Self undercutting - dual operation*
These anchors perform well but are expensive and very slow to install.
*Self undercutting - single operation*
A recent development is unique in this respect. It offers all the advantages of undercut anchors and installation ease of expansion anchors. During setting it cuts an undercut in the sides of the hole.

### FRICTION (Expansion Anchors):

The most commonly used (and abused) of all drill-in fixings which are easy to install in a single operation.

**Load controlled expansion anchors:**

Performance relies upon maintaining bolt preload.
*High-load slip:* Structural and non-structural applications in cracked and non-cracked concrete.
*Low-load slip:* General purpose applications only, light tension loads (e.g < 5kN) and not in cracks.

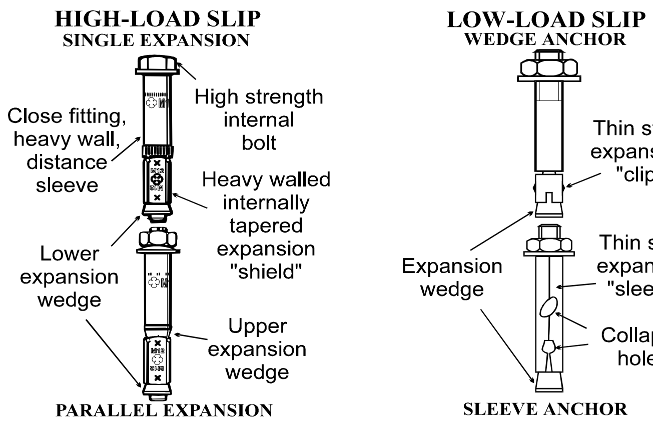



**Figure 9 Load controlled expansion anchors**

**Deformation controlled expansion anchors:**
Performance relies upon the achievement of high expansion preload on setting.
Unreliable and highly sensitive to installation. Useful for low load positional fastening but not suitable or recommended for structural applications. Not suitable for tension loads in cracked concrete.

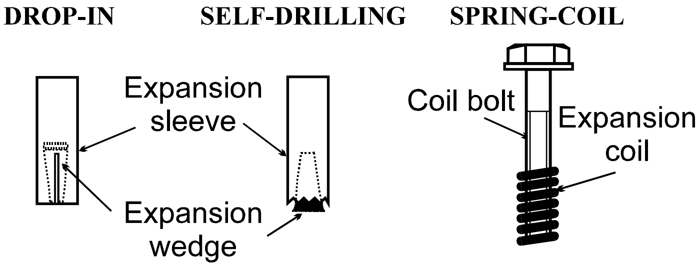



Figure 10 Deformation controlled expansion anchors

**ADHESION (Grouted and Chemical Anchors)**:
Useful close to edges when expansion cannot be tolerated.
Sensitive to installation errors, mixing and hole cleanliness.
Cannot be loaded immediately. Load application before curing damages bond.
Should be proof loaded in structural applications.
Not suitable for tension loads in cracked concrete.

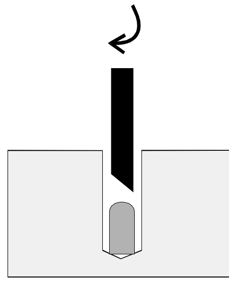


Figure 11 Capsule chemical anchor

*Adhesive (Chemical)*
Shelf life can be limited - generally use within 12 months of manufacture.
Post-mix glass or plastic capsules or pre-mix “injection” packs for large jobs.
Not suitable for applications with heat or potential fire risk.
Can be affected by moisture

*Cementitious grouted anchors*
Subject to shrinkage and loss of bond
Messy and slow to install, long waiting times before loading
Suitable for installations with heat and moisture

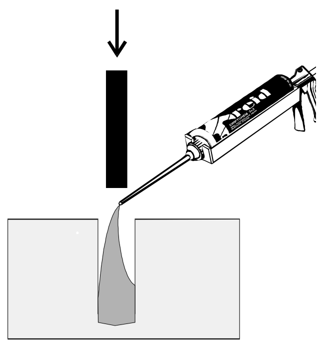


Figure 12 Injection chemical anchor

**CONCLUSIONS**
Fastenings to concrete are subject to strength and serviceability limit states which are not addressed in current Australian construction standards e.g. AS3600.

Fastenings may be conveniently grouped into three principal classes according to the method of anchorage. This assists in the understanding of the relevant failure mechanisms and the selection/design procedure.

Undercut and cast-in headed fastenings are anchored by concrete interlock and have similar performance. Other than undercut anchors, post-installed fastenings are controlled by serviceability limit states.
Some types of fastenings are not suitable for certain applications, their performance being limited by their serviceability constraints. Boundary conditions for these conditions may be applied using capacity reduction factors e.g. $\phi = 0$ for chemical anchors at temperatures > 100ºC.

The published research is sufficient to provide the basis for appropriate capacity reduction factors for the various limit states. Note: This report has drawn extensively on the State of the Art Reports (3, 8) which are comprehensive comprehensive compendia of the most important research in this field.

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