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Literature Review of Post-Installed Anchorage in Concrete

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U.S. DEPARTMENT OF COMMERCE, C. William Verity, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

This report summarizes current knowledge of post-installed anchor behavior in concrete. Load-displacement behavior and ultimate strength of the various types of post-installed anchors are discussed for different loading conditions in both uncracked and cracked concrete. Most knowledge of anchor behavior concerns the response to static tensile loads in uncracked concrete. Many aspects of anchor behavior require further study, especially the behavior of anchors in cracked concrete subjected to combined loadings.

Keywords: anchors; combined loading; concrete; drilled-in anchor; epoxy anchor; expansion anchor; grouted anchor; post-installed anchor; shear; tension.

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1.0 INTRODUCTION

1.1 General

The basic purpose of anchorage is to provide a means of attachment between two or more separate elements. In the construction industry, anchors are used in many applications, including the attachment of structural elements to one another and the attachment of equipment to floors, ceilings, and walls. They are installed primarily in concrete and masonry elements. There are two fundamental types of anchors, cast-in-place and post-installed. Cast-in-place anchors are installed prior to concrete or masonry placement and thus their use must be anticipated before construction. Post-installed anchors, on the other hand, are installed after the concrete or masonry has cured. They are advantageous in that they may be used after construction and knowledge of intended use and location is not required during design.

One important application of post-installed anchors is in strengthening existing buildings. Strengthening is often required to satisfy new building code requirements or to improve the capacity of the building for additional anticipated loads. When using post-installed anchors to strengthen an existing structure, the improved capacity of the structure is often dependent on the capacity of the anchors[27]. Understanding the behavior of anchors in these structures, therefore, is important to ensure adequate serviceability and ultimate capacity of the structure.

1.2 Objective and Scope

The objective of this report is to summarize current knowledge of the behavior of post-installed anchors embedded in concrete. The extent of understanding of anchor behavior in the realm of strengthening is also assessed.

Chapter 2 describes the various types of post-installed anchors. Mechanisms of load transfer to surrounding concrete and methods of installation for typical anchors are presented.

Chapter 3 discusses the behavior of post-installed anchors in concrete. Load-displacement behavior and ultimate capacity are discussed for different loading conditions in both cracked and uncracked concrete.

Chapter 4 presents a summary and conclusions drawn from the literature survey on the current state of knowledge of anchor behavior in the realm of strengthening.

2.0 TYPES OF POST-INSTALLED ANCHORS

2.1 Introduction

Post-installed anchorage is attached to existing concrete structural members. This type of anchorage differs from the cast-in-place type, which is installed prior to concrete placement. For post-installed anchorage, the anchor is inserted into a hole drilled in the surface of the cured concrete member. The different means employed to attach the anchor to the concrete have given rise to three main groups of post-installed anchors: 1) expansion anchors, 2) grouted anchors, and 3) chemical anchors.

Post-installed anchors are usually preloaded in tension. They may either be preloaded during the installation process or after installation. Preloading is beneficial in that it reduces or eliminates anchor displacements under service loads. It also produces a clamping force between the attachments which serves to reduce the effect of cyclical loads on anchors and provides shear transfer resistance. Preloading is accomplished by torquing or jacking a nut on the top of the embedded anchor. High stresses induced around the anchor after preloading cause the concrete to creep and the force in the anchor to relax. Consequently, the preload force decreases with time from its initial value.

2.2 Expansion Anchors

2.2.1 General

Expansion anchors attach inside the drilled hole by mechanical means. For most expansion anchors, load is transferred from the anchor to the concrete by friction between the bottom end of the anchor and the wall of the hole. Two distinct methods are used to expand the anchor to bear against the wall of the hole, as shown in Figure 2.1. The first method is to apply torque to the anchor. Anchors installed in this manner are known as torque-controlled anchors (Type A). The second method is to expand the anchor either by hammering it over an end cone or by hammering a cone into the anchor. Anchors installed by this method have two forms (Type B and C) and are known as deformation-controlled anchors.

2.2.2 Torque-Controlled Anchors

Torque-controlled expansion anchors have some type of sleeve surrounding them and are tapered outward at the bottom end. Torquing forces the tapered end upward into the sleeve, pushing the sleeve against the side of the hole. The amount of expansion is dependent on the magnitude of applied torque and on the deformability of the concrete. As the anchor is torqued during installation, the anchor bolt is preloaded. Subsequent applied loads in excess of the preload cause the cone to be drawn further into the anchor sleeve, resulting in increased expansion forces. Types of torque-controlled expansion anchors, shown in Figure 2.2, include wedge, shell, sleeve, and undercut anchors.

Wedge anchors consist of a steel bolt which is tapered at the bottom end. An expandable pair of wedges lies on the anchor above the taper and a nut is located on the threaded top. When the anchor is placed in the drilled hole and the nut is torqued, the wedges are forced outward against the hole wall by the tapered end.

Shell anchors come in two forms. The first form consists of a two-piece shell which is held together by steel tabs and has a tapered internally-threaded end cone at the bottom. The second form consists of a two-piece shell with tapered cones at the top and bottom held together by a spring at the center. The bottom cone is internally threaded. When a fastener is threaded onto the cone and torqued, the cone is forced upward to expand the shell against the hole wall.

Sleeve anchors consist of a steel bolt which is tapered at the bottom and surrounded by a sleeve. The sleeve is slit at the bottom to allow for expansion. When the nut on the top of the anchor is torqued, the tapered end moves upward, expanding the sleeve against the hole wall.

Undercut anchors have a threaded steel bolt with a tapered expander plug at the bottom end and are surrounded by a sleeve which is slit at the bottom. When the nut is torqued, the plug is forced upward and either expands the sleeve into a predrilled undercut hole or expands the sleeve to create an undercut hole. This type of anchor differs from other torque-controlled anchors in that load transfer from anchor to concrete is accomplished by bearing on the underside of the hole rather than by friction against the hole wall (see Figure 2.2). It is thus possible to develop the tensile strength of the steel in undercut anchors.

Installation of torque-controlled anchors requires preloading. The magnitude of preload, however, is not constant but reduces with time. In Figure 2.3, the results of a relaxation test show how preload diminishes with time for wedge and undercut anchors[5]. Immediately after preloading there is an exponential loss of preload. In time, the preload force approaches a limiting value, which is about 60% and 53% of the initial value for undercut and wedge anchors, respectively[5]. In general, the final preload value of torque-controlled anchors is about 40-60% of the initial value[14]. If anchors are retorqued, the process of relaxation is repeated; however, the final preload value after retorquing has been found to increase[14]. There is a lack of published data on the amount of time required to reach the final preload value, although undercut anchors have been found to reach the final value in about 70 days[5]. There is also a lack of available information on the effect of such variables as concrete strength and preload force on relaxation.

2.2.3 Deformation-Controlled Anchors

There are two types of deformation-controlled expansion anchors. In the first type (Type B), the anchor is expanded by hammering a cone into the outer sleeve of the anchor. In contrast to torque-controlled anchors, all expansion is achieved during installation and subsequent applied loads do not affect expansion of the anchor. The expansion force depends on the lateral expansion displacement, the gap between the anchor and the hole wall, and the deformability of the concrete[14]. This force is usually larger than the expansion force of torque-controlled anchors.

Drop-in anchors, shown in Figure 2.4, are an example of a deformation-controlled, Type B anchor. They consist of a steel shell and a steel expander plug. The lower end of the shell is internally tapered to accept the steel plug and the bottom of the shell is longitudinally slit to allow for expansion. By hammering the plug into the internal taper of the shell, the sides of the shell are forced outward to bear against the hole wall. The top portion of the shell is internally threaded so that a bolt or threaded rod can be attached.

In the second type of deformation-controlled anchor (Type C), the anchor is expanded by hammering the outer shell or sleeve of the anchor over a cone. The outer shell is forced against and into the hole wall, crushing the concrete at the tip of the shell. Like Type B anchors, all expansion is achieved during installation. The expansion force is smaller than that of Type B anchors and load is transferred from anchor to surrounding concrete mainly by mechanical interlock. As shown in Figure 2.5, there are several types of these anchors, including self-drilling, stud, and lead caulking anchors.

Self-drilling anchors consist of a steel shell and a tapered steel plug. The shell has teeth at its tip so that the anchor can drill its own hole. This manner of installation results in a hole which is the exact diameter of the anchor. The anchor is then hammered over the tapered plug, expanding the bottom of the slit shell against and into the wall of the hole. The top of the anchor is internally threaded so that a bolt or threaded rod can be attached.

Stud anchors consist of a steel bolt which has a hole and longitudinal slits at the bottom to accept a tapered steel plug. The upper end of the bolt is threaded. When the anchor is hammered over the tapered plug, the bottom of the anchor expands over the plug against the hole wall.

Lead caulking anchors are of two types. The first type is a single unit anchor consisting of a lead cylinder and a tapered steel cone. The second type, a multiple unit anchor, is used for deeper embedments and consists of a series of lead cylinders and tapered steel cones that are placed on top of each other. Hammering expands the lead over the cone (or cones) and against the hole wall. The bottom cone is internally threaded to accept a bolt or threaded rod.

Installation of deformation-controlled anchors does not involve preloading; however, preloading is often applied after installation. There is a scarcity of published information on the relaxation of deformation-controlled anchors and so it is uncertain how relaxation differs from that of torque-controlled anchors. Stud anchors, however, have been found to relax half as quickly as shell anchors[20].

2.3 Grouted Anchors

Grouted anchors are attached inside the drilled hole by a cement grout. The anchors are inserted into the hole and then the grout, which usually consists of a mixture of cement, sand, and water, is injected into the hole. The manner in which load is transferred from anchor to grout depends on the type of anchor. Headed anchors are the most common type and transfer load primarily by bearing at the end of the anchor. Typical headed anchors are shown in Figure 2.6. Unheaded anchors transfer load near the surface by bond development. Load transfer from grout to surrounding concrete is usually accomplished by bond development between the grout-concrete interface. The hole wall is often roughened to increase the bond strength of the interface and to provide mechanical interlock.

Like deformation-controlled expansion anchors, grouted anchors are not preloaded during installation. However, if they are preloaded after installation, the preload force relaxes with time. Figure 2.7 shows a typical relaxation test of a grouted bolt. The shape of the relaxation curve is similar to that of expansion anchors, although the limiting preload value has been found to be only about 34% of the initial value[5]. The large magnitude of preload loss is attributed to creep of the grout plug at the interface between the grout and concrete[5]. Effects of such variables as grout strength, grout shrinkage, roughness of concrete surface, and anchor type on relaxation have not been reported.

2.4 Chemical Anchors

Chemical anchors are attached inside the drilled hole by chemical adhesives. There are several types of chemical adhesives, including epoxies, polyesters, and vinylesters. In this study, however, different types of adhesives are not distinguished and all types of anchors are collectively referred to as chemical anchors. The manner in which load is transferred from anchor to adhesive depends on the type of anchor. Unheaded anchors, the most common type, transfer load near the surface by bond development. Typical unheaded anchors are shown in Figure 2.8. Headed anchors, on the other hand, transfer load primarily by bearing at the end of the anchor. As in grouted anchors, load transfer to the surrounding concrete interface is by bond development and, if the hole wall is sufficiently rough, by mechanical interlock.

Chemical adhesives are available in four primary forms: glass cartridges, plastic cartridges, tubes, and bulk. Although each form requires a different method of installation, all forms have two-component systems, an active component and a reactant, which are mixed together to cause bonding.

Installation of chemical anchors begins with cleaning the drilling dust from the hole. The adhesive and anchor are then inserted in the hole. When the adhesive is in the form of a glass cartridge, the cartridge is inserted into the hole and crushed when the anchor is driven in behind it. The adhesive and crushed glass are mixed together and bond the anchor to the hole wall. For plastic cartridges, the two-part adhesive is mixed together by a nozzle while being injected into the hole. The anchor is then inserted. In the tube type, the two components are mixed by kneading the tube and then are inserted into the hole. The anchor is then inserted. In the bulk form, the adhesive (usually epoxy) is first mixed, followed by insertion of the adhesive and anchor.

Like grouted anchors, chemical anchors do not require preloading for installation. They are often preloaded after the adhesive has set prior to being subjected to applied loads. Preloaded chemical anchors, because of high stresses in the adhesive bond, relax faster and reach slightly lower final preload values than torque-controlled expansion anchors[2]. However, there is a lack of information on the relaxation of chemical anchors and the effect of such variables as type of adhesive and temperature on relaxation.

3.0 BEHAVIOR OF POST-INSTALLED ANCHORS

3.1 Introduction

The behavior of post-installed anchors in concrete is largely influenced by the type of loading applied to the anchor. There are five primary types of loadings on anchors, as shown in Figure 3.1: 1) tension, 2) shear, 3) combined tension and shear, 4) combined bending and shear, and 5) combined bending, shear, and tension. In addition, the applied load may either be static or dynamic. Since most research to date has been conducted on anchors under static tension or shear, knowledge of anchor behavior is focussed on the response to these two types of loadings.

The behavior of anchors is also strongly influenced by the presence of cracks in concrete. Anchors located in or near cracks have markedly different load-displacement behavior and ultimate strengths than do similar anchors in uncracked concrete. The behavior of anchors in uncracked concrete is discussed first, followed by a discussion of anchor behavior in cracked concrete.

3.2 Behavior in Uncracked Concrete

3.2.1 Tension Loading

3.2.1.1 Load-Displacement Behavior

Load-displacement behavior of anchors loaded in tension depends on the failure mode. Failures in which either the concrete or steel tensile strength is developed have similar displacements at failure[25]. When the anchor pulls out of the hole, displacements are much larger. Load-displacement behavior also depends on whether or not the anchors are preloaded in tension. Anchors that are not preloaded begin to displace immediately with the application of external load.

Figure 3.2 presents typical load-displacement relationships for the three main types of expansion anchors described in Chapter 2. The anchors have no preload and fail by developing the concrete tensile strength. The displacements shown represent the combination of axial deformation of the expansion bolt, deformation of the concrete, and slip of the anchor.

Type B anchors exhibit a relatively small displacement due to the low amount of slip resulting from high expansion forces. The expansion force of Type A anchors is smaller than that of Type B anchors and, as a result, the displacement is larger in Type A anchors. Because Type C anchors transfer load by mechanical interlock, which causes large concrete deformation, they have the largest displacement prior to ultimate load. Undercut anchors, which also transfer load by mechanical interlock, have large displacements as well. Increasing the concrete strength results in an increase in anchor stiffness (slope of the load-displacement curve) and a reduction in anchor displacements[30].

For chemical anchors without preload, the load-displacement behavior is approximately linear to the ultimate load. A typical load-displacement curve for such an anchor is shown in Figure 3.3. Anchor stiffness for both chemical and grouted anchors increases with increasing concrete strength and, for grouted headed anchor bolts, with increasing washer size[13].

The load-displacement behavior of anchors preloaded in tension differs from that of nonpreloaded anchors. Preloaded anchors produce a clamping force which must be overcome before significant anchor displacement can occur. Consequently, there is little displacement until the applied load exceeds the preload force[25]. Since preloading does not affect the ultimate static tensile anchor capacity[22], the ultimate anchor displacement decreases with increasing magnitude of preload force. Preloading has not been found to have any effect on anchor stiffness.

Load-displacement behavior also depends on the manner of loading. Sustained tensile loads influence load-displacement behavior by causing the stressed concrete to creep, resulting in anchor displacement. Torque-controlled expansion anchors subjected to sustained loads of more than 70-80% of ultimate capacity experience time-dependent displacement[2]. Figure 3.4 shows the time-dependent displacement of a torque-controlled anchor for a sustained load of 70% of ultimate. The rate of displacement decreases with time from its initial value and the displacement eventually approaches a limiting value. As the magnitude of sustained load relative to ultimate load capacity increases, the limiting displacement increases. Sustained loads smaller than 70-80% of ultimate capacity do not influence the displacement of torque-controlled expansion anchors at ultimate capacity[2].

Like expansion anchors, chemical anchors experience time-dependent displacement under sustained loads. The rate of displacement decreases with time and eventually approaches zero. However, as shown in Figure 3.5, this rate is temperature-dependent and increases with increasing temperature[18,26]. The magnitude of the limiting displacement depends on the type of anchor. Unheaded anchors have been found to have less long-term displacement and unrecoverable anchor movement than headed anchors[21].

The effect of cyclic loading on anchor displacement can also be significant. However, the displacement at failure has been found to be unaffected by cycling even up to one million load repetitions if the maximum load is less than 50% of the static load capacity[2].

3.2.1.2 Ultimate Strength

3.2.1.2.1 General

The ultimate strength of anchors loaded in tension depends on the controlling failure mode which in turn is dependent on such factors as edge distance, embedment depth, concrete and/or anchor steel strength, type of anchor, and loading condition. As indicated in Figure 3.6, there are four primary failure modes for anchors in tension: 1) steel failure, 2) slip or pullout failure, 3) concrete cone failure, and 4) splitting failure.

3.2.1.2.2 Steel Failure

Steel failure is characterized by anchor fracture and so the ultimate capacity depends on the strength and cross sectional area of steel. The failure load is calculated by the equation:

$$F_u = A_s \times f_{ut} \qquad (1)$$

where

A_s = steel cross sectional area

f_{ut} = steel tensile strength

Due to the relatively ductile and predictable nature of such a failure, it is a desirable mode of failure. Because undercut expansion anchors transfer load by bearing, they are able to develop the tensile capacity of the steel and are ductile in failure[6,32].

3.2.1.2.3 Pullout Failure

In pullout or slip failure, the anchor is pulled out of the concrete in which it is embedded without significant damage to the concrete. For expansion anchors, the applied tensile load is resisted by friction of the expansion device against the wall of the drilled hole. The expansion device enlarges the hole and produces a radial spreading pressure, the summation of which over the contact area yields the spreading force. The failure load is given by the equation:

$$F_u = \mu \times S \qquad (2)$$

where

μ = coefficient of friction

S = spreading force

The pullout capacity of most expansion anchors is governed by friction. The coefficient of friction depends on the roughness of the surfaces in contact and on the spreading force. The spreading force is a function of the amount of radial expansion, the modulus of elasticity of the surrounding concrete, and the magnitude of gap between the anchor and the hole wall[31]. Values of the coefficient of friction have been found to be about 0.2 - 0.3 for Type A anchors and about 0.35 for Type B anchors[31]. Equations for estimating the spreading force are also presented in Ref. 31, based on theoretical considerations. However, it is reported in Ref. 14 that an extensive testing of pullout of expansion anchors found the equations to be unreliable estimates of pullout capacity.

Wedge and sleeve torque-controlled expansion anchors with embedment depths greater than about four bolt diameters typically fail by pullout[25]. The pullout capacity of wedge anchors is affected by the presence of dust which can act as a lubricant to reduce friction, resulting in a lower ultimate capacity[30]. The pullout capacity of wedge anchors is also affected by the presence of nearby empty drilled holes, which most likely reduce the spreading pressure. Holes located nearer than 3 bolt diameters from the anchor reduce the strength unless the holes are filled with mortar[7]. The pullout capacity of expansion anchors has not been found to be affected by edge distance and anchor spacing.

Pullout of grouted anchors is a bond failure that occurs along either the grout-concrete interface, the grout-anchor interface, or both interfaces simultaneously. The particular interface along which failure takes place depends in part on the manner of load transfer from anchor to grout and on the relative bond strength of each interface. For headed anchors, in which load is primarily transferred from anchor to grout by bearing, bond failure is limited to the grout-concrete interface[10]. For unheaded anchors, in which load is transferred from anchor to grout by bond development, failure usually occurs along both interfaces simultaneously. Failures have been reported, however, along only the grout-anchor interface for poorly-consolidated grouts[26].

The pullout capacity of grouted anchors is strongly influenced by shrinkage of grout, which weakens the bond strength at the grout-concrete and grout-anchor interfaces. The pullout strength of unheaded anchors failing along both interfaces simultaneously has been found to be less than that of cast-in-place anchors because of grout shrinkage[26]. In addition, grout shrinkage has been found to alter the mode of failure of headed anchors from steel fracture to bond failure along the grout-concrete interface[10]. Pullout capacity is also dependent on embedment depth. For unheaded anchors that experience bond failure along both interfaces simultaneously, the ultimate strength increases with increasing embedment depth, although for large depths the mode of failure changes to steel fracture[26]. The effect of embedment depth on pullout capacity of headed anchors has not been reported. Edge distance and anchor spacing have not been found to have any influence on pullout capacity of headed or unheaded anchors.

Pullout of chemical anchors is similar to that of grouted anchors in that it involves a bond failure along one or more interfaces. Bond failure along the adhesive-anchor interface is possible for plain unheaded bars. For this type of failure, slight rusting of the steel improves the bond between the adhesive and anchor and increases the pullout capacity[12]. For unheaded chemical anchors, however, bond failure is almost always along the adhesive-concrete interface. Bond strength thus depends on the cleanliness of the drilled hole prior to installation of the anchor[21]. Bond strength also depends on temperature. Bond strengths at 80° C and 50° C are only about 70 - 75% and 85 - 90%, respectively, of the value at 20° C[3,18].

Because load is transferred from anchor to adhesive by bond development, the pullout capacity of chemical anchors increases in proportion to embedment depth. For embedment depths larger than nine anchor diameters, however, the pullout capacity does not increase in proportion to depth because most of the load is transferred near the concrete surface[2]. If the embedment depth becomes large enough, the mode of failure changes from pullout to steel fracture. Pullout failure has been found to control for embedment depths up to 15 anchor diameters[23]. Edge distance or spacing of anchors have not been reported to have any effect on pullout capacity.

3.2.1.2.4 Concrete Cone Failure

Concrete cone failure is a failure of concrete in tension along a conical surface. For expansion anchors with embedment depths less than 10 - 15 cm (4 - 6 in.), the cone angle measured from the axis of the anchor to the failure surface is about 60 - 75°[2,14] and the depth of the cone ranges from 80 - 100% of the depth of the anchor[14]. Figure 3.7 shows a typical failure cone of an expansion anchor with an embedment depth of 13 cm (5 in.). For larger embedment depths, the failure surface becomes a double cone. The cone angle is about 45° at the end of the anchor, but changes to about 60 - 75° at 10 - 15 cm (4 - 6 in.) from the concrete surface[2].

When there is sufficient side cover and anchor spacing, the strength of expansion anchors in concrete cone failure depends mainly on the concrete tensile strength and the depth of embedment[18]. ACI 349, Appendix B[1] assumes that the strength increases in proportion to the surface area of a 45° cone and that the average tensile stress at failure is $4\sqrt{f'_c}$. The ultimate strength of expansion anchors is given by the equation:

$$F_u = 1.043\ \phi\ l_d^2\ \sqrt{f'_c} \quad \text{(in Newtons)} \qquad (3)$$

where

ϕ = capacity reduction factor

l_d = depth of anchor, mm

f'_c = concrete compressive strength, N/mm^2

From an evaluation in Ref. 14 of about 2000 tests on expansion anchors with embedment depths of up to 15 cm (6 in.), it has been found that the strength of such anchors does not increase in proportion to the area of the cone, indicating that the tension force is not resisted by the entire area of the cone for increased embedment depths. Equation (3) of ACI 349, Appendix B[1] was found to be unconservative for embedment depths greater than 20 cm (8 in.). Based on the test results, an equation for the ultimate capacity is presented in Ref. 14 as:

$$F_u = 7.4 \, l_d^{1.54} \, f'_c{}^{2/3} \quad \text{(in Newtons)} \qquad (4)$$

This equation closely agrees with an equation proposed in Ref. 4 which predicts the strength of cast-in-place anchors. The ultimate capacity, then, may be assumed to be nearly independent of the mechanism of load transfer, whether it is by friction (expansion anchors) or by bearing (headed cast-in-place anchors)[14].

These predictive equations are based on the assumption that a sufficient volume of concrete is available to develop an entire conical surface. If the anchor is located near an edge, the failure surface consists of only part of a cone. It has been proposed that when the edge distance is smaller than a critical value, the strength decreases in proportion to e/e_c, where e is the actual edge distance and e_c, given as 1.75 l_d, is the critical edge distance for full anchor strength[14]. The strength predicted by the model has been found to be conservative.

In addition, if anchors in a group are spaced too closely, the failure surfaces overlap and a single combined cone may develop. The strength is reduced when the spacing between anchors decreases below a critical value.

In Ref. 14 it has been proposed that the critical spacing is 3.5 l_d and that the strength of the group decreases linearly as the spacing decreases to zero, at which point the strength of the group is equal to that of a single anchor.

Concrete cone failure of unheaded chemical anchors differs somewhat from that of expansion anchors. The depth of the cone typically ranges from 25 - 40% of the bond depth of the anchor[18]. Along the remaining length of the anchor the bond between the adhesive and concrete is overcome, as shown in Figure 3.8. The cone angle measured from the axis of the anchor to the failure surface is about 50 - 70°[21,26]. The failure cone associated with chemical anchors is closer to the concrete surface than for expansion anchors because chemical anchors transmit most of the applied load near the concrete surface by bond development, whereas expansion anchors transmit all load at the end of the anchor. Because of a smaller concrete cone, the strength of chemical anchors is less than that of expansion anchors for similar embedment depths[18]. Based on test results, an equation has been presented in Ref. 18 to predict the strength of unheaded chemical anchors for large edge distances and anchor spacing:

$$F_u = 0.95\, l_d^2 \sqrt{f'_c} \quad \text{(in Newtons)} \qquad (5)$$

For embedment depths greater than nine anchor diameters, the capacity increases more gradually than that predicted by the Equation (5) because most of the applied load is transferred near the surface[18]. For unheaded chemical anchors with edge distances less than a critical value, the strength depends on edge proximity. In Ref. 18 it is presumed that the critical edge distance is equal to the embedment depth l_d and that the strength decreases linearly with edge distance, similar to that for expansion anchors. For a group of anchors, the strength also depends on anchor spacing. When the spacing is less than a critical value, found to be 2 l_d, the strength of the group decreases with decreasing spacing in a manner similar to that of expansion anchors[18].

Concrete cone failure of debonded headed chemical anchors is different from that of unheaded chemical anchors in that the failure surface is a double cone which extends from the concrete surface to the top of the anchor head. Because the cone is deeper than that in unheaded anchors, the ultimate strength of headed anchors is much larger than that of unheaded anchors[21]. The depth of the lower cone is about 50 - 60% of the depth of the debonded anchor[21,24]. The cone angle measured from the axis of the anchor to the surface of the lower cone ranges from about 55 - 70^o[21,24]. Based on test results and assuming an average concrete tensile strength of 2.28 N/mm^2 (331 psi), an equation is presented in Ref. 21 to predict the ultimate capacity of debonded headed chemical anchors:

$$F_u = 7H (H + D) \quad \text{(in Newtons)} \qquad (6)$$

where

D = hole diameter, mm

H = distance from concrete surface to top of anchor head, mm

If headed chemical anchors are placed in groups, interaction between individual anchors is possible if the spacing is sufficiently small. When the spacing is less than about 2H for headed anchors placed in pairs, the strength of the pair decreases as the spacing decreases[21]. The failure surface is a double cone at the ends and is almost uniform in depth between the anchors. When the spacing is larger than 2H, the capacity is unaffected by spacing and failure is controlled by the pullout of a concrete cone on only one of the anchors[21].

Concrete cone failure of grouted anchors has only been reported for headed anchors, in which the applied force is transferred to the concrete primarily by bearing. For such anchors, the capacity depends mainly on the depth of embedment and the concrete tensile strength. For headed anchors with washers, the washer size has been found to have a slight influence on capacity[26], probably because it increases the area of the conical failure surface. Cone depth and angle of inclination of the failure surface have not been reported. In addition, there is a lack of available information on the effect of type, shrinkage, and strength of grout on the concrete cone capacity.

3.2.1.2.5 Splitting Failure

Splitting failure occurs when splitting cracks form in the concrete at anchor locations. Splitting is usually due to edge proximity of one or more anchors or close spacing of a group of anchors. The strength of expansion anchors that fail by splitting the concrete has been investigated in Ref. 28 by assuming that splitting occurs when tensile stresses averaged over a critical area reach the tensile strength of the concrete. Minimum values of edge distance, anchor spacing, and concrete dimensions to prevent splitting failure have been proposed in Ref. 28. However, they are based on limited test results. Splitting failure associated with grouted or chemical anchors has not been reported.

Splitting failure of concrete may occur for expansion anchors during installation and is more likely for anchors with larger spreading forces. Splitting has been found to occur for wedge anchors with edge distances of less than 6 bolt diameters[2].

3.2.2 Shear Loading

3.2.2.1 Load-Displacement Behavior

Load-displacement behavior of anchors loaded in shear is dependent on whether or not the anchor is pretensioned. Anchors that are not pretensioned displace immediately at the application of load. Figure 3.9 shows a typical load-displacement curve of an expansion anchor without preload. The initial portion of the curve represents movement of the anchor to the wall of the drilled hole. As further load is applied, the anchor bears against the concrete and additional displacement is due to both bending of the anchor and concrete deformation under bearing pressure. Anchor displacement thus depends on the gap between the anchor and the hole wall, the stiffness of the surrounding concrete, and the bending stiffness of the anchor. Decreasing the strength (and stiffness) of the concrete and increasing the size of the hole have been found to increase anchor displacements for undercut anchors[6].

The load-displacement behavior of nonpreloaded chemical and grouted anchors is similar to that of expansion anchors. Displacement of the anchor is due to bending of the anchor and deformation of the concrete. Since the hole is usually completely filled with adhesive or grout, there is no initial movement of the anchor to the side of the hole. A typical load-displacement curve for a chemical anchor is presented in Figure 3.10.

For pretensioned anchors, the friction force between the baseplate and concrete surface must be overcome before significant anchor displacements can occur. Values for the coefficient of friction have been found to be in the range of 0.57 - 0.70 for steel-concrete and steel-grout interfaces[29]. Preloading in tension limits the ultimate deflection and has also been found to affect the dynamic stiffness of wedge and shell expansion anchors[22].

3.2.2.2 Ultimate Strength

3.2.2.2.1 General

The ultimate strength of anchors loaded in shear depends on the mode of failure. There are two main failure modes: 1) steel failure and 2) concrete failure. The controlling mode depends primarily on the edge distance and depth of embedment.

3.2.2.2.2 Steel Failure

Steel failure is marked by anchor rupture and is relatively ductile, usually occurring after large displacements. It is a typical mode of failure for expansion anchors with large edge distances and deep embedments[14]. The ultimate strength depends on the strength and cross sectional area of steel and is given by the equation:

$$F_u = A_s \times f_{us} \qquad (7)$$

where

A_s = steel cross sectional area

f_{us} = steel shear strength

The ultimate strength is also influenced by the magnitude of anchor displacement. For undercut anchors, increasing the anchor displacement by decreasing the concrete stiffness and increasing the hole diameter allows the anchor to develop a greater tensile component of force and hence a larger capacity[6].

3.2.2.2.3 Concrete Failure

As shown in Figure 3.11, concrete failure can take one of two forms, depending on the edge distance. For small edge distance (Figure 3.11a), breakout of the concrete occurs, usually in the form of a cone. When the edge distance is large (Figure 3.11b), the concrete spalls or crushes accompanied by anchor pullout.

For conical concrete breakout failures, the failure surface is inclined at an angle of about 30^{o} with respect to the concrete surface and has a depth of 1.3 - 1.5 times the edge distance of the anchor[16]. The ultimate strength depends primarily on the edge distance e, although the concrete tensile strength and anchor diameter also affect the capacity[16]. Theoretically, the strength should increase in proportion to the area of the failure surface, which is a function of e^2. However, for expansion anchors, the strength increases approximately in proportion to $e^{1.5}$ as indicated in the equation proposed in Ref. 16:

$$F_u = 1.3\ e^{1.5}\ d_b^{0.5}\ \sqrt{f'_c} \qquad \text{(in Newtons)} \qquad (8)$$

where

e = edge distance, mm

d_b = anchor diameter, mm

f'_c = concrete compressive strength, N/mm^2

For chemical anchors, the strength increases only in proportion to e[2]. Furthermore, the shear strength of chemical anchors is lower than the tensile strength for equal edge distance to embedment depth ratios when conical breakout failure controls[18]. No information has been found concerning the influence of edge distance on the strength of grouted anchors in conical breakout failures.

Failure by concrete crushing or spalling followed by anchor pullout has only been reported for grouted anchors. For such anchors, the capacity depends mainly on the resistance of the grout to crushing, in contrast to tensile loading, in which the capacity often depends on bond strength.

Consequently, the shear capacity is not as reliant on the type and shrinkage of grout as is tensile capacity and is larger than the tensile pullout capacity[10].

3.2.3 Combined Tension and Shear Loading

The behavior of anchors under combined tension and shear loading has not been extensively reported. When anchors are subjected to combined loading, the tensile and shear forces interact. For preloaded anchors, the tensile force reduces the shear transfer resistance provided by the clamping force and can reduce the preload in the anchor; however, preload has not been reported to have any effect on the ultimate strength under combined tension and shear. The strength of wedge and shell torque-controlled expansion anchors under combined tension and shear, in fact, has been found to be independent of preload[22].

The load-displacement behavior of anchors is affected by interaction between tensile and shear forces. The stiffness of expansion anchors under combined loading has been found to be smaller than that under either tension or shear loading[9]. The effect of combined loading on the load-displacement behavior of chemical and grouted anchors has not been reported.

The strength of anchors in combined tension and shear depends on the relative magnitude of the two forces. It has been found, for example, that the strength of self-drilling anchors is a minimum when the resultant of the tension and shear forces is oriented at an angle of about 40° with respect to the concrete surface[9]. In Figure 3.12 an interaction diagram is presented from test results of expansion anchors in combined tension and shear in which concrete cone failure controls. Two lines representing predictions of anchor capacity are also plotted. The dashed straight line between pure tension and pure shear, which is recommended by ACI 349, Appendix B[1], is a conservative prediction of strength. The trilinear curve (solid line) proposed in Ref. 25 is less conservative than the straight line and is a reasonable lower bound of the ultimate capacity. It assumes that no reduction in strength occurs when the applied load is either predominantly tension or shear.

An identical trilinear curve has been proposed in Ref. 4 to predict the strength of cast-in-place anchors in combined tension and shear. Based on limited test results, the curve is a reasonable approximation of the lower bound of strength. The strength of anchors in concrete cone failure subjected to combined tension and shear, then, may be assumed to be independent of the type of anchor.

The effect of interaction between tensile and shear forces on the strength of expansion anchors when failure is controlled by steel fracture, anchor pullout, or splitting of concrete has not been reported. In addition, the strength of grouted and chemical anchors in combined tension and shear is not documented. The effect of anchor spacing and edge distance on anchor strength is not established.

3.2.4 Combined Loading With Bending

For other combined loading conditions in which bending is present, little information is available. The cause of failure under such loading conditions is usually anchor fracture. Factors that influence the ultimate strength are the bending resistance of the anchor and its embedment in the concrete[2].

3.2.5 Survivability

Anchors are often subjected to cyclic or vibratory loads instead of static loads. The ability of anchors to sustain such loads depends on several factors, such as the stress range, flexibility of support, and quality of installation.

Anchor survivability under dynamic loads is largely governed by the stress range, since bolts have a low fatigue capacity. Preloading in tension can reduce the stress range by as much as 50 - 75% and can thus improve the fatigue life[13]. Support flexibility also affects the survivability by allowing the base plate underneath the anchor to rotate, which makes the support more passive in resisting transient loads[19]. Proper installation is another important factor in increasing the fatigue life of an anchor[19].

3.3 Behavior in Cracked Concrete

3.3.1 General

The load-displacement behavior and ultimate strength of anchors installed in or near cracks is markedly different from that in uncracked concrete. Anchor behavior in cracked concrete depends on the location, width, and number of cracks. The majority of reported data on anchor behavior in cracked concrete pertains to cracking in one direction only.

3.3.2 Tension Loading

3.3.2.1 Load-Displacement Behavior

The load-displacement behavior in tension of anchors installed in cracked concrete differs from that in uncracked concrete. Figure 3.13 illustrates the effect of the presence of a crack passing through a torque-controlled expansion anchor. The crack reduces the spreading force of the expansion device, resulting in a decrease in strength and an increase in ultimate deflection due to anchor slip. As the figure indicates, anchors set in intersecting cracks are affected more than anchors set in a single crack. It is intuitively assumed that the load-displacement behavior of grouted and chemical anchors would also be influenced by the presence of cracks, although there is no such documented information. The effect of preload on the load-displacement behavior of anchors in cracked concrete is not as significant as in uncracked concrete. In fact, the intersection of flexural cracks with expansion anchors has been found to completely eliminate preload[8].

Load-displacement behavior of anchors in cracked concrete is also affected by the state of stress in the surrounding concrete. When anchors are placed in tensile stress regions of cracked reinforced concrete members, the tensile stresses in the member generated by structural action interact with the tensile stresses induced by the anchor. The displacement of expansion and grouted anchors located in tensile stress regions of reinforced concrete slabs has been found to be dependent on the magnitude of applied moment in the slab[11].

The presence of cracks also affects the displacement of anchors subjected to cyclic tension loading. Under cyclic loading, expansion anchor displacements increase with increasing crack width and load intensity[15]. However, anchor capacity and displacement at failure are not significantly influenced by cyclic loading provided the maximum load is smaller than 50% of the static failure load for expansion anchors set in intersecting cracks[2]. The flexibility of the attachment strongly influences the response of anchors to cyclic loading. Flexible attachments tend to stabilize and decrease the rate of displacement, whereas the rate of displacement of rigid attachments either increases or maintains a steady rate to failure under cyclic loading[8].

3.3.2.2 Ultimate Strength

Cracking in concrete affects the ultimate strength of anchors in tension that fail by pullout of a cone-shaped section of concrete. In uncracked concrete, the stresses in the concrete are radially symmetric about the anchor. The presence of cracks in or near the anchor creates a boundary across which tensile stresses cannot transfer unless the cracks are small enough for aggregate interlock to be effective (less than about 0.4 mm or 0.016 in.). When a crack passes through an anchor, the area onto which load can be transferred to the concrete is potentially smaller than in uncracked concrete. Alternatively, when a crack passes near an anchor, part of the surface of the concrete failure cone may become ineffective. The strength of anchors in concrete cone failure will thus be smaller in cracked concrete than in uncracked concrete.

Expansion anchors are further affected when they are located in cracked concrete because of the reduction in the spreading force of the expansion device. If the spreading force is sufficiently reduced, the failure mode may change from concrete cone to pullout. For torque-controlled expansion anchors (Type A) whose expansion devices expand with the application of load, the spreading force usually remains large enough for relatively small crack widths so that concrete cone failure controls. The effect of crack width on the strength of such expansion anchors located in cracks is shown in Figure 3.14. The strength of the anchors decreases to about 50 - 80% of the strength of similar anchors in uncracked concrete as the crack width increases to about 0.3 - 0.5 mm (0.012 - 0.020 in.)[14]. For cracks much wider than 0.3 - 0.5 mm (0.012 - 0.020 in.), the spreading force can become small enough to change the mode of failure to pullout and further reduce the failure load.

Also shown in Figure 3.14 is the effect of crack width on the strength of deformation-controlled expansion anchors (Types B and C). The strength of the anchors decreases to about 40 - 70% of the strength of similar anchors in uncracked concrete as the crack width increases to about 0.3 - 0.5 mm (0.012 - 0.020 in.)[14]. Since the expansion devices of such anchors do not expand after installation, the intersection of a crack with the anchor is likely to result in a change in failure mode to pullout even for relatively small crack widths[17].

The effect of cracking on the ultimate strength of chemical anchors in concrete cone failure is similar to the effect on the strength of expansion anchors. In Figure 3.15 test results of three different sizes of anchor bolts located in cracks show that the strength of chemical anchors decreases to about 20 - 60% of the strength in uncracked concrete as the crack width increases to 0.3 - 0.4 mm (0.012 - 0.016 in.)[18]. The strength reduction is larger for anchors of smaller diameter[18].

The presence of cracks also influences the ultimate strength of anchors that fail in pullout, which are typically unheaded grouted or chemical anchors. Cracks that intersect anchor locations reduce the bond strength between the grout or adhesive and concrete. However, there are no reported tests of anchors in cracked concrete failing by pullout.

The strength of anchors in which steel failure controls is assumed to be independent of cracks in the concrete since the failure load depends only on the steel area and steel strength. The effect of cracks on splitting failures has not been reported.

The ultimate strength of anchor groups is also affected by cracking. In cracked concrete, some anchors may be located in cracks while others are not. It is reported in Ref. 2 that, based on theoretical and experimental investigations of expansion anchors failing in concrete cone failure, the strength of an anchor group in cracked concrete is about 70% of the strength of a comparable group of anchors in uncracked concrete and is independent of the number of anchors located in cracks. Theoretical studies have also shown such behavior to be valid for different types of anchor groups and for rigid attachments. When cracking causes any of the expansion anchors in a group to slip and pull out of the hole, the failure load of the group is reduced even further[17].

3.3.3 Shear Loading

The behavior of anchors in cracked concrete under shear loading has not been extensively investigated. The effect of cracking on load-displacement behavior is not documented. The effect of cracking on the ultimate capacity depends on edge distance. For anchors with a sufficiently large edge distance and embedment depth, failure is controlled by rupture of the anchor steel. In this circumstance, the strength is not appreciably affected by cracks[16]. Anchors with a small edge distance which fail by breakout of a concrete cone experience a reduction in strength when cracking is present, presumably to about 60% of the strength in uncracked concrete for expansion anchors as in the case of tension loading[16]. For chemical anchors, it is assumed that cracking has less influence on strength reduction in shear than in tension[18]. The effect of cracking on the strength of anchors with large edge distances in which failure is controlled by concrete crushing or spalling has not been reported.

3.3.4 Combined Loading

The behavior of anchors in cracked concrete under any type of combined loading has not been reported. Specifically, no research has been conducted on anchors under combined tension and shear, although it may be presumed that the trilinear interaction curve of Figure 3.12 which predicts the strength of anchors in uncracked concrete would also be valid for similar anchors installed in cracked concrete[16]. No studies on the effect of cracking on anchor behavior for any combined loading involving bending are available.

3.4 Research Needs

There is a substantial amount of reported information on the behavior of post-installed anchors embedded in concrete. However, most of this information concerns the response to static tensile loads in uncracked concrete. There is a lack of detailed knowledge in many areas of anchor behavior, especially for anchors under combined loadings and in cracked concrete. The following list summarizes the particular areas in which additional knowledge is required.

1. <u>Anchors in Uncracked Concrete</u>

   a) Tension Loading

      - effect of cyclic loading on anchor displacement and strength
      - effect of sustained loading on anchor strength
      - predictive equations for anchor capacity in pullout and splitting failures

   b) Shear Loading

      - anchor strength when failure is controlled by concrete spalling or crushing followed by anchor pullout
      - effect of cyclic and sustained loading on anchor displacement and strength

   c) Combined Tension and Shear Loading

      - effect of edge distance and anchor spacing on anchor behavior
      - effect of cyclic and sustained loading on anchor behavior

   d) Combined Loading With Bending

      - effect of interaction on anchor behavior

2. <u>Anchors in Cracked Concrete</u>

   a) Tension Loading

      - effect of cracking on displacement of grouted and chemical anchors

- effect of cracking on grouted anchor capacity in concrete cone failure
- effect of cracking on anchor capacity in pullout and splitting failures

b) Shear Loading

- effect of cracking on anchor displacement and strength

c) Combined Loading

- effect of cracking on anchor behavior under any type of combined loading

4.0 SUMMARY AND CONCLUSIONS

4.1 Summary

This report summarized published and available information concerning the behavior of post-installed anchors embedded in concrete. From this literature survey, the extent of understanding of anchor behavior for various loading conditions, types of anchors, and states of concrete was assessed.

Chapter 2 described the different types of post-installed anchors. Mechanisms of load transfer from anchor to concrete and methods of installation for typical anchors were presented.

Chapter 3 investigated the behavior of post-installed anchors in concrete. Load-displacement behavior and ultimate capacity were discussed for anchors subjected to various loading conditions in both uncracked and cracked concrete. In addition, particular areas in which further understanding of anchor behavior is required were identified.

4.2 Conclusions

A significant amount of published information exists concerning the behavior of post-installed anchors in concrete. However, most studies have dealt with the behavior of anchors subjected to tensile loads in uncracked concrete. While there is a thorough understanding of the load-displacement behavior and ultimate capacity of anchors in tension embedded in uncracked concrete, there are other conditions in which anchor behavior is not well known. In particular, knowledge of the behavior of anchors subjected to any type of combined loading involving tension, shear, or bending is incomplete.

One aspect of anchor behavior under combined loading in which further understanding is needed is the response of anchors to combined tension and shear. Although a limited amount of research has been conducted by several researchers on anchors in uncracked concrete subjected to combined tension and shear[9,22,25], full knowledge of the effects of interaction on load-displacement behavior and ultimate capacity is lacking. In addition, there is no information on the behavior of anchors subjected to combined tension and shear in cracked concrete.

The understanding of anchor behavior in combined tension and shear is important in strengthening existing buildings. Many methods currently used to strengthen existing structures involve the attachment of additional elements to structural members by means of post-installed anchors. A thorough literature review of strengthening methodologies has reported that such anchors are often subjected to combined tension and shear loadings[27].

Furthermore, the structures which require strengthening are often cracked or damaged. In order to describe the behavior of anchors in strengthened structures, it is necessary to have a thorough understanding of the behavior of anchors in combined tension and shear in both uncracked and cracked concrete.

REFERENCES

1. ACI Committee 349, Code Requirements for Nuclear Safety Related Concrete Structures, Appendix B, American Concrete Institute, Detroit, 1980.

2. ACI Committee 355, "State-of-the-Art Report on Anchorage to Concrete," American Concrete Institute, Detroit, unpublished.

3. Beveridge, R.L.W., "Resin Anchors," Civil Engineering, London, August 1976, pp. 71-75.

4. Bode, H. and Roik, K., "Headed Studs-Embedded in Concrete and Loaded in Tension," Anchorage to Concrete, SP 103-4, American Concrete Institute, Detroit, 1987, pp. 61-88.

5. Burdette, E., Perry, T., and Funk, R., "Load Relaxation Tests," Anchorage to Concrete, SP 103-15, American Concrete Institute, Detroit, 1987, pp. 297-311.

6. Burdette, E., Perry, T., and Funk, R., "Tests of Undercut Anchors," Anchorage to Concrete, SP 103-8, American Concrete Institute, Detroit, 1987, pp. 133-152.

7. Burdette, E., Sen, S., and Ismen, E., "Effect of Abandoned Holes on Capacity of Wedge Bolts," Journal of the Structural Division, Vol. 108, ST4, ASCE, April 1982, pp. 743-752.

8. Cannon, R.W., "Expansion Anchor Performance in Cracked Concrete," ACI Journal, Vol. 78, No. 6, November-December 1981, pp. 471-479.

9. Cannon, R.W., Burdette, E.G., and Funk, R.R., "Anchorage to Concrete," Report No. CEB 75-32, Tennessee Valley Authority, Knoxville, TN, 1975.

10. Conard, R.F., "Tests of Grouted Anchor Bolts in Tension and Shear," ACI Journal, Vol. 66, No. 9, September 1969, pp. 725-728.

11. Copley, J.D. and Burdette, E.G., "Behavior of Steel-to-Concrete Anchorages in High Moment Regions," ACI Journal, Vol. 82, No. 2, March-April 1985, pp. 180-187.

12. Daws, G., "Resin Anchors," Civil Engineering, London, October 1978, pp. 71-75; December 1978, pp. 61-63.

13. Elfgren, L., Broms, C., Cederwall, K., and Gylltoft, K., "Anchor Bolts in Reinforced Concrete Foundations," Anchorage to Concrete, SP 103-3, American Concrete Institute, Detroit, 1987, pp. 47-60.

14. Eligehausen, R., "Anchorage to Concrete by Metallic Expansion Anchors," Anchorage to Concrete, SP 103-10, American Concrete Institute, Detroit, 1987, pp. 181-201.

15. Eligehausen, R., "Metallic Expansion Anchors in Nuclear Power Plants," ACI Symposium on Anchorage to Concrete, Phoenix, March 1984.

16. Eligehausen, R. and Fuchs, W., "Load-Bearing Behavior of Anchor Fastenings Under Shear, Combined Tension and Shear or Flexural Loading," Betonwerk + Fertigteil-Technik, Vol. 2, February 1988, pp. 48-56.

17. Eligehausen, R., Fuchs, W., and Mayer, B., "Loadbearing Behavior of Anchor Fastenings in Tension," Betonwerk + Fertigteil-Technik, Vol.12, December 1987, pp. 826-832; Vol. 1, January 1988, pp. 29-35.

18. Eligehausen, R., Mallee, R., and Rehm, G., "Fixings Formed With Resin Anchors," Betonwerk + Fertigteil-Technik, Vol. 10, October 1984, pp. 686-692; Vol. 11, November 1984, pp. 781-785; Vol. 12, December 1984, pp. 825-829.

19. Guthrie, R., Funk, R., and Burdette, E., "Survivability of Concrete Anchorage in Vibration Environments," Anchorage to Concrete, SP 103-6, American Concrete Institute, Detroit, 1987, pp. 107-116.

20. Hyde, L.L., "Load Relaxation of Concrete Expansion Anchors," ACI Symposium on Anchorage to Concrete, Atlanta, January 1982.

21. Lee, N.K., Mayfield, B., and Snell, C., "Resin Anchors in Concrete," Civil Engineering, London, April 1980, pp. 35-41; June 1980, pp. 47-53.

22. Lindquist, M.R., "Final Report, USNRC Anchor Bolt Study, Data Survey and Dynamic Testing," NUREG/CR-2999, Report No. HEDL-MISC-7246, December 1982.

23. Liu, T. and Holland, T., "Dowels for Anchoring New Concrete Facing to Existing Lock Walls," Anchorage to Concrete, SP 103-1, American Concrete Institute, Detroit, 1987, pp. 1-25.

24. Mayfield, B., Bates, M.W., and Snell, C., "Resin Anchorages," Civil Engineering, London, March 1978, pp. 63-65.

25. Meinheit, D.F. and Heidbrink, F.D., "Behavior of Drilled-In Expansion Anchors," Concrete International, Design and Construction, Vol. 7, No. 4, April 1985, pp. 62-66.

26. Nordlin, E.F., Ames, W.H., and Post, E.R., "Evaluation of Concrete Anchor Bolts," Research Report No. 19601-762500-36390, State of California, Department of Public Works, Division of Highways, Materials and Research Department, June 1968.

27. Phan, L.T., Lew, H.S., and Johnson, M.K., "Literature Review of Strengthening Methodologies of Existing Structures," NBSIR, National Bureau of Standards, 1988, in press.

28. Pusill-Wachtsmuth, P., "Behavior of Metallic Expansion Anchors in Unreinforced Concrete Under Tensile Loading," Doctoral Thesis, University of Stuttgart, Stuttgart, 1982, in German.

29. Rabbat, B.G. and Russell, H.G., "Friction Coefficient of Steel on Concrete or Grout," Journal of Structural Engineering, Vol. 111, No. 3, ASCE Structural Division, March 1985, pp. 505-515.

30. Schwarz, F., "Wedge-Type Expansion Anchor Performance in Tension," Anchorage to Concrete, SP 103-5, American Concrete Institute, Detroit, 1987, pp. 89-106.

31. Wagner-Grey, U., "Theoretical Considerations on Loadbearing Behavior of Expansion Anchors," Anchorage to Concrete, SP 103-13, American Concrete Institute, Detroit, 1987, pp. 257-282.

32. Wiewel, H., "Performance Characteristics of Undercut Anchors," ACI Symposium on Anchorage to Concrete, Phoenix, March 1984.

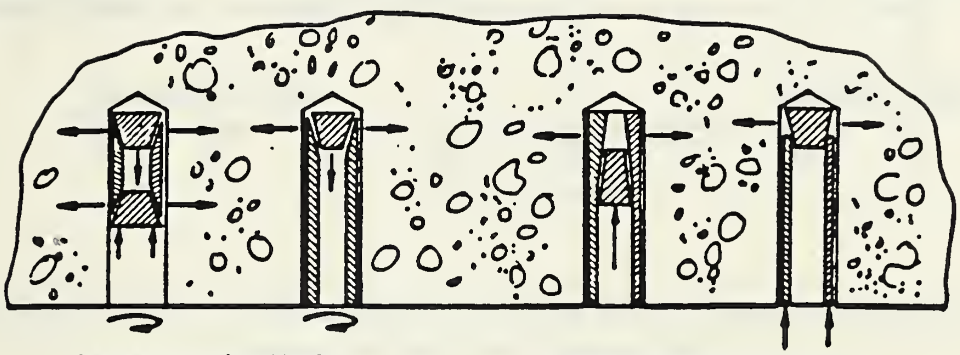
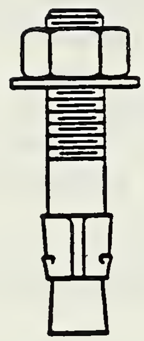
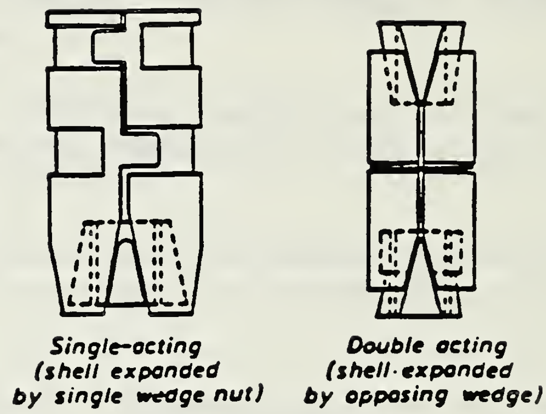


Figure 2.1 Classifications of Expansion Anchors (From [14])

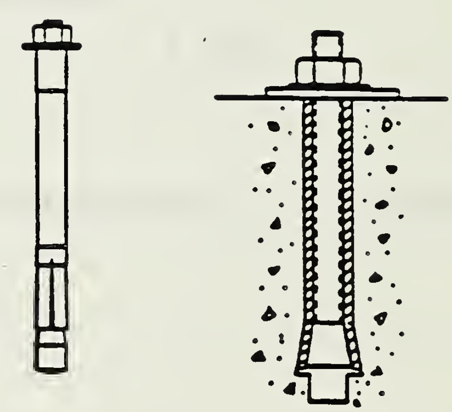


Wedge Anchor



Shell Anchor

Sleeve Anchor



Undercut Anchor

Figure 2.2 Torque-Controlled Expansion Anchors (Type A)

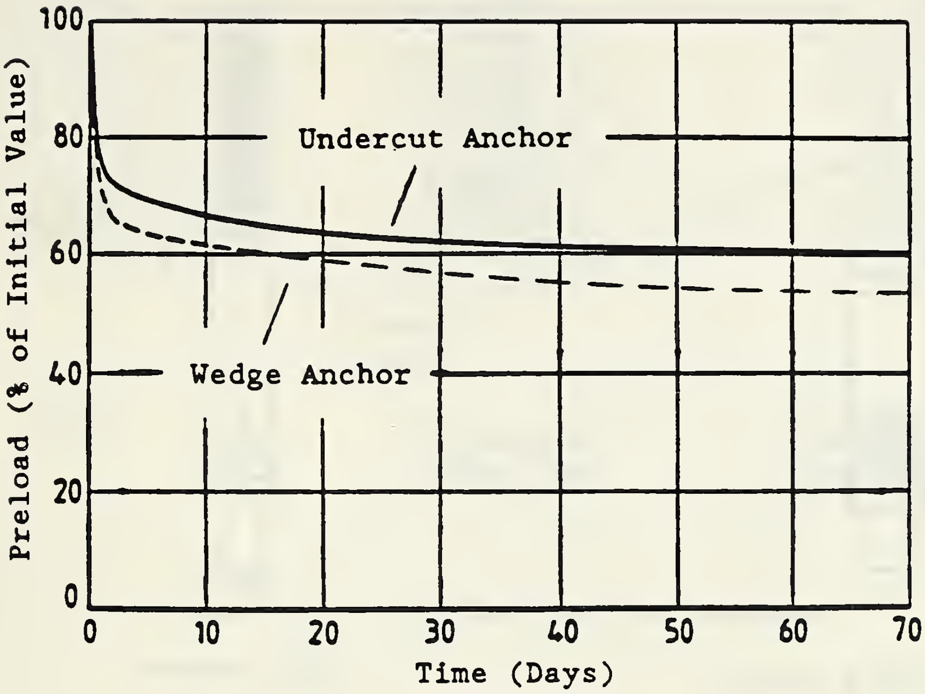
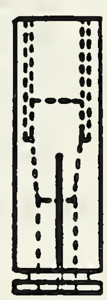
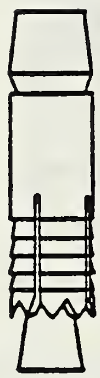


Figure 2.3 Relaxation of Preload in Torque-Controlled Expansion Anchors (From [5])

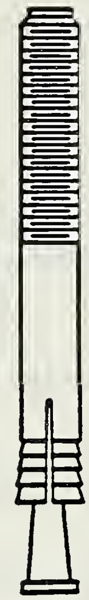


Drop-In Anchor

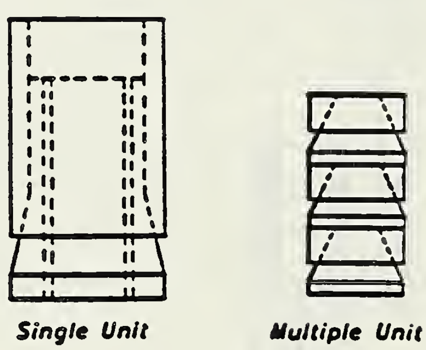
Figure 2.4 Deformation-Controlled Expansion Anchor (Type B)



Self-Drilling Anchor



Stud Anchor



Lead Caulking Anchor

Figure 2.5 Deformation-Controlled Expansion Anchors (Type C)

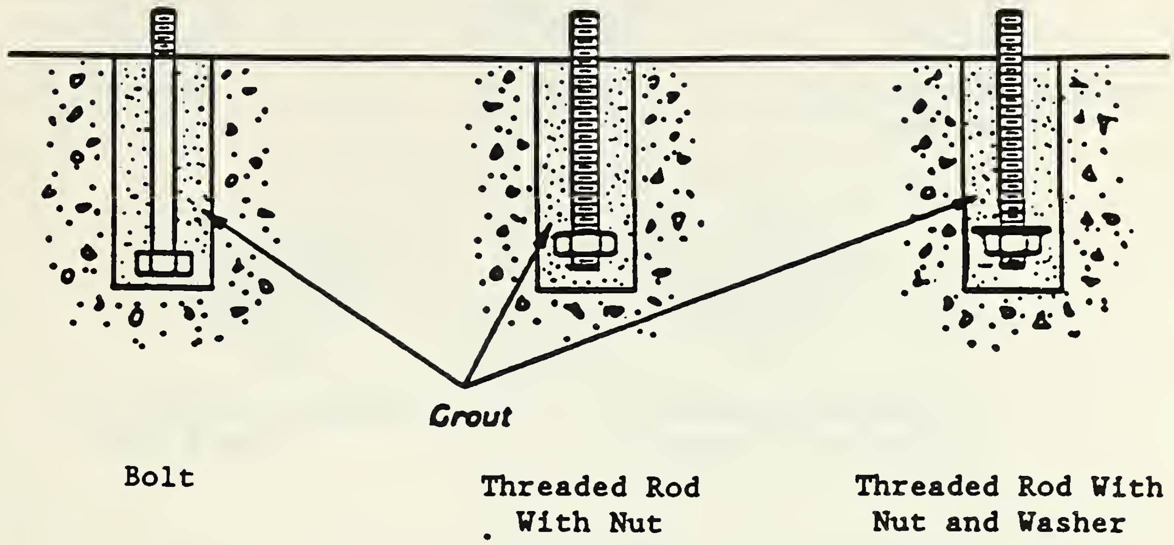


Figure 2.6 Typical Grouted Anchors

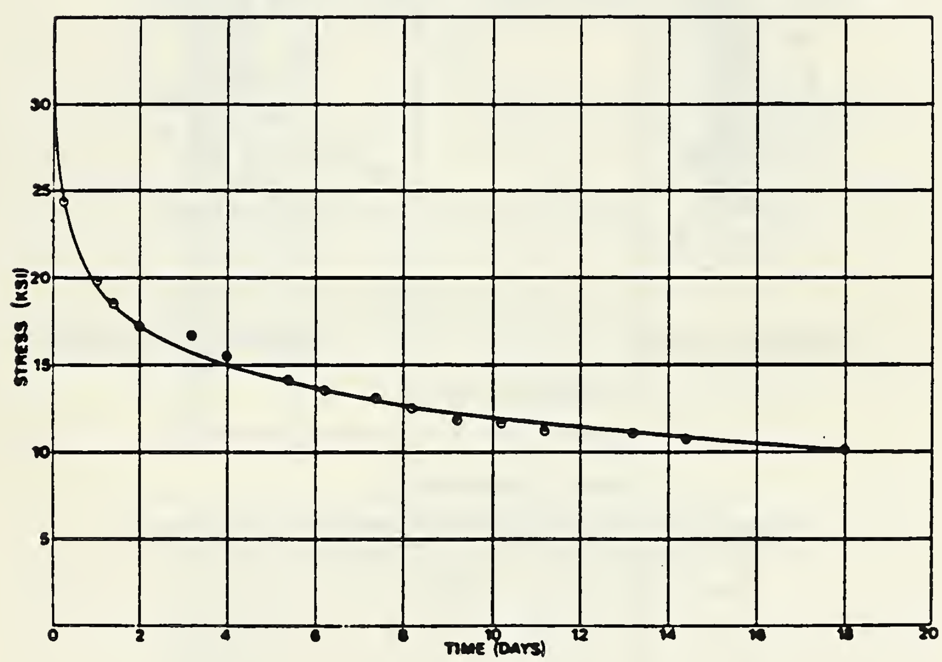


Figure 2.7 Relaxation of Preload in Grouted Anchors (From [5])

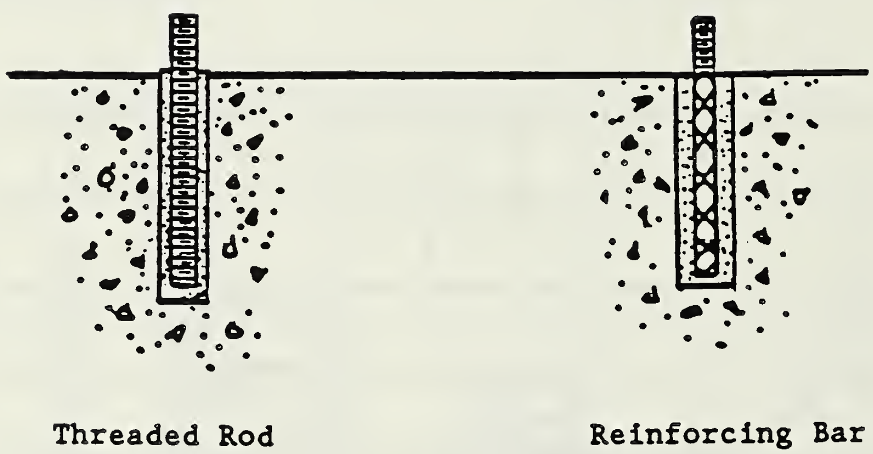


Figure 2.8 Typical Chemical Anchors

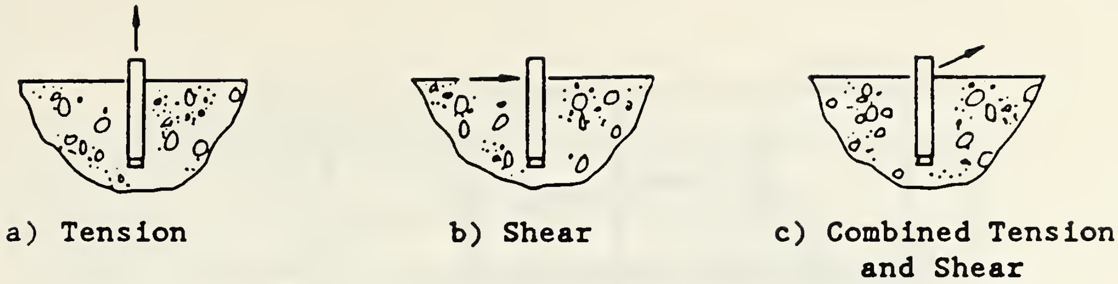
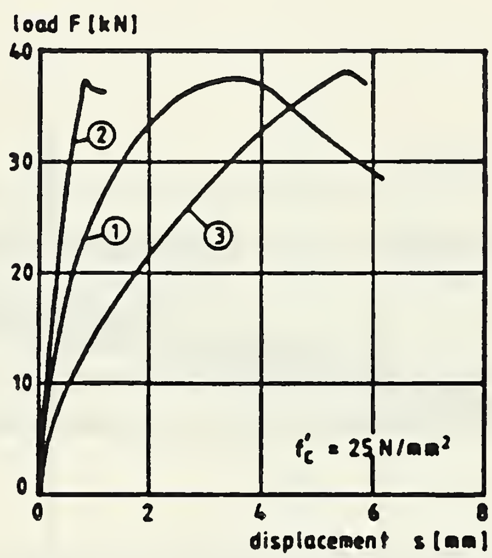


Figure 3.1 Types of Loadings on Anchors



line	anchor type	bolt diameter mm	anchorage depth mm
①	A	10	65
②	B	16	65
③	C	16	63

Figure 3.2 Typical Load-Displacement Relationship of Expansion Anchors in Tension (From [14])

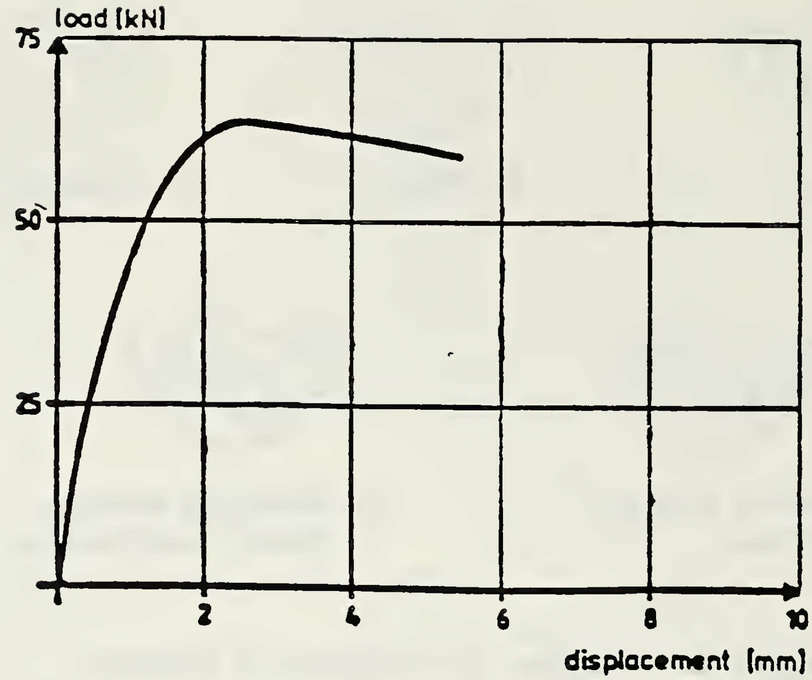


Figure 3.3 Typical Load-Displacement Relationship of Chemical Anchors in Tension (From [18])

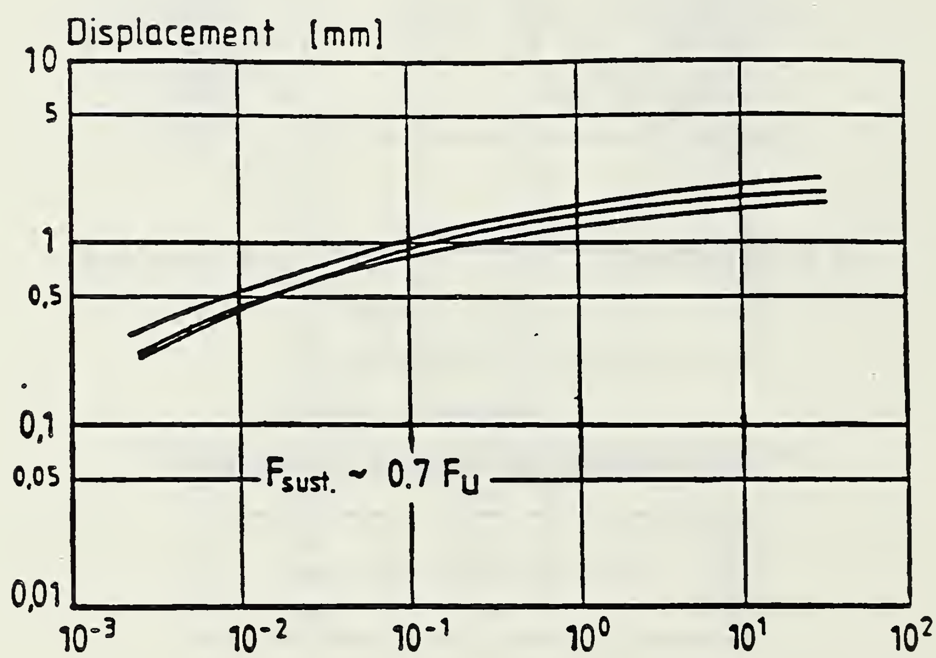


Figure 3.4 Effect of Sustained Tension Loads on Displacement of Torque-Controlled Expansion Anchors (From [2])

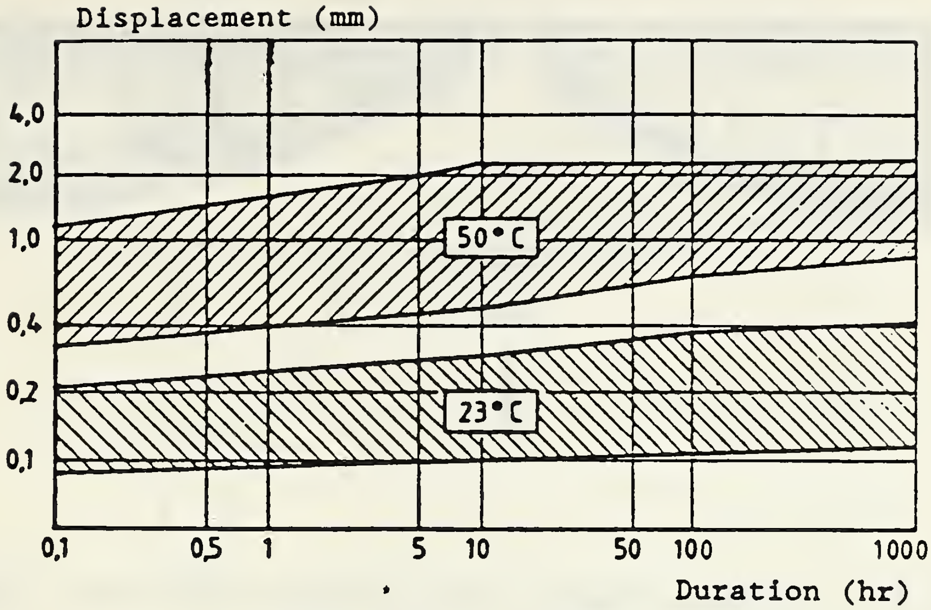


Figure 3.5 Effect of Sustained Tension Loads on Displacement of Chemical Anchors (From [18])

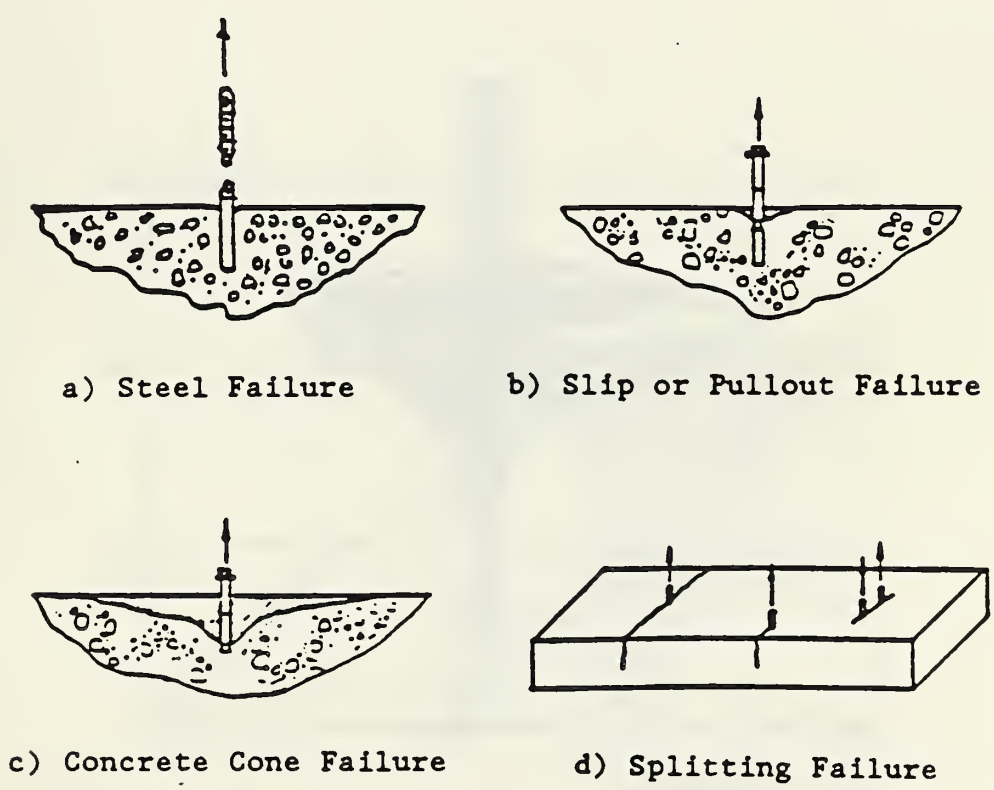


Figure 3.6 Types of Failures of Anchors in Tension

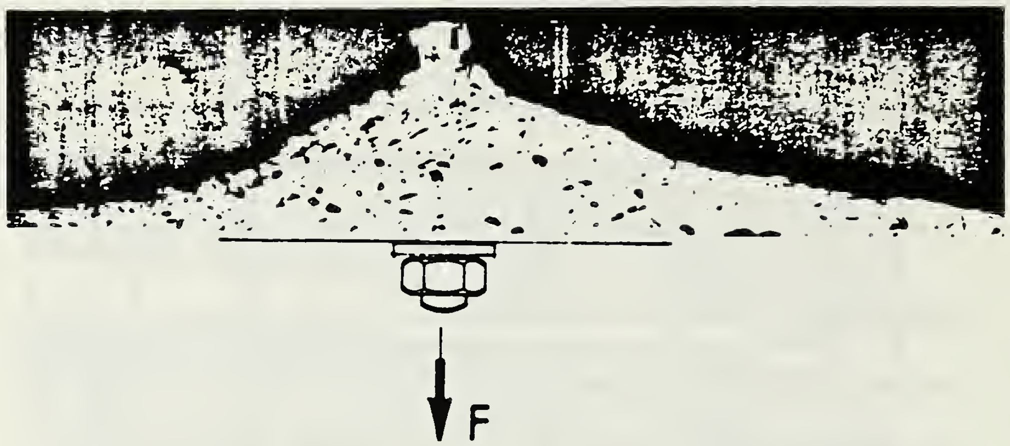


Figure 3.7 Typical Failure Cone of Expansion Anchors (From [14])

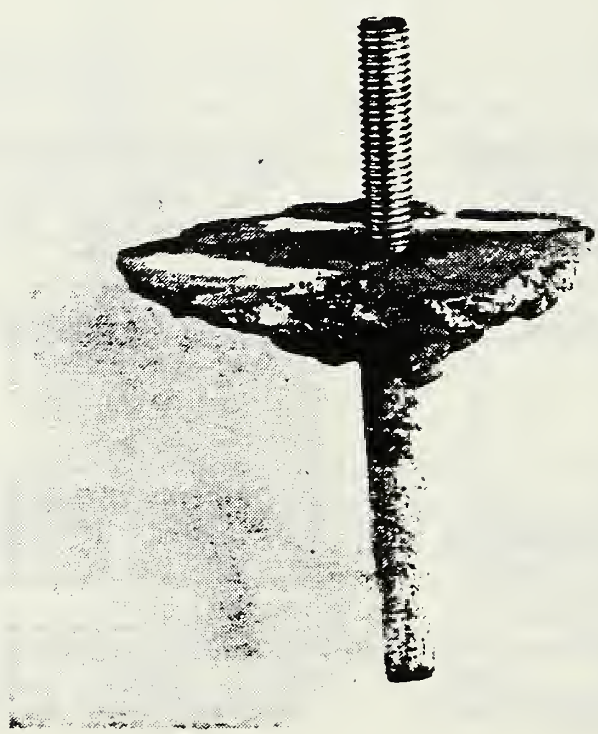


Figure 3.8 Typical Failure Cone of Chemical Anchors (From [18])

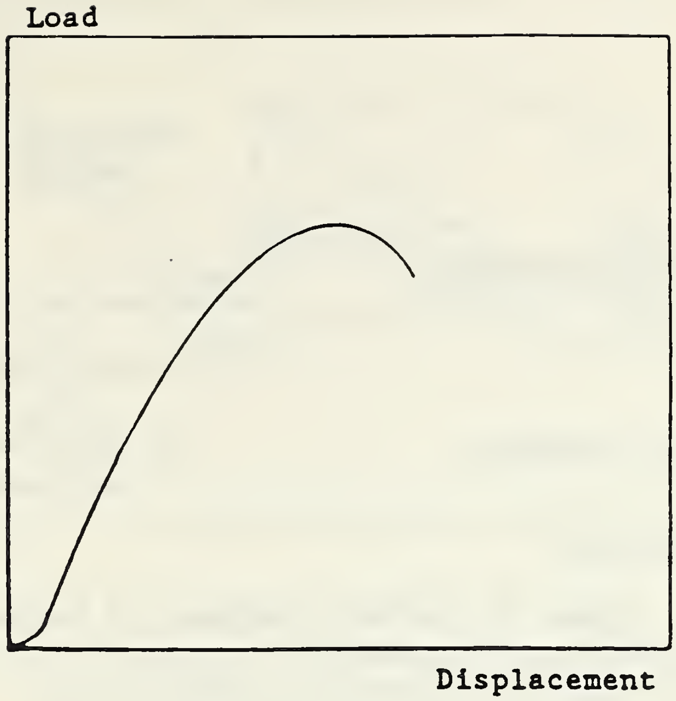


Figure 3.9 Typical Load-Displacement Relationship of Expansion Anchors in Shear (From [16])

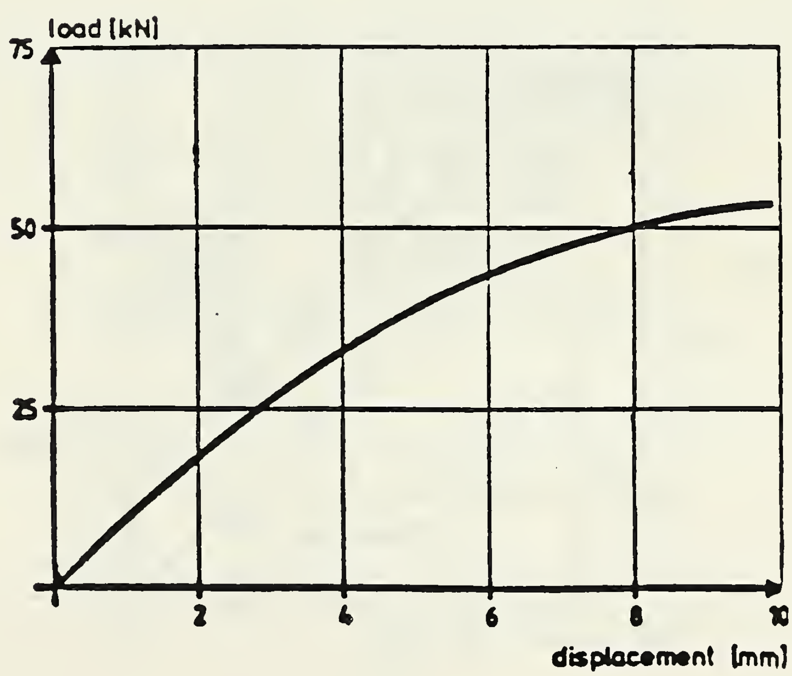
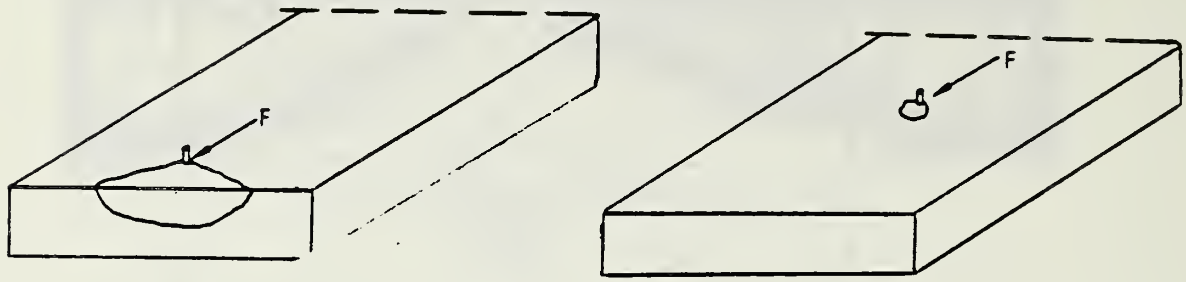


Figure 3.10 Typical Load-Displacement Relationship of Chemical Anchors in Shear (From [18])



a) Conical Breakout

b) Spall or Crush of Concrete

Figure 3.11 Types of Concrete Failures of Anchors in Shear

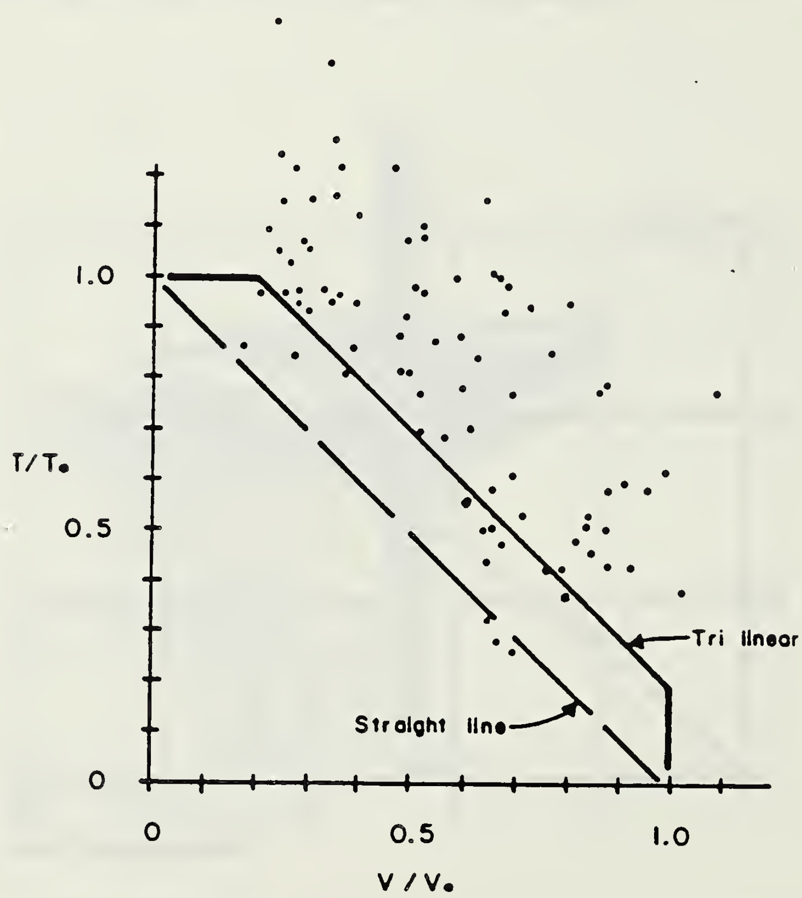


Figure 3.12 Tension-Shear Interaction Diagram for Expansion Anchors (From [25])

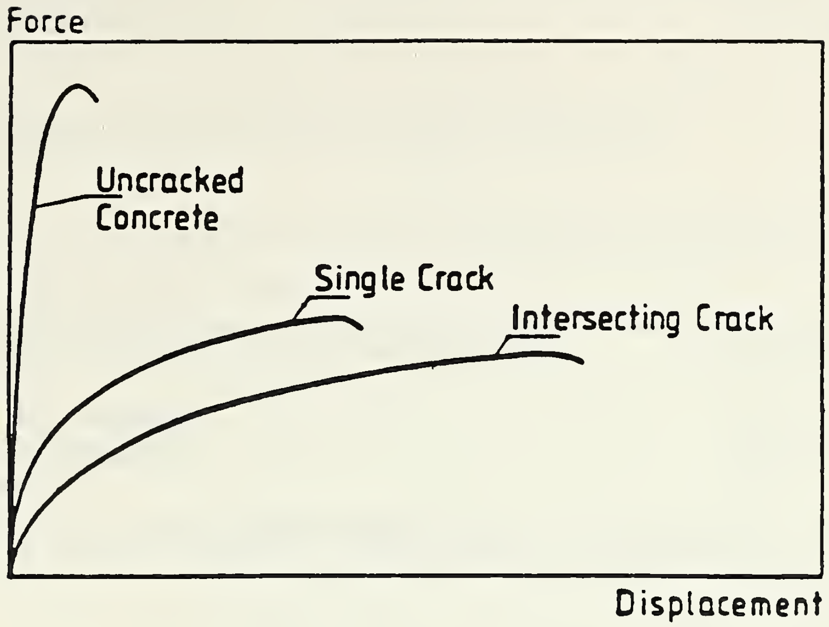


Figure 3.13 Influence of Cracking on Load-Displacement Relationship of Torque-Controlled Expansion Anchors in Tension (From [14])

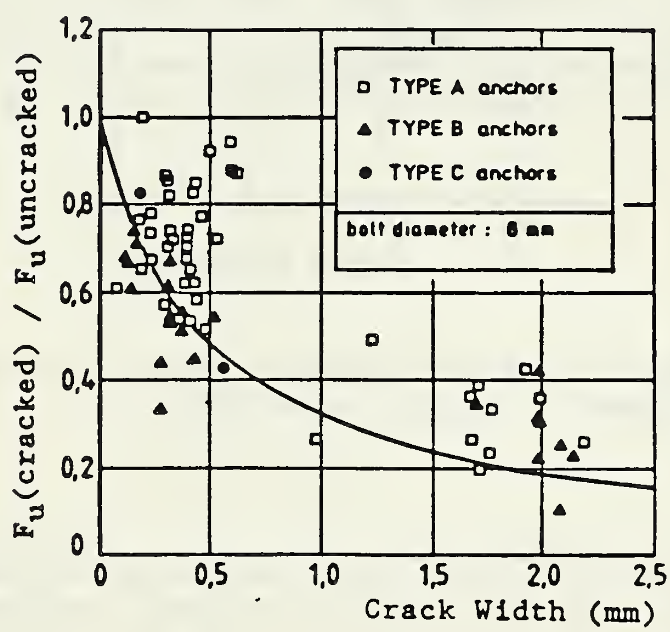


Figure 3.14 Influence of Crack Width on Strength of Expansion Anchors in Tension (From [14])

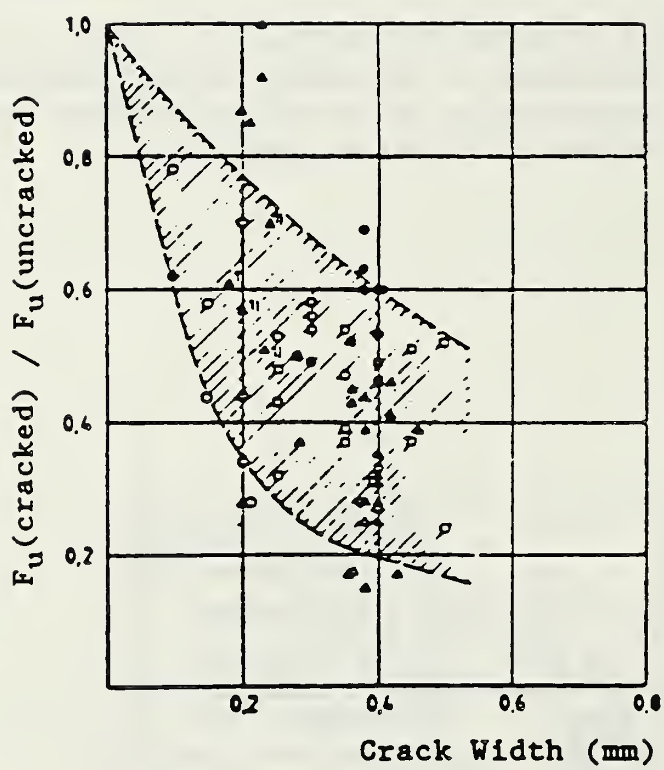


Figure 3.15 Influence of Crack Width on Strength of Chemical Anchors in Tension (From [18])

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This report summarizes current knowledge of post-installed anchor behavior in concrete. Load-displacement behavior and ultimate strength of each type of post-installed anchor are discussed for different loading conditions in both uncracked and cracked concrete. Most knowledge of anchor behavior concerns the response to static tensile loads in uncracked concrete. Many aspects of anchor behavior require further study, especially the behavior of anchors in cracked concrete subjected to combined loadings.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

anchors; combined loading; concrete; drilled-in anchor; epoxy anchor; expansion anchor; grouted anchor; post-installed anchor; shear; tension.

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