Anchorage of Steel Building Components to Concrete

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Anchorage of steel building components to concrete is a fact of life. It has been used, and will continue to be used, in essentially all steel industrial structures. It would seem logical that the behavior and consequently the design principles concerning such anchorages are as well understood, for instance, as those concerning flexure of the components themselves. However, such has not always been the case. Because of this situation, recent work has been undertaken to enhance understanding of anchorage behavior. Much of this work has been brought about as a result of the stringent quality assurance programs of the nuclear power industry with the corresponding stringent design requirements for anchorage to concrete. While the nuclear industry's design requirements are rather rigorous relative to the needs of the industrial building industry, much of the information obtained to meet these requirements can be utilized in industrial building applications. The purpose of this paper is to describe various types of anchorage devices, discuss their behavior and present appropriate design guidelines for implementation in industrial building construction.

ANCHORAGE TYPES

Anchorage of steel attachments and structural elements to concrete has been accomplished by a variety of methods. In the past a gap in both knowledge and standardization of anchorage devices has existed. Utilization and design of anchorages have been accomplished by precedent, code information and manufacturer's data. However, recent work has done much to advance understanding of anchorage behavior, and this increased understanding provides a more rational basis for their design.

Some basic anchor types have evolved which fall into two categories—cast-in-place and drilled-in anchors. Cast-in-place anchors, as the name implies, are set before the concrete is placed or are inserted while the concrete is still fresh. On the other hand, drilled-in anchors are set after the concrete is fully hardened.

Cast-in-Place Anchors

Cast-in-place anchors are available primarily in the following forms: wire-form inserts, studs, common bolts, smooth and deformed bars which may be straight or bent and structural shapes. Typically, embedded anchors have formed heads as illustrated in Fig. 1. These heads provide a bearing surface between the embedment and the

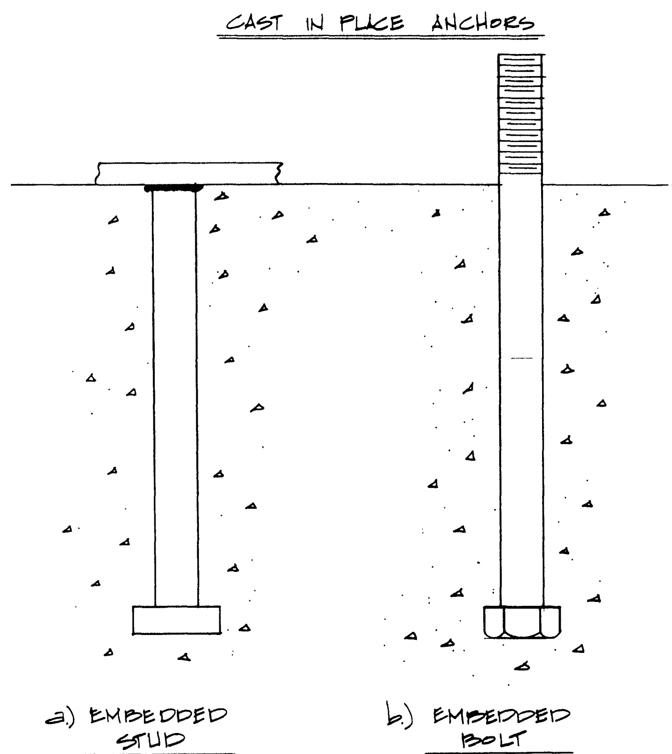

Fig. 1. Illustrations of anchor types

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concrete, thus enhancing the anchors' resistance to pull out. Deformed bars may be used without such a positive bearing surface, provided proper anchorage is achieved through adequate development lengths. Development lengths should conform with those specified in the ACI 318 design code.[1] Smooth bars quite often are hooked on their embedment end to assure proper anchorage. However, it is the authors' opinion that a bearing head should be used with these type anchorages since a hooked, smooth bar will straighten and pull out unless an extremely long embedment length is provided. A smooth bar offers much less development of strength along its length than a deformed bar does. Welded studs, common bolts and deformed bars possess a positive bearing surface. In fact, studs and bolts offer enough bearing surface, as they are, to develop the full strength of the anchor, provided adequate embedment depth and edge distance are available. The use of washers and plates above the bolt head to increase pull-out strength generally should be avoided.[2] The failure mechanism for an adequately embedded bolt or stud is pull-out of a cone of concrete radiating outward from the head of the bolt to the concrete surface. The presence of a washer or plate over the head only serves to spread the pull-out cone outward from the bolt centerline. It does little to enhance the strength of the embedment and can cause severe problems with edge distances as well as with adjacent anchorages.

Cast-in-place anchorages with bearing heads have the distinct advantage of being able to positively engage the concrete in confined bearing. These anchorages can usually be detailed to develop the full strength of the steel embedment. They are typically very stiff since the bearing surface cannot slip.

The strength and stiffness advantages of cast-in-place anchorages may be offset by the inherent difficulty of accurately locating and maintaining alignment of the anchorage configuration before and during concrete placement. It may also be difficult and quite often is impossible to anticipate future required embedments. For these reasons, drilled-in anchors have evolved and are in wide usage. These are placed in hardened concrete and offer flexibility in precisely locating the anchorage positions. And they allow future, unforeseen anchorages to be placed with relative ease.

Drilled-in Anchors

Drilled-in anchors come in a myriad of types. Three general types which are widely used are discussed here. These include self-drilling anchors, wedge bolts and undercut anchors (see Fig. 2). The mechanism by which the first two types of anchors work is basically the same, but small differences in each type cause their behavior to be highly varied. Drilled-in anchors are placed in holes drilled into hardened concrete. Some type of mechanism is used to draw a mandrel between pieces of metal which

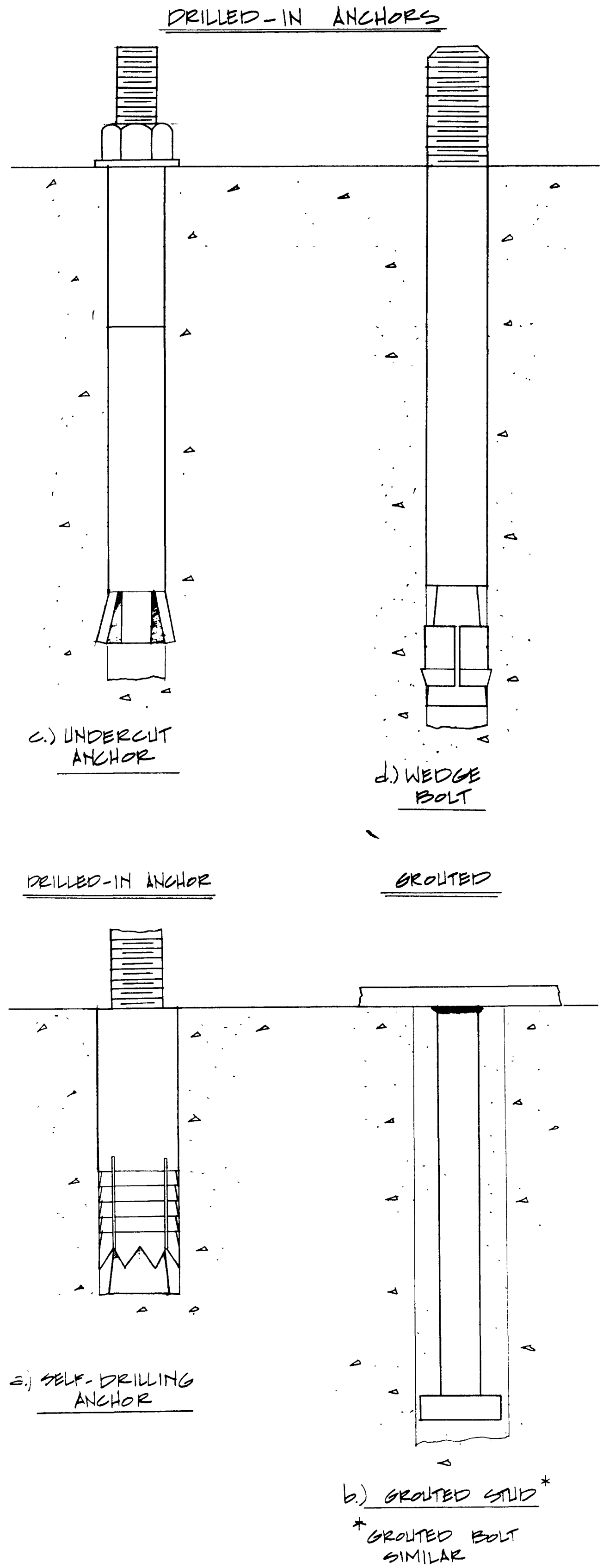

Fig. 2. Illustrations of anchor types

engage the side of the hole. Then, friction between the metal and the sides of the hole resists pull-out of the anchor.

Self-drilling anchors are unique in that their casings are used to drill the holes. Thus the need for a separate drill bit is eliminated. However, a special tool is required to connect the anchor shell or casing with an appropriate hammer drill. Once the hole is drilled, the shell is removed and all debris and dust removed from the hole. The shell is then reinserted with the mandrel in place. The hammer drill is then used to hammer the shell down over the mandrel, causing the outer edges of the shell to engage the sides of the hole. Thus, tension on the anchorage is resisted by friction. The self-driller has the inherent weakness of never becoming any tighter than it is when it is seated, since the direction in which force is applied to the anchor is precisely opposite to that in which it is seated. However, the usual mode of failure of self-drilling anchors is pull-out of a small cone of concrete because of its shallow embedment. Accordingly, this anchor should only be used for light to medium loads and where no preload is required.

Wedge bolts are somewhat better than self-drilling anchors in terms both of preload and the load levels they can sustain. They are set by simply drilling a proper size hole into hardened concrete and driving the wedge bolt into it to the appropriate depth. For a wedge bolt the hole depth is not critical as long as it is at least as large as the embedment depth. The anchor is seated by applying torque to a nut on the end of the anchor. This pulls the anchor's mandrel up through the wedges, forcing the wedges to engage the side of the hole. The anchorage resists pull-out by friction developed between the wedges and the side of the hole.

The wedge bolt has several distinct and important advantages over self-drilling anchors. First, the direction in which a tensile load is applied is also the same as that required to seat the anchor. Thus, the application of additional tensile load tends to tighten the anchor. Second, the depth of embedment of wedge bolts is substantially greater than that of self-drillers. The added depth allows more force to be developed in the anchor since the surrounding concrete does not control capacity. The two advantages just cited tend to make the wedge bolt a very tough anchor in terms of potential failure by pull-out. The anchor does, by nature, slip, which reduces its stiffness, and failure typically occurs by slip. It does exhibit a relatively high degree of ductility before failure. Where existing reinforcement, edge distances and neighboring anchors do not interfere with the wedge bolt, it can be used to support substantial loads.

The undercut anchor provides still greater strength and toughness for a drilled-in anchor. They are in a somewhat different category from self-drilling and wedge-bolt anchors since they possess a positive bearing surface against confined concrete. This feature makes them comparable to embedded bolts and studs.

Undercut anchors are installed by drilling a proper size hole into hardened concrete. A special tool is then used to flare or undercut the hole at a predetermined depth. This depth is usually set by the undercutting tool which in turn is matched to the particular anchor being installed. Once the hole is undercut, the anchor itself is dropped into place and the bolt torqued, thereby drawing the mandrel up into the bolt's shell. This causes the shell to expand into the undercut part of the hole. The anchor is thus seated and possesses a positive bearing surface to resist pull-out.

The undercut anchor has the advantage of having been subjected to a proof load. In other words, when the anchor is set, it is also proofed as the shell expands into the flare or undercut at the bottom of the hole.

BEHAVIOR

Tension

Anchors which have embedment heads directly bearing on concrete may fail under tensile loading by pulling out a cone of concrete. This type failure occurs when embedment depth is inadequate to develop the tensile strength of the anchor itself. The concrete is then the weak link, thus fails first. The anchor types to which this behavior primarily applies are embedded bolts, studs and undercut anchors. Wedge bolts and other anchors which have a tendency to slip rarely cause sufficient tensile force to be developed in the concrete to produce this type failure. Proper embedment depth of a tensile anchor will avert failure by concrete pull-out. The simplest case to consider is a single embedded anchor, shown in Fig. 3. Two separate strengths must be determined: (1) the tensile strength of the anchor itself; and (2) the tensile strength of the resisting concrete. For a ductile anchorage the tensile strength provided by the concrete must exceed the strength of the steel. This can be assured by providing sufficient embedment depth.

Since concrete failure occurs by pull-out of a cone of concrete, the strength of the anchorage, as governed by the concrete, is determined by applying a nominal tensile stress perpendicular to the surface of the cone. The cone

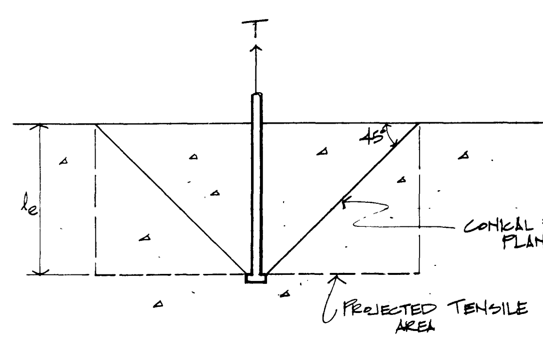

Fig. 3. Failure cone of an embedded anchor

is defined by a failure surface radiating from the anchor head to the surface at an assumed angle of 45°. In lieu of applying the nominal stress perpendicular to the cone, a simpler approach is to apply the nominal stress to the projected tensile area, as shown in Fig. 3. This resolves the area to be considered to a single plane, which makes the concrete strength calculation much simpler when multiple, overlapping stress cones are involved.

Typically, the tensile strength of concrete may be taken as $6\sqrt{f'_c}$. The distribution of tensile stress along the sides of the failure cone varies from a maximum at the embedment end to zero at the surface. For this reason, an average stress of $4\sqrt{f'_c}$ is assumed to act uniformly along the failure surface. By statics, this same stress can be applied to the projected area. Experimental studies have generally verified the predictions of this method. The 45°-angle assumed with this method is reasonable except for shallow embedments. For these type embedments (5 in. or less), a wider angled cone will be pulled out. The method outlined using a 45°-angle will thus underpredict the concrete strength.[3]

If embedments are placed close enough to one another, the potential failure (stress) cones may overlap. When this occurs, the area of concrete effective in resisting pull-out is reduced. The tensile strength of the entire embedment group is likewise decreased. A rational way to calculate the tensile resistance of the concrete is to apply the nominal stress, $4\sqrt{f'_c}$, to the effective projected area of the group. The effective area accounts for a reduction in area due to overlapping.

If an anchor is located close enough to a free edge, reduction of tensile resistance may again occur. The effect of this must be accounted for. If the anchor lies within a certain distance of the side, a bursting or blow-out failure may occur (see Fig. 4). This type failure arises from the high bearing stresses developed in the vicinity of the anchor head. The shape of the potential blow-out is essentially conical like the tension stress cone. The Commentary to Appendix B of ACI 349[2] offers a method for calculating the minimum side cover necessary to prevent lateral bursting failures.

The preceding discussion neglects the effects of stress present due to applied loads other than those on the anchorage. It is possible that tension or compression in the concrete supporting an anchor could be present, and this condition must be accounted for. For instance, if significant biaxial tension is present in the plane of the structure, then the assumed 45°-failure cone is not truly applicable. Reinforcement must be added to resist the effects of the tension. However, if reinforcement is added in accordance with ACI 318,[1] the maximum crack width will be restricted. Thus, it has been stated that use of the 45°-stress cone would still be approximately valid.[4] On the other hand, a state of biaxial compression would enhance an anchor's strength since added confinement is present.

The amount of preload applied to an anchorage has an important effect on anchorage behavior. The behavior of a preloaded anchor is discussed in an appendix to this paper.

Shear

Transfer of shear from an anchor bolt into the surrounding concrete is accomplished primarily through bearing. The applied shear tries to bend the bolt away from the load. This bending of the bolt causes the concrete ahead of the bolt to crush or spall near the surface. Tests have shown that a wedge of concrete, roughly one-fourth of the bolt diameter in depth, may spall off [2] (see Fig. 5). This behavior will almost certainly result if a base plate is not present to confine the concrete.

The presence of a base or cover plate restricts the concrete wedge from moving. As the wedge tries to translate, it also tries to move upward. This upward movement cannot occur if a base plate is present. Thus, an upward thrust on the plate results rather than movement. This increases the tensile load in the bolt, which in turn increases the clamping force exerted by the plate. Translation of the wedge is then restricted further.

If a base plate is not present, the potential concrete wedge is free to form and break away entirely. The stiffness of the anchorage in shear is reduced in this case. The shear stiffness is also related to the distance between the line of action of the applied shear and the surface of the concrete. As the distance increases, bending deflections

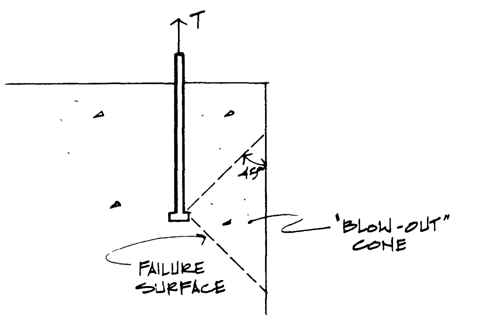

Fig. 4. Lateral blow-out cone caused by insufficient edge distance

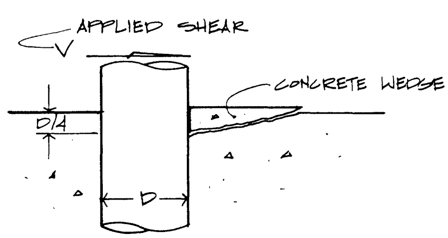

Fig. 5. Spalling of concrete wedge due to shear

of the bolt will become more significant, reducing the stiffness of the connection in shear. An example of this type of connection is a column base plate which is separated from the primary concrete by a grout pad. The presence of the grout pad allows bending deformation of the bolts to occur under a shear load. As the bolts are deflected laterally by a shearing force, tensile stresses are developed in the bolts. Generally, this tension is insufficient to cause tensile failure of the anchors since the embedment depth required for tension is greater than that required for shear.

From the preceding discussion it is apparent that shear strength of an anchor is a function of both steel strength and the distance between the plane of applied shear and the concrete surface. If shear is applied to a group of anchor bolts via a base plate, then the most effective distribution of load occurs when the plate is embedded in the concrete (see Fig. 6). The enhanced behavior is due to the increased confinement of the concrete in addition to bearing stresses developed on the leading edge of the base plate.

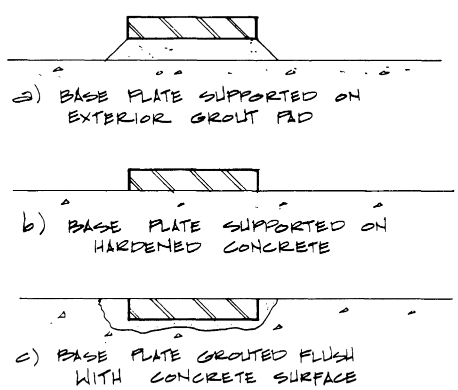

Fig. 6. Base-plate support conditions

There are not enough data available at the present time to quantify precisely the shear strength in terms of the variables just discussed. Appendix B of the ACI 349 code outlines a method for determining shear strength which takes account of these variables. However, that method is based on the concept of shear-friction. The mode of shear transfer in an anchorage is bearing rather than shear-friction. Since the distance between the applied shear and the concrete surface affects the shear strength, factors much like those taken for shear-friction can be used. A set of factors, recommended by the writers, is listed in Table 1. While the use of these factors give results similar to those in ACI 349, Appendix B, they are not related to coefficients of friction.

Shear capacity is limited by inadequate edge distance if a shear load is applied toward that edge. Failure occurs by splitting off a half cone of concrete. The apex of this

Table 1. Recommended Design Shear Strengths

The design shear strength of an embedment may be based on an allowable steel stress equal to ϕF_y. The yield strength, F_y, should not exceed 120 ksi. The following values of ϕ may be used.

(1) ϕ = 0.45 for a plate supported on an exterior grout pad (Fig. 6a)

(2) ϕ = 0.60 for a plate supported on hardened concrete surface (Fig. 6b)

(3) ϕ = 0.80 for a plate embedded flush with concrete surface (Fig. 6c)

half cone is located where the bolt bears against the concrete surface. This is illustrated in Fig. 7.

If insufficient edge distance is known to exist, it is possible to reinforce against a potential shear cone type failure. Hairpin reinforcement has been used when such conditions prevail. Guidelines for calculating necessary edge distances and for designing such reinforcement are given in Appendix B of the ACI 349[2] code. The requirements outlined in that code are generally quite conservative. There remain inadequacies in the methods for calculating edge distance and for proportioning shear cone reinforcement. More data need to be gathered and assimilated to improve the existing methods for design of anchorages subjected to shear toward a free edge.[5]

Combined Shear and Tension

At present, the interaction of shear and tension is not fully understood, and a straight-line interaction relationship is generally assumed. This method predicts steel areas by adding the area required for shear to that required for tension. This method is certainly conservative, but is warranted since test data concerning combined shear and tension are lacking for most anchors. It is suggested that a straight-line interaction be assumed, unless test data are available for a particular anchor indicating that some other interaction form is applicable. A more detailed treatment of tension, shear and their combined effects may be found in Appendix B of the ACI 349 code.[2]

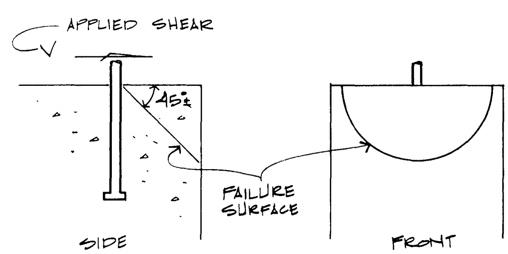

Fig. 7. Shear toward a free edge

Ductility

Ductility has been defined as the ability of a structure or a structural component to undergo deformation in the inelastic range. If an anchor can undergo significant inelastic deformation, it is said to be ductile and thought of as a "tough" anchor. The ability to anchor a piece of steel in concrete and then fail the steel itself, while leaving the concrete relatively undamaged, is what designers would like to achieve. An embedded bolt or stud, if properly embedded, will "fail steel" with little trouble. However, when thoughts turn to drilled-in anchors, the concept of a ductile anchor becomes more elusive.

Some types of drilled-in anchors are not ductile. For instance, self-drilling anchors simply do not have enough embedment depth to fail steel. On the other hand, undercut anchors are quite capable of fully developing the strength of the steel. Somewhere in between the self-drillers and the undercut anchors lie the wedge bolts. These bolts fail by slip, but it takes a lot of slip before the bolts ultimately lose the capacity to carry their maximum load. Thus, while this type anchor does not fall into the can fail steel category, it is, in a sense, ductile because it fits the basic definition of ductility. It can sustain significant deformation in the inelastic range.

DESIGN CODES

Cannon, Godfrey and Moreadith[4] have proposed a modification of Appendix B of the ACI 349 nuclear structures code which would apply to industrial buildings and other structures not requiring the stringent design criteria used in nuclear applications. The Tennessee Valley Authority has developed an anchorage design specification, DS-C1.7.1,[6] which is relatively comprehensive. Many of the requirements set forth in the TVA specification were developed from tests performed at The University of Tennessee.

It is important to realize that design codes governing anchorage design have ductility as their central theme. If ductility is not a feature of a particular anchor, then the anchor is severely penalized in terms of allowable load levels.

REFERENCES

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3. *Klinger, R.E. and J.A. Mendonca* Tensile Capacity of Short Anchor Bolts and Welded Studs: A Literature Review *ACI Journal, July-August 1983.*
4. *Cannon, R.W., D.A. Godfrey and F.L. Moreadith* Guide to the Design of Anchor Bolts and Other Steel Embedments *Concrete International, July 1981.*
5. *Bailey, John W. and Edwin G. Burdette* Edge Effects on Anchorage to Concrete *Civil Engineering Research Series No. 31, The University of Tennessee, Knoxville, August 1977.*
6. *Tennessee Valley Authority* Civil Design Standard, DS-C1.7.1, General Anchorage to Concrete *May 1983.*

APPENDIX—PRELOAD

When steel attachments, such as base plates, are connected to concrete with anchor bolts, the bolts are usually pretensioned or preloaded. This preloading pulls the attachment tightly onto the concrete. The anchors usually are preloaded to some predetermined magnitude of bolt load or elongation. Preloading the bolts does not make the anchorage any stronger. Preload will, however, make the anchorage significantly stiffer in terms of reducing deflections which will occur for any given applied load.

The behavior of preloaded bolts is best understood if considered in terms of the deformations which occur in both the bolts and the concrete. Consider the bolt anchorage shown in Fig. A1. The initial load conditions are as follows: The anchor bolts are preloaded to a certain level. No tensile load P is yet applied to the assembly. The base plate is assumed to be relatively stiff so that it behaves essentially as a rigid plate. The initial loads thus cause both elongation of the bolts and a slight compression of that concrete which is directly under the base plate.

For this load condition a free body diagram, as seen in stage 0 of Fig. A1, can be drawn for the base plate. The following equation of equilibrium can then be written as:

$$\cancel{P}^{0} - 2F_B + \sigma A = 0 \qquad (1)$$

where
F_B = load in each bolt
σ = compressive stress exerted by the concrete
A = area of the base plate

Equation 1 shows that the total force exerted by the two bolts on the base plate is equal to the force applied by the concrete to the base plate.

As a tensile load P is applied to the assembly, the result is to reduce the deformation of the concrete under the base plate. Simultaneously the bolts are elongated an amount corresponding to the reduction of concrete deformation.

The concrete is relatively stiff and the area of the base plate is large compared to the area of the bolts. Thus, the reduction of strain in the concrete results in a much larger change of compressive force than the increase in bolt tension due to the same change in strain. For this reason the tensile load P is equilibrated primarily by the reduction of the stress exerted by the concrete on the base plate. This condition corresponds to Stage 1 of Fig. A1.

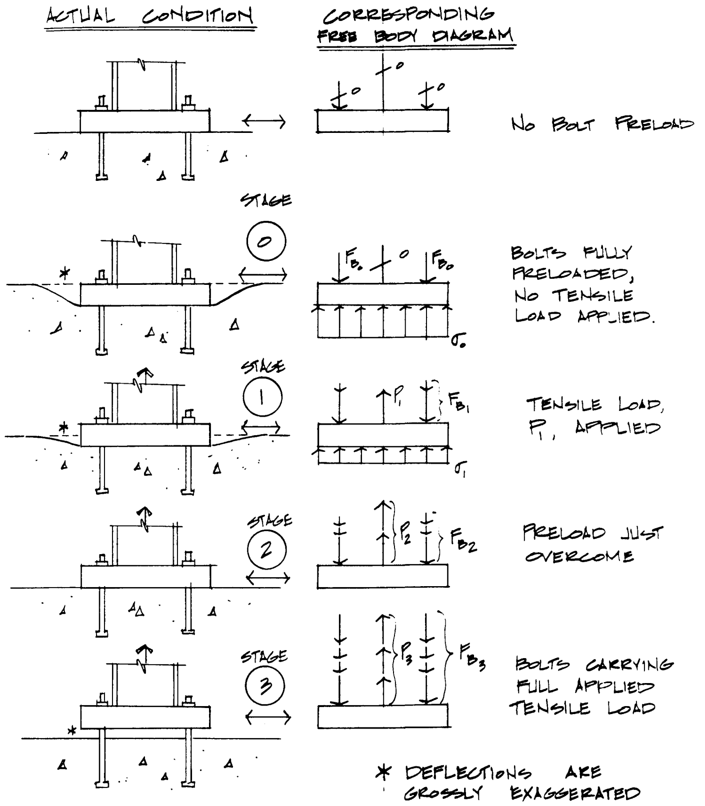

Fig. A1. Preload illustrated

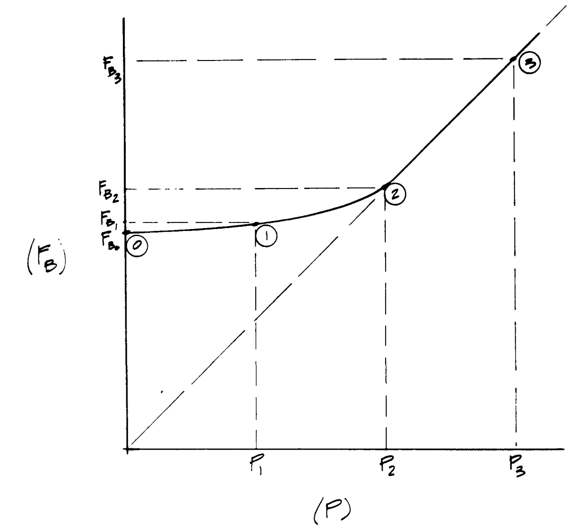

Fig. A2. Bolt load F_B vs. load on connection P

As the tensile load P is increased, the compressive strain in the concrete is reduced further. At some point, the load P is sufficiently large to overcome the compressive force exerted by the concrete entirely. This is seen in Stage 2 of Fig. P1. When this occurs, the whole of the tensile load P is resisted by the bolts alone. The effect of preload is overcome at this point. The anchors behave, from this point on to failure, as if preload had never been present.

The strain required to develop a high compressive force in the concrete is actually quite small because the base plate area is much larger than the total bolt area. Thus the incremental strain experienced by the bolts between the point of no applied tensile load P and that tensile load required to overcome preload is also small. For this reason the load in the bolts does not increase appreciably until the preload is overcome. A typical plot of bolt load F_B vs. tensile load P is shown in Fig. A2.