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reinforcing bar, or a headed bolt, rod, or stud inserted into a predrilled hole in hardened concrete using structural grout as the bonding agent between the concrete and the steel. Grouted anchors are typically installed with a cementitious or polymer grout in a predrilled hole having a diameter at least 50% larger than the diameter of the fastener. For the purpose of this article, grouted anchors are defined as anchors having a hole diameter 50% or larger than the anchor diameter and adhesive anchors are defined as having hole diameters less than 50% of the anchor diameter.

Adhesive anchors

Adhesive anchors are often preferred over other anchorage systems due to their rapid curing cycle that can be as low as a few hours. Adhesive anchor products can be divided into epoxies, polyesters, vinylesters, and hybrid systems.[2] These structural adhesives are composed of a two-part system consisting of a resin and a curing agent. After proper mixing, the resin and curing agent undergo an exothermic reaction that forms a polymer matrix, which becomes the chemical adhesive.[2]

Adhesive anchors transfer the applied load to the concrete by chemically binding to the concrete and by mechanical interlock. From extensive research performed on adhesive anchors, it is known that these anchors can exhibit the four different embedment failure modes presented in Fig. 3.[2,3] The most common embedment failure modes are those involving a bond failure with a shallow concrete cone. It is difficult, however, to distinguish between bond failures at the adhesive/concrete, steel/adhesive, or a combination bond failure due to the small difference between the diameter of the hole and that of the anchor. This was taken into consideration by Cook et al.,[2] who reported that the bond strength of an adhesive anchor could be accurately predicted by using the uniform bond stress model applied at the anchor diameter regardless of the failure mode. Another failure mode observed only in bonded anchors with a small embedment depth is a full concrete cone breakout failure. Cook et al.[2] and McVay, Cook, and Krishnamurthy[4] showed that failure loads of adhesive anchors producing this failure mode were related to bond and could be appropriately predicted using the uniform bond stress model.

Grouted anchors

Bonding agents used in grouted anchors can be classified as polymers or cementitious-based products. A polymer grout consists mainly of a resin and a curing agent combined with fine aggregates that are not found in adhesive anchor products. Anchors installed with a polymer grout are typically placed in clean dry holes to obtain maximum bond strength. Polymer grouts can be loaded only a few hours after installation. Such a rapid curing rate is something that cannot be accomplished with cementitious products. Cementitious

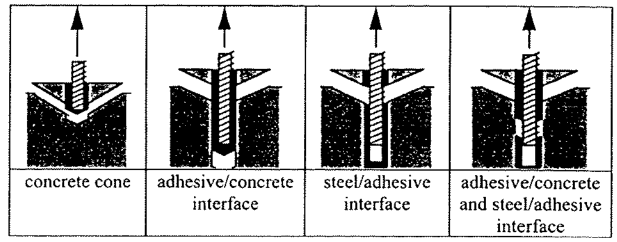


Fig. 3—Potential embedment failure modes for adhesive anchors.

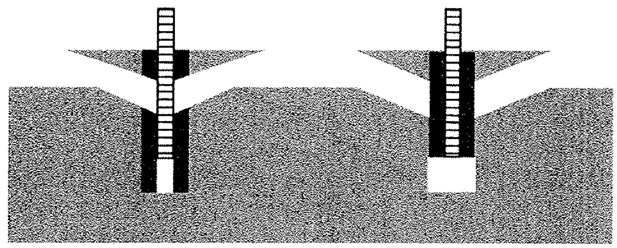
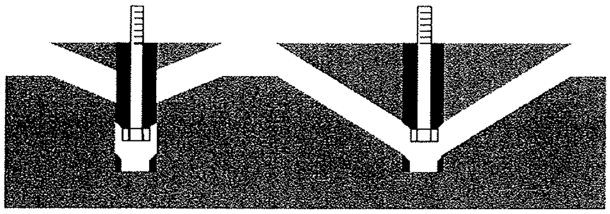


Fig. 4—Expected failure modes for unheaded grouted anchors.

grouts are primarily made up of a mixture of cement, water, and sand. These types of grouts are usually prepackaged in bags containing set amounts of cement, sand, and proprietary additives. Part of the installation process is deciding how much water to add to the mixture. Manufacturers usually suggest the amount of water required for proper mixing under a wide range of flow conditions. It is then left to the installer to make the decision regarding the viscosity required for installation. Cementitious grouts are usually installed in clean damp holes to obtain optimal bond strength between the grout and the concrete. Predrilled holes are usually filled with water approximately 12 to 24 h prior to installation. The water is then removed prior to installation of the anchor. This process reduces the loss of water from the grout to the surrounding concrete and ensures that there is not a decrease in grout strength due to excessive water loss.

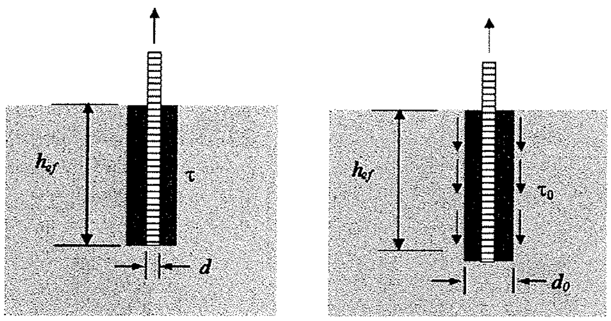
Grouted anchors can be distinguished from adhesive anchors due to their larger hole diameter-to-anchor diameter ratio. As shown in Fig. 2, they can be installed with or without a head at the embedded end, which ultimately affects the load transfer mechanism. Headed anchors installed with a bolt or smooth bar with a nut at the embedded end transfer the load to the grout by bearing on the anchor head. Alternatively, unheaded anchors installed with a threaded rod or reinforcing bar transfer the load by bond and mechanical interlock to the grout. Headed anchors installed with threaded rods use a combination of both forms of load transfer mechanisms to transfer the load to the grout. In both cases (headed and unheaded), the grout then transfers the load to the concrete mainly by bond and mechanical interlock.

Similar to adhesive bonded anchors, failure modes of grouted anchors were expected to be dependent on the physical parameters of the anchorage systems. Unheaded grouted anchors were expected to develop either a bond failure at the steel/grout interface or a bond failure at the grout/concrete interface (Fig. 4). Bond failures were anticipated to develop in conjunction with a shallow concrete cone, which is regularly seen in adhesive anchors. Headed grouted anchors were



Grout/concrete bond failure Concrete breakout failure

Fig. 5—Expected failure modes for headed grouted anchors.



(a) Bond failure at steel/grout interface (b) Bond failure at grout/concrete interface

Fig. 6—Uniform bond stress model applied to possible failure surfaces.

expected to develop either a bond failure at the grout/concrete interface or a full concrete breakout failure (Fig. 5). Previous research has shown that concrete breakout and grout/concrete failure modes occur in headed anchors.[5]

RESEARCH SIGNIFICANCE

The first design standards for anchorage to concrete appeared in the mid-1970s when ACI 349[6] and the *PCI Design Handbook*[7] addressed this issue; however, these two publications only proposed design methods for cast-in-place headed anchors. Design methods for post-installed anchor systems were not addressed. ACI 318-02[8] includes an Appendix D that covers the design of both cast-in-place and post-installed mechanical anchors. Currently, ACI 318-02[8] Appendix D does not cover adhesive and grouted anchors. New research has led to the development of design recommendations for adhesive bonded anchors.[2] With design standards for adhesive anchors, grouted anchors are left as the only bonded fastening system without recommended design procedures.

BEHAVIORAL MODELS

Grouted anchors were expected to behave similarly to both cast-in-place headed anchors and post-installed adhesive anchors depending on the anchor configuration (headed or unheaded) and material properties. Therefore, behavioral models previously shown to accurately predict the strength of cast-in-place and adhesive anchors were used to evaluate the behavior of grouted anchors. The two models investigated in this research project included the concrete capacity design (CCD) model and the uniform bond stress model. The CCD model has been used effectively to predict the behavior of cast-in-place headed anchors,[1] whereas the uniform bond stress model has been used successfully to predict the behavior of post-installed adhesive anchors.[2,3] Each model predicts the strength of a different failure mechanism and its application is dependent on the installation parameters of the grouted anchor system. The following presents a general discussion of the behavioral models.

CCD model

The CCD model evolved from a series of concrete breakout models that were developed for anchors that formed full concrete breakout cones at failure. These behavioral models assumed that the concrete failed in tension and that a full concrete breakout cone formed from the embedded end of the anchor to the surface of the concrete. The CCD model has been incorporated into ACI 318-02 Appendix D.[8]

Proposed in 1995 by Fuchs, Eligehausen, and Breen,[1] the CCD method was developed for headed cast-in-place anchors and post-installed mechanical anchors loaded in tension or in shear. The CCD equation used to predict the mean tensile strength of a headed cast-in-place anchor from concrete breakout failure in uncracked concrete is as follows

$$N_{b,0} = 16.7\sqrt{f'_c}\,h_{ef}^{1.5}\ (N) \qquad (1)$$

Uniform bond stress model

The uniform bond stress model has been shown to predict the behavior and failure loads of adhesive anchors by assuming a uniform bond stress throughout the embedment length of the anchor system.[2,3,9] The general form of this model that predicts the mean tensile strength for bond failure at the steel/grout interface or grout/concrete interface is shown in Fig. 6 and is given by Eq. (2) and (3) where τ and τ_0 are mean values for the uniform bond stress at the steel/grout interface and at the grout/concrete interface, respectively, for a particular product.

$$N_{\tau,0} = \tau\pi d h_{ef}\ (N) \qquad (2)$$

$$N_{\tau_0,0} = \tau_0\pi d_0 h_{ef}\ (N) \qquad (3)$$

For adhesive anchors, with the hole diameter less than 50% larger than the anchor diameter, it is difficult to establish the precise failure mode developed by the anchor system. Taking this into consideration, Cook et al.[2] demonstrated that the tensile capacity of adhesive anchors could be calculated efficiently using the nominal anchor diameter with the bond stress τ associated with each product (Eq. (2)). This is not the case for grouted anchors where the hole diameter is generally 50% or larger than the anchor diameter, making it less difficult to distinguish between failure mechanisms at the steel/grout or grout/concrete interface. Therefore, for the case of grouted anchors, the bond strength should be evaluated at both potential failure surfaces and Eq. (2) and Eq. (3) should be used to evaluate the strength of the anchor.

EXPERIMENTAL PROGRAM

The objective of this test program was to determine the behavior of grouted anchors and to evaluate methods for predicting anchor strength. To properly evaluate the grouted system, some anchor parameters were varied and others kept constant. The investigation included parameters typically encountered during design and installation including bonding agent (cementitious or polymer), anchor configuration (headed or unheaded), anchor and hole diameters, embedment depth, and concrete strength. The experimental program was divided into