BEHAVIOR AND DESIGN OF GROUTED ANCHORS LOADED IN TENSION INCLUDING EDGE AND GROUP EFFECTS AND QUALIFICATION OF ENGINEERED GROUT PRODUCTS

By

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Chair: Ronald A. Cook
Major Department: Civil and Coastal Engineering

Based on experimental test results, a set of design equations were developed for computing the tensile pullout resistance of headed and unheaded single and group grouted anchors. Edge distance and group spacing effects are considered, and values for the critical edge distance and critical anchor spacing are proposed. The results of this testing program, along with those from previous experimental programs, were analyzed to ascertain grout susceptibility to various installation and in-service factors. Stemming from these results, a series of product approval tests was proposed to determine if an engineered grout product is suitable for a desired application.

CHAPTER 1
INTRODUCTION

A typical grouted anchor consists of a steel rod and the grout product installed into a hole drilled in hardened concrete. Grout products can be either cementitious or polymer based and installed into the hole with a headed or unheaded anchor. This paper explores the behavior of both single and groups of grouted anchors loaded in tension in uncracked concrete. The parameters considered are hole drilling technique, anchor diameter, edge effects, and group effects. These results, along with the results from existing test databases, form the basis for a proposed design model for grouted anchors and product approval tests for engineered grout products.

The American Concrete Institute (ACI) 318-02 (ACI 2002) includes a new Appendix D addressing anchorage to concrete. Design procedures for cast-in-place anchors and post-installed mechanical anchors are included in Appendix D. As a result of extensive testing, the ACI 318 committee is currently working on including adhesive anchors in Appendix D. Grouted anchors are also being considered for inclusion.

CHAPTER 2
BACKGROUND

2.1 Types of Anchor Systems

Anchor fastenings to concrete can be divided into two main categories: cast-in-place and post-installed anchors. Figure 2-1 presents a diagram summarizing the types of anchors available and the products used for installation.

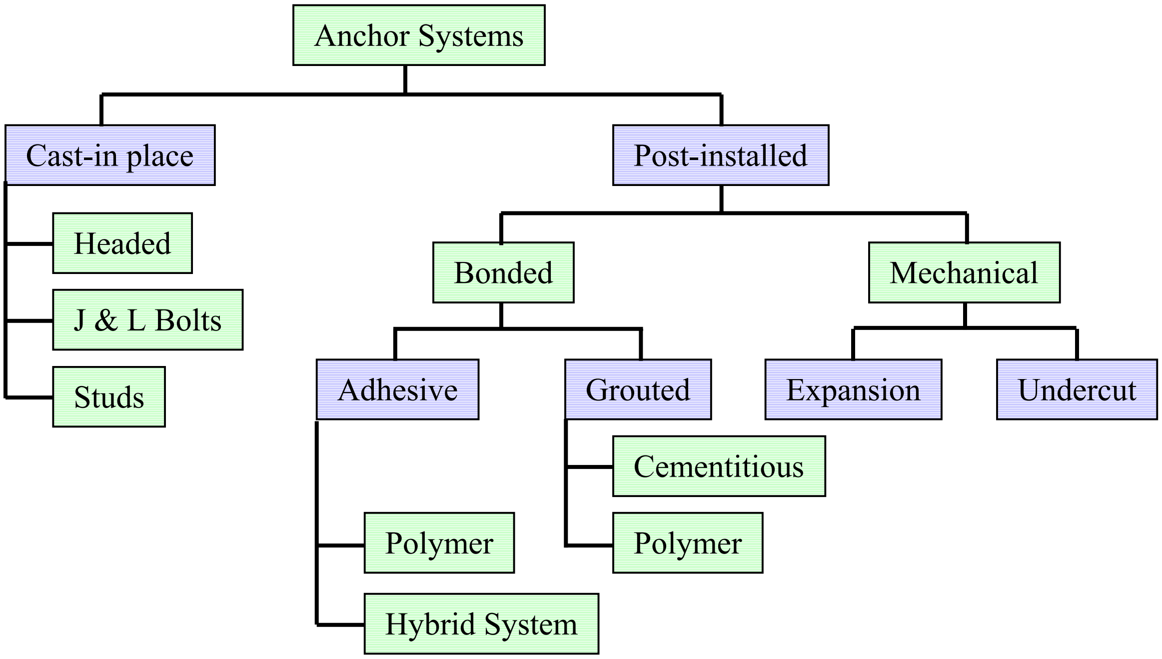


Figure 2-1 Types of anchor systems

Cast-in-place anchors are installed by first connecting them to the formwork prior to pouring concrete. A cast-in-place anchor is typically composed of a headed steel bolt or stud. The main load transfer mechanism is through bearing on the head. Extensive testing has been performed on cast-in-place anchors, and a design model has been developed to accurately predict their behavior. Systems comprised of cast-in-place anchors behave predictably but are fixed in their location after the concrete is cast.

Post-installed anchors offer more flexibility, and their use is now common. Systems of post-installed anchors include: mechanical (expansion and undercut) and bonded (adhesive and grouted) anchors. Expansion anchors are installed by expanding the lower portion of the anchor through either torque-controlled or displacement-controlled techniques, and load is transferred through friction between the hole and the expanded portion of the anchor. Undercut anchors are installed in a similar manner to expansion anchors, but they possess a slightly oversized hole at the base of the anchor embedment. Load is transferred through bearing of the base of the undercut anchor on the hole. Both adhesive and grouted anchors fall under the heading of bonded anchors. This paper is primarily concerned with the comparison of grouted anchors to cast-in-place and adhesive anchors.

2.2 Bonded Anchors

Post-installed bonded anchors can be categorized as either adhesive or grouted. An adhesive anchor can be either an unheaded threaded rod or a deformed reinforcing bar and is inserted into hardened concrete in a predrilled hole that is typically 10 to 25 percent larger than the diameter of the anchor. These anchors are bonded into the hole using a two-part structural adhesive consisting of a resin and a curing agent to bind the concrete and steel together.

Contrastingly, a grouted anchor can be an unheaded threaded rod, a deformed reinforcing bar, a headed bolt, a headed stud, a smooth rod with a nut on the embedded end, or a threaded rod with a nut on the embedded end. Grouted anchors are installed into hardened concrete in predrilled holes that are typically 50 to 200 percent larger than the diameter of the anchor. For the purposes of this paper, the break point between an adhesive anchor and a grouted anchor is when the hole diameter is equal to one and a half times the anchor diameter; all anchors installed in holes greater than or equal one and a half times the anchor diameter shall be considered as grouted anchors.

Engineered grouts can be cementitious or polymer based. Cementitious grouts are composed of primarily fine aggregates, portland cement, and water; polymer grouts are similar in nature to the structural adhesive used to bind adhesive anchors to concrete but also contain a fine aggregate component.

2.2.1 Adhesive Anchors

The curing time of adhesive products is rapid, which makes them ideal for situations requiring a quick set. Different products can be used to install adhesive anchors. These products can be polymers (epoxies, polyesters, or vinylesters) or hybrid systems. Cook et al. (1998) explain that when the resin and curing agent are mixed, the products undergo an exothermic reaction resulting in the formation of a polymer matrix that binds the anchor and the concrete together. Adhesive anchors are typically installed in clean dry holes to attain maximum bond strength. Applied load is transferred from the adhesive anchor to the concrete by one of two mechanisms: mechanical interlock or chemical binding to the concrete.

Cook et al. (1998) proposed a model to design adhesive anchors and to predict anchor strength. This model was developed by comparing the test results from an international test database of single adhesive anchors to several different design models. The uniform bond stress model was proposed and provided the best fit to the database.

McVay et al. (1996) also showed the uniform bond stress model to be rational through comparison of predictions from nonlinear computer analysis to experimental results.

Product approval standards and guidelines for adhesives currently exist in several published documents. The International Congress of Building Officials Evaluation Service (ICBO ES) AC58 (ICBO ES 2001) lists and describes various tests for evaluating adhesive performance under different anchor configurations and installation conditions. The mandatory tests include single anchor tests in tension and in shear, critical edge distance tests for single anchors in tension, tests for critical anchor spacing in anchor groups, and tests for sensitivity to in-service temperature conditions. The Florida Method of Test FM 5-568 (FDOT 2000) describes the tests required by the Florida Department of Transportation (FDOT) for determining the bond strength and sensitivity to installation and service conditions of adhesive bonded anchors and dowels. This document references both the American Society for Testing and Materials (ASTM) E 488-96 (ASTM 2001d) and ASTM E 1512-01 (ASTM 2001e) in respect to how tests on anchor systems should be performed. The FM 5-568 recommends that tension tests, damp hole installation tests, elevated temperature tests, horizontal orientation tests, short-term cure tests, and long-term loading tests be performed on anchor systems. Cook and Konz (2001) experimentally investigated the sensitivity of 20 adhesive products to various installation and service conditions through 765 tests. Installation factors examined included variations in the condition of the drilled hole, concrete strength, and concrete aggregate. Service conditions considered included short-term cure and loading at an elevated temperature.

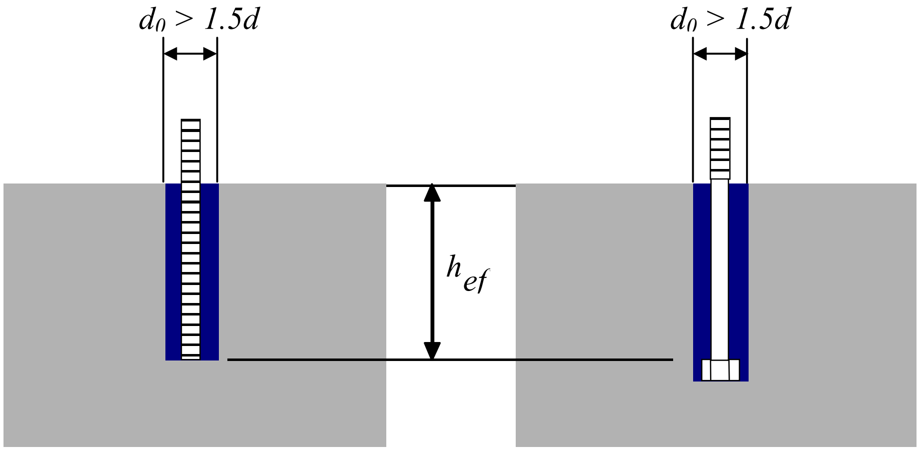
2.2.2 Grouted Anchors

Grouted anchors can be bonded to concrete with either polymer or cementitious products. Anchors bonded with a polymer grout are intended to be installed into dry holes and under similar conditions as adhesive anchors. Polymer grouts are very similar to adhesive products in composition. Both polymer adhesive products and polymer grouts contain a resin component and a curing agent (hardener), and polymer grouts are additionally comprised of a third component, a fine aggregate that serves as a filler. Polymer grouts usually have a rapid cure time, and anchors can be loaded hours after installation.

The dry components of cementitious grout products are usually prepackaged. Water is added at the time of installation, according to the manufacturer's guidelines, to achieve the desired viscosity. Anchors bonded with a cementitious grout are intended to be installed in clean, damp holes in order to prevent excess water loss into the concrete from the grout, which would reduce the bond strength of the grout. To ensure that this does not occur, the holes are usually saturated by filling them with water for a minimum of 24 hours prior to installation unless otherwise stated in the manufacturer's directions.

Grouted anchors can be installed with or without a head at the embedded end, as shown in Figure 2-2. The presence of a head, or the lack thereof, affects the load transfer mechanism from the anchor to the grout. However, load is transferred from the grout to the concrete primarily through bond and mechanical interlock regardless of the presence or absence of a head.

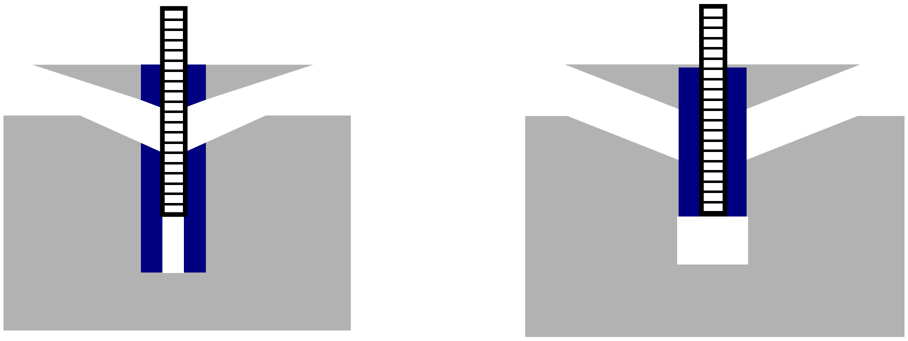
Unheaded anchors installed by using a threaded rod or a deformed reinforcing bar transfer load to the grout through bond and mechanical interlock. These anchors are expected to experience a bond failure either at the steel/grout interface or the grout/concrete interface with a secondary shallow concrete cone. Previous testing performed at the University of Florida by Kornreich (2001) and Zamora (1998) confirms that these failure modes occur. Figure 2-3 shows the typical failure modes for unheaded grouted anchors.



Unheaded grouted anchor

Headed grouted anchor

Figure 2-2 Examples of typical unheaded and headed grouted anchors



Bond failure at
steel/grout interface

Bond failure at
grout/concrete interface

Figure 2-3 Typical bond failures at the steel/grout and grout/concrete interfaces for unheaded grouted anchors

Headed anchors installed with a headed bolt or a smooth rod with a nut at the embedded end of the anchor transfer load to the grout through bearing on the head.

These anchors are expected to fail either in a bond failure at the grout/concrete interface with a secondary shallow cone or in a full concrete cone breakout depending on the bond strength of the grout. Failure at the steel/grout interface is precluded due to the presence of the head. Similar to unheaded grouted anchors, previous testing performed at the University of Florida by Kornreich (2001) and Zamora (1998) confirms these failure modes occur. Figure 2-4 shows the typical failure modes for headed grouted anchors.


Bond failure at grout/concrete interface

Concrete breakout failure

Figure 2-4 Typical bond failure at the grout/concrete interface and concrete cone breakout failure of headed grouted anchors

2.3 Previous and Current Studies with Grouted Anchors

Experimental and analytical studies focusing on the strength and behavior of grouted anchors under tensile load have been presented in published literature. In the earlier stages of grouted anchor research, the theoretical behavior of polymer grouts was examined. James et al. (1987) presented an analysis of post-installed epoxy (polymer) grouted anchors in reinforced concrete based on linear and nonlinear finite element models and comparisons to previously reported experimental data. Parameters considered in this study included various ratios of embedment depth to bolt diameter, different grout properties, and two concrete failure theories: the maximum tensile stress criteria and the Mohr-Coulomb criteria. According to James et al. (1987), when bond failure occurs at the grout/concrete interface, testing has shown that the load capacity was directly related to the size of the drilled hole. As the hole size increased, the load capacity of the epoxy was increased due to the increase in bond area and displacement of the head of the bolt also increased. If higher strength grouts are utilized, the shear strength of the concrete will control, and failure at the grout/concrete interface is precluded. Additionally, the location of the reaction ring was crucial because, if it was too close to the anchor, it could result in falsely inflated anchor strength.

Other studies were experimental in nature and examined the behavior of polymer and cementitious grouts while varying physical parameters. One such experimental study was reported by Zamora (1998) and contained 290 tension tests on post-installed unheaded and headed grouted anchors. The bond strength of unheaded and headed grouted anchors was tested for influence of anchor diameter, hole diameter, embedment depth, grout product (cementitious or polymer), installation conditions, and concrete strength. A product approval test program for grout products was also investigated, and the following tests were performed: damp hole installation, elevated temperature, threaded rod versus deformed reinforcing bar, regular hex nut versus heavy hex nut, and a test series to establish bond stress at the grout concrete interface. Portions from Zamora (1998) pertaining to behavior and design of grouted anchors installed in uncracked concrete away from a free edge and under tensile load are presented in Zamora et al. (2003). Test results showed unheaded grouted anchors experienced a bond failure and, in general, behaved similar to adhesive anchors, and headed grouted anchors experienced either a bond failure at the grout/concrete interface or a concrete cone breakout. This study recommended that the strength of unheaded grouted anchors be predicted using the uniform bond stress model; the strength of headed grouted anchors was recommended to be taken as the smaller strength of a bond failure at the grout/concrete interface or a concrete cone breakout. Differences in bond strengths were found to exist between installation of threaded rods and deformed reinforcing bars when cementitious grouts were utilized. Cementitious grouts experienced a lower bond strength when installed using a heavy hex nut as opposed to a regular hex nut; the effect was opposite for the one polymer grout product tested. Additionally, tests indicated that the bond strength of polymer grouts was generally reduced with an increase in temperature or damp hole installation. These results are discussed in detail in Chapter 7.

In a more recent experimental program, Kornreich (2001) tested post-installed headed and unheaded grouted anchors by varying several parameters. Tests included: grout strength versus curing time, bond of grout to smooth steel, bond of grout to concrete, and basic bond strength at the steel/grout interface. Based on the results obtained, recommended design equations were presented including capacity reduction factors.

In the present paper, the results of post-installed headed grouted anchor tests examining the effects of hole drilling technique, edge distance effects, and group spacing effects are presented. The results from previous studies and existing test databases on headed and unheaded grouted anchors and cementitious and polymer grouts are considered. All of this information is combined into recommendations for design specifications for grouted anchors and product approval tests for engineered grout products.

CHAPTER 3
BEHAVIORAL MODELS

3.1 General

In previous testing programs, grouted anchors were expected to behave in a similar manner to either cast-in-place headed anchors or post-installed adhesive anchors depending on whether the anchors were headed or unheaded. Both cast-in-place headed anchors and post-installed adhesive anchors have been extensively studied, and behavioral models have been developed that accurately predict anchor strength. The Concrete Capacity Design (CCD) method and the uniform bond stress model were therefore used to evaluate the behavior of grouted anchors in this test program, as well as in previous test programs. The development, applicability, and general equations of these models are presented in the following sections.

3.2 Concrete Capacity Design (CCD) Method

Fuchs et al.(1995) first proposed the CCD method in 1995. This model was created to predict the failure loads of cast-in-place headed anchors and post-installed mechanical anchors loaded in tension or in shear that form a full concrete cone. The mean tensile capacity for single cast-in-place headed anchors installed in uncracked concrete is predicted by the following equations:

$$N_{c,0} = 40\sqrt{f'_c}\,h_{ef}^{1.5} \quad \text{(lbf)} \tag{1a}$$

or

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

Similarly, the CCD method predicts the tensile capacity of cast-in-place headed anchor groups using the following equations:

$$N_c = \frac{A_N}{A_{N0}} \Psi_{c,e} N_{c,0} \quad \text{(lbf or N)}$$

$$\text{where } \Psi_{c,e} = 0.7 + 0.3\frac{c}{1.5h_{ef}} \tag{2}$$

Figures 3-1 and 3-2 are adapted from figures found in ACI 318-02 Appendix D (ACI 2002). Figure 3-1 illustrates the calculation of A_{N0}. Figure 3-2 depicts the projected areas for single anchors and groups of anchors for the CCD method as well as the calculation of A_N.

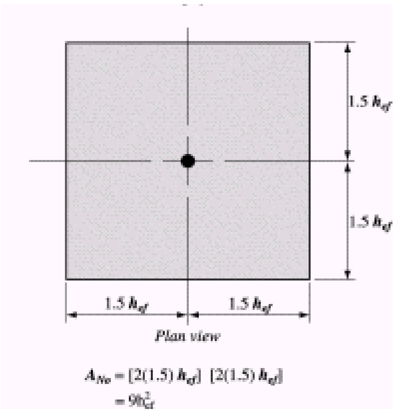


Figure 3-1 Calculation of A_{N0} for the CCD method

3.3 Uniform Bond Stress Model

As mentioned in the previous chapter, Cook et al. (1998) compared several different models, and the uniform bond stress model using the anchor diameter was found to be the best fit to the test database. As a result, a uniform bond stress can be assumed along the entire embedment depth of the adhesive anchor and accurately predict the bond strength when the embedment length does not exceed 25 times the anchor diameter. For grouted anchors with the hole diameter greater than or equal to one and a half times the anchor diameter, bond failure can be distinguished at either the steel/grout interface or at the grout/concrete interface. Zamora et al. (2003) presented two variations of this model to account for failure at the inner and outer surfaces of the bonding agent as shown in the following equations for single anchors installed away from a free edge:

$$N_{\tau,0} = \tau \pi \, d \, h_{ef} \quad \text{(lbf or N)} \tag{3}$$

$$N_{\tau_0,0} = \tau_0 \pi \, d_0 \, h_{ef} \quad \text{(lbf or N)} \tag{4}$$

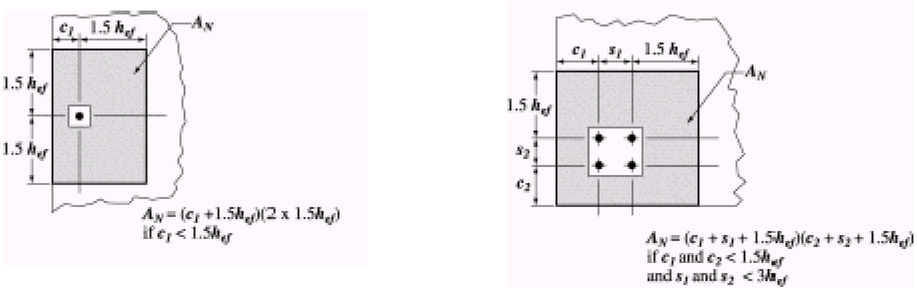


Figure 3-2 Projected areas for single anchors and anchor groups for the CCD method

Lehr and Eligehausen (2001) proposed an extension of the uniform bond stress model for unheaded adhesive anchor groups shown below in Equation (5). This equation could also be applied to grouted anchor groups that experience a bond failure at the steel/grout interface. When bond failure occurs at the grout/concrete interface, Equation (5) may be revised as shown in Equation (6). In this way, the tensile capacity of anchor groups can be predicted by the uniform bond stress model using the following equations:

$$N_\tau = \frac{A_N}{A_{N0}} \Psi_{\tau,e} N_{\tau,0} \quad \text{(lbf or N)} \tag{5}$$

$$\text{where } \Psi_{\tau,e} = 0.7 + 0.3 \frac{c}{8d}$$

$$N_{\tau_0} = \frac{A_N}{A_{N0}} \Psi_{\tau_0,e} N_{\tau_0,0} \quad \text{(lbf or N)} \tag{6}$$

$$\text{where } \Psi_{\tau_0,e} = 0.7 + 0.3 \frac{c}{8d_0}$$

Figures 3-3 through 3-6 are adapted for the uniform bond stress model from similar figures for the CCD method found in ACI 318-02 Appendix D (ACI 2002). Figures 3-3 and 3-5 show the calculation of A_{N0} for bond failure at the steel/grout and grout/concrete interfaces, respectively. Figures 3-4 and 3-6 depict the projected areas for single anchors and groups of anchors for the uniform bond stress model as well as the calculation of A_N at the steel/grout and grout/concrete interfaces, respectively.

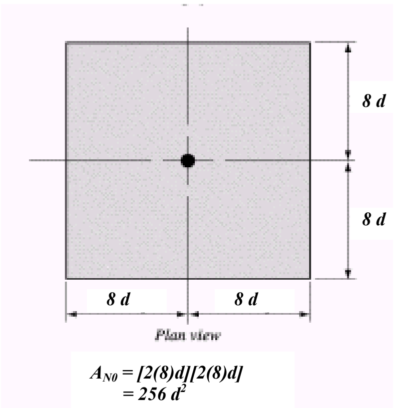


Figure 3-3 Calculation of A_{N0} for the uniform bond stress model using the anchor diameter

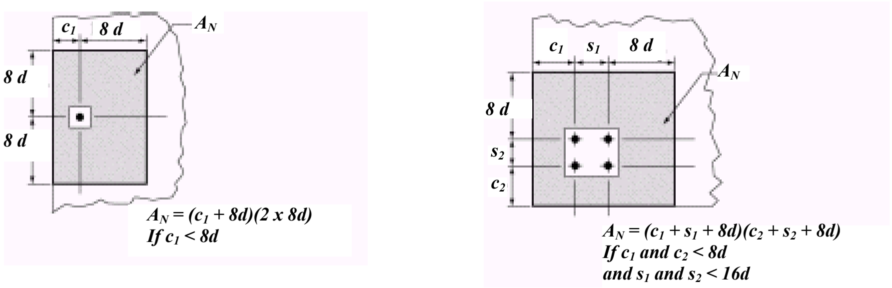


Figure 3-4 Projected areas for single anchors and anchor groups for the uniform bond stress model using the anchor diameter

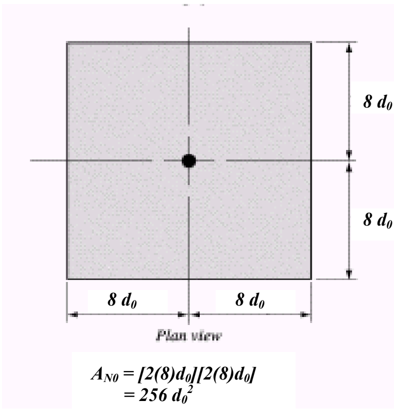


Figure 3-5 Calculation of A_{N0} for the uniform bond stress model using the hole diameter

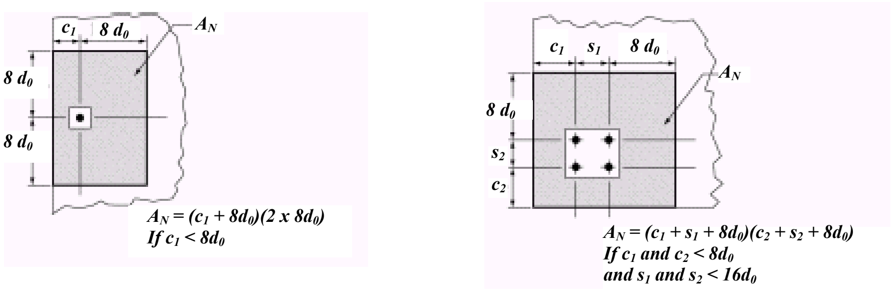


Figure 3-6 Projected areas for single anchors and anchor groups for the uniform bond stress model using the hole diameter

Since adhesive anchors are typically installed in holes with diameters only 10 to 25 percent larger than the anchor diameter, Zamora (1998) conjectured that it is difficult to differentiate between a failure at the steel/grout interface and the grout/concrete interface. However, grouted anchors are usually installed in holes with diameters ranging from 50 to 200 percent larger than the anchor diameter. The larger hole size makes it easier to determine at which interface a bond failure occurred.

Equation (3) has been shown by Cook et al. (1998) to be a good approximation of single adhesive anchor tensile strength even though the interface at which bond failure occurred is not always readily apparent. Similarly, Equation (5) is applicable to groups of adhesive anchors according to Section 7.12 of the Structures Design Guidelines for Load and Resistance Factor Design (FDOT 2002b). In general, both Equation (3) and Equation (4) are applicable to evaluating the strength of single grouted anchors since the interface at which bond failure occurred is more easily observed. For headed grouted anchors experiencing bond failure, only Equation (4) should be considered when determining the tensile strength since failure at the steel/grout interface is precluded by the presence of the head. The applicability of Equation (6) to headed grouted anchor groups will be examined in this test program.

CHAPTER 4
DEVELOPMENT OF TEST PROGRAM

4.1 General

The objective of this test program was to perform additional grouted anchor tests in order to provide a more complete picture of the behavior of engineered grout products. The results of these tests, along with current test databases, will be used to evaluate the applicability of existing design models, to recommend a design model to predict strength of grouted anchors, and to advocate a series of product approval tests to perform in the assessment of engineered grouts. Previous test programs have not fully addressed the failure mode of grouted anchors at the grout/concrete interface. In order to develop a complete design model, this failure mode needs to be further examined.

To investigate the behavior of grouted anchors experiencing this failure mode, this test program chose certain parameters in an attempt to force a failure at the grout/concrete interface. Concrete strength was selected to prevent a concrete cone breakout failure. All anchor specimens were post-installed with a non-shrink cementitious grout product, CA (cementitious grout product A) for the purposes of this paper, as headed anchors to preclude a failure at steel/grout interface. In addition, the hole diameter was minimized, allowing only a small clearance between the heavy hex nut of the headed anchor and the side of the hole, to promote a grout/concrete bond failure.

To properly evaluate this failure mode, other anchor parameters were varied. The experimental program included factors often encountered during design and installation of anchors including hole drilling technique (diamond-headed core drill or rotary impact hammer drill), anchor diameter, edge distance effects, and group spacing effects. Embedment depth was held constant. The test program was separated into two primary sections: single and group grouted anchor tests. In general, each single anchor series consisted of at least three repetitions, and each group anchor series consisted of three repetitions.

4.2 Single Grouted Anchor Test Program

In the single grouted anchor test program, three separate installations of headed grouted anchors were conducted. Each installation contained a baseline series of anchors grouted into core-drilled holes. All baseline series consisted of three repetitions except the first baseline series, which contained five tests. Other installation parameters were explored in addition to the baseline series of tests to establish which factors affect the general anchor strength and to quantify this effect where present.

The first installation in the single grouted anchor test program was comprised of ten anchors, separated into two series of five, and aimed to test the potential effects of hole drilling techniques. All ten anchors were 0.625 inch (15.9 mm) in diameter, smooth steel rods with threaded ends, and headed using a heavy hex nut. In addition, the embedment depth was 5 inches (127.0 mm) measured from the top of the nut to the top of the concrete, and the edge distance of 12 inches (304.8 mm) was sufficiently large to eliminate concern of edge distance effects. The baseline series consisted of five of the aforementioned anchors damp-installed into core-drilled holes 1.5 inches (38.1 mm) in diameter. The second single anchor series in the first installation varied one factor from the baseline series; these five anchors were damp-installed into hammer-drilled holes 1.5 inches (38.1 mm) in diameter.

The second installation in this test program consisted of 11 anchors with the purpose of examining edge effects and to further inquire into effects arising from hole drilling techniques. All anchors in this installation were 0.75 inch (19.1mm) in diameter, smooth steel rods with threaded ends, and headed using a heavy hex nut. As in the previous installation, all anchors were embedded 5 inches (127.0 mm), and all holes were 1.5 inches (38.1 mm) in diameter. The baseline series consisted of three anchors damp-installed into core-drilled holes. The second series in this installation contained three anchors damp-installed into hammer-drilled holes. All anchors in both of these series were installed a minimum of 15 inches (381 mm) from the edge of the concrete block to eliminate the possibility of edge effects. The final test series on this installation was comprised of five anchors damp-installed in proximity to a single edge. These anchors were 7.5 inches (190.5 mm) from one edge and a minimum of 24 inches (609.6 mm) from all additional edges.

The third installation contained 13 anchors and endeavored to observe edge distance effects in more detail. All anchors in this installation were 0.75 inch (19.1 mm) in diameter, smooth steel rods with threaded ends, and headed with a heavy hex nut. Again, all anchors were embedded 5 inches (127.0 mm); all holes were core-drilled and 1.5 inches (38.1 mm) in diameter. The baseline series consisted of three anchors damp-installed and placed a minimum of 15 inches (381 mm) from all edges to preclude this type of effect. The two edge effects series included five anchors damp-installed 6 inches (152.4 mm) from one edge and five anchors damp-installed 4.5 inches (114.3 mm) from one edge. All ten anchors were placed a minimum of 24 inches (609.6 mm) from the remaining edges.

4.3 Group Grouted Anchor Test Program

In the group grouted anchor test program, two separate installations of quadruple fastener headed grouted anchor groups were carried out. In order to evaluate the group effect, the single anchor strength N_0 must be established. For this reason, a baseline series, as discussed in the previous section, was installed in the same concrete on the same day as the group specimens. This allowed for a direct comparison of group strength to the strength of a single anchor.

The first quadruple fastener series of three tests was installed in the first installation. Each anchor group contained four anchors 0.625 inch (15.9 mm) in diameter with smooth steel shafts, threaded ends, and headed using heavy hex nuts. All anchors were embedded 5 inches (127.0 mm) deep in holes 1.5 inches (38.1 mm) in diameter and spaced 5 inches (127.0 mm) from each adjacent anchor to form a square.

The second series of three tests was installed in the third installation. Each anchor group included four anchors 0.75 inch (19.1 mm) in diameter with smooth steel shafts, threaded ends, and headed using heavy hex nuts. All anchors were embedded 5 inches (127.0 mm) deep in holes 1.5 inches (38.1 mm) in diameter and spaced 9 inches (228.6 mm) from each adjacent anchor to form a square.

CHAPTER 5
IMPLEMENTATION OF TEST PROGRAM

5.1 General

This test program consisted of two concrete pours and three sets of anchor installations. All tests were unconfined tension tests and performed in general accordance with applicable sections of ASTM E 488-96 (ASTM 2001d) and ASTM E 1512-01 (ASTM 2001e). General test methods for single and group post-installed and cast-in-place anchorage systems are presented in ASTM E 488. More specific testing procedures for bonded anchors are addressed in ASTM E 1512.

5.2 Concrete

For both pours, concrete was ordered from a local ready-mixed plant that batched, mixed, and delivered the concrete to the University of Florida Structures Laboratory. The first pour occurred on February 22, 2002; the second pour occurred on July 18, 2002. All concrete was FDOT Class II to achieve the compressive strengths necessary to preclude a concrete cone breakout failure. The mix design specified a 28-day compressive strength of 3400 psi, but cylinder tests yielded a compressive strength of 6460 to 7670 psi. Wooden formwork was utilized to construct the seven rectangular blocks in each pour: six blocks 4x4x1.25 feet (1219x1219x381 mm) and one block 4x8x1.25 feet (1219x2438x381 mm). Each block contained a single steel reinforcing mat to accommodate handling stresses and prevent cracking. The reinforcement was located 9 inches (228.6 mm) down from the top surface of the concrete. This distance was greater than the embedment depth of the anchors, which avoided any interactions during testing and failure. After the concrete was poured, consolidated, and smoothed, the blocks were covered with plastic sheets for three days to cure; the blocks were then removed from the formwork. Blocks were allowed to sit for a minimum of 28 days after pouring to attain adequate strength before drilling holes. Concrete compressive strength was determined through cylinder tests performed in accordance with ASTM C 39-01 (ASTM 2001a).

5.3 Specimen Preparation

Once the concrete had sufficiently cured, the required holes for the anchors were drilled into the concrete blocks by using either a core drill or a hammer drill. The holes were drilled deeper than the desired embedment depth to provide room for the nut, the end of the anchor, and a pocket of grout at the base of each hole. A summary of the dimensions, hole drilling technique, type of anchor installed, and the type of test being performed can be found in Table 5-1.

After the completion of hole drilling, the holes were cleaned according to the grout manufacturer’s directions. This was accomplished by first vacuuming out the loose matter resulting from the drilling process. Next, the holes were flushed several times with clean water, and the water was vacuumed out each time. The holes were then brushed, while damp, using a bottlebrush in accordance with the grout manufacturer’s directions. The holes were flushed several more times with clean water, and the water was vacuumed out each time. Then the holes were prepared for installation according to the grout manufacturer’s instructions. This consisted of filling the cleaned holes with water for a minimum of 24 hours to allow for a damp hole installation. The holes were sealed with duct tape to prevent foreign matter from entering. Just prior to anchor installation, the duct tape was removed and excess water was vacuumed out. The anchors were cleaned prior to installation using paint thinner as a degreaser according to the grout manufacturer's recommendations.

Table 5-1 Summary of testing program for grout product CA

Installation #	Tested Effect	Hole Type	Anchor Diameter d, in (mm)	Hole Diameter d_0, in (mm)	Embedment Depth h_{ef}, in (mm)	Edge Distance c, in (mm)[a]	Spacing s, in (mm)[b]	# of Tests n
1	Baseline	Core	0.625 (15.9)	1.5 (38.1)	5.0 (127.0)	N/A	N/A	5
1	Hammer	Hammer	0.625 (15.9)	1.5 (38.1)	5.0 (127.0)	N/A	N/A	5
1	Group	Core	0.625 (15.9)	1.5 (38.1)	5.0 (127.0)	N/A	5.0 (127.0)	3
2	Baseline	Core	0.750 (19.1)	1.5 (38.1)	5.0 (127.0)	N/A	N/A	3
2	Hammer	Hammer	0.750 (19.1)	1.5 (38.1)	5.0 (127.0)	N/A	N/A	3
2	Edge	Core	0.750 (19.1)	1.5 (38.1)	5.0 (127.0)	7.5 (190.5)	N/A	5
3	Baseline	Core	0.750 (19.1)	1.5 (38.1)	5.0 (127.0)	N/A	N/A	3
3	Edge	Core	0.750 (19.1)	1.5 (38.1)	5. (127.0)	4.5 (114.3)	N/A	5
3	Edge	Core	0.750 (19.1)	1.5 (38.1)	5.0 (127.0)	6.0 (152.4)	N/A	5
3	Group	Core	0.750 (19.1)	1.5 (38.1)	5.0 (127.0)	N/A	9.0 (128.6)	3

[a] Edge distances designated as N/A refer to anchors installed at $\geq 8d_0$.
[b] Spacing between anchors designated as N/A refers to anchors installed at $\geq 16d_0$.

5.4 Installation Procedure

Three separate anchor installations were performed at the University of Florida Structures Laboratory in 2002. All installations were conducted similarly, and grout cubes were also cast whenever anchors were installed. The compressive strength of the grout product was determined through the testing of grout cubes in accordance to ASTM C 109-99 (ASTM 2001b). The holes were filled approximately 75% full, and the headed anchors were inserted. The anchors were shifted about in the holes to remove any entrapped air and then supported in position at the proper embedment depth. Moist curing occurred for seven days by wrapping the anchors with saturated paper towels and covering the slabs with plastic sheets to retain the moisture.

For the first installation, a field representative from the grout manufacturer was on site to oversee, train, and assist in the installation process. This ensured that the grout was proportioned, mixed, and installed to the manufacturer's specifications. For all installations, the grout product CA was mixed to a fluid consistency with a high torque electric drill and mixing paddle for five minutes. The grout mixture was then subjected to a standard 1725 mL flow cone test in accordance with ASTM C 939-97 (ASTM 2001d). The grout product, date of installation, flow rate, and minimum cure time from all three installations are summarized in Table 5-2. The flow rates fell within the manufacturer's requirements of 25 to 30 seconds with a tolerance of ± 1 second.

Table 5-2 Grout installation summary

Installation #	Date of Installation	Grout Product	Flow Rate (seconds)	Minimum Grout Cure Time (days)
1	April 11, 2002	CA	31	28
2	July 11, 2002	CA	26	14
3	August 22, 2002	CA	25	14

5.5 Apparatus

A schematic diagram of the equipment used in the tension tests for the single grouted anchors can be seen in Figure 5-1. The tests performed were unconfined, since the position of the reactions was in accordance with ASTM E 488. Figure 5-3 shows the positions of these reactions in relation to the anchor specimen. The equipment setup was designed to allow direct measurement of the load and displacement of the single anchor specimens. The test apparatus consisted of the following parts:

- Reaction ring $\left(Diameter \geq 4h_{ef}\right)$
- Two steel wide range flange section
- Three steel bearing plates for center apparatus
- One 120 kip (534 kN) hydraulic ram
- One 200 kip (890 kN) load cell

- One 1.125 inch (28.6 mm) diameter pull bar/coupling rod and retaining nut
- Coupling nut
- Steel plate for Linear Variable Differential Transformers (LVDT's)
- Two LVDT's (2 inch range)

The edge distance tests used two steel channels instead of the reaction ring due to the anchor proximity to one edge of the concrete block.

The equipment used in the group grouted anchor tension tests is shown in the schematic diagram in Figure 5-2. These tests were also unconfined due to the position of the reactions as shown in Figure 5-3. The equipment setup was designed to allow direct measurement of the load and displacement for each individual anchor as well as the whole group. The test apparatus consisted of the following parts:

- Reaction ring $\left(Diameter \geq 4h_{ef} + s\right)$
- Two steel wide range flange section
- Two steel channels
- Three steel bearing plates for center apparatus
- One pull plate 12x12x2 inches (304.8x304.8x50.8 mm)
- One 120 kip (534 kN) hydraulic ram
- One 200 kip (890 kN) load cell
- Four 100 kip (445 kN) load washers
- One 1.125 inch (28.6 mm) diameter pull bar/coupling rod and retaining nut

- Four steel angles
- Two steel frames for potentiometers
- Four steel bearing plates for single anchors
- Four potentiometers (1.5 inch range)
- C-Clamps of various sizes

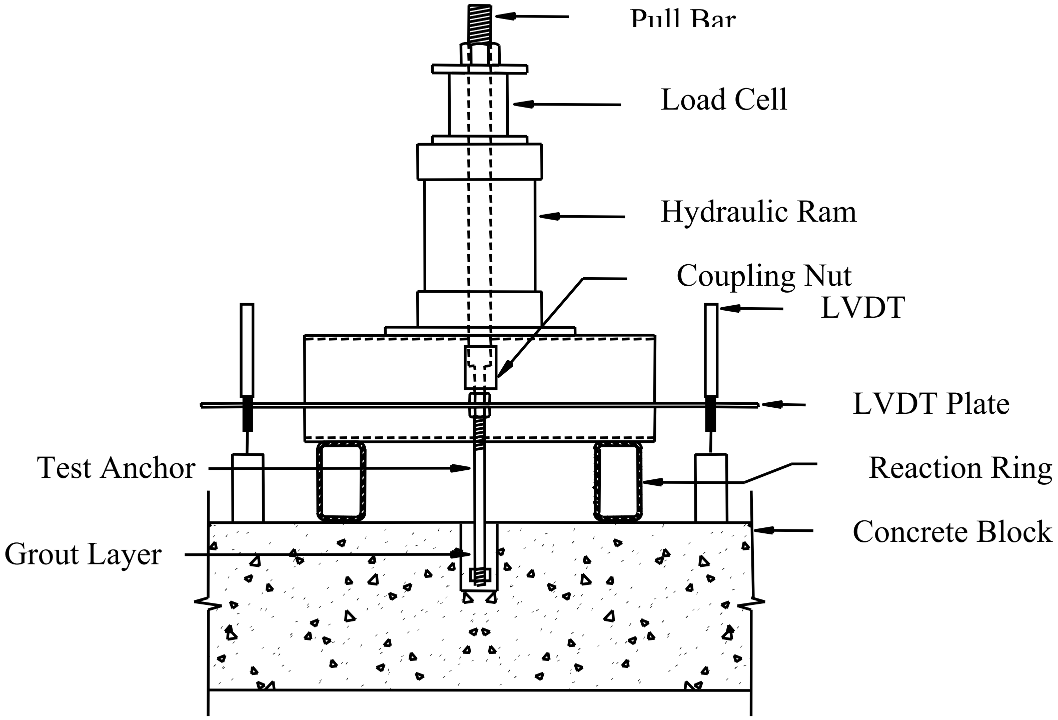


Figure 5-1 Single anchor test apparatus

5.6 Loading Procedure

To pull out a single grouted anchor, the anchor was connected to the coupling rod using a coupling nut. The reaction ring/steel channels and steel flanges were arranged to provide an unconfined test surface. The hydraulic ram was placed atop these supports so that the pull rod passed through its center. The load cell was placed between two bearing plates above the hydraulic ram. Finally, a retaining nut was tightened down the coupling rod to the topmost bearing plate, and the LVDT's were secured in position.

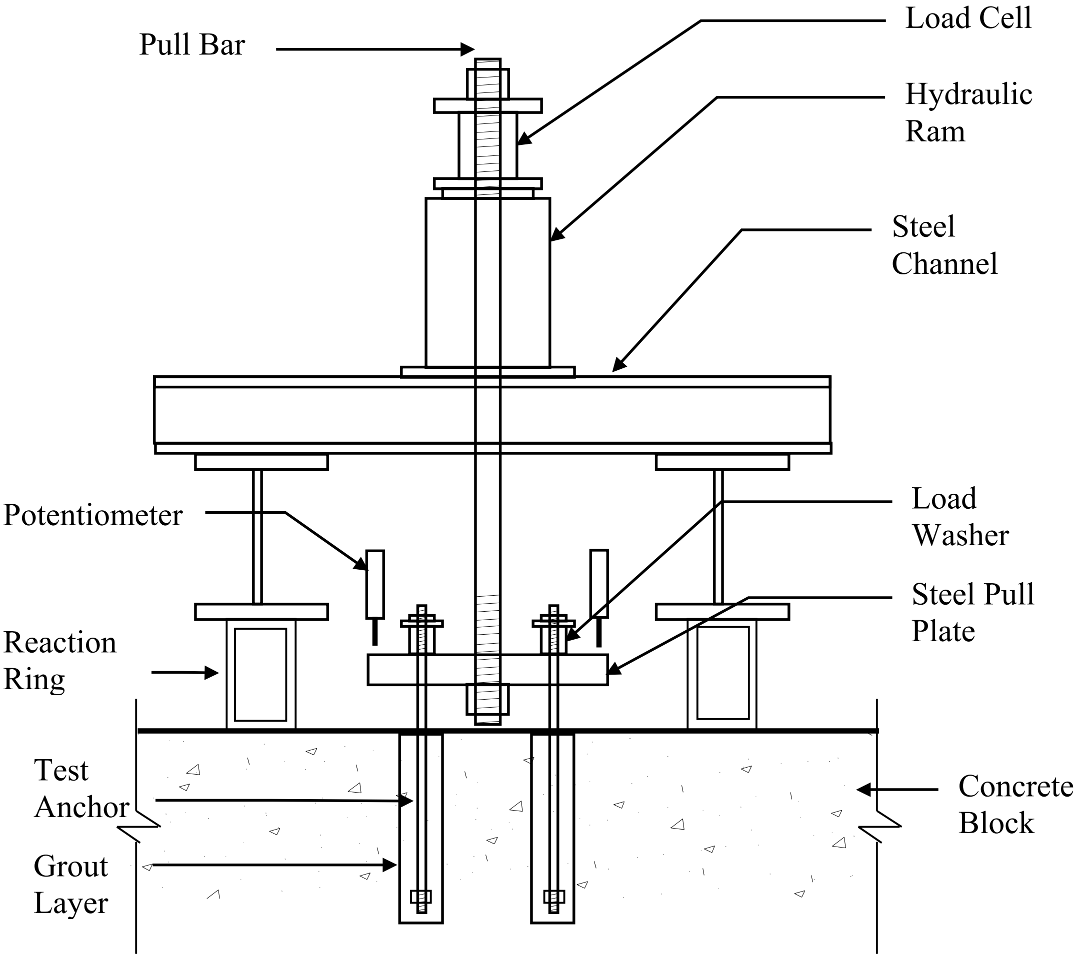


Figure 5-2 Group anchor test apparatus

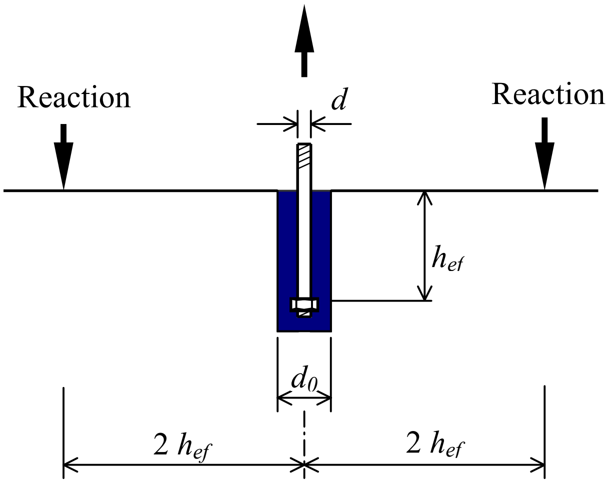


Figure 5-3 Minimum reaction positions of test apparatus for headed anchors

The hydraulic ram was powered and advanced using a 10,000 psi (68,950 MPa) electric pump. The pump was outfitted with two valves. The first controlled the supply to the ram from the pump. The other regulated a bypass from the ram to the oil reservoir. These valves were manually adjusted to control the load applied to the anchor specimen. This setup was used in tandem with a data acquisition system capable of continuously measuring and recording the load and displacement readings.

The typical single anchor testing procedure contained the following steps:

1. Assembling the test apparatus as described above
2. Start data acquisition and LabVIEW software (NI 1999)
3. Adjust the LVDT's to be in range
4. Start pump and pull out anchor
5. Stop test and disassemble apparatus

The loading procedure for the group tests was similar to the single anchor tests. Each anchor passed through holes in the pull plate, and the coupling rod passed through the center hole and was secured with a nut. A load washer was placed on top of each anchor and secured with a bearing plate and a nut. The rest of the test apparatus was assembled as shown in Figure 5-2. The hydraulic ram was operated in the same manner as in the single anchor tests. The data acquisition program was also similar but modified to record the readings from the main load cell, the four load washers, and the four potentiometers.

The typical group anchor testing procedure contained the following steps:

1. Assembling the test apparatus as described above
2. Start data acquisition and LabVIEW software (NI 1999)

3. Adjust the potentiometers to be in range
4. Start pump and pull out anchor
5. Stop test and disassemble apparatus

5.7 Data Reduction

5.7.1 Displacement Calculations for Single Anchor Tests

Single anchor specimens were located directly under the coupling rod. Two LVDT's were used to measure displacement readings. The displacement of a single anchor during testing was calculated by taking the mean of these two readings.

5.7.2 Displacement Calculations for Group Anchor Tests

For each test conducted, the potentiometers were placed at the same location on the pull plate. This position was 5 inches (127 mm) measured from the center of the pull plate through the center of the sides and 7.07 inches (179.6 mm) measured from the center of the pull plate through the corners. Thus, the potentiometers formed a square 10 inches (254 mm) on each side.

All anchor displacements were calculated assuming that the pull plate was rigid. The deflection of each anchor relative to the concrete block was found using displacement readings and the geometry of the test setup.

The overall displacement of the group was computed as the mean of the four potentiometers:

$$d_{tot} = \frac{(d_1 + d_2 + d_3 + d_4)}{4} \quad \text{(inches or mm)} \tag{7}$$

The displacement of the single anchors within the group was calculated according to the test geometry as shown in Figure 5-4:

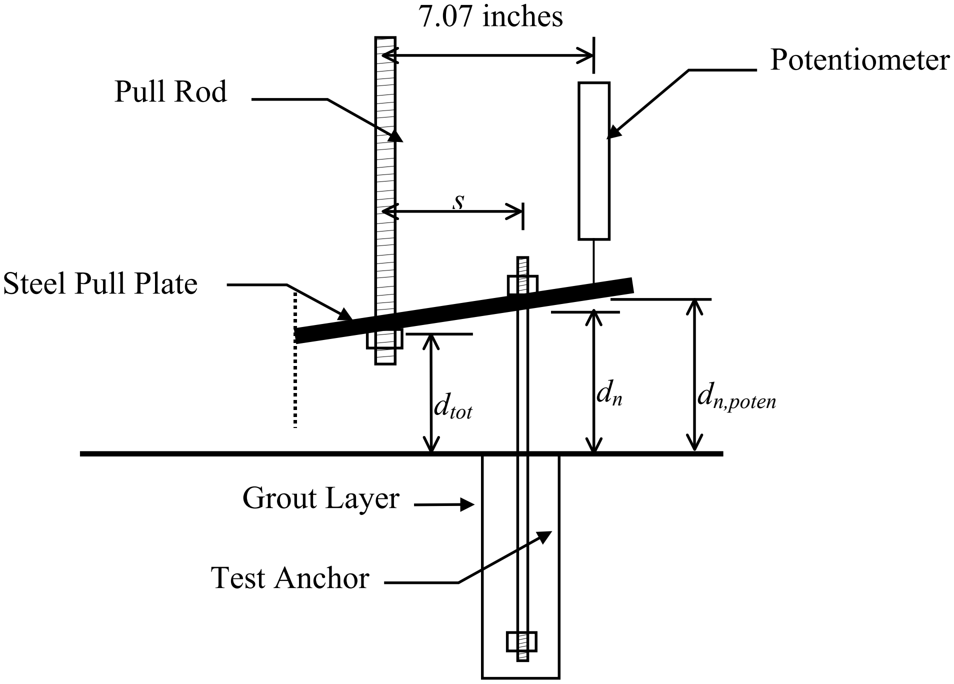


Figure 5-4 Diagram of displacement calculation for individual anchor in group test

$$d_n = d_{tot} + \frac{(d_{n,poten} - d_{tot})s}{7.07} \quad \text{(inches)} \tag{8a}$$

or

$$d_n = d_{tot} + \frac{(d_{n,poten} - d_{tot})s}{179.6} \quad \text{(mm)} \tag{8b}$$

CHAPTER 6
TEST RESULTS

6.1 General

The following sections provide a summary of all test series performed. All tests were performed using the same cementitious grout product, CA. A total of three installations were performed. All anchors were post-installed as headed with an effective embedment depth of 5 inches. Appendix B provides the load-displacement graphs and detailed results for baseline and hole drilling technique anchor tests. The load-displacement graphs and detailed results for anchors installed near one edge are presented in Appendix C. Finally, Appendix D contains the load-displacement graphs and detailed results for the quadruple fastener group anchor tests.

6.2 Single Grouted Anchor Test Results

Three types of single anchor tests were performed. First, baseline anchors were installed in core-drilled holes. Second, anchors testing the effects of hole drilling technique were installed in hammer-drilled holes. Finally, anchors were installed in core-drilled holes at various distances from one edge of the concrete block and subsequently tested.

Table 6-1 provides a summary of the test results for each type of single anchor test performed that resulted in bond failure (i.e. tests exhibiting steel failure are excluded from Table 6-1). In general, single anchors experienced a failure at the grout/concrete interface accompanied frequently by the formation of a shallow secondary concrete cone as evidenced by the diagonal cracking that was observed in the concrete after testing.

Frequently, this secondary concrete cone did not remain attached to the anchor during the tension tests, and cracking and spalling of the concrete was observed on the surface of the concrete block in addition to the internal diagonal cracks aforementioned. Photographs of representative failed specimen are contained in Appendix E.

Table 6-1 Summary of single anchor test results exhibiting bond failure

Installation #	Test Series	Tested Effect	N_0 kips (kN)	A_{bond} in^2 (mm^2)	τ_0 psi (MPa)	*COV*	# of Tests in Calculation
1	CD 1	Baseline	29.4 (131)	23.6 (15200)	1250 (8.60)	0.046	5
1	HD 1	Hammer	30.3 (135)	23.6 (15200)	1290 (8.90)	0.012	2
2	CD 2	Baseline	35.1 (156)	23.6 (15200)	1490 (10.3)	0.040	3
2	HD 2	Hammer	29.0 (129)	23.6 (15200)	1230 (8.50)	0.326	3
2	E 7.5	Edge 7.5	31.9 (142)	23.6 (15200)	1350 (9.30)	0.099	5
3	CD 3	Baseline	39.3 (175)	23.6 (15200)	1670 (11.5)	0.097	3
3	E 4.5	Edge 4.5	28.7 (128)	23.6 (15200)	1220 (8.40)	0.086	5
3	E 6.0	Edge 6.0	32.5 (145)	23.6 (15200)	1380 (9.50)	0.070	5

For the first installation, the average bond stress for the baseline series of core-drilled holes was 1250 psi (8.60 MPa) with a coefficient of variation of 0.046. For the test series containing hammer-drilled holes, three of the specimens experienced a steel failure at a level below the ultimate anchor stress capacity specified by the manufacturer. The average bond stress for the remaining two specimens installed in hammer-drilled holes was 1290 psi (8.90 MPa) with a coefficient of variation of 0.012. Normalizing the mean of the hammer-drilled series with the mean of the baseline series yields a ratio of 1.03 times the baseline series bond stress.

In the second installation, the average bond stress for the baseline series of core-drilled holes was 1490 psi (10.3 MPa) with a coefficient of variation of 0.040. Anchors installed in hammer-drilled holes were also tested and resulted in an average bond stress of 1230 psi (8.50 MPa) and a coefficient of variation of 0.326. Normalizing the mean of the hammer-drilled series with the mean of the baseline series yields a ratio of 0.826

times the baseline series bond stress. Anchors were also tested for edge effects in the second installation. The average bond stress for anchors installed in core-drilled holes 7.5 inches away from one edge was 1350 psi (9.30 MPa) with a coefficient of variation of 0.099. Normalizing the mean of the edge distance series with the mean of the baseline series yields a ratio of 0.909 times the baseline series bond stress.

Baseline anchors, as well as those installed near one edge, were tested in the third installation. The average bond stress for the baseline series of anchors installed in core-drilled holes was 1670 psi (11.5 MPa) with a coefficient of variation of 0.097. Anchors installed in core-drilled holes 4.5 inches away from one edge had an average bond stress of 1220 psi (8.40 MPa) with a coefficient of variation of 0.086. Normalizing the mean of the edge distance series with the mean of the baseline series yields a ratio of 0.730 times the baseline series bond stress. Finally, the average bond stress of anchors installed in core-drilled holes 6.0 inches away from one edge was 1380 psi (9.50 MPa) with a coefficient of variation of 0.0700. Normalizing the mean of the edge distance series with the mean of the baseline series yields a ratio of 0.827 times the baseline series of the bond stress.

For further comparison, all 11 baseline test results from the three installations were combined into one database. The average bond stress was 1390 psi (9.60 MPa) with a coefficient of variation of 0.192. The coefficient of variation is less than 0.200, which generally indicates that the grout product’s behavior is reasonably consistent when repeated in the given application. FDOT Section 937 (FDOT 2002a) limits the coefficient of variation for uniform bond stress to 20%, which serves as a basis for using this limit for the purposes of this paper. Table 6-2 provides a summary of the tests performed to establish τ_0 for grout product CA in the current paper.

Table 6-2 Summary of baseline single anchor test results

Installation #	N_0 kips (kN)	τ_0 psi (MPa)	*COV*	*n*
1	29.4 (131)	1250 (8.60)	0.046	5
2	35.1 (156)	1490 (10.3)	0.040	3
3	39.3 (175)	1670 (11.5)	0.097	3
All	32.7 (145)	1390 (9.58)	0.192	11

6.3 Group Grouted Anchor Test Results

Two sets of quadruple fastener group anchor test series were installed and tested. All anchors were installed in core-drilled holes. All parameters, except anchor spacing, were held constant. Table 6-3 provides a summary of the group test series results.

In the first anchor installation, groups of grouted anchors were installed in core-drilled holes with an anchor spacing of 5 inches. All of the repetitions in this test series experienced a concrete cone breakout failure. Due to this, an average bond stress could not be calculated. The average total tensile failure load was 64.1 kips (285 kN) with a coefficient of variation of 0.040. According to the CCD method shown in Equation (2), the predicted strength of the grouted anchor groups with anchor spacing of 5 inches was 69.6 kips.

Groups of grouted anchors were also installed in core-drilled holes in the third installation. In this test series, the anchor spacing was increased to 9 inches. All of the repetitions in this test series exhibited a bond failure at the grout/concrete interface. The average total tensile failure load was 104 kips (460 kN) with a coefficient of variation of 0.027. The average bond stress of the anchor group was 1100 psi (7.60 MPa). The predicted strength of the grouted anchor groups using the diameter of the hole in the uniform bond stress model was 74.4 kips. This value is conservative, and a revision to the critical spacing will be presented in the proposed design model in Chapter 8.

Table 6-3 Summary of multiple anchor test results

Installation #	Tested Effect	Group in Series	f'_c at test psi (MPa)	Failure Mode[a]	N_{test} kips (kN)	$\tau_{0,test}$ psi (MPa)
1	G 5.0	1	7670 (52.9)	cone	63.4 (282)	NA
1	G 5.0	2	7670 (52.9)	cone	66.9 (298)	NA
1	G 5.0	3	7670 (52.9)	cone	62.0 (276)	NA
N					64.1 (285)	
COV					0.040	
3	G 9.0	1	7330 (50.5)	g/c	105 (465)	1110 (7.65)
3	G 9.0	2	7330 (50.5)	g/c	106 (469)	1119 (7.72)
3	G 9.0	3	7330 (50.5)	g/c	100 (446)	1065 (7.34)
N					104 (460)	
COV					0.027	

[a] Tests in which a failure at the grout/concrete interface occurred are designated as g/c.

CHAPTER 7
TESTED FACTORS INFLUENCING GROUT BOND STRENGTH

7.1 General

Grouted anchor performance can be influenced by a wide variety of factors ranging from grout properties, to installation conditions, to loading and environmental conditions while in-service. It is important to understand the effects that various conditions have on grout bond strength to enable proper design of a structure. Testing of a variety of potential effects were performed over the course of several grouted anchor testing programs with the purpose of determining what types of product approval tests might apply to engineered grout products. The following is a written summary of these results. Graphical representations of these results can be found in Appendix F.

7.2 Strength versus Curing Time

Kornreich (2001) performed tests on unheaded threaded rods installed using three different grout products: one polymer (PB) and two cementitious (CA and CG) grouts. Tests were performed at 24 hours, 3 days, 7 days, 14 days, and 28 days. The rate at which the grouts attained their full bond strength appeared to be product dependent. However, the polymer based grout product seemed to reach its full bond strength in a shorter time period; product PB appeared to reach full strength after only 24 hours. Grout CG matured to full strength after 7 days, and grout CA did not attain full strength until 14 days after installation. Currently, FM 5-568 (FDOT 2000) only requires a short-term cure test for adhesive anchors in which tests are performed at only 24 hours.

7.3 Threaded Rod versus Deformed Reinforcing Bar

Zamora (1998) performed tests to investigate the potential differences between the grout bond strength of unheaded threaded rods and deformed reinforcing bars. Four cementitious grout products were examined. Three of the four products experienced a lower bond strength when the grout was installed with a deformed reinforcing bar. Two of these showed small decreases; products CB and CF experienced a reduction in bond strength of 9% and 4%, respectively. However, the bond strength of product CD diminished by 27%. The fourth product, CC, showed a 104% increase in bond strength when installed with deformed reinforcing bars. However, this product is no longer marketed for this application and should not be used to draw conclusions. The effect on bond strength appears to be product dependent, and products should be tested to observe if a significant strength variation, defined as over 20% for the purposes of this paper, occurs. This limit on bond strength variation is similar to the limit set forth in ICBO ES AC58 (ICBO ES 2001) for variation between strengths obtained from testing anchors installed in damp holes and in baseline dry holes.

7.4 Threaded Rod versus Smooth Rod

Kornreich (2001) compared the bond strength of grouts for unheaded threaded rods and unheaded smooth rods for both cementitious and polymer grout products. For all three products tested, the bond strength for smooth rods was lower than that for threaded rods. However, the amount of bond strength reduction seemed dependent on the type of grout product installed. Grout products CA and CG experienced an 91% and a 81% reduction in bond strength, respectively. The polymer grout product tested, PB, exhibited a 53% decrease in bond strength. All of these reductions in bond strength are sufficiently large such that it is recommended that unheaded smooth rods should not be relied upon in tension.

7.5 Regular Hex Nut versus Heavy Hex Nut

Zamora (1998) performed a test series to examine the possible effects that the use of various types of nuts in headed anchor applications have on pullout resistance. The study found that a difference in pullout resistances existed depending on the type of nut that was used.

The pullout resistance of anchors installed with cementitious grouts decreased when a heavy hex nut was used. Products CA, CB, and CC demonstrated a reduction in pullout resistance of 15%, 19%, and 8%, respectively, when installed with a heavy hex nut. Contrastingly, the pullout resistance increased by 10% when anchors were installed using polymer grout product PA and a heavy hex nut instead of a regular hex nut. Since only one polymer grout product was tested, it is unclear if all polymer grouts behave in a similar manner. When installed with a regular hex nut, products CA, CB, CC, and PA exhibited a coefficient of variation of 0.052, 0.136, 0.070, and 0.066, respectively. Products CA, CB, CC, and PA had a coefficient of variation of 0.124, 0.150, 0.093, and 0.034, respectively, when a heavy hex nut was used for installation. The change in pullout resistance appears to be dependent on the grout product used. However, when the regular hex nut and heavy hex nut tests are considered in tandem for each product, the coefficients of variation are 0.126, 0.187, 0.086, and 0.058 for products CA, CB, CC, and PA, respectively. These coefficients of variation are not significant as they are less than 20%, and, therefore, it seems that it is unnecessary to test products using different types of nuts.

7.6 Hole Drilling Technique

Two test series comparing headed anchors installed in hammer-drilled holes to those installed in core-drilled holes were performed in the testing program of the current paper. In one test series, there was essentially no difference between the bond strength of anchors installed in the two types of holes. When anchors were installed in hammer-drilled holes, the bond strength increased by 3% with a coefficient of variation of 0.012. A subsequent test series examined the same grout product, CA. It was found that the results of anchors installed in hammer-drilled holes were widely scattered with a coefficient of variation of 0.326, and the average bond strength was 17% lower than the bond strength of the baseline anchors installed in core-drilled holes. Combining the results of both test series yielded a coefficient of variation of 0.244. These tests from different installations could be considered together since each series was normalized with respect to the baseline series of that installation.

It is possible that when the holes were hammer-drilled the pores in the concrete became filled with dust from the drilling process. The presence of this dust could have prevented the grout product from fully bonding to the concrete even though the cleaning procedures recommended by the manufacturer were performed. This could account for the scatter observed in one of the two installations. It is recommended that tests be performed on cementitious grouts to determine if sensitivity to hole drilling technique exists whenever they are to be installed in holes drilled in a manner other than that recommended by the manufacturer.

7.7 Damp Hole Installation

This test series consisted of anchors installed in damp holes free of standing water. Zamora (1998) tested three polymer grouts: PA, PB, and PC. Two of the products had a noticeable bond strength reduction when installed in damp holes rather than dry holes. Product PB experienced a 17% strength reduction, and product PC exhibited a 27% decrease in bond strength. A third product, PA, experienced a bond strength increase 11%. The effect of a damp hole installation on bond strength seems significant and product dependent. Therefore, polymer grout products should be tested for the effects of this variable on bond strength.

7.8 Elevated Temperature

Anchors installed with polymer grouts are believed to be more sensitive to temperature variations than cementitious products. Zamora (1998) tested two polymer grouts, PA and PB, at elevated temperatures and found a reduction in bond strength of 6% for both products when compared to those tested at ambient temperature. It appears that the bond strengths of these two products are not greatly influenced by elevated temperatures.

However, Cook and Konz (2001) performed similar elevated temperature sensitivity tests on 15 adhesive products. Of the 15 products tested, ten exhibited a bond strength variation of greater than 20%. Adhesive products consist of two components: a resin and a hardener. Polymer grouts contain similar components as adhesives with a filler for the additional third component. Since adhesive products are strongly influenced by elevated temperatures and polymer grout products are similar in composition, it is important to test polymer grout products being for sensitivity to elevated temperature.

7.9 Summary

Previous testing programs, as well as the current testing program, have tested the bond strength sensitivity of various grouts to several installation conditions. The effects of strength versus curing time, threaded rod versus deformed reinforcing bar for cementitious grouts, threaded rod versus smooth bar, varying types of nuts on headed anchors, hole drilling technique for cementitious grouts, damp hole installation for polymer grouts, and elevated temperature were tested for polymer grouts. Table 7-1 provides a brief summary of the tested variable of interest, the type of grout product installed, and a short explanation of the results of testing.

Table 7-1 Summary of tested factors influencing grout bond strength

Test	Grout Type	
	Cementitious	Polymer
Strength vs. Curing Time	Effect appears product dependent; generally slower than polymer	One product tested
Threaded Rod vs. Deformed Reinforcing Bar	Effect appears product dependent	Not tested
Threaded Rod vs. Smooth Bar	Large reduction in bond strength for both products tested	Reduction in bond strength; one product tested
Regular Hex Nut vs. Heavy Hex Nut	Reduction in pullout resistance for heavy hex; amount appears product dependent	Increase in pullout resistance for heavy hex; unclear if this is a general pattern for polymer products
Hole Drilling Technique	Effect is not consistent and results are at times widely scattered	Not tested
Damp Hole Installation	Not tested	Effect appears product dependent
Elevated Temperature	Not tested	Reduction in bond strength

CHAPTER 8
DISCUSSION ON DESIGN METHOD FOR GROUTED ANCHORS

8.1 Current Models

Previous studies have developed design models for adhesive anchors as well as cast-in-place anchors. Cook et al. (1998) found the uniform bond stress model to be an adequate predictor of adhesive anchor behavior. Similarly, Fuchs et al. (1995) found that the strength of cast-in-place anchors can be accurately predicted using the CCD method. Equations describing the uniform bond stress model and the CCD method are shown in Chapter 3. Modification factors can be applied to both models to account for anchors near a free edge or spaced close enough to act as an anchor group.

8.2 Predicted Model for Grouted Anchor Behavior

Grouted anchors can experience one of three different embedment failure modes: failure at the steel/grout interface, failure at the grout/concrete interface, or concrete cone breakout failure. Steel failure may also occur. The embedment failure mode and strength can be predicted from equations that represent the behavior of each failure mode. The lowest of these predicted strengths indicates the expected failure mode unless this failure mode is prevented by physical constraints of the anchor configuration. For example, failure at the steel/grout interface is not possible if a headed anchor is utilized.

As previously mentioned, equations to predict anchor strength when failure occurs from a concrete cone breakout or at the steel/grout interface have undergone extensive testing. Zamora (1998) proposed using the hole diameter instead of the anchor diameter in the uniform bond stress model to predict anchor strength when failure occurs at the grout/concrete interface. This substitution was shown previously in Equation (4). Using the failure load obtained from testing, the bond stress, τ_0, can be calculated.

Anchors in the current test program were designed to exhibit a failure at the grout/concrete interface. It was predicted that the bond strength would correspond to the failure load calculated using the hole diameter in the uniform bond stress model. Therefore, the critical edge distance was expected to be $8d_0$, and the critical spacing between adjacent anchors was anticipated to be $16d_0$ as shown previously in Figure 3-6. However, Figures 8-1 and 8-2 show that the coefficients of 8 and 16 are overly conservative for predicting the mean anchor bond strength for anchors installed near a free edge and in fastener groups, respectively. Figure 8-1 depicts a plot of the normalized anchor strength versus edge distance. To normalize, the test result and the predictive curve were divided by the predicted strength of a single anchor installed away from an edge and surrounding anchors. Figure 8-2 presents a graph of the normalized anchor group strength versus anchor spacing. The test result and predictive curve were divided by four times the predicted strength of a single anchor installed away from an edge and surrounding anchors to normalize. Therefore, the behavior of grouted anchors experiencing a bond failure at the grout/concrete interface can be better represented if the critical edge and spacing distances are revised.

The following sections provide recommended equations and modification factors for determining the design strength of single grouted anchors and groups of grouted fasteners in uncracked concrete using Load and Resistance Factor Design (LRFD).

8.3 Proposed Critical Edge Distance and Critical Anchor Spacing Revision

Different values for the critical edge distance and anchor spacing were considered by graphically fitting design equations to the test data. It was assumed that the critical

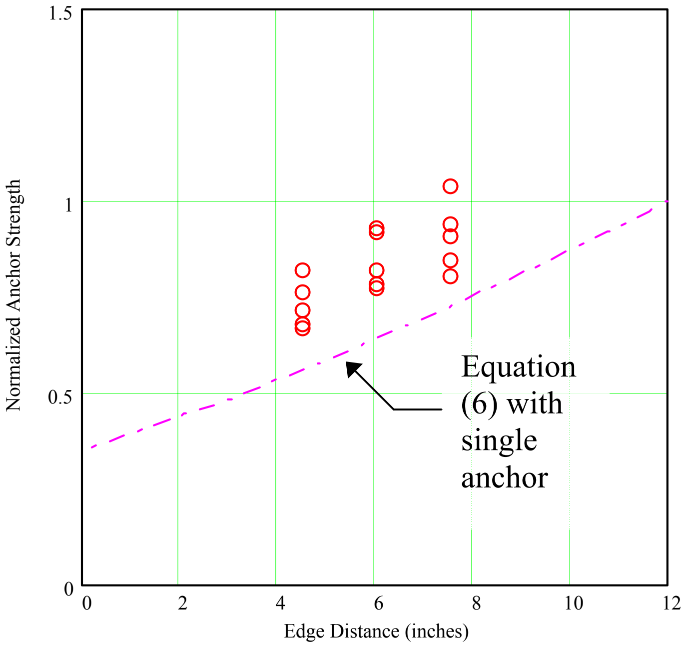


Figure 8-1 Critical edge distance of $8d_0$ compared to experimental results

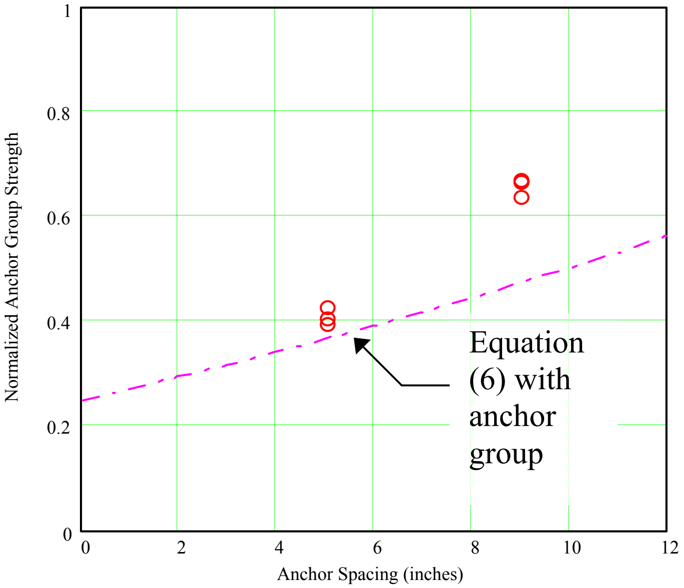


Figure 8-2 Critical anchor spacing of $16d_0$ compared to experimental results

anchor spacing is twice the critical edge distance, similar to the existing uniform bond stress model. The values chosen to best fit the experimental data of the current paper's test program were $5d_0$ for the critical edge distance and $10d_0$ for the critical spacing between anchors. Figures 8-3 and 8-4 display how these new coefficients more accurately predict the mean failure loads obtained during testing and are normalized as discussed in the previous section for Figures 8-1 and 8-2. In Figure 8-4, the proposed equation predicts a higher strength for bond failure at the grout/concrete interface than that found from testing when the anchor spacing equals 5 inches. This was as expected since the failure mode observed during testing was a concrete cone breakout which occurred at a lower load than a failure at the grout/concrete interface.

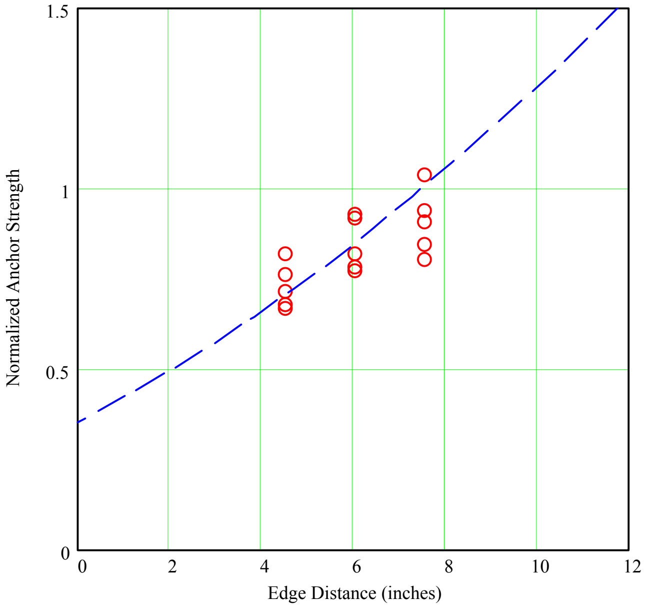


Figure 8-3 Critical edge distance of $5d_0$ compared to experimental results

8.4 Proposed Model for Single Grouted Anchors

For single unheaded grouted anchors, it is recommended that the design strength be taken as the smaller of the bond strengths calculated at the steel/grout interface and at the grout/concrete interface using Equation (9) and Equation (10), respectively. The following design equations are based on the uniform bond stress model and a 5% fractile.

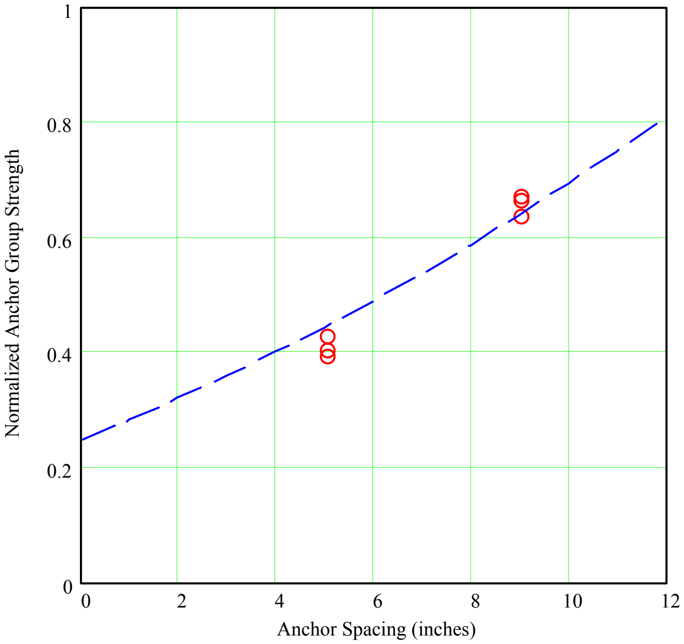


Figure 8-4 Critical anchor spacing of 10d_0 compared to experimental results

$$\phi_b N'_{\tau,0} = \phi_b (\Psi_{\tau,e}\, \tau' \pi\, d\, h_{ef}) \quad \text{(lbf or N)} \tag{9}$$

$$\phi_b N'_{\tau_0,0} = \phi_b (\Psi'_{\tau_0,e}\, \tau'_0\, \pi\, d_0\, h_{ef}) \quad \text{(lbf or N)} \tag{10}$$

$$\text{where } \Psi'_{\tau_0,e} = 0.7 + 0.3\frac{c}{5d_0}$$

For single headed grouted anchors, it is recommended that the design strength be taken as the smaller of the bond strength calculated at the grout/concrete interface and the concrete cone breakout strength using Equations (10) and (11a or 11b), respectively. The following design equations are based on the CCD model and a 5% fractile.

$$\phi_c N'_{c,0} = \phi_c (\Psi_{c,e} 30\sqrt{f'_c}\, h_{ef}^{\ 1.5}) \quad \text{(lbf)} \tag{11a}$$

or

$$\phi_c N'_{c,0} = \phi_c (\Psi_{c,e} 12.6 \sqrt{f'_c} h_{ef}^{1.5}) \quad \text{(N)} \tag{11b}$$

8.5 Proposed Design Model for Grouted Anchor Groups

For groups of unheaded grouted fasteners, it is recommended that the design strength be taken as the smaller of the bond strengths calculated at the steel/grout interface and at the grout/concrete interface using Equations (12) and (13), respectively. The following design equations are based on the uniform bond stress model and a 5% fractile.

$$\phi_b N'_{\tau} = \phi_b (\frac{A_N}{A_{N0}} N`_{\tau,0}) \quad \text{(lbf or N)} \tag{12}$$

$$\phi_b N'_{\tau_0} = \phi_b (\frac{A_N}{A_{N0}} N`_{\tau_0,0}) \quad \text{(lbf or N)} \tag{13}$$

For groups of headed grouted anchors, it is recommended that the design strength be taken as the smaller of the bond strength calculated at the grout/concrete interface and the concrete cone breakout strength using Equations (13) and (14), respectively. The following design equation is based on the CCD model and a 5% fractile.

$$\phi_c N'_{cone} = \phi_c (\frac{A_N}{A_{N0}} N'_{c,0}) \quad \text{(lbf or N)} \tag{14}$$

In Equations (12 and 14), A_N and A_{N0} are calculated as shown in Figures 3-4 and 3-2, respectively. In Equation (13), A_N and A_{N0} are calculated as shown in Figure 3-6 except using a critical edge distance of $5d_0$ and a critical anchor spacing of $10d_0$.

CHAPTER 9
DISCUSSION ON PROPOSED PRODUCT APPROVAL TESTS

9.1 General

A good grout product will possess the following desirable qualities:

- flowability for ease of placement and sufficient working time
- low sensitivity to hole drilling technique
- low sensitivity to hole cleaning technique
- low sensitivity to moisture condition of hole
- low sensitivity to temperature differentials
- rapid development of bond strength
- consistent bond strength when installed using various types of anchors

The following sections present the proposed product approval tests to evaluate engineered grout products. In all of the following, the maximum coefficient of variation is limited to 20% unless otherwise stated by the Engineer for the given application. This is similar to the aforementioned limit placed on the coefficient of variation for uniform bond stress in FDOT Section 937 (FDOT 2002a) for adhesives. As mentioned in Section 7.3, the level that constitutes a significant change in bond strength is 20% for the purposes of this paper. Additionally, in all sections a minimum of five repetitions should be performed in accordance with ASTM E 488 (ASTM 2001d). When only steel failure occurs, ASTM E 488 requires a minimum of three repetitions.

9.2 Grout/Concrete Bond Stress (τ_0)

This proposed product approval test allows the grout/concrete bond stress (τ_0) to be determined for a given grout product. This value can be calculated from the anchor strength if a bond failure occurs at the grout/concrete interface. Failure at the grout/concrete interface is a failure mode that occurs infrequently, but test parameters can be configured to force this failure mode to occur. This failure mode can be achieved by using a headed anchor to preclude failure at the steel/grout interface and minimizing the hole diameter. Additionally, a bond failure at the grout/concrete interface can be achieved by using a higher strength concrete such that the tensile capacity associated with a grout/concrete bond failure will be less than the breakout capacity of the concrete. All anchors shall be installed per manufacturer instructions using a 0.75 inch diameter anchor headed with a heavy hex nut and installed in a 1.5 inch diameter hole with an embedment length of 5 inches measured from the top of the nut. Once τ_0 is determined for a grout product, it can be used in calculations for predicting the strength of various anchor configurations such as edge distance and group tests.

9.3 Test Series to Establish Steel/Grout Bond Stress (τ)

This test series allows the steel/grout bond stress (τ) to be determined for a given grout product. This value can be calculated from the bond strength if a failure is forced at the steel/grout interface. This failure mode can be initiated by using unheaded anchors installed in concrete whose breakout capacity is greater than the bond capacity of the grout product. All anchors shall be installed in accordance with the manufacturer's instructions and as unheaded to promote a failure at the steel/grout interface. All anchors shall be installed per manufacturer instructions using a 0.75 inch diameter unheaded anchor installed in a 1.5 inch diameter hole with an embedment length of 5 inches measured from the base of the anchor. Once τ has been determined for a grout product, it can be used in subsequent strength prediction calculations.

9.4 Strength versus Curing Time

In certain scenarios, it may be necessary for an anchor to sustain loading a short time after installation. It is advantageous to know when a product develops sufficient strength so that premature loading, and the resulting problems, may be avoided. In the same vein, construction time may be saved if it is known that a particular grout product achieves sufficient strength in a short amount of time.

Anchors shall be installed according to manufacturer directions and as unheaded. Polymer grouted and quick setting cementitious grouted anchors should be tested at 24 hours and 7 days. Non-quick setting cementitious grouted anchors should be tested at 7 days and 28 days. A minimum of five anchors should be tested at each interval. The interval at which the bond strength reaches a sufficient value should be noted. This knowledge can be used in construction scheduling as well as in choosing a grout product whose strength development fits into a given time frame.

9.5 Threaded Rod versus Deformed Reinforcing Bar

It is important to compare the bond strength a grout product possesses for threaded rods and deformed reinforcing bars. Both of these materials are commonly installed in the field, so being able to predict how they will behave while in-service is imperative. This test program should investigate the performance of unheaded grouted anchors installed with a threaded rod and compare this behavior to that when a deformed reinforcing bar is installed. Installation using a threaded rod shall be considered as the baseline series. Unheaded anchors must be used to try to force a failure at the steel/grout interface. A failure at this location will allow calculation of the bond stress, τ, directly from the bond strength.

All anchors shall be installed in accordance with the manufacturer's directions and as unheaded. The resulting bond strengths should be compared. Ideally, the grout product would exhibit similar bond strengths for both types of anchors. The results from testing of threaded rods and reinforcing bars should be compared. If the deformed reinforcing bar average bond strength is more than 20% less than the average bond strength of threaded rods, or if the coefficient of variation of the deformed reinforcing bar test series exceeds the aforementioned maximum, the grout product should be limited to installation with threaded rods.

9.6 Hole Drilling Technique

Anchor test series should include the baseline series of installing headed anchors in core-drilled holes according to the manufacturer's directions as well as a series of headed anchors installed per manufacturer instructions except in holes drilled with the hole drilling technique to be evaluated. In order to evaluate the effect of the hole drilling technique, a bond failure at the grout/concrete interface must occur. Therefore, all anchors shall be installed using the type of nut, anchor diameter, hole diameter, and embedment depth described in Section 9.2. If either the coefficient of variation for the tested hole drilling technique or the reduction in the bond strength between the baseline and the variable test series exceed the limit of 20%, the grout product tested should not be installed in holes drilled using the tested hole drilling technique.

9.7 Moisture Condition of Hole

Bond strength can be influenced by the moisture condition of the hole depending on the type of grout product used for anchor installation. Cementitious grout products commonly require installation in damp holes to prevent excessive water loss from the grout to the concrete, which could reduce the bond strength of the grout. Polymer grouts are usually installed in dry holes to allow the chemical reactions to occur, thus binding the grout to the concrete. If a polymer grouted anchor is installed in a damp hole (i.e. a core-drilled hole that has not been given sufficient time to dry), the presence of water could impede the bonding process, thus reducing the bond strength. Grout products being evaluated should be tested for sensitivity to damp or dry hole conditions. In order to evaluate the effect of the moisture condition of the hole, it is necessary for failure to occur at the grout/concrete interface. Therefore, all anchors shall be installed using the type of nut, anchor diameter, hole diameter, and embedment depth described in Section 9.2.

In the damp hole installation test series, polymer grouted anchors should be installed as headed and according to the manufacturer's instructions, except the holes shall be damp at the time of installation as described in Section 5.3. Additionally, a baseline series needs to be installed as per manufacturer instructions. The bond strength from the baseline series and the damp hole installation series should be compared. ICBO ES AC58 (ICBO ES 2001) states that all dampness specimen results shall be at least 80% of the average of the baseline specimens. The appropriate restrictions, if any, should be assigned to the polymer grout product based on the bond strength results evaluated in accordance with ICBO ES AC58 and the maximum coefficient of variation as set forth in this paper.

In the dry hole installation test series, cementitious grouted anchors should be installed in accordance with the manufacturer's instructions, except the holes shall be dry at the time of installation. Additionally, a baseline series needs to be installed per manufacturer instructions. The bond strength from the baseline series and the dry hole installation series should be compared. Dry specimen shall be considered in a similar manner to dampness specimen. All dry hole installation specimen results shall be at least 80% of the average of the baseline series. The coefficient of variation of the dry hole installation series shall be less than the aforementioned maximum. The appropriate restrictions, if any, should be assigned to the cementitious grout product based on the bond strength results.

9.8 Elevated Temperature

This parameter is considered more critical for polymer grouts as they are believed to be more sensitive to temperature changes. Test series of headed and unheaded anchors installed, cured, and tested at elevated temperature (110º F; 43.3º C) should be performed. The anchors should be installed in accordance with the manufacturer's directions, except at elevated temperature. The bond strengths from each series should then be compared. The grout product may be approved for use in elevated temperature applications if the average bond strength at elevated temperature is not more than 20% less than the bond strength of the baseline series and the coefficient of variation of the elevated temperature series is less than the limit set forth in this paper.

9.9 Horizontal and Overhead Hole Orientation (Optional)

Bond strength has the potential to be significantly reduced when anchors are installed at an orientation other than vertically downward. This reduction is due to the grout settling unevenly or flowing out of the hole. For a horizontal installation, the anchor is perpendicular to the vertical face of the concrete. The anchor potentially settles against the lower surface of the hole resulting in a non-uniform grout thickness around the anchor. Additionally, air voids can form along the upper hole surface. This diminishes the bond area and thus results in a corresponding reduction in bond strength.

For an overhead orientation, the anchor is installed vertically upward. The grout wants to flow out of the hole, and the anchor potentially settles in an outward movement. This settlement can result in a reduction in the effective embedment depth and corresponding losses of bond area and bond strength.

In order to minimize the punitive effects an alternate hole orientation can have on bond strength, it is highly recommended that cementitious grouts should not be installed in this type of application. Non-quick setting cementitious grouts are not sufficiently viscous, and their initial set time is too long to make their use practical for alternate hole orientation installations. Similarly, polymer grouts possessing low viscosities should also not be utilized.

In the optional horizontal hole orientation test series, grouted anchors shall be installed in accordance with manufacturer directions, except in horizontally oriented holes. The bond strength from the baseline series installed in vertical holes and horizontal hole orientation series should be compared. If the bond strength is reduced by more than the limit set forth in this paper when installed horizontally, or if the coefficient of the horizontal hole test series exceeds the aforementioned maximum, the grout product shall be excluded from installation in horizontally oriented holes.

Similar optional tests to those performed on anchors in the horizontal hole orientation test series should be performed on grouted anchors installed in overhead holes. This test series should also be compared to the baseline series. Similarly, if the reduction in bond strength or the coefficient of variation of the overhead test series exceed the limits set forth in this paper, the grout product shall be excluded from use in this application.

9.10 Long-term Load (Optional)

Anchors subjected to sustained tension loading may undergo displacements due to creep. If the rate of displacement does not attenuate, the anchor displacement will reach unacceptable levels. The variable of interest is the amount of displacement. Therefore, the applied load should not induce failure. The applied load should be a service level load that can be taken as a percentage of the tensile load that incites failure. Similar to FM 5-568 (FDOT 2000), it is recommended that a tensile load that is 40% of the mean failure load value from the baseline series be used.

This test series is optional unless sustained long-term load is anticipated. Both headed and unheaded anchors shall be tested. In these test series, anchors should be installed per the manufacturer's directions. In accordance with FM 5-568, creep tests shall be performed at elevated temperature.

Displacements should be measured more frequently near the beginning of the loading period. It is recommended that displacement data should be sampled for a minimum of 42 days. At the end of 42 days, the load can be removed from the anchors. In accordance with FDOT Section 937 (FDOT 2002a), the rate of displacement shall decrease during the 42 day loading period. Also, at the end of the loading period, the total creep displacement shall be less than 0.03 inch (0.75 mm) and less than 0.003 inch (0.075 mm) during the last 14 days of loading.

The anchors that have not exceeded the predefined displacement limit should then be reloaded in tension and tested to failure. The bond strength from these reloaded anchors should be compared to that of the baseline test series. If the coefficient of variation or the reduction in bond strength of the creep test series exceed the limits set forth in this paper, it may be appropriate to limit the use of the product to applications in which service loads would not need to be sustained long-term. If the level of creep displacement exceeds the limit, the anchor can be considered to have failed.

9.11 Additional Factors

Other factors may also need to be considered when determining whether a grout product can be used in a certain application. Some additional factors are: repeated loads, freezing and thawing cycles, seismic (shear and tension), cracked concrete, and concrete aggregate. Testing methods for these factors are outside the scope of this report.

CHAPTER 10
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

10.1 Summary

This thesis addresses the behavior of headed and unheaded grouted anchors installed in uncracked concrete tested in tension. Data from this test program as well as a summary of data from other test programs are presented. A variety of products, anchor configurations, installation conditions, edge distances, and group anchor spacings have been tested. Test results were used to establish if existing behavioral models for adhesive and cast-in-place anchors could be extended to accurately predict the strength of grouted anchors. These models are the uniform bond stress model and the concrete capacity design model, respectively. Additionally, factors that constitute a desirable grout product are discussed. The results from various installation and service condition tests are analyzed, and product approval tests for grouts are proposed.

10.2 Conclusions

Grouted anchor behavior varies depending on the product used for installation, whether the anchor is installed as unheaded or headed, installed near an edge, installed in an anchor group, and what installation and service conditions the anchor is exposed to. Four different failure modes exist for grouted anchors: bond failure at the steel/grout interface, bond failure at the grout/concrete interface, concrete breakout failure, and steel failure. Ignoring steel failure, unheaded grouted anchors predominantly experience a bond failure at the steel/grout interface, but a bond failure at the grout/concrete interface has also been observed. Again, ignoring steel failure, headed grouted anchors may experience either a bond failure at the grout/concrete interface or a concrete cone breakout.

In general, the capacity of unheaded grouted anchors can be predicted by the uniform bond stress model (Equations (3) and (5)), which is based on the bond stress (τ) at the steel/grout interface. If the grout/concrete bond stress (τ_0) is low enough, a bond failure may occur at the grout concrete interface (Equations (4) and (6)). The failure mode can be predicted based on which equation yields the smaller bond strength. For design, the expected anchor strength can be taken as the lesser of Equation (9) and Equation (10).

Bond failure at the steel/grout interface is precluded for headed grouted anchors by the presence of the head. The capacity of headed grouted anchors can be predicted by either the uniform bond stress model (Equations (4) and (6)) or the concrete capacity design model (Equations (1a or 1b) and (2)). The failure mode can be predicted by which of these two models yields the lower result. For design, the expected anchor strength can be taken as the lesser of Equation (10) and Equations (11a or 11b).

The test program reported in this thesis indicated that the critical edge distance and critical anchor spacing of the uniform bond stress model currently used for adhesive anchors were not accurate for grouted anchors. The data were analyzed, and the critical edge distance for grouted anchors was found to be $5d_0$; the critical anchor spacing for grouted anchors was found to be $10d_0$.

This report includes an analysis of tests of installation and service conditions. The tests performed in the current test program and in previous testing programs led to the following conclusions:

- Products develop strength at different rates. In general, polymer grouts develop a significant portion of strength more rapidly than cementitious grouts.
- The type of grout product used to install the anchor can greatly influence the anchor strength. Unheaded smooth rods should not be relied upon in tension.
- Headed grouted anchors are not sensitive to the type of nut (regular hex or heavy hex) used on the embedded end during installation.
- The moisture condition of the hole affects the bond strength of anchors installed with polymer grouts, and it is conjectured that cementitious grouts can also be sensitive to the moisture condition of the hole.
- Polymer grouts are believed to be sensitive to elevated temperatures since they are similar in composition to adhesives, which have been shown to possess this sensitivity.

10.3 Recommendations

Based on the test results presented in this thesis, the following tests are proposed to establish grout product properties and sensitivities:

- Establish τ_0.
- Establish τ.
- Establish strength development curve.
- Compare threaded rod versus deformed reinforcing bar.
- Evaluate sensitivity to hole drilling technique.

- Evaluate sensitivity to moisture condition of hole.
- Evaluate sensitivity to elevated temperature.

Additionally, hole orientation and long-term loading (creep) tests are proposed as optional tests.

A comprehensive design model for grouted anchors is needed, and the CCD method and modifications to the uniform bond stress model were shown to accurately predict anchor capacity. It was observed that installation and service conditions will affect the behavior of grouted anchors, and product approval tests were proposed to investigate some of these effects. Further testing is recommended to establish safety factors for the aforementioned installation and service conditions. Future study is recommended for the following topics not addressed in this paper:

- The effect of repeated loads on the performance of grouted anchors.
- The effect of freezing and thawing cycles on the performance of grouted anchors.
- The effects of seismic forces (shear and tension) on the performance of grouted anchors.
- The effect of cracked concrete members on the performance of grouted anchors.
- The effect of various concrete aggregates on the performance of grouted anchors.

APPENDIX A
NOTATION

c = distance from center of an anchor shaft to the edge of concrete, in (mm).

c_1 = distance from the center of an anchor shaft to the edge of concrete in one direction, in (mm).

c_2 = distance from the center of an anchor shaft to the edge of concrete in the direction orthogonal to c_1, in (mm).

d = diameter of the anchor, in (mm).

d_0 = diameter of the hole, in (mm).

d_i = net potentiometer displacement; subscript ranges from 1 to 4 for quadruple fastener anchor groups, in (mm).

d_n = distance from the surface of the concrete to the bottom of the pull plate at each anchor in an anchor group; subscript ranges from 1 to 4 for quadruple fastener anchor groups, in (mm).

$d_{n,poten}$ = distance from the surface of the concrete to the bottom of the pull plate at each potentiometer in an anchor group; subscript ranges from 1 to 4 for quadruple fastener anchor groups, in (mm).

d_{tot} = overall displacement of an anchor group, in (mm).

f'_c = concrete compressive strength, psi (N/mm^2).

h_{ef} = effective anchor embedment depth, in (mm).

k = factor based on a 5% fractile, 90% confidence, and number of tests performed.

n = number of tests performed.

s = anchor center-to-center spacing, in (mm).

s_1 = anchor center-to-center spacing in one direction, in (mm).

s_2 = anchor center-to-center spacing in the direction orthogonal to s_1, in (mm).

A_{bond} = bonded surface area between grout and concrete, in^2 (mm^2).

A_N = projected concrete failure area of an anchor or group of anchors, for calculation of strength in tension, in^2 (mm^2).

A_{N0} = projected concrete failure area of one anchor, for calculation of strength in tension when not limited by edge distance or spacing, in^2 (mm^2).

N = general mean tensile strength for an anchor group with unspecified failure mode, lbf (N).

N_0 = general mean tensile strength for a single anchor with unspecified failure mode, lbf (N).

$N_{c,0}$ = mean tensile strength for concrete cone breakout of a single anchor, lbf (N).

$N_{\tau,0}$ = mean tensile strength for steel/grout failure of a single anchor, lbf (N).

$N_{\tau 0,0}$ = mean tensile strength for grout/concrete failure of a single anchor, lbf (N).

N_c = mean tensile strength for concrete cone breakout of an anchor group, lbf (N).

N_{test} = tensile strength of a single anchor or an anchor group for one test repetition, lbf (N).

N_τ = mean tensile strength for steel/grout failure of an anchor group, lbf (N).

$N_{\tau 0}$ = mean tensile strength for grout/concrete failure of an anchor group, lbf (N).

$N'_{c,0}$ = nominal tensile strength for concrete cone breakout of a single anchor, lbf (N).

$N'_{\tau,0}$ = nominal tensile strength for steel/grout failure of a single anchor, lbf (N).

$N'_{\tau 0,0}$ = nominal tensile strength for grout/concrete failure of a single anchor, lbf (N).

N'_{cone} = nominal tensile strength for concrete cone breakout of an anchor group, lbf (N).

N'_τ = nominal tensile strength for steel/grout failure of an anchor group, lbf (N).

$N'_{\tau 0}$ = nominal tensile strength for grout/concrete failure of an anchor group, lbf (N).

COV = coefficient of variation.

ϕ_b = strength reduction factor for bond failure (0.85 is recommended).

ϕ_c = strength reduction factor for concrete cone breakout (0.75 is recommended).

τ = mean uniform bond stress at the steel/grout interface, psi (MPa).

τ_0 = mean uniform bond stress at the grout/concrete interface, psi (MPa).

$\tau_{0,test}$ = uniform bond stress at the grout/concrete interface for a single anchor or an anchor group in one test repetition, psi (MPa).

τ' = $\tau(1-kCOV)$, nominal uniform bond stress at the steel/grout interface, psi (MPa).

τ'_0 = $\tau_0(1-kCOV)$, nominal uniform bond stress at the grout/concrete interface, psi (MPa).

$\Psi_{\tau,e}$ = modification factor, for strength in tension, to account for edge distances when bond failure occurs at the steel/grout interface.

$\Psi_{\tau 0,e}$ = modification factor, for strength in tension, to account for edge distances when bond failure occurs at the grout/concrete interface.

$\Psi_{c,e}$ = modification factor, for strength in tension, to account for edge distances when concrete cone breakout failure occurs.

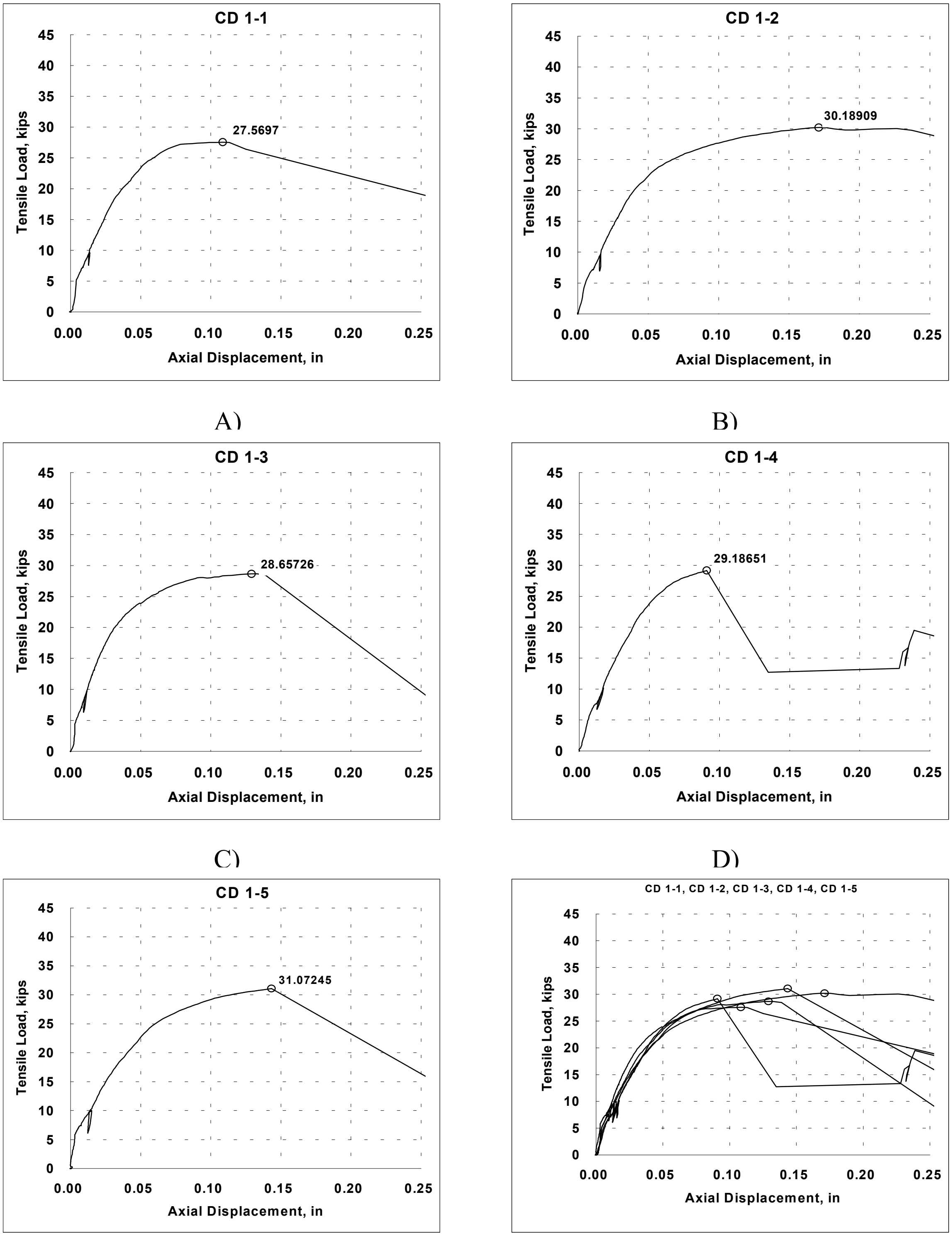
APPENDIX B

TENSILE LOAD VS. DISPLACEMENT GRAPHS FOR BASELINE AND HOLE DRILLING TECHNIQUE TEST SERIES

This appendix contains the results from testing of single anchors installed away from an edge. Table B-1 lists the details about each test performed including the installation number, the effect being tested, the anchor number in the given test series, the average concrete compressive stress at the time of testing, the failure mode, the tensile strength of the anchor, and the bond stress of the anchor. Figures B-1 through B-5 depict the axial tensile load versus the vertical displacement for the various tests performed. The title of each graph within the figures denotes information about the test being performed. The first two letters in the title specify the type of hole drilled. Core-drilled holes are represented by CD, and hammer-drilled holes are represented by HD. The first number identifies the test series of the hole type. The second number identifies the individual anchor in the series.

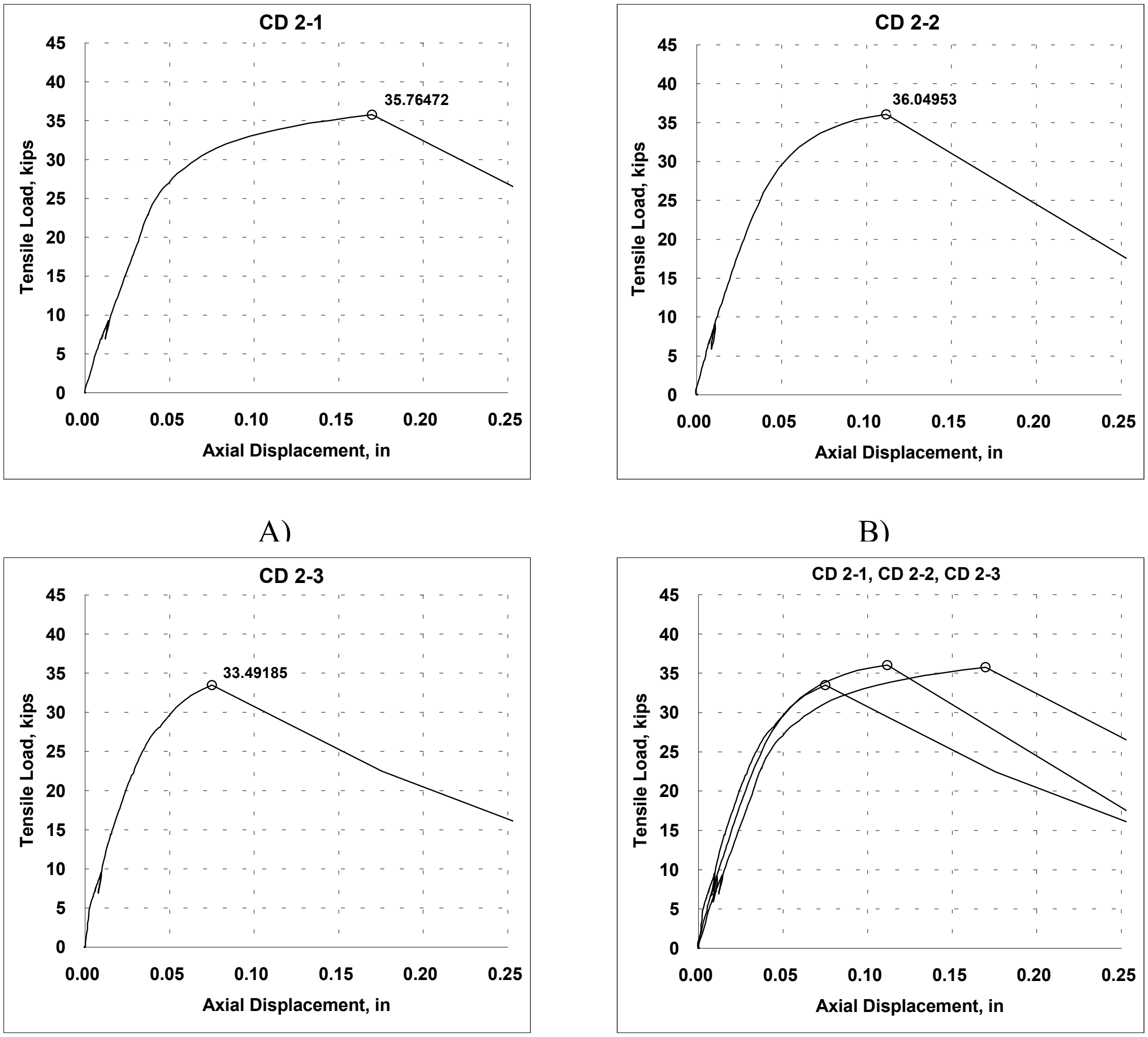
Table B-1 Individual baseline and hole drilling technique anchor test results

Installation #	Tested Effect	Anchor in Series	$f'c$ at test psi (MPa)	Failure Mode	N_{test} kips (kN)	$\tau_{0,test}$ psi (MPa)
1	Baseline	1	6600 (45.5)	g/c	27.6 (123)	1170 (8.07)
1	Baseline	2	6600 (45.5)	g/c	30.2 (134)	1280 (8.84)
1	Baseline	3	6680 (46.1)	g/c	28.67 (127)	1220 (8.39)
1	Baseline	4	6680 (46.1)	g/c	29.2 (130)	1240 (8.54)
1	Baseline	5	6680 (46.1)	g/c	31.1 (138)	1320 (9.09)
1	Hammer	1	6600 (45.5)	g/c	30.0 (134)	1280 (8.79)
1	Hammer	2	6600 (45.5)	steel	26.1 (116)	NA
1	Hammer	3	6680 (46.1)	g/c	30.6 (136)	1300 (8.94)
1	Hammer	4	6680 (46.1)	steel	24.4 (109)	NA
1	Hammer	5	6680 (46.1)	steel	24.1 (107)	NA
2	Baseline	1	7200 (49.6)	g/c	35.8 (159)	1520 (10.5)
2	Baseline	2	7200 (49.6)	g/c	36.1 (160)	1530 (10.6)
2	Baseline	3	7200 (49.6)	g/c	33.5 (149)	1420 (9.80)
2	Hammer	1	7200 (49.6)	g/c	38.9 (173)	1650 (11.4)
2	Hammer	2	7200 (49.6)	g/c	20.0 (89.2)	851 (5.86)
2	Hammer	3	7200 (49.6)	g/c	28.0 (125)	1190 (8.19)
3	Baseline	1	7330 (50.5)	g/c	41.7 (186)	1770 (12.2)
3	Baseline	2	7330 (50.5)	g/c	41.3 (184)	1750 (12.1)
3	Baseline	3	7330 (50.5)	g/c	34.9 (155)	1480 (10.2)



A) B) C) D) E) F)

Figure B-1 Graphs of test results of first installation of core-drilled anchors A) First test in series; B) Second test in series; C) Third test in series; D) Fourth test in series; E) Fifth test in series; F) Comparison of all test in series



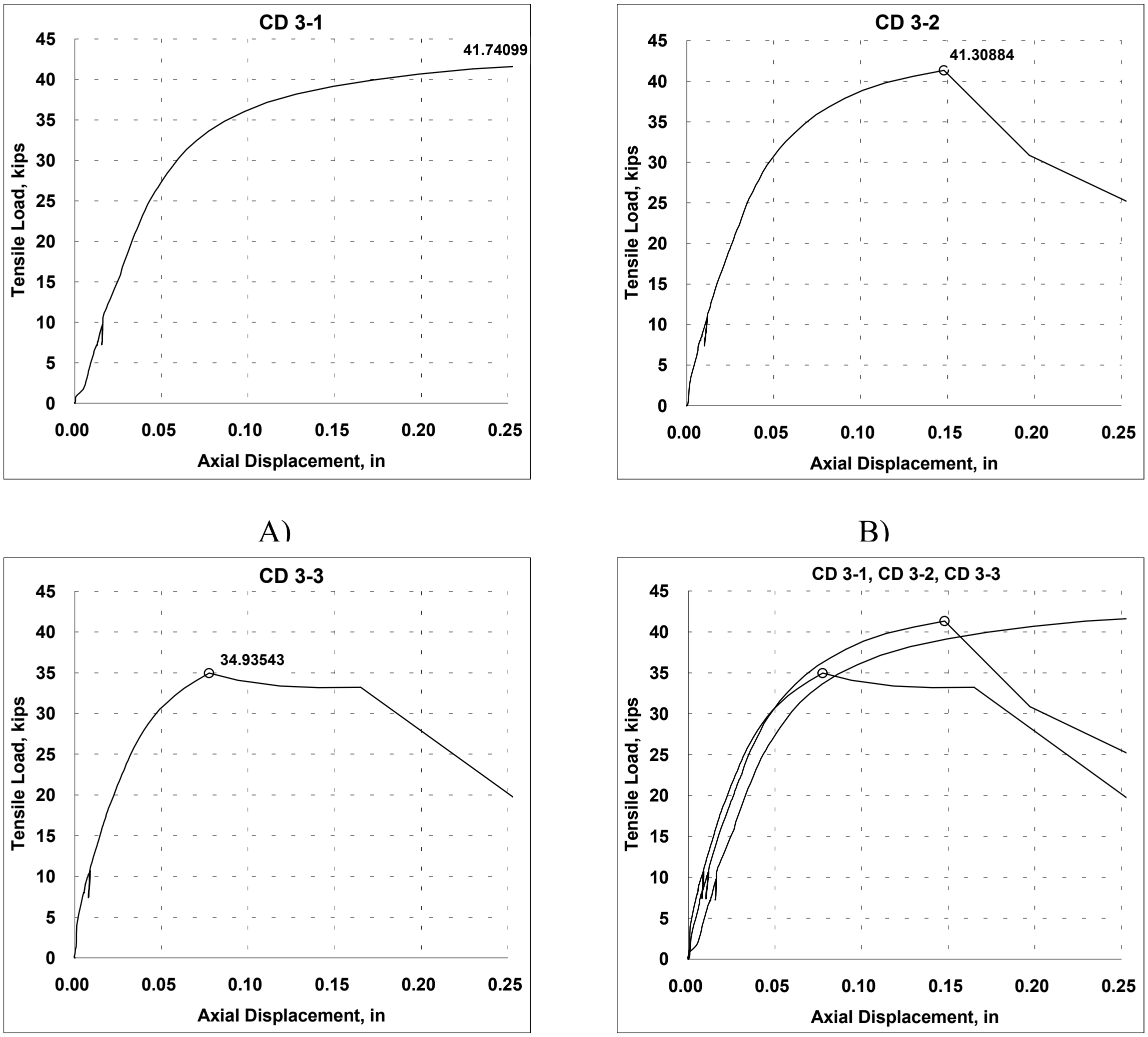
A)

B)

C)

D)

Figure B-2 Graphs of test results of second installation of core-drilled anchors A) First test in series; B) Second test in series; C) Third test in series; D) Comparison of all test in series



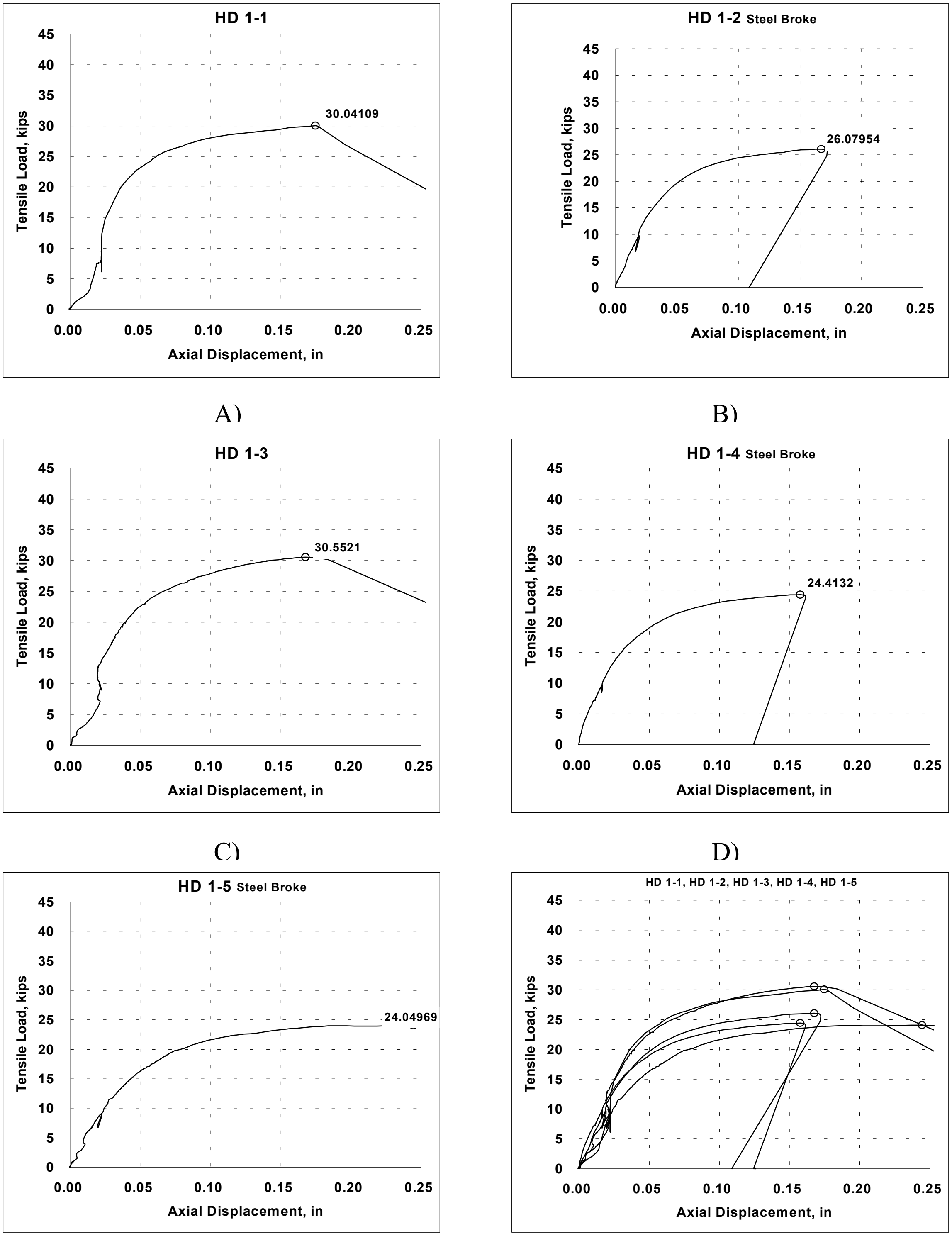
A)

B)

C)

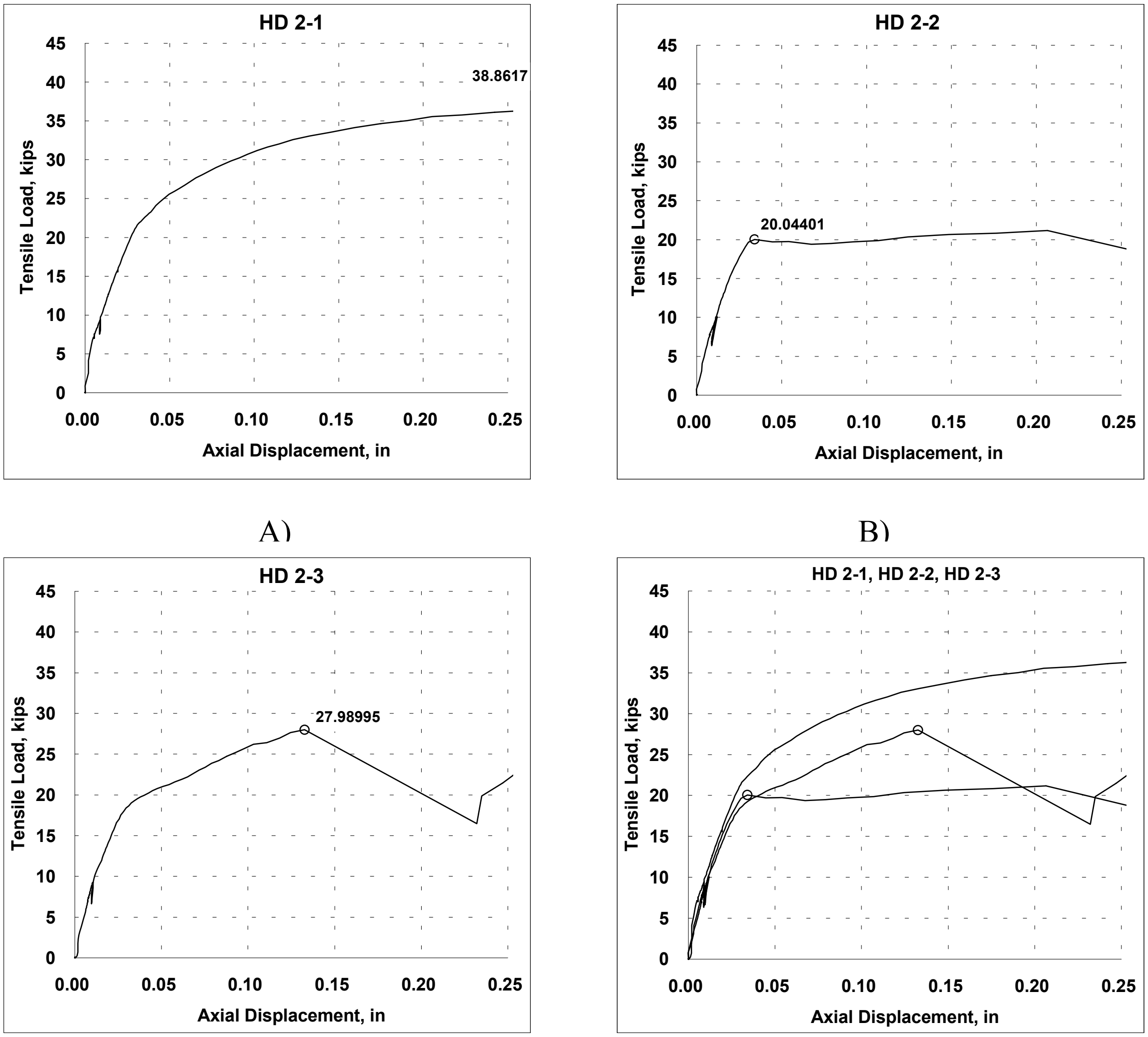
D)

Figure B-3 Graphs of test results of third installation of core-drilled anchors A) First test in series; B) Second test in series; C) Third test in series; D) Comparison of all test in series



A) B) C) D) E) F)

Figure B-4 Graphs of test results of first installation of hammer-drilled anchors A) First test in series; B) Second test in series; C) Third test in series; D) Fourth test in series; E) Fifth test in series; F) Comparison of all test in series



A)　B)

C)　D)

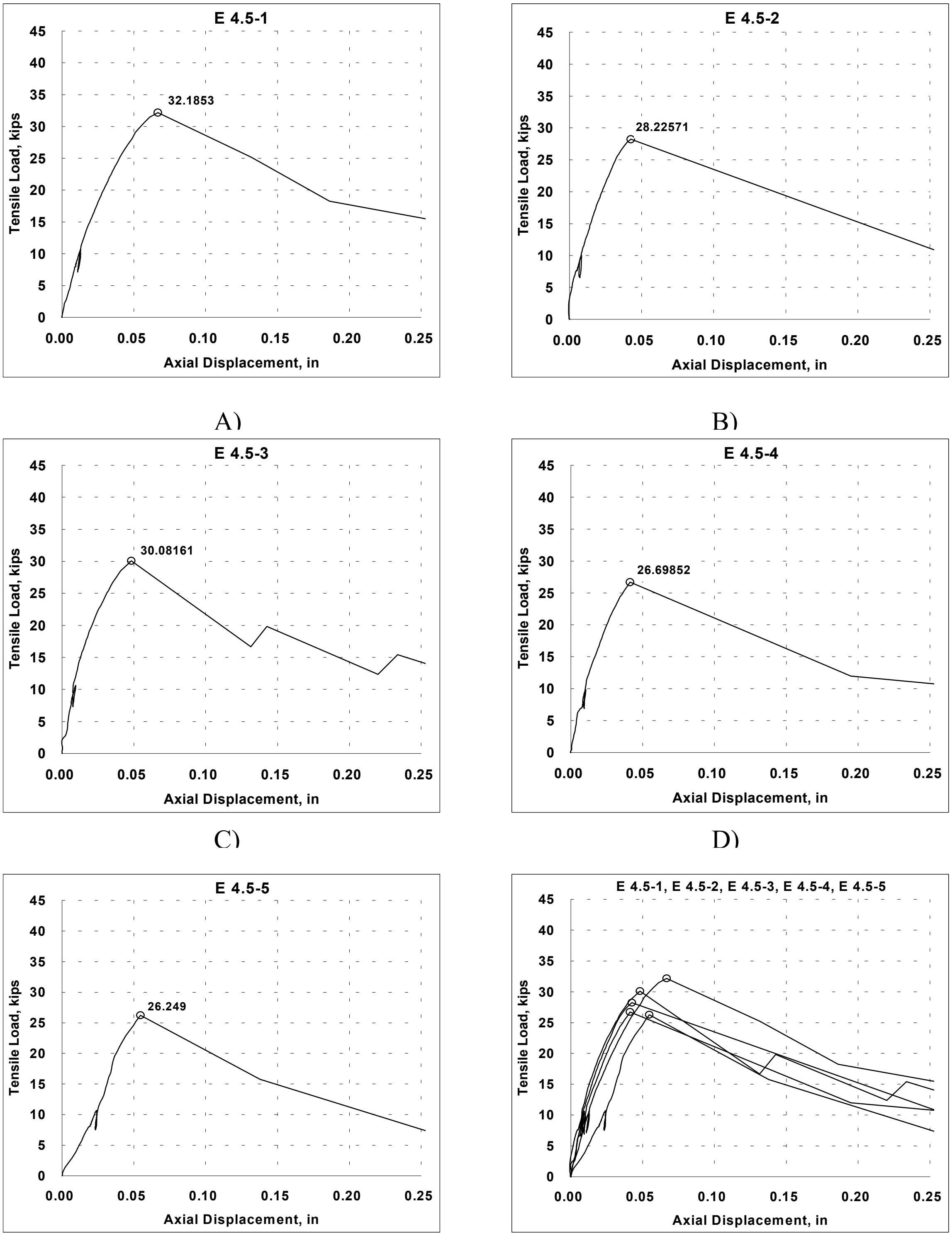
Figure B-5 Graphs of test results of second installation of hammer-drilled anchors
A) First test in series; B) Second test in series; C) Third test in series; D) Comparison of all test in series

APPENDIX C
TENSILE LOAD VS. DISPLACEMENT GRAPHS FOR EDGE DISTANCE TEST SERIES

This appendix contains the results from testing of single anchors installed near one edge. Table C-1 lists the details about each test performed including the installation number, the effect being tested, the anchor number in the given test series, the average concrete compressive stress at the time of testing, the failure mode, the tensile strength of the anchor, and the bond stress of the anchor. Figures C-1 through C-3 depict the axial tensile load versus the vertical displacement for the various tests performed. The title of each graph within the figures denotes information about the test being performed. The first letter in the title specifies that an edge test is being performed. The first number identifies the edge distance of the test series. The second number identifies the individual anchor in the series.

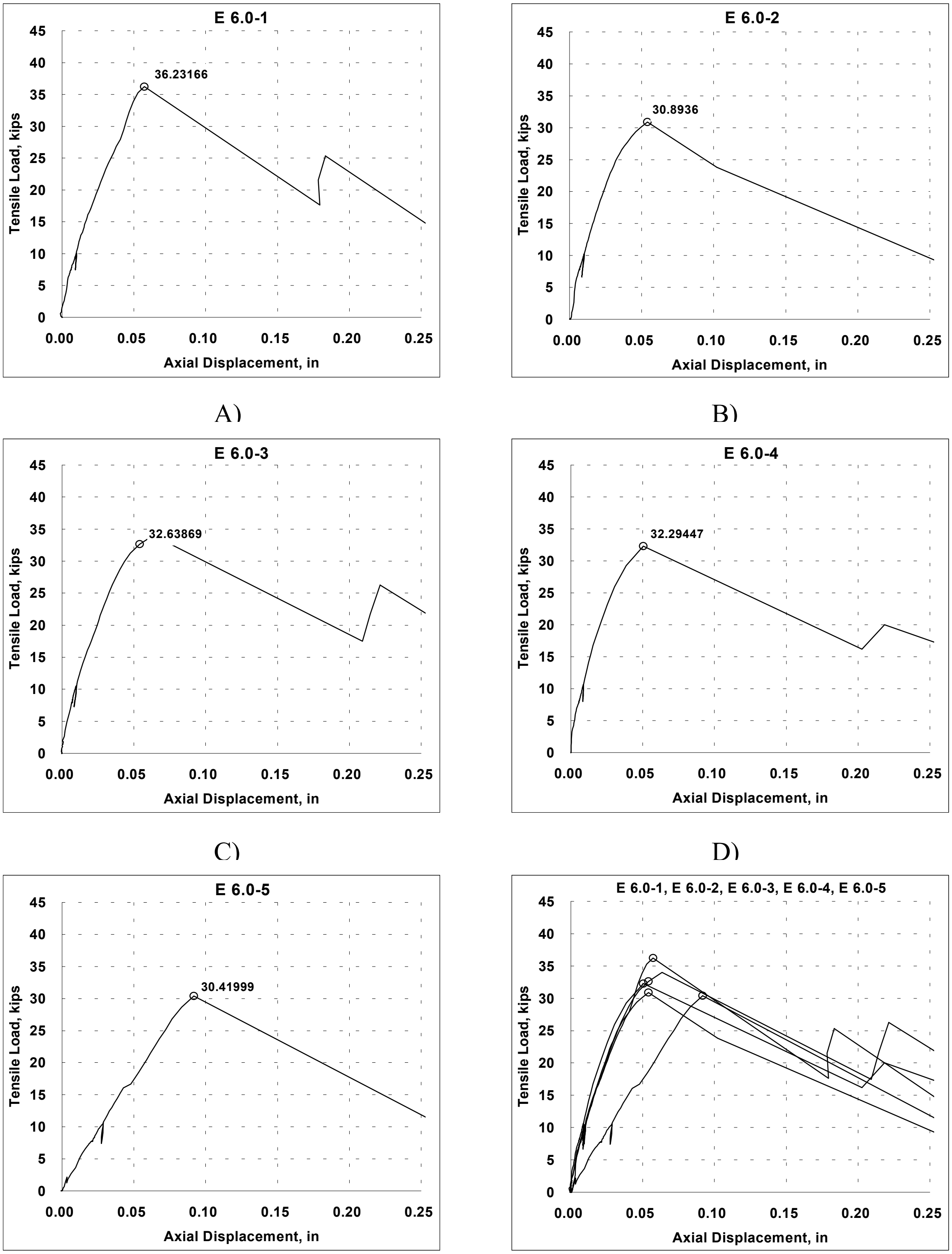
Table C-1 Individual edge distance anchor test results

Installation #	Tested Effect	Anchor in Series	$f'c$ at test psi (MPa)	Failure Mode	N_{test} kips (kN)	$\tau_{0,test}$ psi (MPa)
2	Edge 7.5	1	6460 (44.5)	g/c	29.7 (132)	1260 (8.70)
2	Edge 7.5	2	6460 (44.5)	g/c	31.95 (142.14)	1360 (9.35)
2	Edge 7.5	3	6460 (44.5)	g/c	36.5 (162)	1550 (10.7)
2	Edge 7.5	4	6460 (44.5)	g/c	33.1 (147)	1400 (9.67)
2	Edge 7.5	5	6460 (44.5)	g/c	28.3 (126)	1200 (8.29)
3	Edge 4.5	1	7600 (52.4)	g/c	32.2 (143)	1370 (9.42)
3	Edge 4.5	2	7600 (52.4)	g/c	28.2 (126)	1200 (8.26)
3	Edge 4.5	3	7600 (52.4)	g/c	30.1 (134)	1280 (8.80)
3	Edge 4.5	4	7600 (52.4)	g/c	26.7 (119)	1130 (7.81)
3	Edge 4.5	5	7600 (52.4)	g/c	26.3 (117)	1110 (7.68)
3	Edge 6.0	1	7330 (50.5)	g/c	36.2 (161)	1540 (10.6)
3	Edge 6.0	2	7330 (50.5)	g/c	30.9 (137)	1310 (9.04)
3	Edge 6.0	3	7330 (50.5)	g/c	32.6 (145)	1390 (9.55)
3	Edge 6.0	4	7330 (50.5)	g/c	32.3 (144)	1370 (9.45)
3	Edge 6.0	5	7330 (50.5)	g/c	30.4 (135)	1290 (8.90)



A) B) C) D) E) F)

Figure C-1 Graphs of test results of core-drilled anchors installed 4.5 inches away from one edge A) First test in series; B) Second test in series; C) Third test in series; D) Fourth test in series; E) Fifth test in series; F) Comparison of all test in series

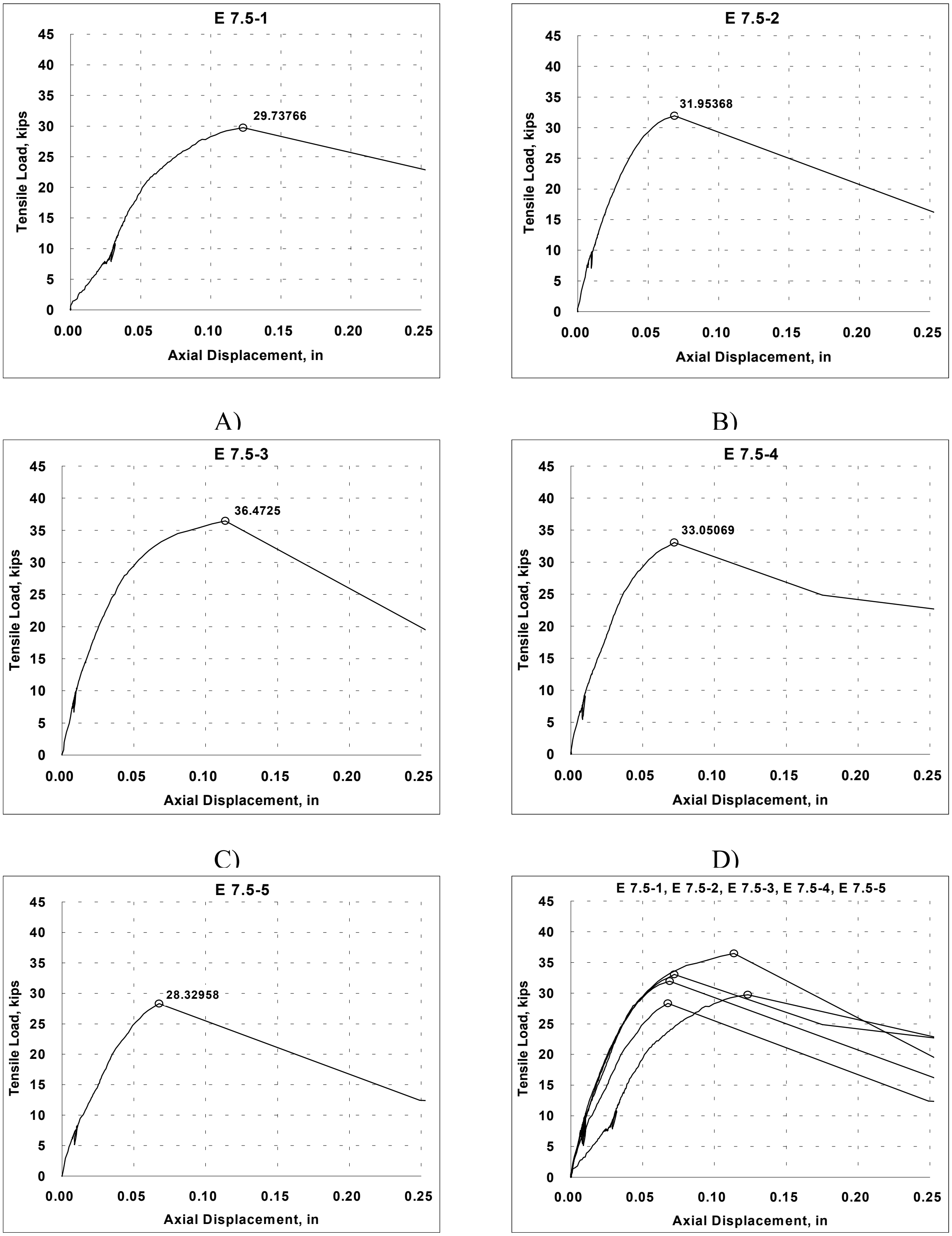


A) B)

C) D)

E) F)

Figure C-2 Graphs of test results of core-drilled anchors installed 6.0 inches away from one edge A) First test in series; B) Second test in series; C) Third test in series; D) Fourth test in series; E) Fifth test in series; F) Comparison of all test in series



A) B)

C) D)

E) F)

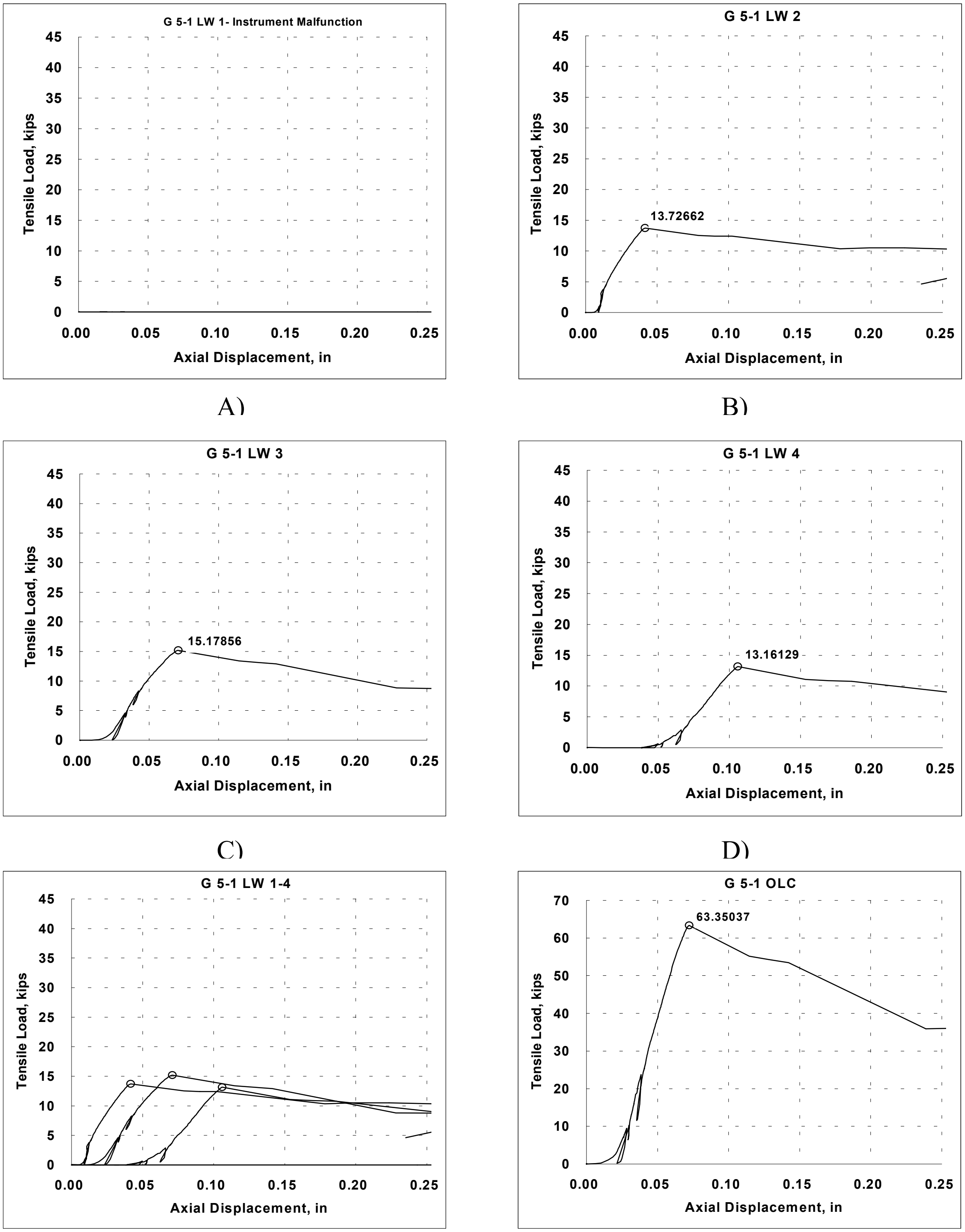
Figure C-3 Graphs of test results of core-drilled anchors installed 7.5 inches away from one edge A) First test in series; B) Second test in series; C) Third test in series; D) Fourth test in series; E) Fifth test in series; F) Comparison of all test in series

APPENDIX D
TENSILE LOAD VS. DISPLACEMENT GRAPHS FOR GROUP TEST SERIES

This appendix contains the results from testing of anchor groups. Table D-1 lists the details about each test performed including the installation number, the effect being tested, the group number in the given test series, the average concrete compressive stress at the time of testing, the failure mode, the anchor number in the given test series, the tensile strengths of the individual anchors as well as the anchor group, and the bond stresses of the individual anchors and the anchor group. Figures D-1 through D-6 depict the axial tensile load versus the vertical displacement for the various tests performed. The title of each graph within the figures denotes information about the test being performed. The first letter in the title specifies that a group test is being conducted. The first number identifies the anchor spacing of the test series. The second number identifies the group in a series. The remaining letters specify the load measuring instrument being used. The load washer on each anchor is represented by LW, and the overall load cell for the anchor group is represented by OLC. The third number identifies the individual anchor on which data is being measured.

Table D-1 Individual group anchor test results

Installation #	Tested Effect	Group in Series	$f'c$ at test psi (MPa)	Failure Mode	Anchor	N_{test} kips (kN)	$\tau_{0,test}$ psi (MPa)
1	G 5.0	1	7670 (52.9)	cone	1	Error	NA
					2	13.7 (61.1)	NA
					3	15.2 (67.5)	NA
					4	13.2 (58.5)	NA
					All	63.4 (282)	NA
1	G 5.0	2	7670 (52.9)	cone	1	Error	NA
					2	13.8 (61.2)	NA
					3	16.1 (71.8)	NA
					4	16.2 (72.1)	NA
					All	66.9 (298)	NA
1	G 5.0	3	7670 (52.9)	cone	1	Error	NA
					2	16.7 (74.1)	NA
					3	13.67 (60.8)	NA
					4	15.0 (66.6)	NA
					All	62.0 (276)	NA
3	G 9.0	1	7330 (50.5)	g/c	1	Error	Error
					2	27.5 (122)	1170 (8.05)
					3	28.6 (127)	1210 (8.37)
					4	25.3 (112)	1070 (7.39)
					All	105 (465)	1110 (7.65)
3	G 9.0	2	7330 (50.5)	g/c	1	Error	Error
					2	22.2 (98.7)	942 (6.49)
					3	24.3 (108)	1030 (7.10)
					4	32.7 (145)	1390 (9.57)
					All	106 (469)	1120 (7.72)
3	G 9.0	3	7330 (50.5)	g/c	1	Error	Error
					2	21.1 (93.7)	894 (6.16)
					3	23.4 (104)	991 (6.83)
					4	25.5 (114)	1080 (7.47)
					All	100 (446)	1070 (7.34)

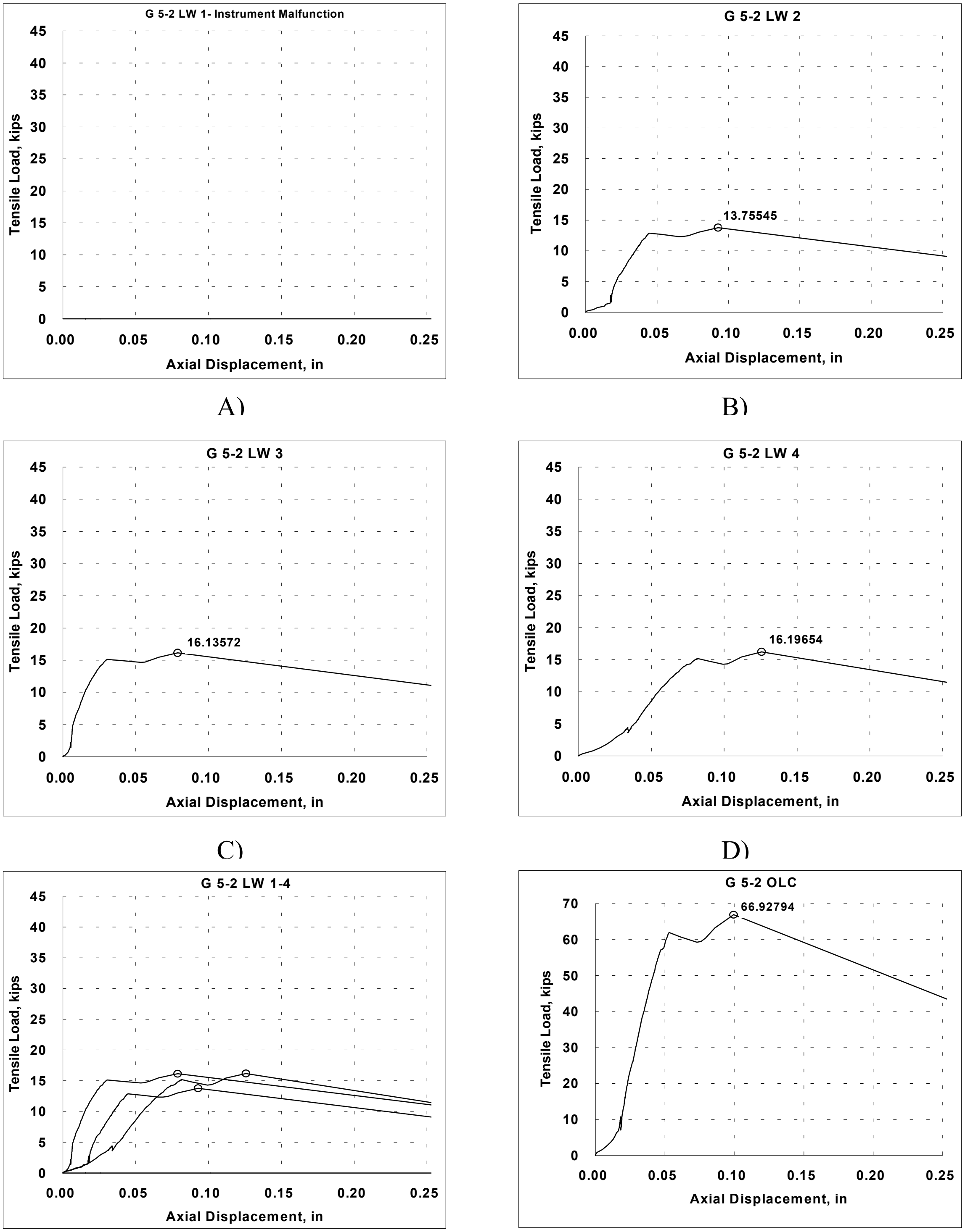


A) B)

C) D)

E) F)

Figure D-1 Graphs of results of first core-drilled anchor group installed with anchor spacing of 5.0 inches A) Load on first anchor; B) Load on second anchor; C) Load on third anchor; D) Load on fourth anchor; E) Comparison of all anchor loads in test; F) Load on entire anchor group



A)

B)

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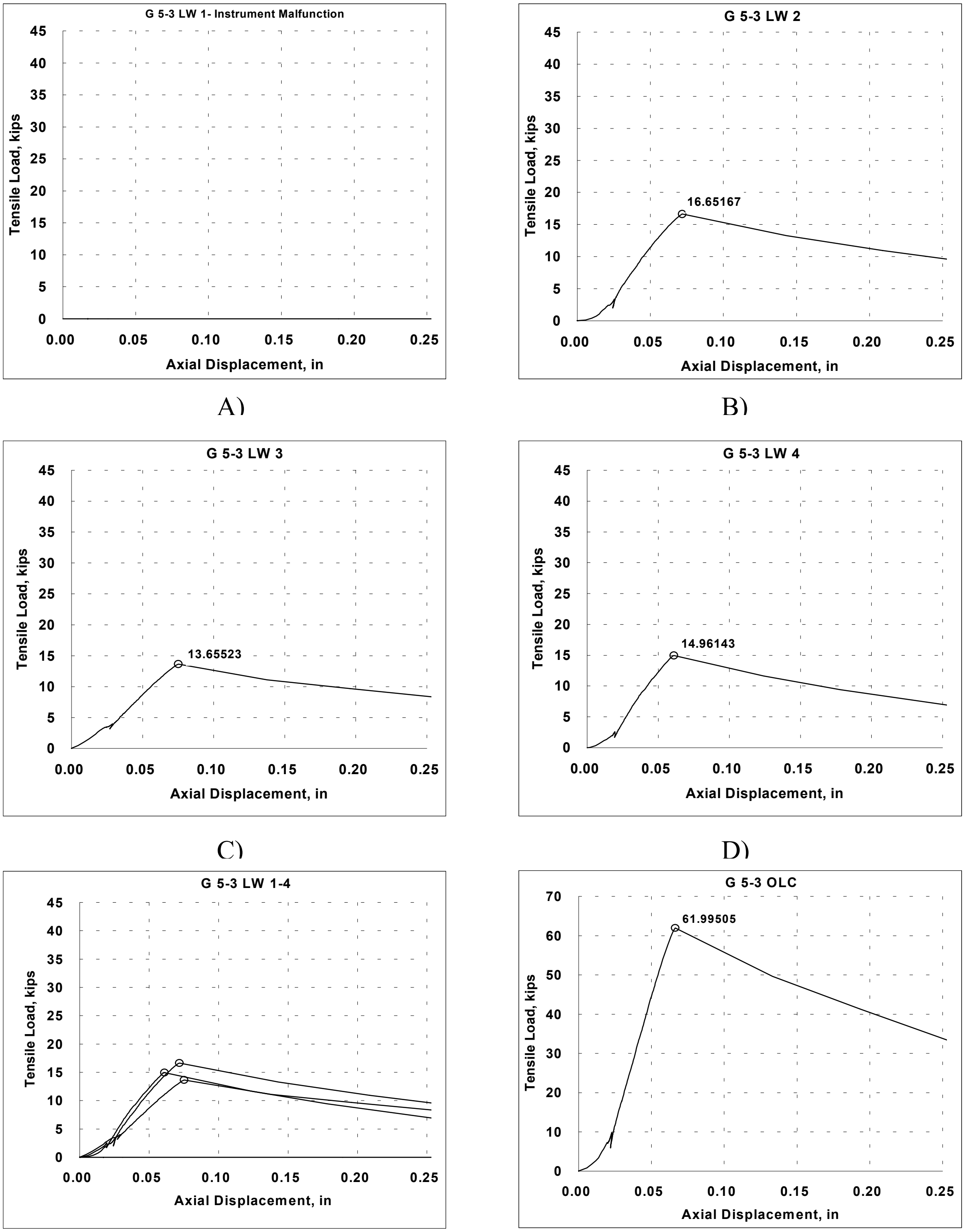
Figure D-2 Graphs of results of second core-drilled anchor group installed with anchor spacing of 5.0 inches A) Load on first anchor; B) Load on second anchor; C) Load on third anchor; D) Load on fourth anchor; E) Comparison of all anchor loads in test; F) Load on entire anchor group

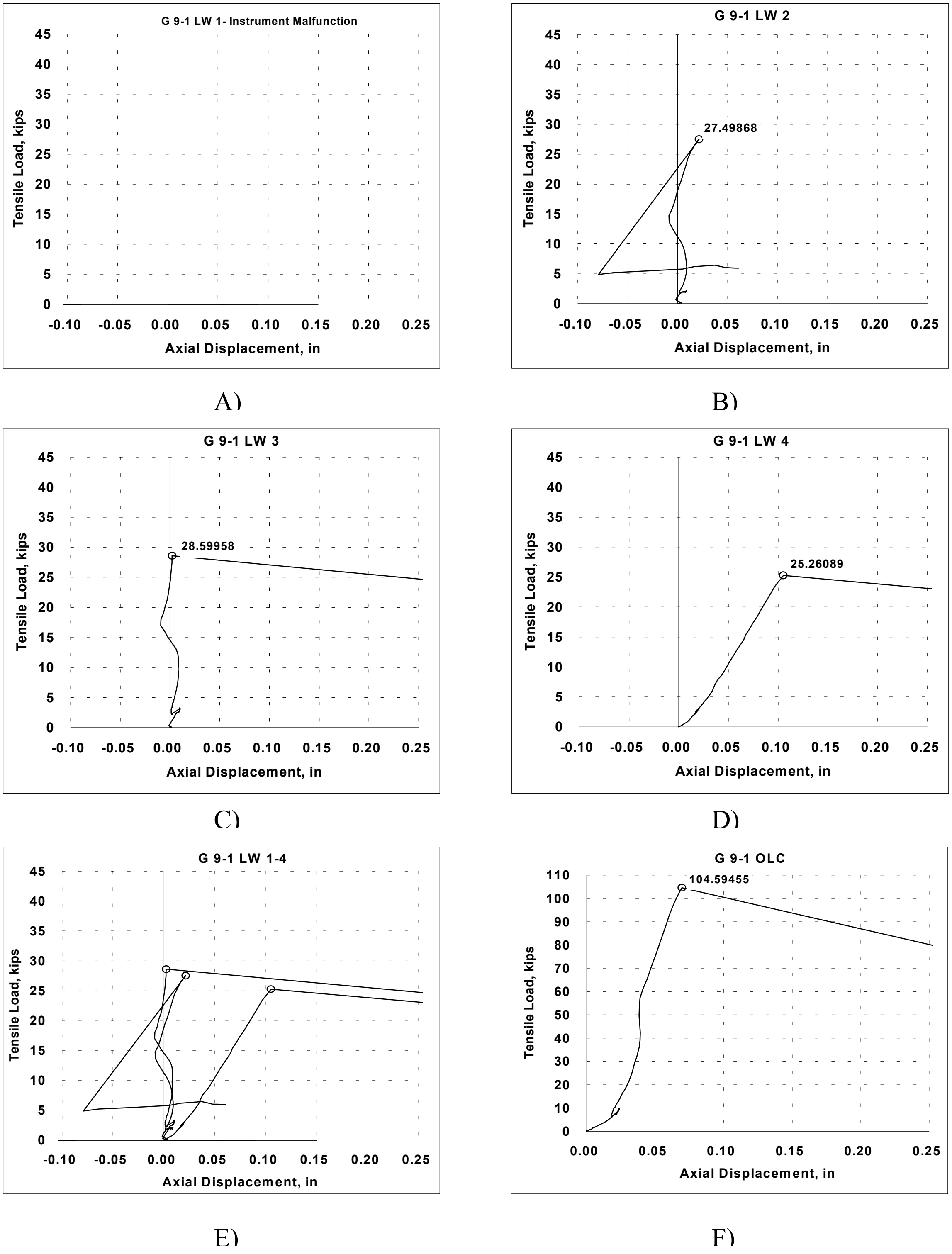


A) B)

C) D)

E) F)

Figure D-3 Graphs of results of third core-drilled anchor group installed with anchor spacing of 5.0 inches A) Load on first anchor; B) Load on second anchor; C) Load on third anchor; D) Load on fourth anchor; E) Comparison of all anchor loads in test; F) Load on entire anchor group



A)

B)

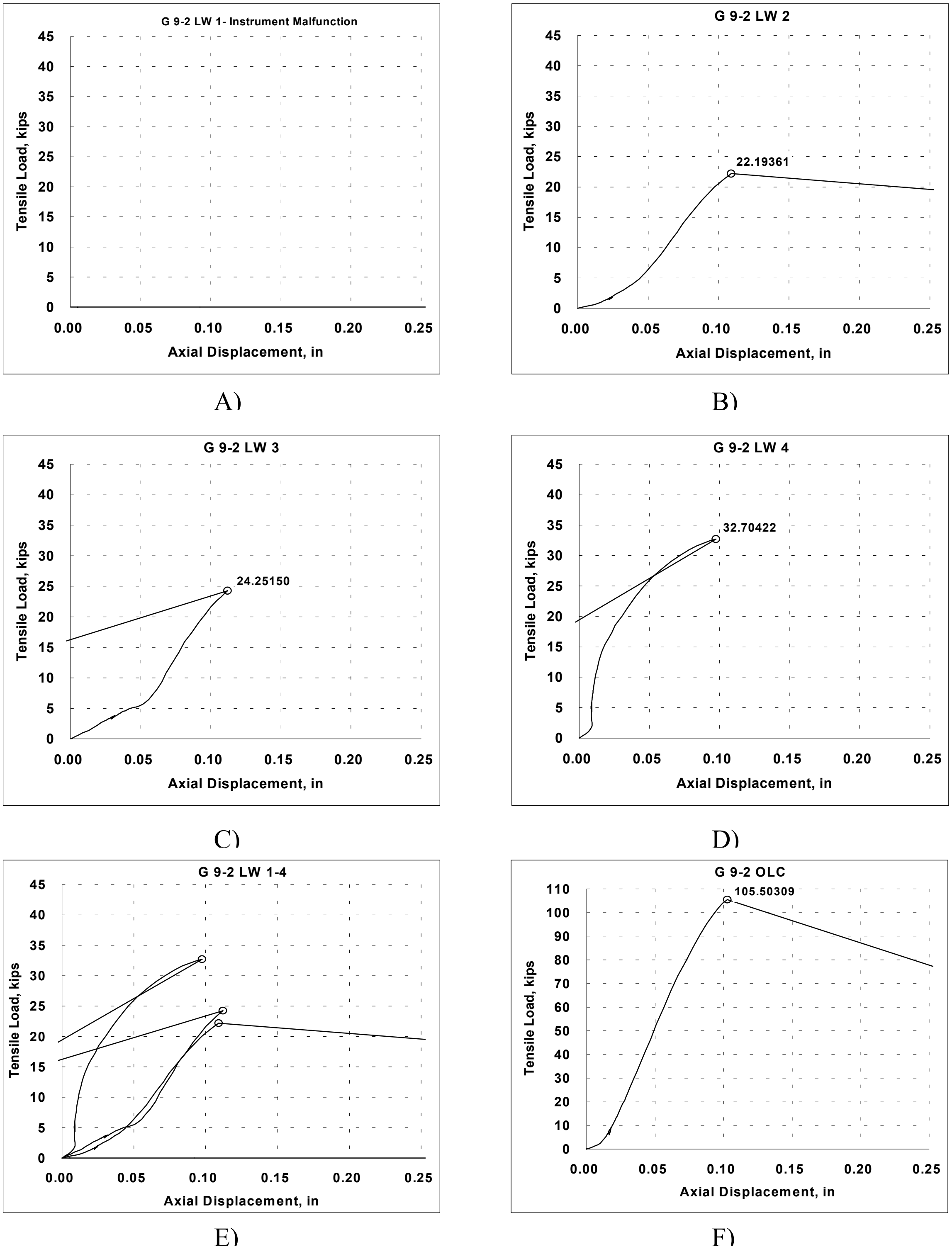
C)

D)

E)

F)

Figure D-4 Graphs of results of first core-drilled anchor group installed with anchor spacing of 9.0 inches A) Load on first anchor; B) Load on second anchor; C) Load on third anchor; D) Load on fourth anchor; E) Comparison of all anchor loads in test; F) Load on entire anchor group



A)

B)

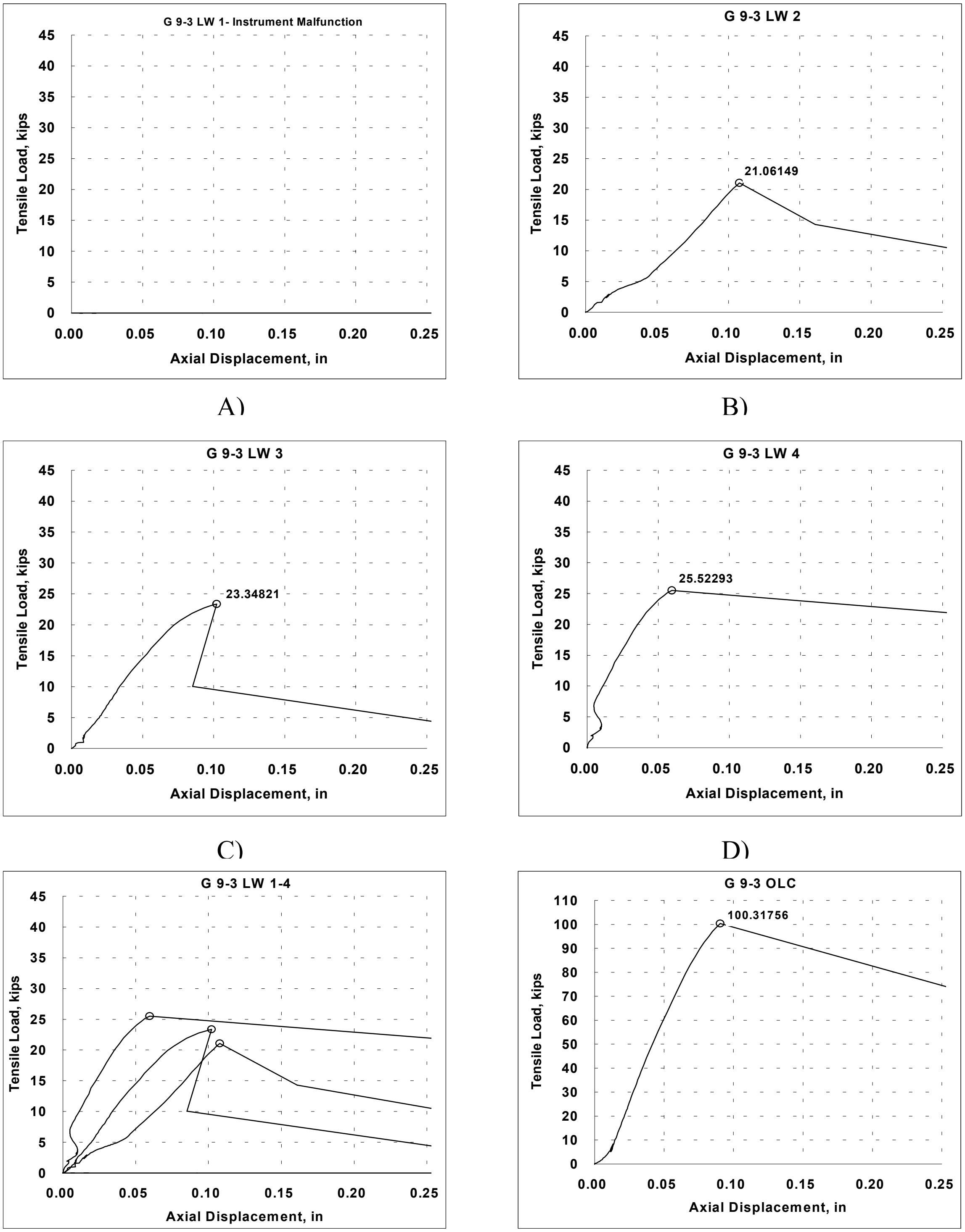
C)

D)

E)

F)

Figure D-5 Graphs of results of second core-drilled anchor group installed with anchor spacing of 9.0 inches A) Load on first anchor; B) Load on second anchor; C) Load on third anchor; D) Load on fourth anchor; E) Comparison of all anchor loads in test; F) Load on entire anchor group



A) B)

C) D)

E) F)

Figure D-6 Graphs of results of third core-drilled anchor group installed with anchor spacing of 9.0 inches A) Load on first anchor; B) Load on second anchor; C) Load on third anchor; D) Load on fourth anchor; E) Comparison of all anchor loads in test; F) Load on entire anchor group

APPENDIX E
REPRESENTATIVE PHOTOGRAPHS OF ANCHOR SPECIMENS FROM TESTING

Figure E-1 Typical grout/concrete bond failure of single core-drilled anchor with grout plug

Figure E-2 Typical grout/concrete bond failure of single anchor with secondary shallow concrete cone

Figure E-3 Grout/concrete bond failure of single core-drilled anchor with secondary shallow cone removed and grout plug exposed

Figure E-4 Typical grout/concrete bond failure of single hammer-drilled anchor with grout plug

Figure E-5 Typical grout/concrete bond failure of single hammer-drilled anchor with secondary shallow concrete cone and grout plug

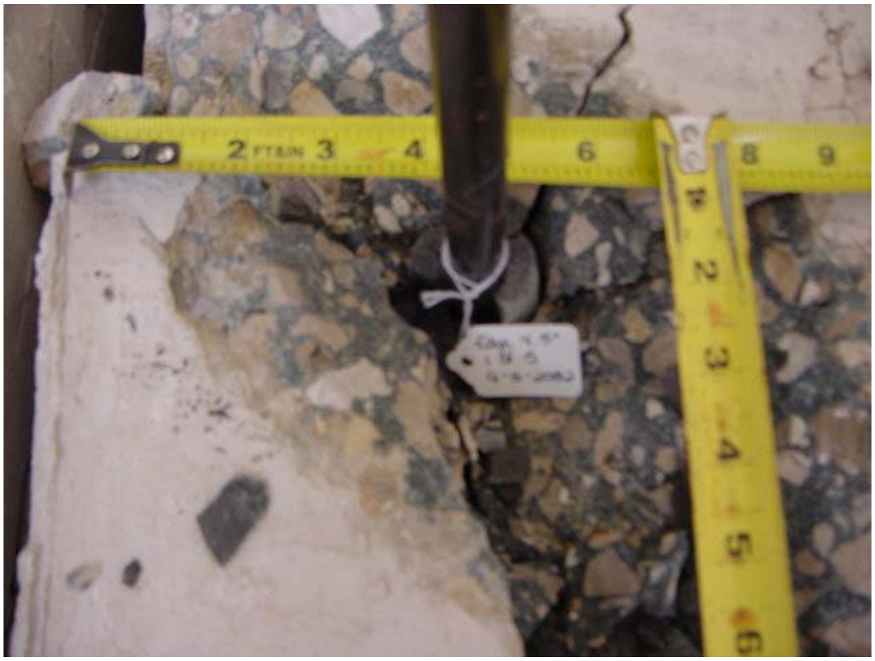


Figure E-6 Typical grout/concrete bond failure of single core-drilled anchor installed 4.5 inches from one edge with grout plug and diagonal cracking of surrounding concrete

Figure E-7 Typical grout/concrete bond failure of single core-drilled anchor installed 6.0 inches from one edge with grout plug

Figure E-8 Typical grout/concrete bond failure of single core-drilled anchor installed 7.5 inches from one edge with grout plug

Figure E-9 Typical surface view of cone failure of quadruple fastener anchor group with anchor spacing of 5 inches

Figure E-10 Typical dissection view of cone failure of quadruple fastener anchor group with anchor spacing of 5 inches

Figure E-11 Typical grout/concrete failure of quadruple fastener anchor group with anchor spacing of 9 inches

APPENDIX F
COMPILATION OF PRODUCT APPROVAL TEST RESULTS

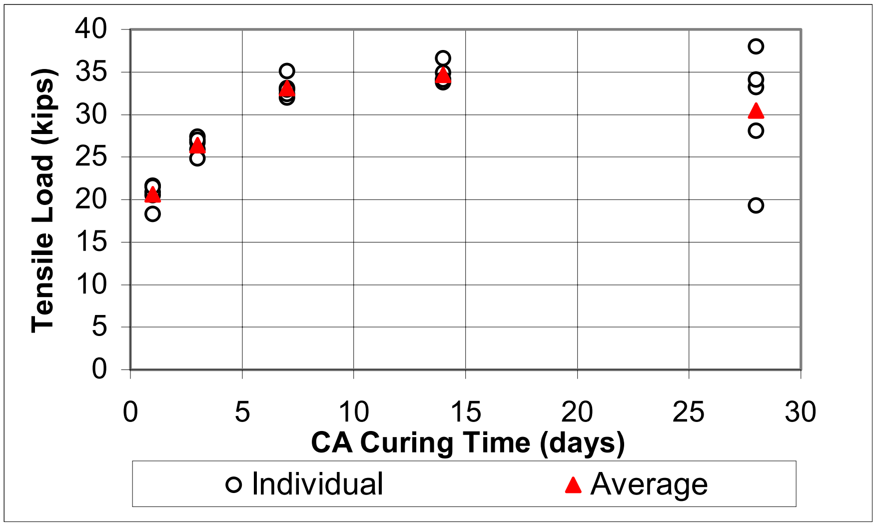


Figure F-1 Strength versus curing time for product CA

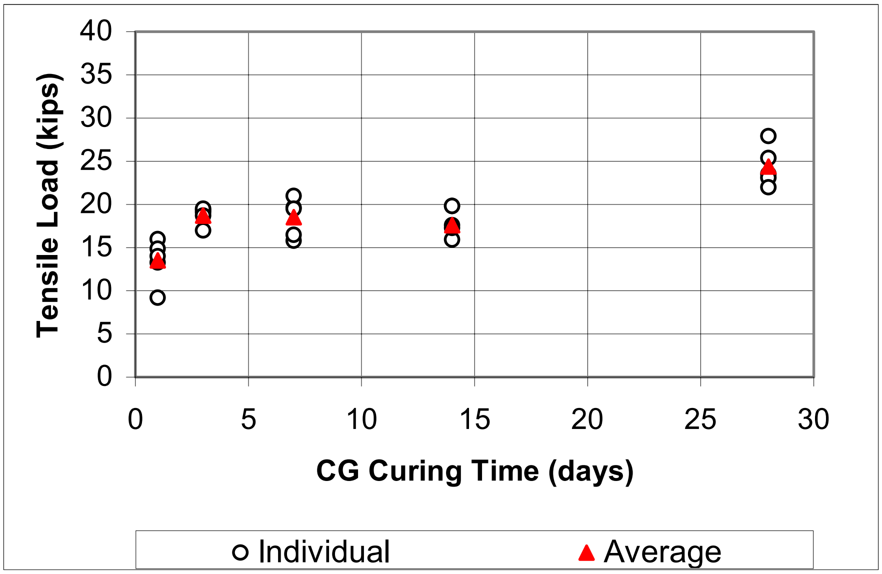


Figure F-2 Strength versus curing time for product CG

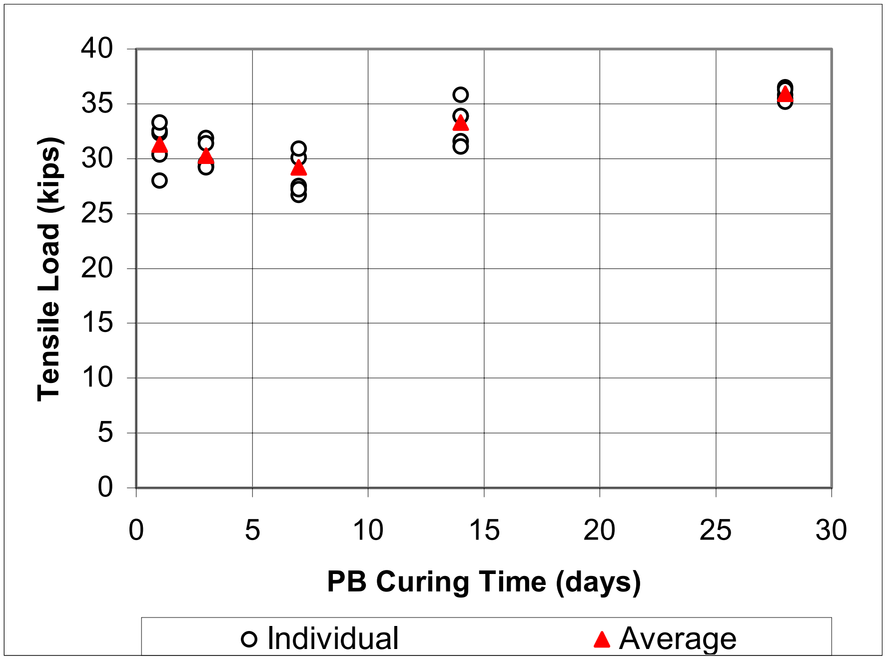


Figure F-3 Strength versus curing time for product PB

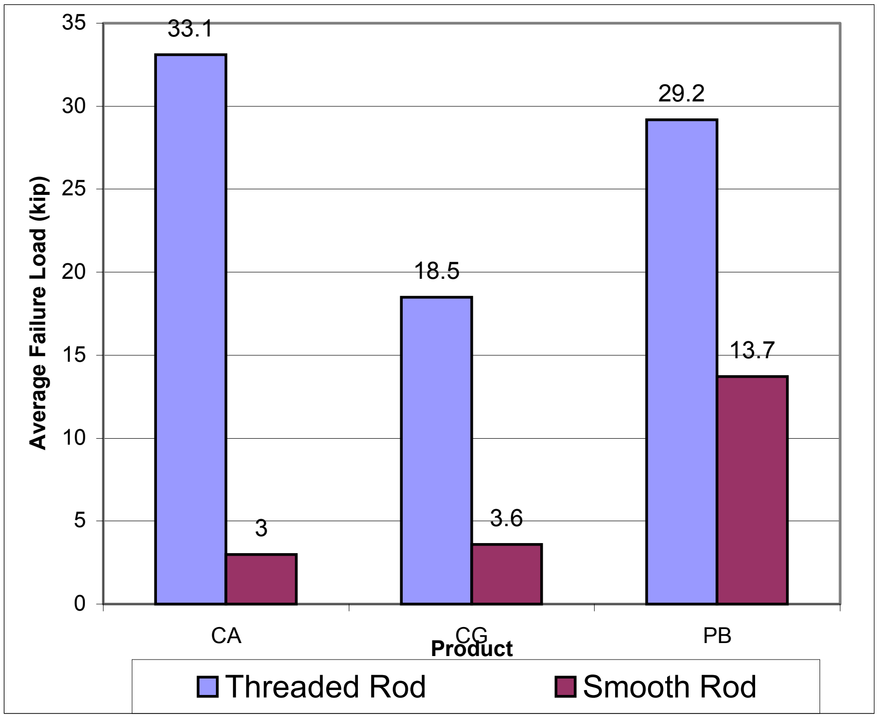


Figure F-4 Comparison of average failure loads for installation with threaded rods and smooth rods

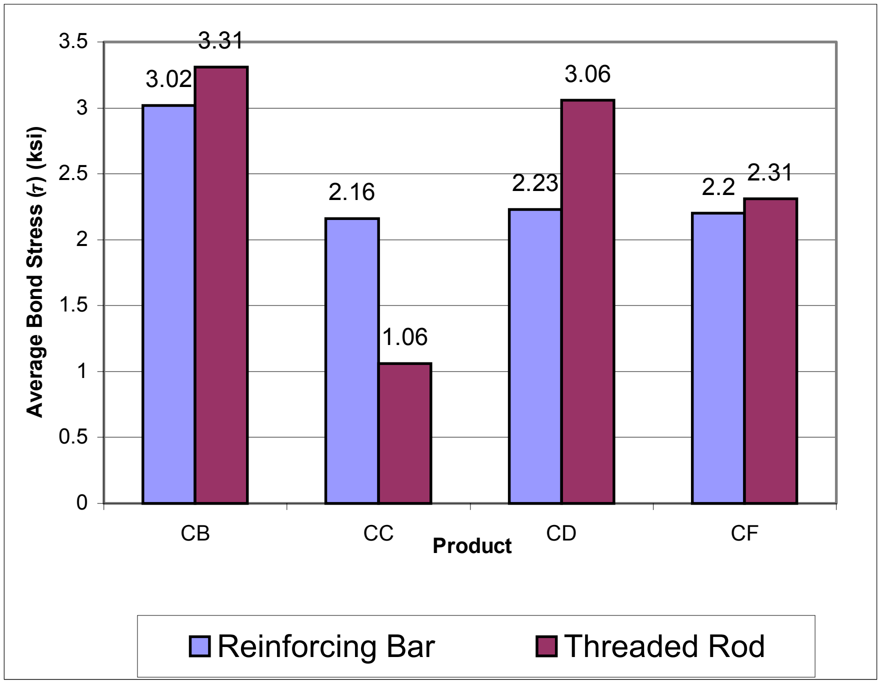


Figure F-5 Comparison of average bond stresses for installation with threaded rods and reinforcing bars

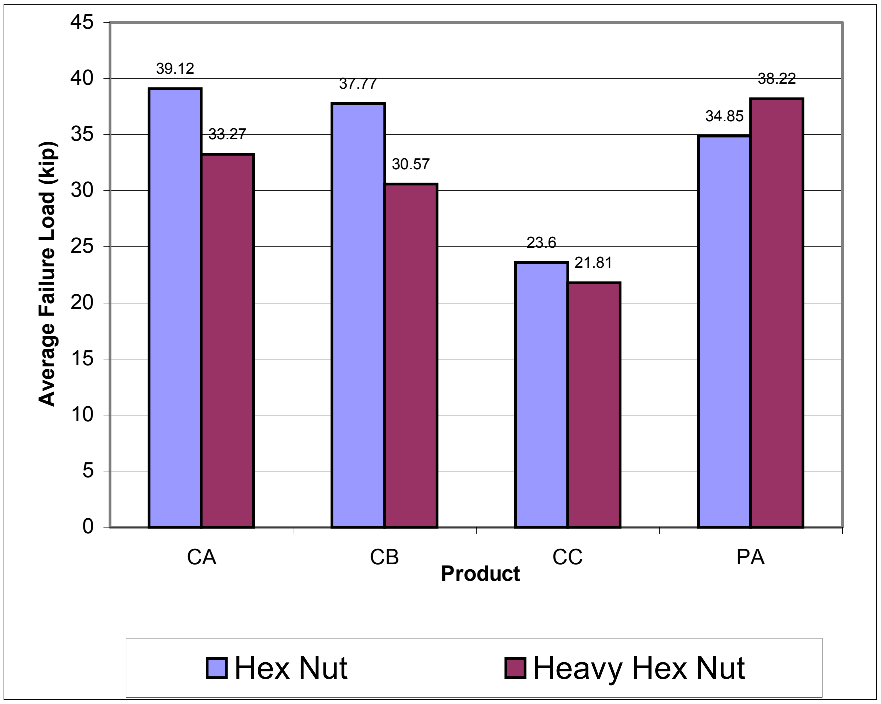


Figure F-6 Comparison of average failure loads for installation of headed anchors with regular hex nuts and heavy hex nuts

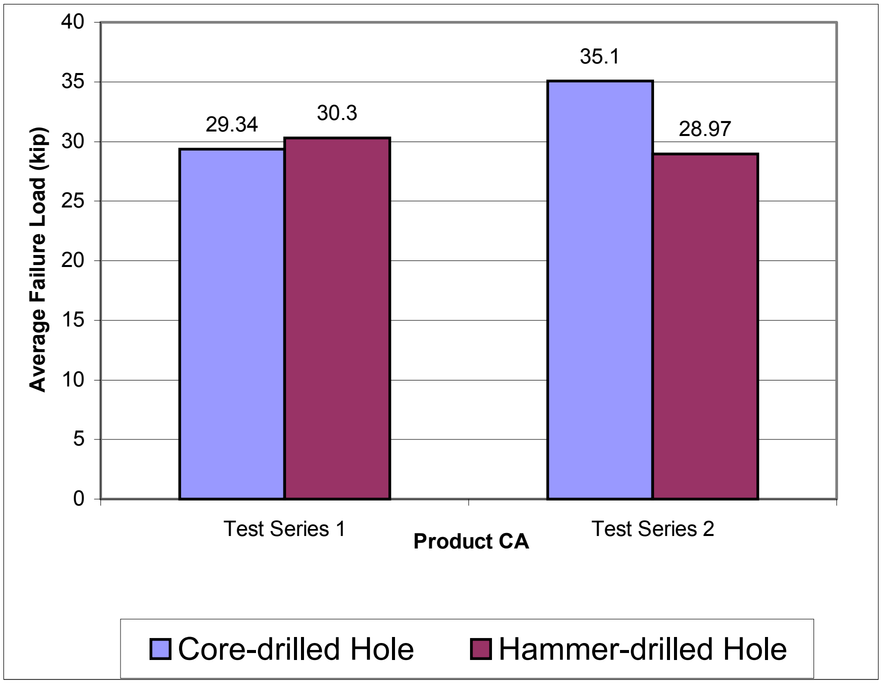


Figure F-7 Comparison of average failure loads for installation in core-drilled and hammer-drilled holes

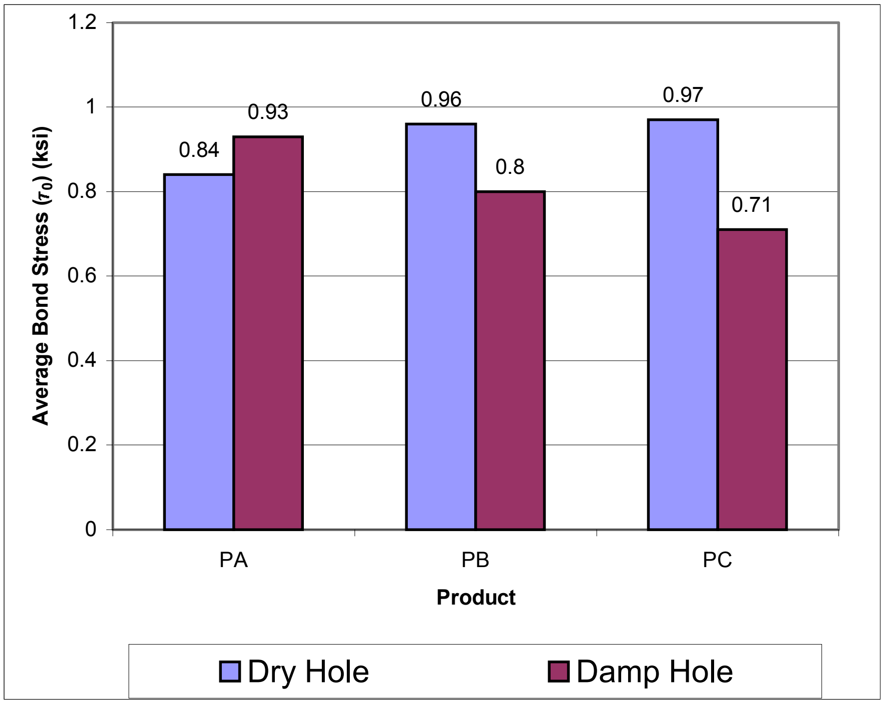


Figure F-8 Comparison of average bond stresses for installation in damp and dry holes

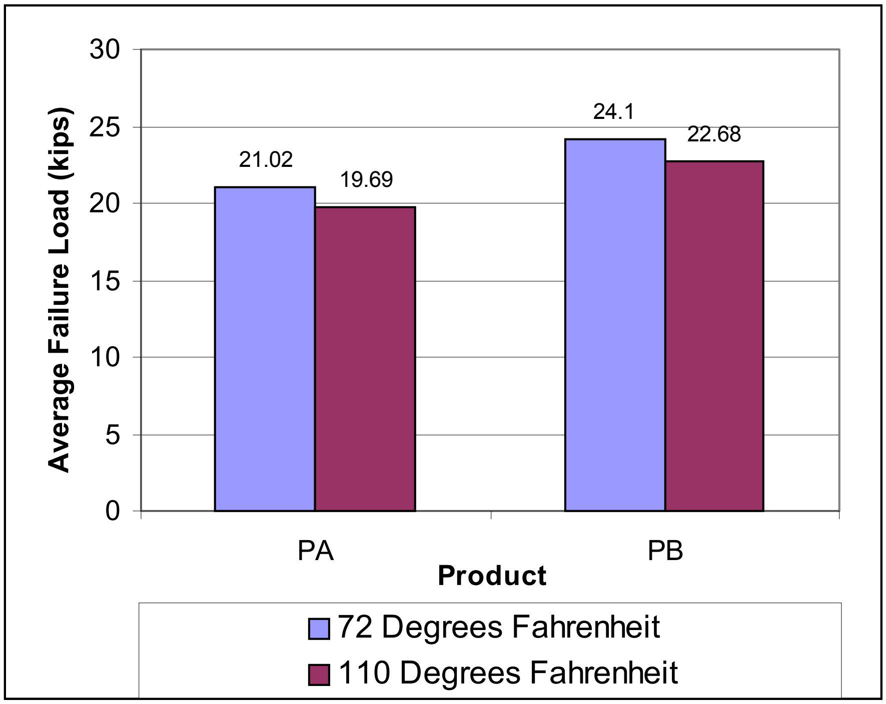


Figure F-9 Comparison of average failure loads for tests performed at ambient and elevated temperatures

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BIOGRAPHICAL SKETCH

The author was born on November 4, 1979, in Florida. She began attending the Massachusetts Institute of Technology in September 1998 after graduating from high school in Davie, Florida. After receiving the degree of Bachelor of Science in Civil Engineering from the Massachusetts Institute of Technology in June 2001, she began graduate school in the College of Engineering at the University of Florida. She plans to receive her Master of Engineering degree in August 2003, with a concentration in civil engineering structures after which time she will pursue a career in structural design. The author is a member of American Society of Civil Engineers, Chi Epsilon, and Tau Beta Pi.