BEHAVIOR OF ANCHORS IN UNCRACKED CONCRETE UNDER STATIC AND DYNAMIC TENSILE LOADING

by

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THESIS

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DISCLAIMER

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Chapter 1

Introduction

1.1 Introduction

The U.S. Nuclear Regulatory Commission (NRC) has designated "Seismic Qualification of Equipment in Operating Plants" as an Unresolved Safety Issue (USI) [1]. As a result, an objective of the NRC is to develop alternative seismic qualification methods and acceptance criteria that can be used to assess the capability of mechanical and electrical equipment to perform their intended safety functions in operating power plants. Since equipment is usually anchored to concrete through anchors, it is therefore necessary to ensure that the anchors are capable of resisting seismic loads.

1.2 Objective and Scope of Research Program

To this end, the NRC is sponsoring a multi-year testing program at The University of Texas at Austin. The objective of this research is to study the behavior of anchors under dynamic and static loading. The research includes the study of single and multiple anchors in tensile loading, and of near-edge anchors and multiple-anchor connections in tensile and shear loading.

The NRC test program consists of 5 main Tasks:

Task 1: Static and Dynamic Behavior of Single Tensile Anchors

Task 2: Static and Dynamic Behavior of Multiple Tensile Anchors

Task 3: Static and Dynamic Behavior of Near-Edge Anchors

Task 4: Static and Dynamic Behavior of Multiple-Anchor Connections

Task 5: Submission of Final Report

The main purpose of Task 1 is to provide background information regarding the tensile behavior of single anchors in cracked and uncracked concrete. Task 2 involves the behavior of multiple-anchor connections under tensile loading. In Task 3, the behavior of near-edge anchor under tensile and shear loadings is studied. Task 4, the behavior of multiple-anchor connections under eccentric loading is studied. The last task, Task 5, is a summary of the above tasks, and thu wº%vall/Î[€Fm□□□"þ□„

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- Type of coarse aggregate
- Concrete compressive strength
- Types of anchor
- Effect of reinforcement

Chapter 2
Background

2.1 General Description

This chapter presents background material on anchors used for fastening to concrete. Such anchors are described and their failure modes are discussed. Additional background material on anchor behavior is given in Reference 2.

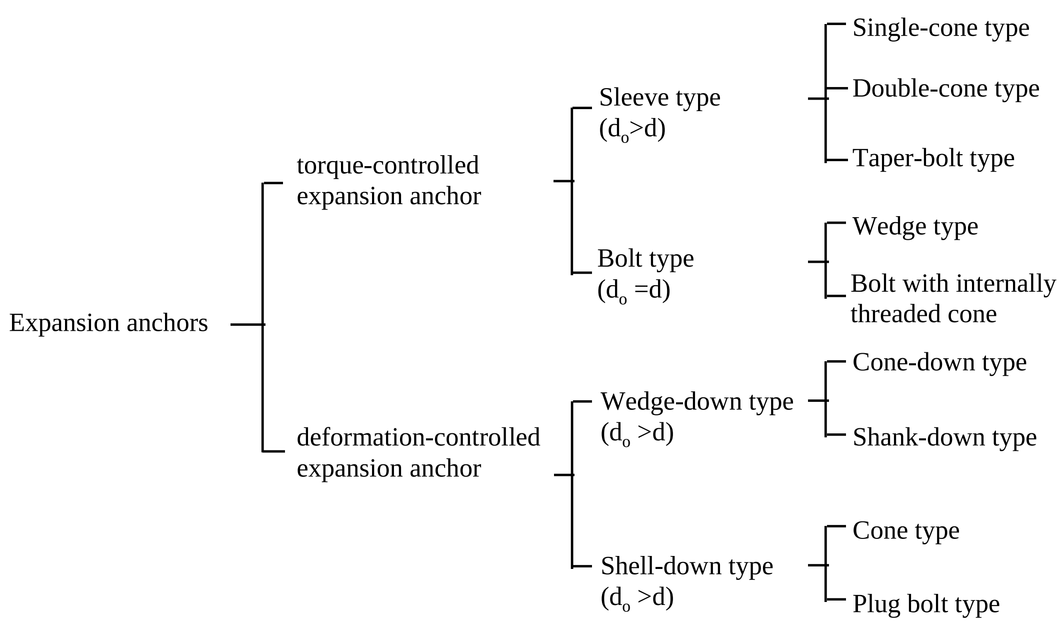
2.2 Anchor Classification

The primary purpose of an anchor is to attach a structure or piece of equipment to concrete or masonry. Anchors transmit tension and shear due to externally applied loads into the concrete. Basically, there are two categories of anchors: cast-in-place and post-installed (retrofit). As their name suggests, cast-in-place anchors are held in place in fresh concrete. Post-installed anchors, however, are installed into hardened concrete.

Based on their installation characteristics, there are four types of post-installed or retrofit anchors: 1) self drilling, 2) bonded, 3) expansion, and 4) undercut. Self-drilling anchors are screw-type anchors installed by drilling them into the concrete. Bonded anchors use adhesives such as epoxies, vinylesters, polyesters, or cementitious grout; they are installed by mixing the adhesive components and placing them, with the anchor, into a pre-drilled hole. Expansion anchors are placed within a pre-drilled hole and are torqued to expand a sleeve. Undercut anchors are installed using a special bit that makes an undercut at the bottom of the hole. The anchor is then torqued so that its base expands within the undercut. This thesis discusses the following three types of anchors: expansion, undercut, and bonded anchors.

2.3 Expansion Anchors

There are two kinds of expansion anchors: torque-controlled and deformation-controlled. Both classes of anchors consist of two pieces: an anchor body; and an expansion mechanism that fits around the steel cone of the anchor body. The installation and load-carrying characteristics for each class are somewhat different. Each class is further subdivided as shown in Figure 2.1.



(d_o =diameter of hole, d=diameter of anchor)

Figure 2.1 Classification of expansion anchors

Torque-controlled anchors are installed to the torque specified by the manufacturer. During installation, the expansion mechanism is held in place by friction between the expansion mechanism and the surrounding concrete. As torque is applied, the steel cone is drawn toward the free surface, causing the expansion mechanism to expand over the steel cone.

Externally applied loads are resisted by friction between the concrete and the anchor shaft. Additional load causes further expansion of the expansion mechanism.

Deformation-controlled anchors are installed with a displacement prescribed by the manufacturer, usually 3 to 5 turns of the nut. When a displacement is applied, an expansion mechanism expands around a steel cone similar to that of torque-controlled anchors. However, externally applied loads do not cause additional spreading of the expansion mechanism.

The following section describes the expansion anchors used in the NRC testing program prepared for the NRC. The anchors used are a wedge anchor and a single-cone type expansion anchor with follow-up expansion capability.

2.3.1 Wedge-type anchor used for NRC Testing

The wedge-type anchor is an anchor body, one end of which is threaded, and the other end of which has the load-transfer mechanism shown in Figure 2.2. The anchor is installed in a pre-drilled hole slightly larger in diameter than the anchor shaft. The expansion mechanism is called a wedge; its action depends on the friction forces between

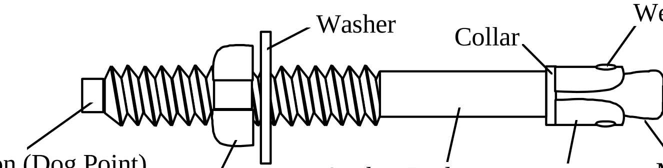


Figure 2.2 Wedge-type anchor used for NRC testing

the wedge and the mandrel, and between the wedge and the concrete. This friction force controls how much the wedge will expand, and depends on the mandrel geometry.

2.3.2 Single-cone type anchor

The single-cone type anchor belongs to the general category of sleeve-type anchors. As shown in Figure 2.3, it has a complex configuration compared to the wedge type anchor. The expansion mechanism is called an expansion sleeve; its action depends on the friction forces, like a wedge-type anchor, but it has an extra sleeve that pushes the expansion sleeve to start the expansion process.

The expansion sleeve has a special geometry. The sleeve increases in thickness with increasing distance from the cone, as shown in Figure 2.4.

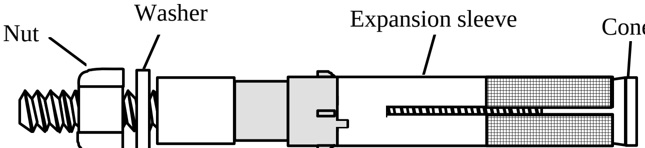


Figure 2.3 Torque-controlled expansion anchor with follow-up expansion capability (heavy-duty sleeve anchor) user for NRC testing

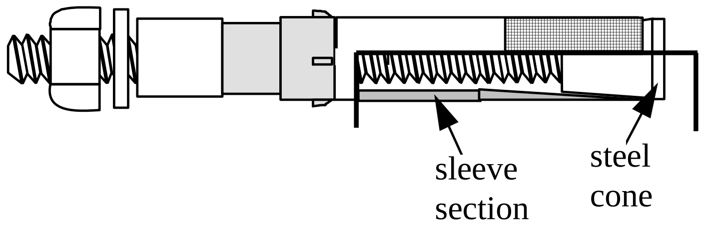


Figure 2.4 Section through heavy duty sleeve anchor

2.4 Undercut Anchor

Undercut anchors transfer load to the concrete by mechanical interlock. The anchor, shown in Figure 2.5, consists of a threaded rod with a steel cone and an expansion sleeve. The expansion sleeve is the mechanism for transferring load to the concrete.

The undercut anchor system requires a pre-drilled hole whose diameter is enlarged at the bottom. This "undercutting" operation can be carried before or during anchor installation. The installation sequence for an undercut anchor whose undercut is made before anchor installation, is shown in Figure 2.6.

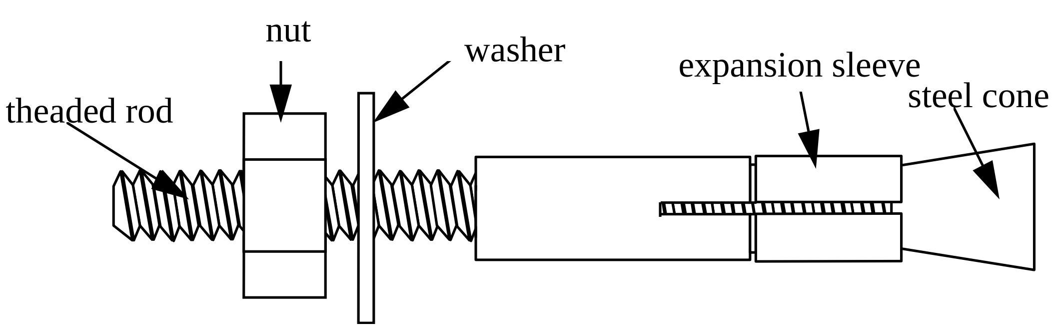


Figure 2.5 Typical undercut anchor

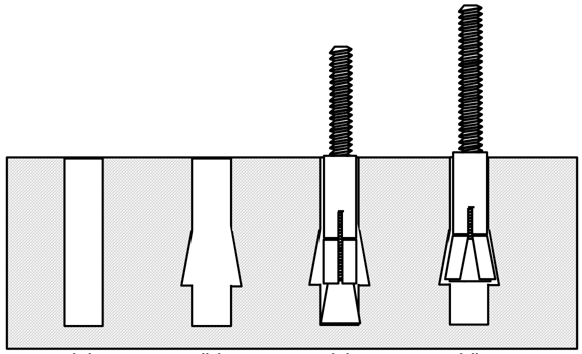


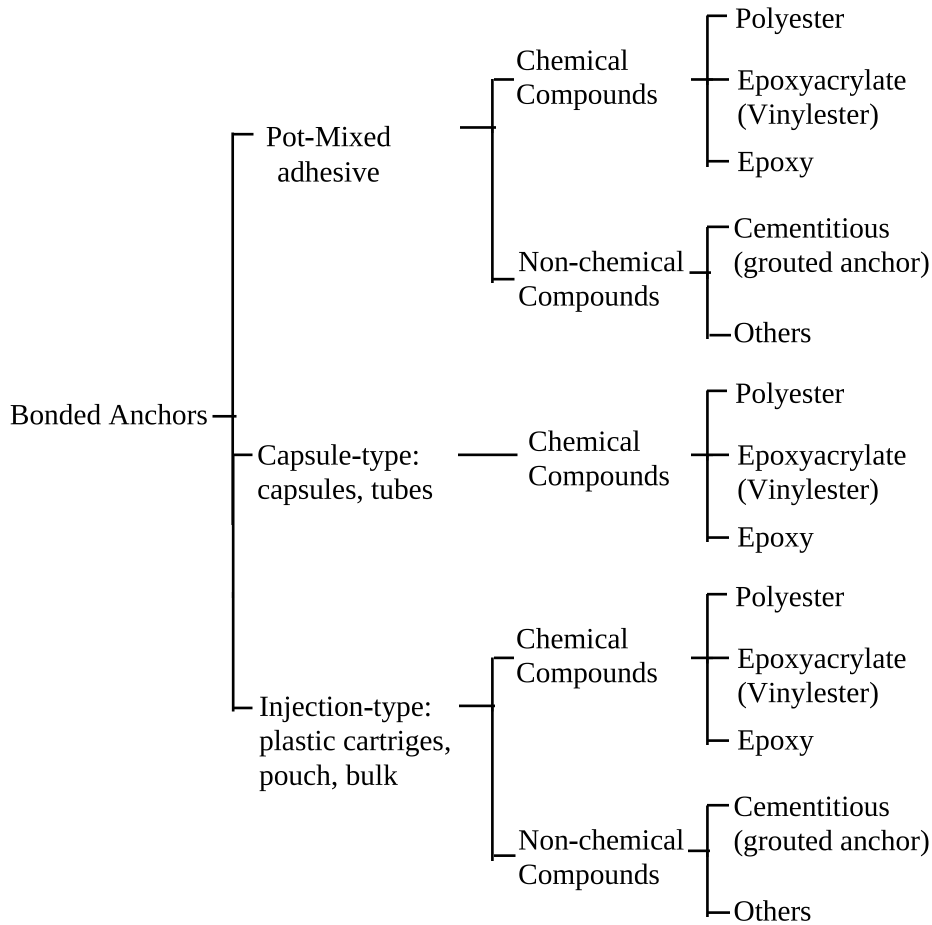
Figure 2.6 Illustration of operation of typical undercut anchor:
(a) drilled hole; (b) after undercutting, (c) undercut anchor inside the hole
(d) undercut anchor after expansion

2.5 Bonded Anchors

Bonded anchors include the entire range of mortar-filled embedments, including cementitious and polymeric-based systems. Bonded anchors are further subdivided according to the method of placement, as shown in Figure 2.7.

Bonded anchors transfer the load to the concrete, as the name suggests, bonding the anchor rod and the mortar and between the mortar and the wall of the pre-drilled or cored hole. To ensure better bonding between the mortar and the anchored element, deformed bars or threaded rods are recommended.

Figure 2.7 Classification of bonded anchors



2.5.1 Grouted Anchors Tested in the Study

The grouted anchor uses a standard headed bolt embedded in a cementitious grout placed in a cored or drilled hole. The layout is shown in Figure 2.8. The grout provides the bond between the bolt and the concrete.

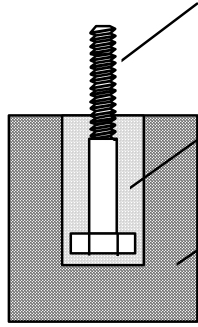


Figure 2.8 Grouted anchor

2.6 Failure Mode of Anchors Tested in this Study

The behavior of the anchor under static tensile force depends on interaction of the following parameter: concrete strength; steel strength; friction force between the concrete and the steel; and friction force between steel components of the anchor. The lowest parameter controls the capacity of the anchor. Each anchor can develop some or all of these forces, depending on the anchor type.

The most common anchor failure modes are cone breakout, steel yield, pull-out and pull-through. The following section presents each failure. For designs of anchors for critical applications, the desired failure mode is ductile; that is, governed by yield and fracture of the anchor shank. Pull-out and pull-through are undesirable because they are less predictable and are often highly anchor-dependent. Cone breakout failure, while less desirable than steel failure, is more predictable than pull-out or pull-through failure.

2.6.1 Cone Breakout Failure

A cone breakout failure, shown in Figure 2.9, is the failure of the concrete in which the anchor is embedded. Failure begins with the formation of microcracks in the concrete surrounding the anchor head. With increasing load, the microcracks join to form a macrocrack which propagates to the concrete surface, generating a conical breakout body. Whether the anchor is physically included in the cone failure is irrelevant; the capacity to carry load depends in the strength of the concrete. The concrete cone failure surface is generally inclined at about 35 degrees with respect to the free surface.

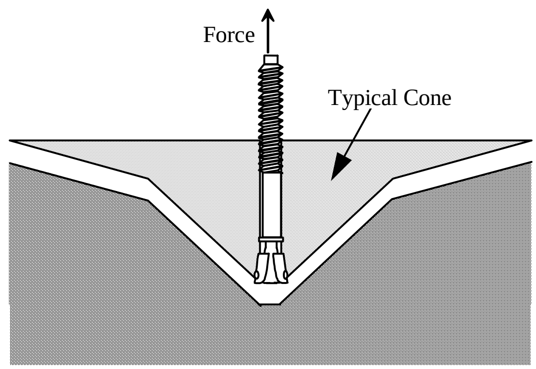


Figure 2.9 Cone breakout failure

Experimental results [3] show that the cone failures depend on the strength of the concrete and on the anchor embedment depth. The following empirical formula [3] has been shown to be most accurate for design [4,5] used:

$$P_n = k * \left(\sqrt{f'_c}\right) * h_{eff}^{1.5}$$

P_n = Tensile cone breakout capacity, lbs

k = constant

= 35.05 for expansion and undercut anchors

= 40.24 for headed anchors

f'_c = Specified concrete compressive strength, psi

h_{eff} = effective embedment, in.

2.6.2 Steel Failure

Steel failure is characterized by yield and fracture of the steel. The failure starts with yielding and necking of the steel, followed by steel fracture, as shown in Figure 2.10. The load depends only on the strength of the steel.

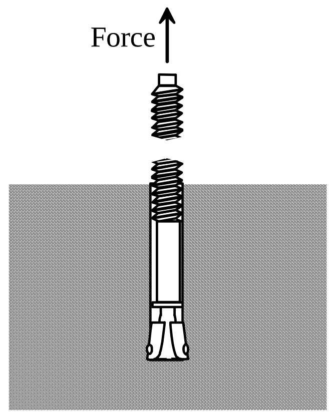


Figure 2.10 Steel failure

2.6.3 Pull-Through Failure

Pull-through failure consists of relative movement between the expansion mechanism and the steel cone. The anchor body comes out of the hole while the expansion mechanism stays inside the hole, as shown in Figure 2.11. The pull-though force depends on the friction force between the expansion mechanism and the steel cone. The surface condition of those steel elements significantly affects the anchor behavior. The normal force producing the friction force depends on the inclination of the steel cone, and on the tensile force in the anchor.

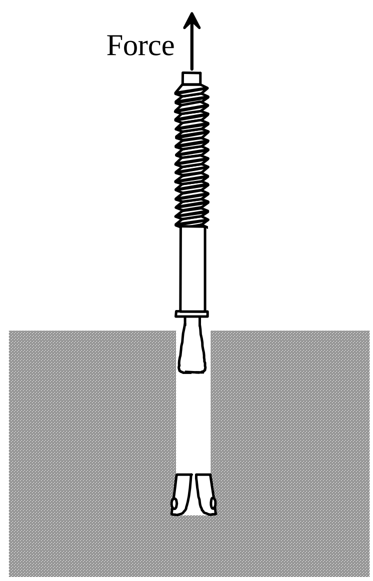


Figure 2.11 Pull-through failure

2.6.4 Pull-Out Failure

Pull-out failure occurs when friction between the concrete and the expansion mechanism is overcome by the applied force. The anchor comes out of the hole completely, as shown in Figure 2.12. This friction force depends on the coefficient of friction between the concrete and the expansion mechanism.

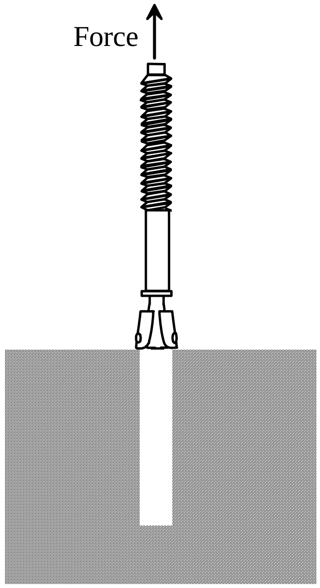


Figure 2.12 Pull-out failure

Chapter 3

NRC Testing Program

3.1 General Description

In this chapter the NRC testing program is presented, and test procedures are described. Test variables, specimen, matrix, nomenclature, anchors and installation procedures are discussed.

3.2 Concrete Characteristics

NRC data indicated that most concrete found in existing nuclear plants has a compressive strength between 4000 and 5500 psi (25.6 and 37.9 MPa) and that some may be in 3000 psi (20.7 MPa) [6] range. The testing program therefore emphasizes concrete with compressive strengths between 4000 and 5500 psi (25.6 and 37.9 MPa), and includes some tests in 3000-psi (20.7 MPa) concrete. Concrete with soft limestone aggregate generally represents the most conservative case, because soft aggregate deforms under local bearing stresses. However, some concrete with river gravel aggregate of medium hardness was also used.

3.3 Type of Tensile Loading

Most static loads in the test program were applied using a hand-controlled electrical pump, applying load at a constant rate. For dynamic loads, two quite distinct loading patterns were used. For the initial dynamic testing covered in the test program, it was desired to examine the effects of earthquake-type dynamic loading on anchor capacity as governed by factors other than steel failure. Equipment response to strong earthquake depends on the earthquake, and also on the dynamic characteristics of the equipment. Unlike fatigue loading, earthquake response usually consists of relatively few reversed cycles of load, at frequencies of 3 Hz or less. It was initially considered appropriate to subject anchors to such pulses. However, for purposes of this test program, it was necessary to load the anchors dynamically to failure, as governed by mechanisms other than steel yield and fracture.

Previous research [7] had shown that anchors loaded by triangular pulses would not fail under low-cycle fatigue unless the load level exceeded the static failure load. Therefore, it would be necessary to subject the anchors to a dynamic, triangular load pulse whose magnitude would need to exceed the anchor capacity (which would not be known in advance). Under these circumstances, it was reasoned that it would make no difference whether the pulse were a triangle or simply an increasing ramp load, since the test would be ended in any event by anchor failure. As a result, the dynamic load selected for the test was a ramp load to failure. As shown in Figure 3.1, the rise time of this load (about 0.1 seconds) was set to correspond to that of typical earthquake response.

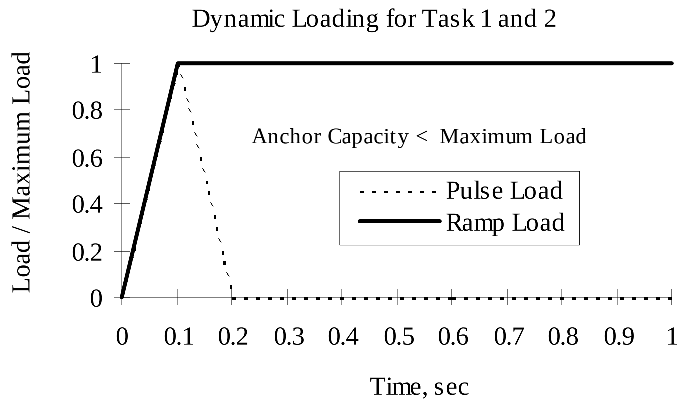


Figure 3.1 Ramp-type dynamic loading used for Task 1 and 2

3.4 Anchors

Based on surveys of existing anchors in nuclear applications, the NRC was primarily interested in documenting the behavior of selected wedge-type expansion anchors, of selected undercut anchors, and also of anchors in cementitious grout. The testing program for test program originally emphasized one wedge-type expansion anchor (referred to here as “Expansion Anchor”), with some tests on one undercut anchor (“U/C Anchor 1”), and other tests on anchors in one type of cementitious grout (“Grouted Anchor”). As the testing progressed, several more anchors were added: a variant on the expansion anchor (“Expansion Anchor II”); another undercut anchor (“U/C Anchor 2”); and a heavy-duty sleeve-type single-cone expansion anchor (“Sleeve Anchor”). Based on current use in nuclear applications, it was decided to test anchors ranging in diameter from 3/8 to 1 inch (9.2 to 25.4 mm), with emphasis on 3/4-inch (19.1 mm) diameter.

3.5 Embedment Depths

For nuclear applications, the overall anchor design objective is to have failure governed by yield and fracture of anchor steel. Because the dynamic behavior of the anchor steel itself is relatively well understood, the embedments were shallow enough so that behavior would be governed by pull-through, pull-out, or concrete cone breakout. Information on dynamic capacity as governed by those failure modes can be used to ensure ductile behavior in later phases of the NRC testing program, and also in practice.

3.6 Reinforced Concrete Configuration

Most specimens were designed without reinforcement in the area that would be affected by the concrete breakout cone. Specimens in series labeled “reinforced concrete” had a curtain of #8 bars spaced at 8 inches (203 mm) in each direction, placed with 1-1/2 inch (38.1 mm) cover, and intended to simulate reinforcement in a heavily reinforced wall.

3.7 Test Matrix for Task 1

The test matrix was developed using the following variables :

- Concrete characteristics
- Anchors
- Types of tensile loading
- Type of reinforced concrete

The test program for Task 1 was divided into 7 series, each of which involved different combinations of the above variables. Five replicates of each test were conducted.

3.7.1 Series 1-0

The first series, termed Series 1-0, was conducted to compare the two types of wedge anchor (Expansion Anchor and Expansion Anchor II). The comparison was made between two embedments: the manufacture's standard embedment, and the minimum recommended embedment (4.75 inches {120.7 mm} and 3.25 inches {82.6 mm}, respectively). All tests were performed in 4700-psi (32.4 MPa) uncracked concrete with limestone aggregate. As shown in Table 3.1, 40 tests were performed.

It had been known from the beginning of the test program that the wedge-type Expansion Anchor emphasized in the original Task 1 testing program was no longer commercially available in its original form (that found in many nuclear power plants). The current version of the anchor (identified here as Expansion Anchor II) was thought to behave quite differently from the previous version. After this test series, the results obtained differed from what was expected; as a result, the original test program was modified. The following descriptions refer to the test series of the modified test program.

Table 3.1 Test matrix for Series 1-0

Description	Concrete Strength	Anchors Tested (5 replicates)
Static comparison tests at standard embedment	4700 psi limestone	Expansion Anchor, 3/4" Expansion Anchor II, 3/4"
Dynamic comparison tests at standard embedment	3000 psi limestone	Expansion Anchor, 3/4" Expansion Anchor II, 3/4"
Static comparison tests at minimum embedment	4700 psi limestone	Expansion Anchor, 3/4" Expansion Anchor II, 3/4"
Dynamic comparison tests at minimum embedment	3000 psi limestone	Expansion Anchor, 3/4" Expansion Anchor II, 3/4"

3.7.2 Series 1-1 and Series 1-2

The second and third series of tests, termed Series 1-1 and Series 1-2, involved static and dynamic tensile loading respectively. The tests were made with three different types of anchor: Expansion Anchor II; U/C Anchor 1; and grouted anchors. Other variables used were the type of aggregate and the concrete compressive strength. Embedments were 4.0 inches (101.6 mm) for the 3/4-inch (19.1 mm) anchor, and 2.25 inches (57.2 mm) for the 3/8-inch (9.5 mm) anchor. As shown in Tables 3.2 and 3.3, 35 tests were conducted in each of these two series.

Table 3.2 Test matrix for Series 1-1

Description	Concrete Strength	Anchors Tested (5 replicates
Static tensile tests of single anchors in unreinforced concrete	4700 psi limestone	Expansion Anchor II, 3/8" Expansion Anchor II, 3/4" U/C Anchor 1, 3/4" Grouted anchor, 3/4"
Static tensile tests of single anchors in unreinforced concrete	3000 psi limestone	Expansion Anchor II, 3/4"
Static tensile tests of single anchors in unreinforced concrete	4700 psi river gravel	Expansion Anchor II, 3/4"
Static tensile tests of single anchors in unreinforced concrete	3000 psi river gravel	Expansion Anchor II, 3/4"

Table 3.3 Test matrix for Series 1-2

Description	Concrete Strength	Anchors Tested
Dynamic tensile tests of single anchors in unreinforced concrete	4700 psi limestone	Expansion Anchor II, 3/8" Expansion Anchor II, 3/4" U/C Anchor 1, 3/4" Grouted Anchor, 3/4"
Dynamic tensile tests of single anchors in unreinforced concrete	3000 psi limestone	Expansion Anchor II, 3/4"
Dynamic tensile tests of single anchors in unreinforced concrete	4700 psi river gravel	Expansion Anchor II, 3/4"
Dynamic tensile tests of single anchors in unreinforced concrete	3000 psi river gravel	Expansion Anchor II, 3/4"

3.7.3 Series 1-3 and Series 1-4

The fourth and fifth series, termed Series 1-3 and Series 1-4, were performed in reinforced concrete. The concrete strength was 4700 psi (32.4 MPa); the aggregate was limestone; and the embedment was 4 inches (101.6 mm). Series 1-3 was carried out with static tensile loading, and Series 1-4 with dynamic tensile loading. As shown in Table 3.4 and 3.5, 5 tests were performed for each series.

Table 3.4 Test matrix for Series 1-3

Description	Concrete Strength	Anchors Tested (5 replicates)
Static tensile tests of single anchors in reinforced concrete	4700 psi limestone	Expansion Anchor II, 3/4"

Table 3.5 Test matrix for Series 1-4

Description	Concrete Strength	Anchors Tested (5 replicates)
Dynamic tensile tests of single anchors in reinforced concrete	4700 psi limestone	Expansion Anchor II, 3/4"

3.7.4 Series 1-5 and Series 1-6

The last two series, termed Series 1-5 and Series 1-6, are described in Tables 3.6 and 3.7. These series, a modification of the original test program, were introduced to permit comparative evaluations of the performance of two additional anchor types. The test program added a 3/8-inch (9.5 mm) diameter and a 3/4-inch (19.1 mm) U/C Anchor 1, tested in 3000 psi (20.7 MPa) limestone concrete and 4700 psi (32.4 MPa) river gravel concrete. Also added were two anchors: a single-cone type expansion anchor (Sleeve Anchor); and another undercut anchor (U/C Anchor 2). The Sleeve Anchor was tested in two diameters (3/8 and 3/4 inches{9.5 and 19.1 mm}) in 4700-psi (32.4 MPa) concrete with limestone aggregate. U/C Anchor 2 was tested in 3/4-inch (19.1 mm) diameter in 4700 psi (32.4 MPa) concrete with limestone aggregate. Series 1-5 and 1-6 were conducted using static and dynamic tensile loading, respectively. Each series had a total of 30 tests.

Table 3.6 Test matrix for Series 1-5

Description	Concrete Strength	Anchors Tested (5 replicates)
Additional static tensile tests of single anchors in unreinforced concrete	4700 psi limestone	U/C Anchor 1, 3/8" U/C Anchor 2, 3/4" Sleeve Anchor, 3/8” Sleeve Anchor, 3/4”
Additional static tensile tests of single anchors in unreinforced concrete	4700 psi river gravel	U/C Anchor 1, 3/4"
Additional static tensile tests of single anchors in unreinforced concrete	3000 psi limestone	U/C Anchor 1, 3/4"

Table 3.7 Test matrix for Series 1-6

Description	Concrete Strength	Anchors Tested (5 replicates)
Additional static tensile tests of single anchors in unreinforced concrete	4700 psi limestone	U/C Anchor 1, 3/8" U/C Anchor 2, 3/4" Sleeve Anchor, 3/8” Sleeve Anchor, 3/4”
Additional static tensile tests of single anchors in unreinforced concrete	4700 psi river gravel	U/C Anchor 1, 3/4"

Additional static tensile tests of single anchors in unreinforced concrete	3000 psi limestone	U/C Anchor 1, 3/4"

3.7.5 Nomenclature for Specimen Identification

The test specimen nomenclature consists of an eight-digit combination of numbers and letters. Table 3.8 shows the variables and the significance of each digit. For example, 2DKL5401 is a test from Series 2 with dynamic tensile loading, with Expansion Anchor II, in a specimen with limestone aggregate and 4700-psi (32.4 MPa) concrete, with a 3/8-inch (9.5 mm) anchor; and it is the first test of the series. Table 3.8 shows the variables and the significance of each digit.

The first digit represents the task series, and can have values from zero to six. The second digit is an "S" or "D", corresponding to static or dynamic tensile loading respectively. The third digit refers to the type of anchor tested. The letters used were "K" for Expansion Anchor II, "O" for Expansion Anchor, "M" for U/C Anchor 1, "S" for U/C Anchor 2, "H" for Sleeve Anchor, and "G" for Grouted Anchor. The fourth and fifth digits represent the specimen properties: the fourth digit represents the type of aggregate; and the fifth digit, the strength of the specimen. Types of aggregate used were

Table 3.8 Nomenclature for specimen identification

First Digit	Second Digit	Third Digit	Fourth Digit	Fifth Digit	Sixth Digit	Seventh and Eighth Digits
Series	Loading	Anchor	Aggregate	fc (psi)	Diameter	Position
0 **1** **2** **3**	**D**: Dynamic **S**: Static	**K**: E. A II **O**: E. A. **M**: U/C 1 **S**: U/C 2	**L**: Limestone **R**: River Gravel	**5**: 4700 **3**: 3000	**4**: 0.375 in **7**: 0.75 in	01 to Number of tests in the Series

4 **5** **6**		**H**: S.A.1 **G**: Grout				

limestone ("L") and river gravel ("R"). Specimens with 4700-psi (32.4 MPa) concrete were designated by the number "5."; and those with 3000-psi (20.7 MPa) concrete, by the number “3.” The sixth digit represents the diameter of the bolt. A diameter of 0.375 inches (9.5 mm) was represented by "4."; and a diameter of 0.75 inches (19.1 mm) by "7." The last two digits signify the test number within each series.

3.8 Testing Procedure for Task 1 Tests

The following procedure was used for Task 1 tests:

- anchors were installed in the concrete specimen
- loading equipment was set up
- instrumentation and data acquisition equipment were set up
- the anchor was tested
- data were reduced and plotted

3.9 Concrete Specimen

The typical test specimen, shown in Figure 3.2, was a concrete block 39.5 inches (1 m) wide, 24 inches (0.6 m) deep, and 87.5 inches (2.2 m) long. Seven #6 longitudinal reinforcing bars were placed in the middle of each block to provide safety when the block was moved. This reinforcement was placed at the mid-height of the block to permit testing anchors on both the top and bottom surfaces, while precluding interference with anchor behavior. Four lifting loops were located at the mid-height of the blocks, permitting transport by overhead crane.

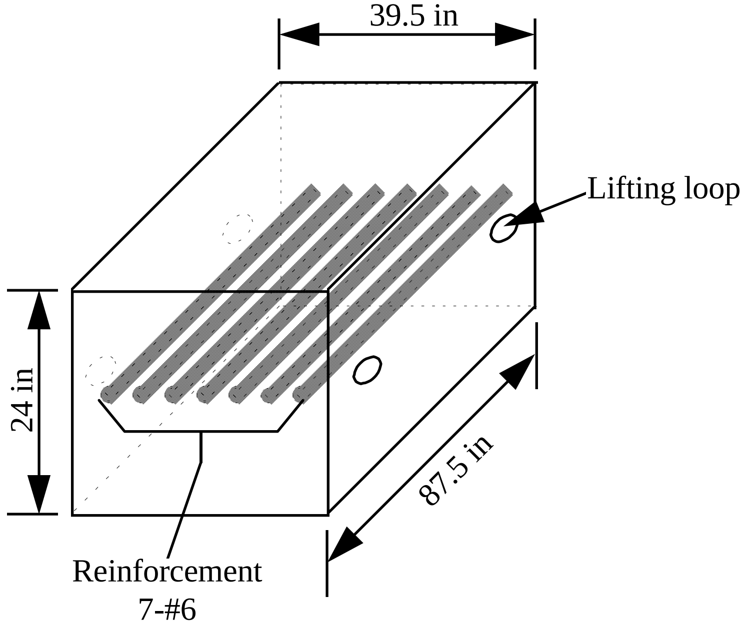


Figure 3.2 Block configuration

3.9.1 Mix Design

The project required four different types of concrete, involving the mix designs shown in Table 3.9. The main differences among mix designs are the type of coarse aggregate (limestone or river gravel), and the concrete strength (3000 or 4700 psi {20.7 or 32.4 MPa}). All the mix designs included a retarding admixture for placing the concrete. To reduce the variability in water demand in mixes with limestone aggregate, that aggregate was sprinkled (at the batch plant) for 24 hours prior to batching.

Table 3.9 Mix designs used for Task 1 testing

Concrete	**Concrete Design**				
	Cement (lb/yd^3)	**Coarse Aggregate (lb/yd^3)**	**Fine Aggregate (lb/yd^3)**	**Water (lb/yd^3)**	**Retarding (oz/yd^3)**
3000 psi Limestone	360	1884	1435	266	10.5
4700 psi Limestone	390	1876	1432	250	48.0
3000 psi River Gravel	360	1884	1435	266	10.5
4700 psi River Gravel	390	1876	1432	250	48.0

3.10 Anchor Installation

All anchors were installed according to their respective manufacturer's instructions. To duplicate the effects of loss of prestress due to concrete relaxation, anchors were torqued to manufacturer's specifications, and then loosened and re-torqued to half the specified value.

3.11 Test Setup

The test setup consists of a concrete specimen, loading equipment, and a data acquisition system. In Figure 3.3, a schematic layout of the test setup is shown. The connection between the setup and the anchor to be tested is shown in detail in Figures 3.4 and 3.5.

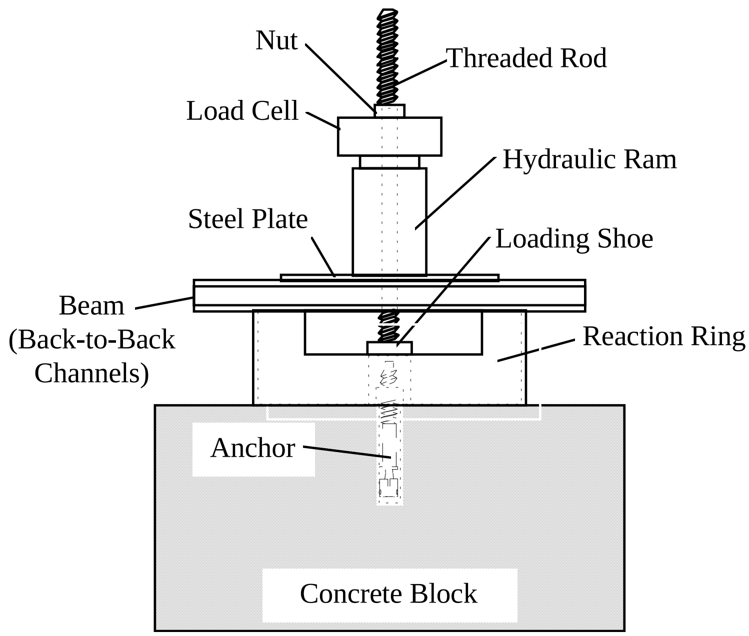


Figure 3.3 Diagram of test setup

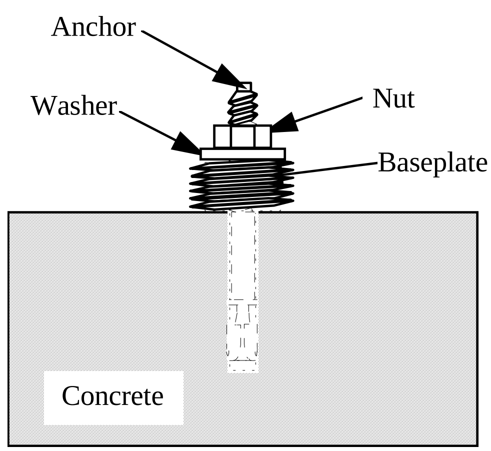


Figure 3.4 Detailed view of anchor with baseplate

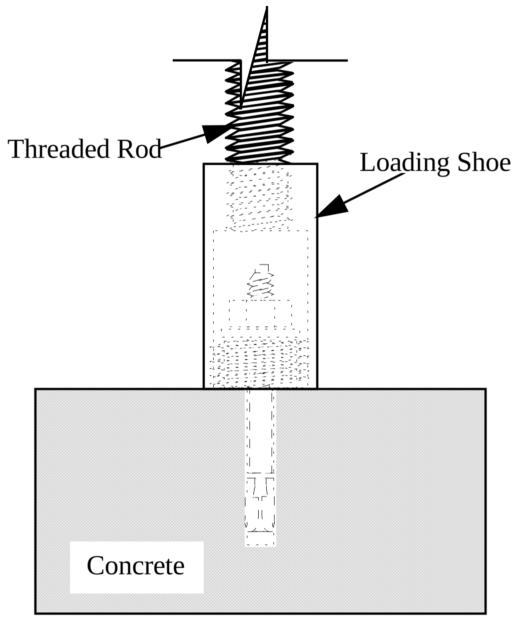


Figure 3.5 Detailed view of loading shoe

3.12 Loading Equipment

Static tensile loads were applied by a hand pump connected to 60-ton (534 kN) centerhole hydraulic ram, shown in Figure 3.6.

Dynamic tensile loads were applied by a 60-ton (534 kN) Enerpac double-action hydraulic centerhole ram, shown in Figure 3.7. Oil was supplied to the ram through a 27-gpm (102.2 lpm) electric pump, a 20-gpm (75.7 lpm) line tamer, and a 15-gpm (56.8 lpm) servo-valve controlled through a Pegasus servo-controller driven by an MTS function generator.

Figure 3.6 Static loading setup

Figure 3.7 Dynamic loading setup

3.13 Instrumentation and Data Acquisition

The data acquisition system is shown in Figure 3.8. Data from the load cell were amplified and fed to a Hewlett Packard HP 7090a plotter/data acquisition system (DAS), for recording and storage in a temporary buffer. Data from the linear potentiometer were fed directly to the DAS, where they were recorded and temporarily stored in a buffer. After each test, the buffer was down-loaded to an IBM-compatible personal computer and stored on diskettes in comma-separated value (CSV) format. Finally, data were reduced from voltages to load and displacement values using conventional spread sheet programs.

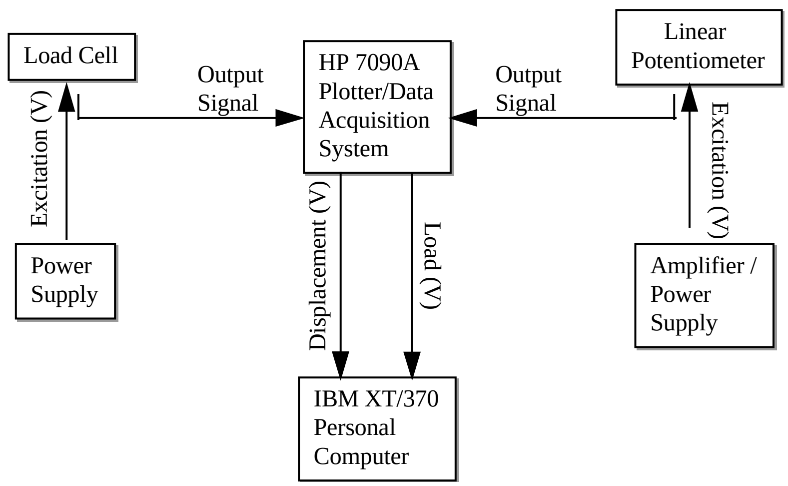


Figure 3.8 Data acquisition system

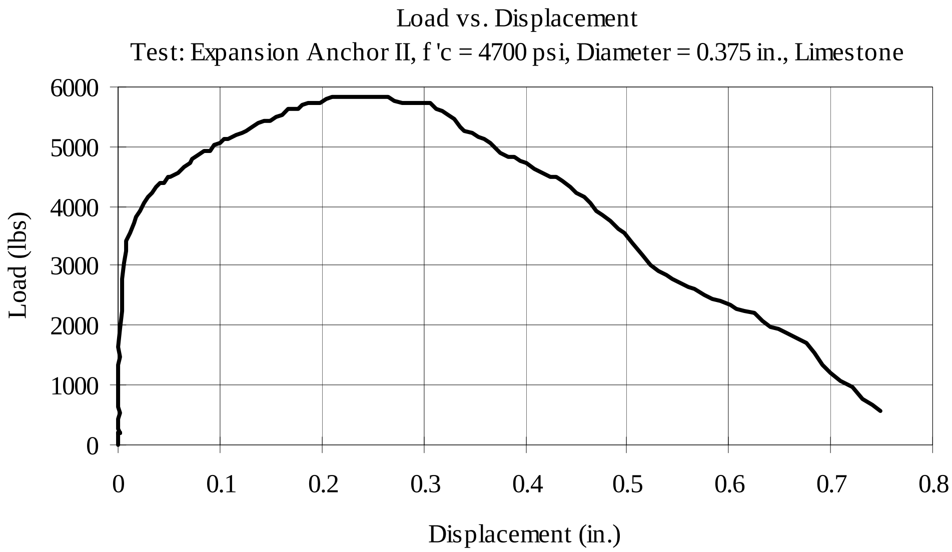


Figure 4.8 Series 1-2: Test performed in Expansion Anchor II, f 'c = 4700 psi and 0.375 in. diameter

Table 4.3 Results of Series 1-2

Concrete Strength	**Anchors Tested**	**Average of Maximum Load lb. (N)**	**COV %**	**Average of Displacement at Maximum Load in. (mm)**	**COV %**
4700 psi limestone	E. A. II, 3/8 E. A. II, 3/4 U/C A. 1, 3/4 Grouted, 3/4	5941 (26426) 16522 (73490) 26877 (119549) 31273 (139102)	6.9 6.6 4.6 4.4	0.250 (6.35) 0.245 (6.22) 0.195 (4.95) 0.074 (1.88)	38.6 29.1 28.2 37.2
3000 psi limestone	E. A. II, 3/4	12249 (54484)	20.8	0.162 (4.11)	94.3
4700 psi river gravel	E. A. II, 3/4	17530 (77973)	8.6	0.257 (6.53)	49.5
3000 psi	E. A. II, 3/4	13855 (61627)	5.2	0.320 (8.13)	22.7

river gravel					

4.5 Results of Series 1-3

Figure 4.9 shows a representative curve of anchor load-displacement behavior for one single anchor load-displacement test in reinforced concrete. The results of Series 1-3 are displayed in Table 4.4. All anchor tests had cone failures.

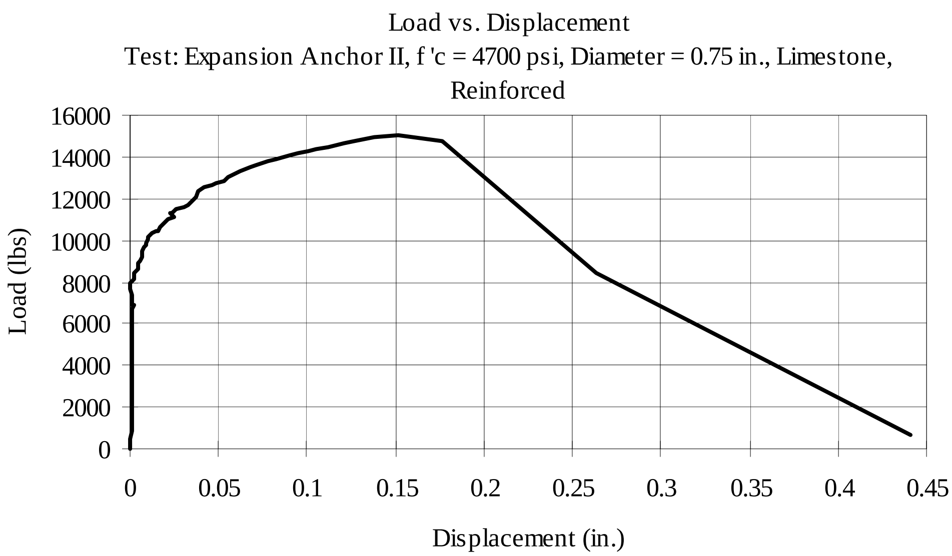


Figure 4.9 Series 1-3: Test performed in reinforced concrete, f ‘c = 4700 psi and 0.75 in. diameter

Table 4.4 Result of Series 1-3

Concrete Strength	**Anchors Tested**	**Average of Maximum Load lb. (N)**	**COV (%)**	**Average of Displacement at Maximum Load in. (mm)**	**COV (%)**

4700 psi limestone	Expansion Anchor II, 3/4	15383 (68424)	4.5	0.202 (5.13)	26.3

4.6 Results of Series 1-4

Figure 4.10 shows a typical load-displacement curve for one single-anchor load-displacement test in reinforced concrete under dynamic loading. Table 4.5 shows the results of Series 1-4. The failures for this Series were cone, pull-out and pull-through.

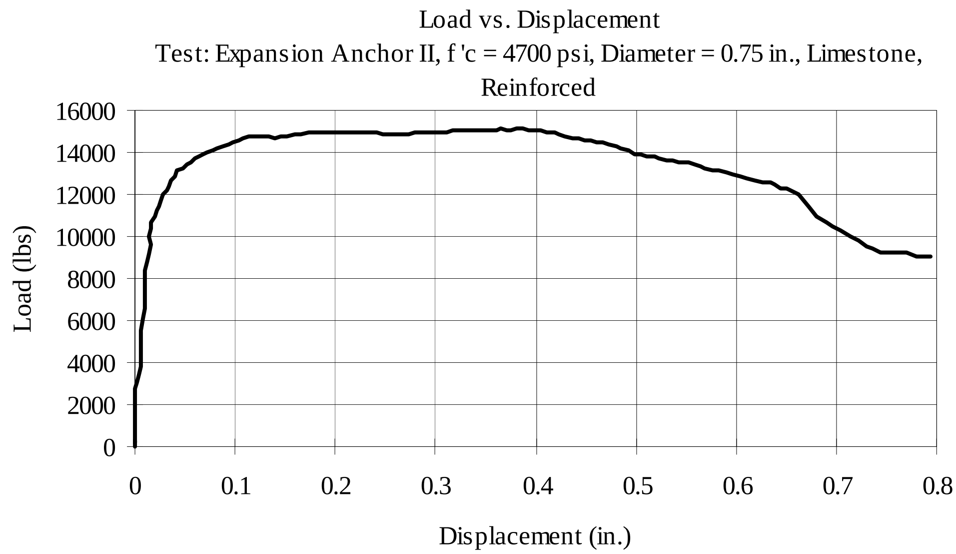


Figure 4.10 Series 1-4: Test performed in reinforced concrete, f 'c = 4700 psi and 0.75 in. diameter

Table 4.5 Result of Series 1-4

Concrete Strength	**Anchors Tested**	**Average of Maximum Load lb. (N)**	**COV (%)**	**Average of Displacement at Maximum Load in. (mm)**	**COV (%)**

4700 psi limestone	Expansion Anchor II, 3/4	16811 (74775)	10.5	0.296 (7.52)	28.3

4.7 Results of Series 1-5

Typical load-displacement behavior is shown in Figures 4.11, 4.12 and 4.13. Each graph shows one single-anchor load-displacement curve, with its respective variables. In Table 4.6, the test results are presented. All tests had cone failure.

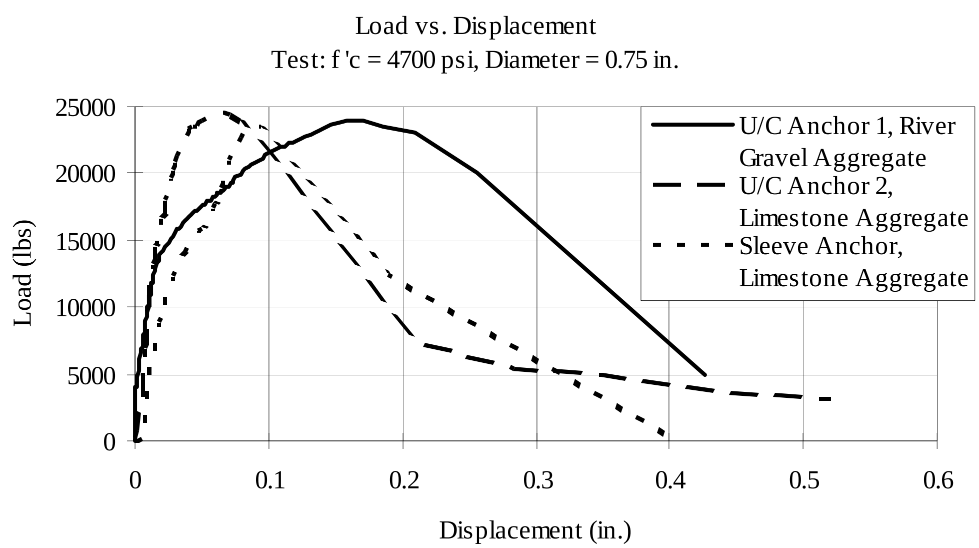


Figure 4.11 Series 1-5: Test performed in f ‘c = 4700 psi and 0.75 in. diameter

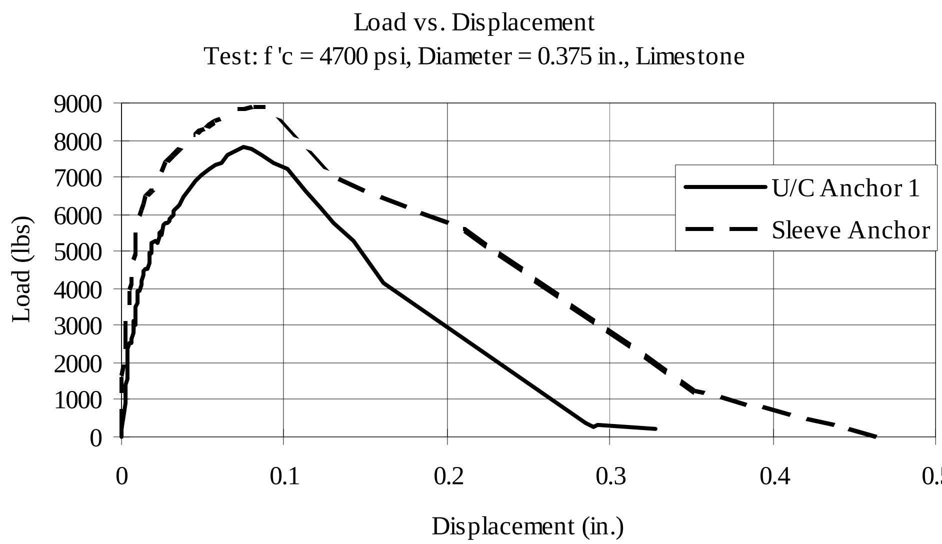


Figure 4.12 Series 1-5: Test performed in f ‘c = 4700 psi and 0.375 in. diameter

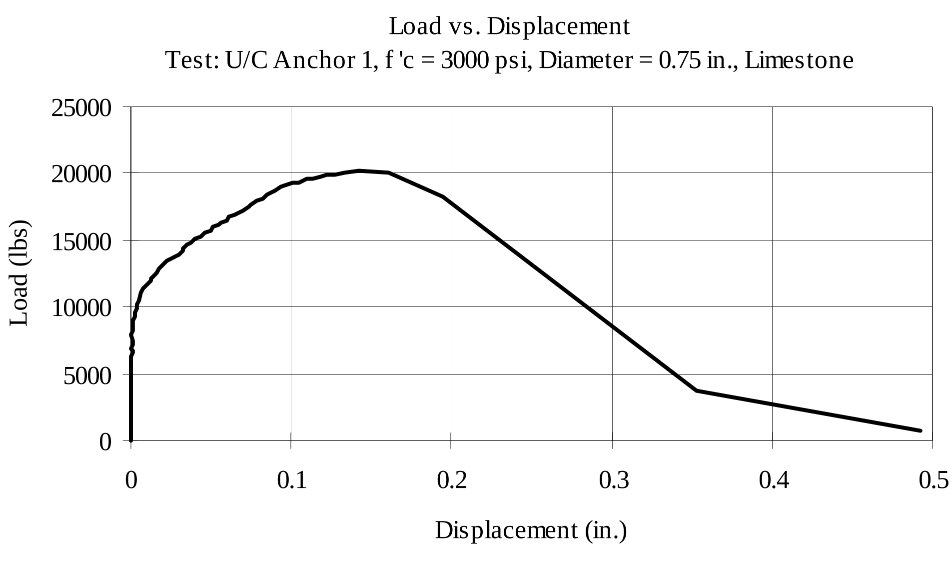


Figure 4.13 Series 1-5: Test performed in 3000 psi and 0.75 in. diameter

Table 4.6 Results of Series 1-5

Concrete Strength	Anchors Tested	Average of Maximum Load lb. (N)	COV (%)	Average of Displacement at Maximum Load in. (mm)	COV (%)
4700 psi limestone	U/C Anchor 1, 3/8 U/C Anchor 2, 3/4 Sleeve Anchor, 3/8 Sleeve Anchor, 3/4	8601 (38257) 23950 (106530) 8643 (38444) 24285 (108020)	10.6 7.3 11.3 5.7	0.099 (2.51) 0.067 (1.70) 0.122 (2.84) 0.151 (3.84)	37.5 19.5 24.0 37.7
3000 psi limestone	U/C Anchor 1, 3/4	19478 (86638)	7.4	0.136 (3.45)	33.4
4700 psi river gravel	U/C Anchor 1, 3/4	23781 (105780)	5.4	0.135 (3.43)	26.3

4.8 Results of Series 1-6

Typical load-displacement behavior is presented in Figures 4.14, 4.15 and 4.16. Each graph shows the result of one single-anchor test with its respective variables. The results are in Table 4.7. All tests had cone failure.

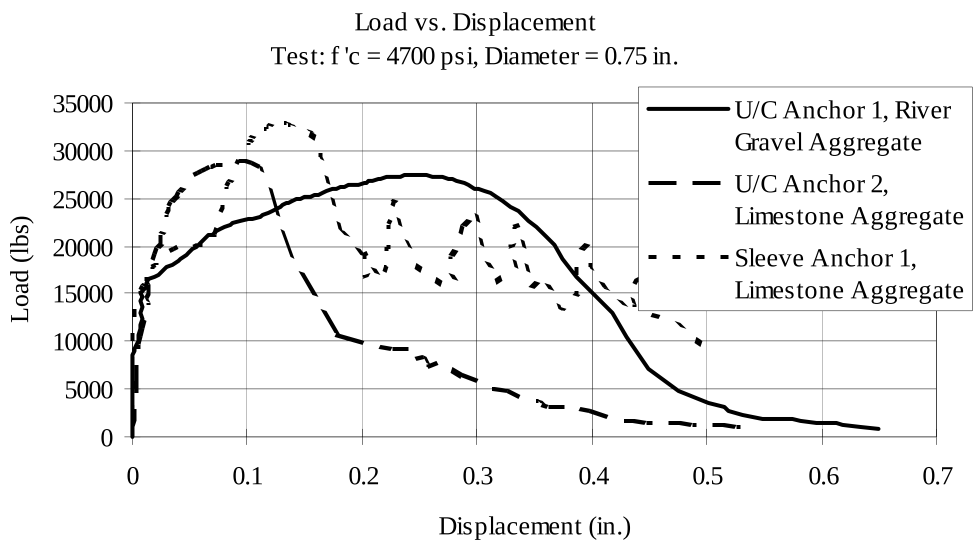


Figure 4.14 Series 1-6: Test performed in 4700 psi and 0.75 in. diameter

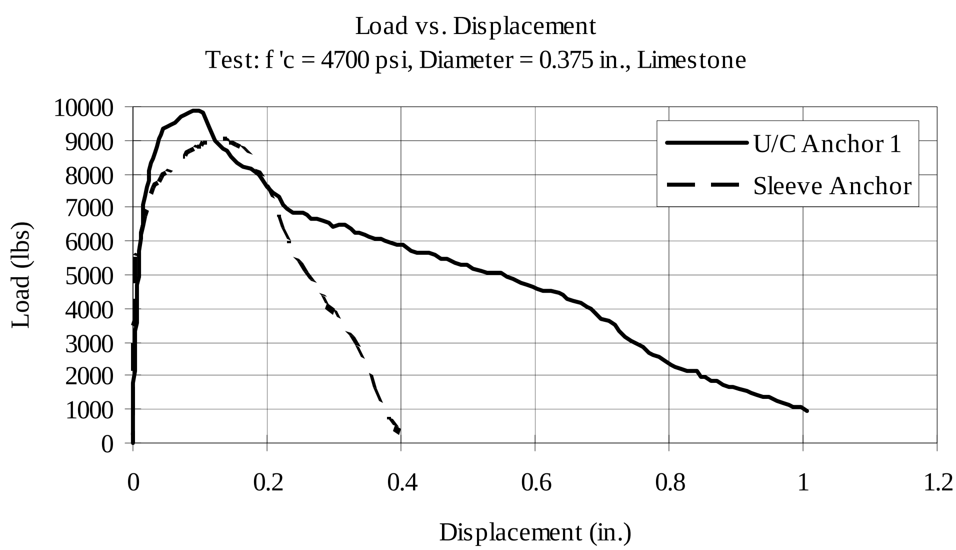


Figure 4.15 Series 1-6: Test performed in 4700 psi and 0.375 in. diameter

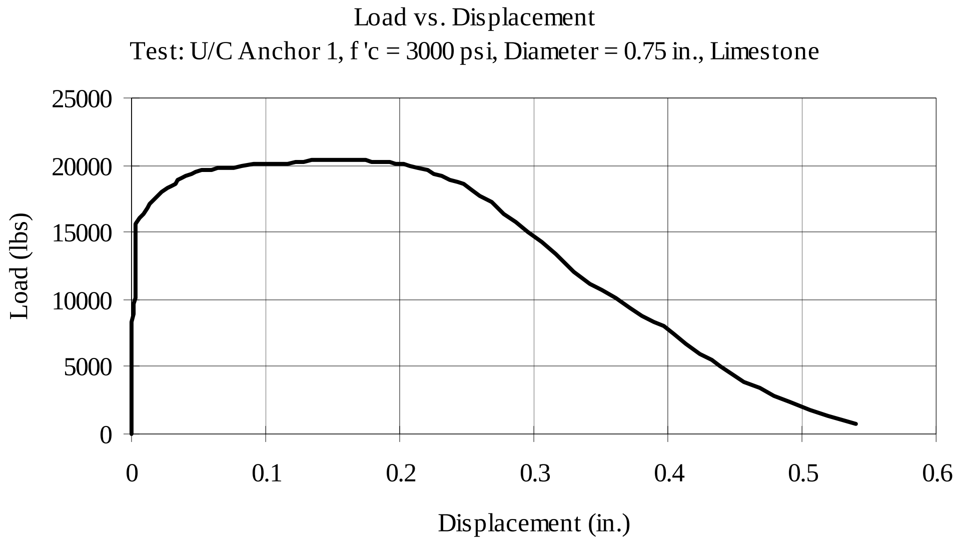


Figure 4.16: Test performed in 3000 psi and 0.75 in. diameter

Table 4.7 Results of Series 1-6

Concrete Strength	**Anchors Tested**	**Average of Maximum Load lb. (N)**	**COV (%)**	**Average of Displacement at Maximum Load in. (mm)**	**COV (%)**
4700 psi limestone	U/C Anchor 1, 3/8 U/C Anchor 2, 3/4 Sleeve Anchor, 3/8 Sleeve Anchor, 3/4	10283 (45739) 29418 (130851) 8944 (39783) 30201 (134334)	12.3 4.0 9.2 8.0	0.136 (1.78) 0.096 (2.45) 0.089 (2.26) 0.147 (3.73)	54.7 16.1 40.5 45.9
3000 psi limestone	U/C Anchor 1, 3/4	20865 (92808)	10.8	0.165 (4.19)	58.1
4700 psi river gravel	U/C Anchor 1, 3/4	26442 (117614)	2.7	0.233 (5.92)	23.4

Chapter 5

Discussion of Results from Series 1 Tests

5.1 General Description

The following sections are devoted to a discussion of the test results from Series 1 in graphical and tabular form.

5.2 Presentation of Results

To facilitate comparison of results among different anchor types, embedments, and concrete strengths, results are presented in terms of a normalized tensile capacity, k:

$$k \equiv \frac{P_n}{h_{eff}^{1.5}\sqrt{f_c}}$$

k = constant (Normalized Tensile Capacity)

P_n = Observed tensile capacity, lbs

f_c = Tested concrete compressive strength, psi

h_{eff} = Effective embedment, in.

As shown in Figure 5.1, the effective embedment was measured from the concrete surface to the end of the expansion sleeve or to the point of the clip in contact with the concrete. Table 5.1 shows all the effective embedments used for each anchor.

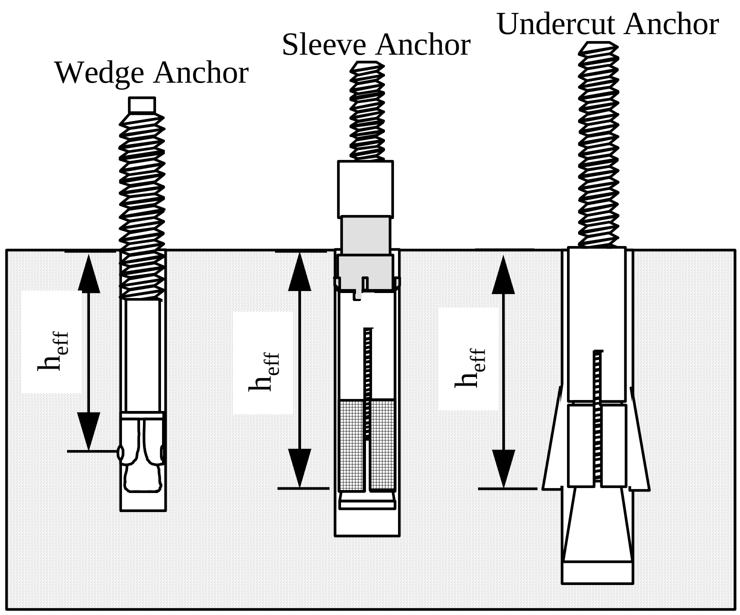


Figure 5.1 Effective Embedment of the anchors

Table 5.1 Embedment and effective embedment used for each anchor

Anchor and Diameter	Embedment in.	Effective Embedment in.
Expansion Anchor, 0.75 in.	3.25 4.75	2.44 3.94
Expansion Anchor II, 0.375 in	2.25	1.94
Expansion Anchor II, 0.75 in	3.25 4.00 4.75	2.69 3.44 4.19
U/C Anchor 1, 0.375 in.	2.25	2.25
U/C Anchor 1, 0.75 in.	4.00	4.00
U/C Anchor 2, 0.75 in.	4.00	4.00
Sleeve Anchor, 0.375 in.	2.25	2.25
Sleeve Anchor, 0.75 in.	4.00	4.00
Grouted Anchor, 0.75 in.	4.00	4.00

5.3 Behavior of Anchors Tested in Series 1

In the following sections, the behavior of the anchors is discussed.

5.3.1 Behavior of Expansion Anchors Tested in Series 1

The load-displacement curves of the Expansion Anchor, under static and dynamic loading with standard embedment, typically showed pull-through behavior. Pull-through behavior allows more displacement than cone breakout or steel behavior before the maximum load is reached. For static loading with minimum embedment, the curves typically showed cone breakout failure. Cone breakout failure typically has less displacement at maximum load (than pull-through failure), and has a steeper descending branch in the load-displacement curve. For dynamic loading with minimum embedment, the behavior is ambiguous, because the failure can occur either by cone breakout or by pull-through.

The start of all curves shows a small amount of load with no displacement. This happens because of the preload, which must be overcome before the anchor displaces. Because the manufacture's recommended torque is usually much less than that required to yield the anchor, the load at which displacement is first observed tends to be considerably below the maximum load.

5.3.2 Behavior of Expansion Anchor II Tested in Series 1

For Expansion Anchor II, the load-displacement curves for static loading with standard and minimum embedment, and for dynamic loading with minimum embedment, typically showed cone breakout behavior. For dynamic loading with standard embedment, the behavior is ambiguous because the failures can be either by pull-out with cone or by pull-through failure. Pull-out failure is characterized by a succession of slips. This process continues until either the anchor is completely out of the hole, or the embedment is reduced sufficiently to cause cone breakout failure.

The Expansion Anchor II (in 0.375- and 0.75- inch {9.1 and 19.5 mm} diameters) allows more displacement at maximum load than do other anchors, as shown in Figures 5.2 and 5.3. The expansion mechanism permits the movement. The anchor pulls through until the pressure created by the expansion mechanism produces cone breakout failure, as shown in Figure 5.4. Pull-through reduces the effective embedment, and thereby causes uncertainty in predicting the cone breakout failure load.

5.3.3 Behavior of Sleeve Anchor Tested in Series 1

The Sleeve Anchor (0.75 inches {19.1 mm} diameter) shows peculiar behavior. The anchor tested has a step inside the expansion sleeve, as shown in Figure 5.5. This step inside sleeve creates a different behavior of the anchor. Figure 5.6 presents a two single-anchor tests that illustrate this behavior. Both static and dynamic loading present similar behavior. In dynamic loading, however, the behavior is more pronounced. The first part of the curve, as shown in Figure 5.6, is defined by the steel cone sliding inside the expansion sleeve. The steel cone slides until it reaches the step, or until concrete cone breakout failure occurs. The second part of the curve begins when the steel cone hits the step inside the expansion sleeve. The friction between the steel and the concrete increases

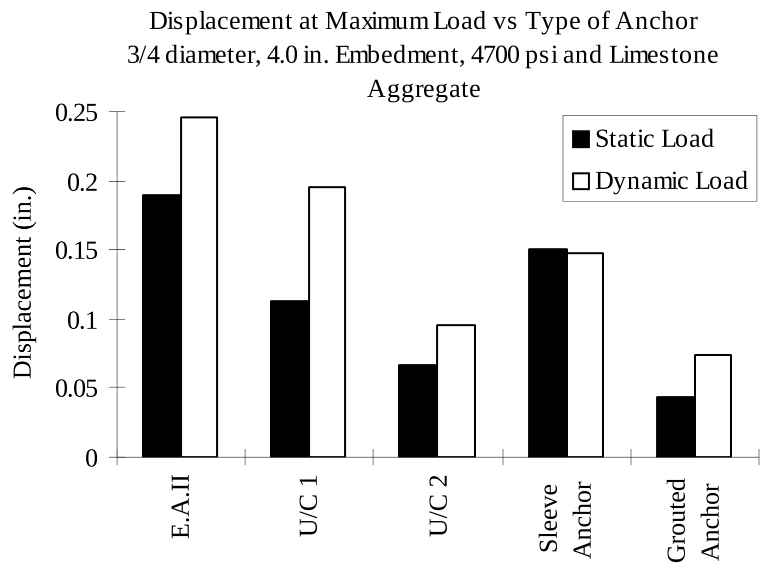


Figure 5.2 Displacement at maximum load vs Type of anchor (3/4 inches diameter, 4.0 embedment)

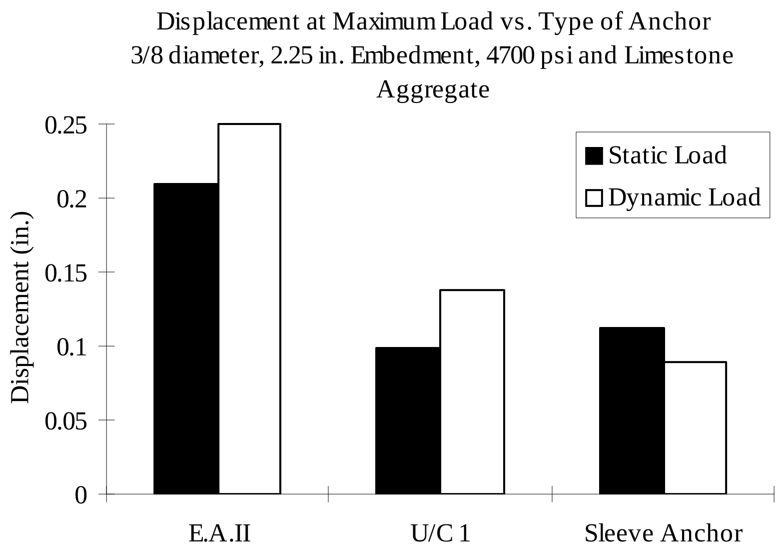


Figure 5.3 Displacement at maximum load vs Type of Anchor (3/8 inches diameter and 2.25 in. embedment)

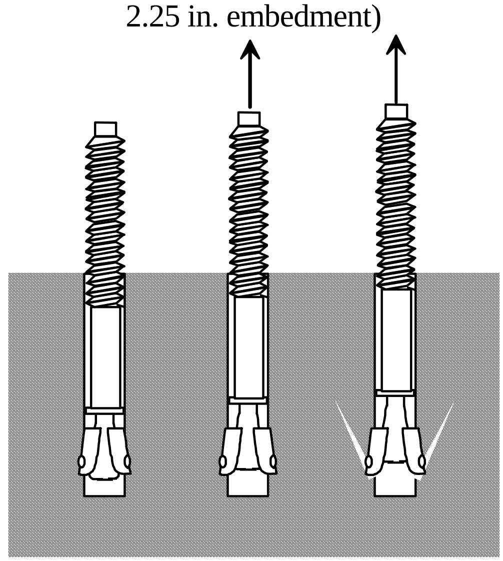


Figure 5.4 Displacement of Expansion Anchor II
(a) after installation; (b) under load; pull-through
(c) under load; cone breakout failure occurs

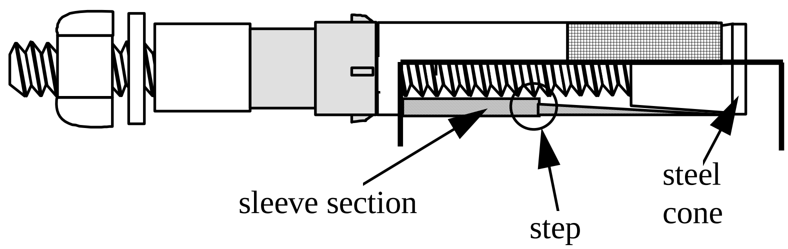


Figure 5.5 Cross-section of Sleeve Anchor

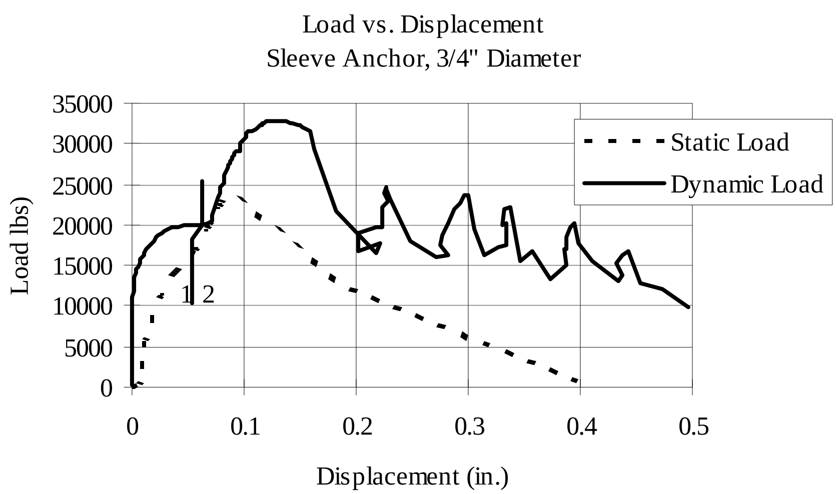


Figure 5.6 Load-Displacement curves of sleeve anchor
1-pull-through behavior
2-hit step, increase of load

very rapidly, so that the load increases rapidly with time (even faster than the rate of external load application). The increase of the load is caused by the step inside the expansion sleeve. Figure 5.7 illustrates a cross section of what happens inside the expansion sleeve because of the step.

The 0.375-inch (9.5 mm) Sleeve Anchor does not have this step in the expansion sleeve. As a result, its has a load-displacement curve behavior typical of cone breakout failure and does not show this peculiarity.

5.3.4 Behavior of Undercut 1, Undercut 2 and Grouted Anchors Tested in Series 1

The Undercut Anchors and the Grouted Anchor typically show a cone breakout failure. In comparison with the wedge-type expansion anchors tested in this program,

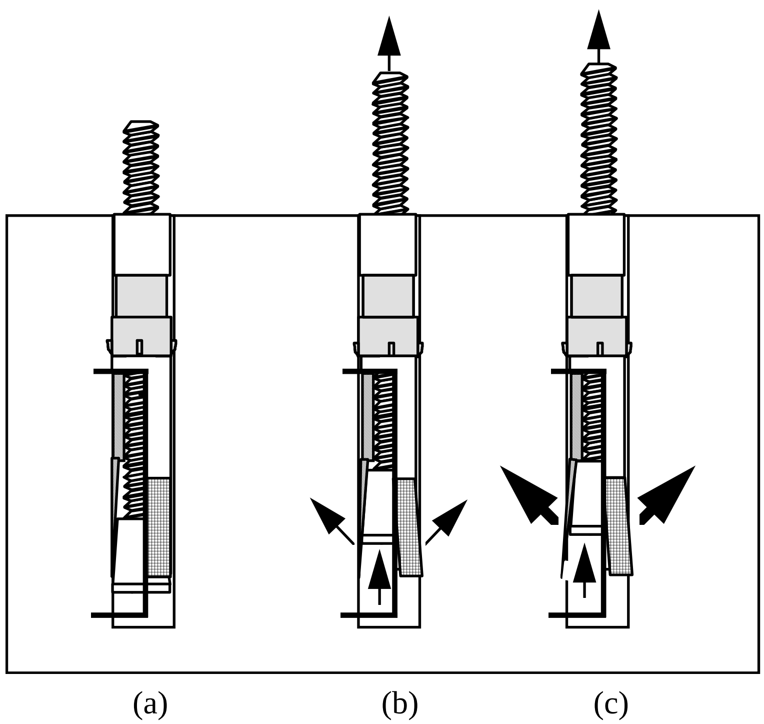


Figure 5.7 Effect of step on tensile behavior of sleeve anchor under dynamic load (a) after installation; (b) cone slides inside expansion sleeve; (c) cone hits step inside expansion sleeve

these anchors were stiffer, and their maximum loads occurred at smaller displacements.

5.4 Effect of Embedment Depth, Concrete Strength, and Aggregate Type on Expansion Anchors Tested in Series 1

Figure 5.8 shows the values of the normalizing constant, k, for Expansion Anchor II, for different concrete strengths and aggregate types. Each bar represents the average of 5 tests. The figure shows that as embedment depth decreases, normalized tensile capacity increases. The reason for this is that at deeper

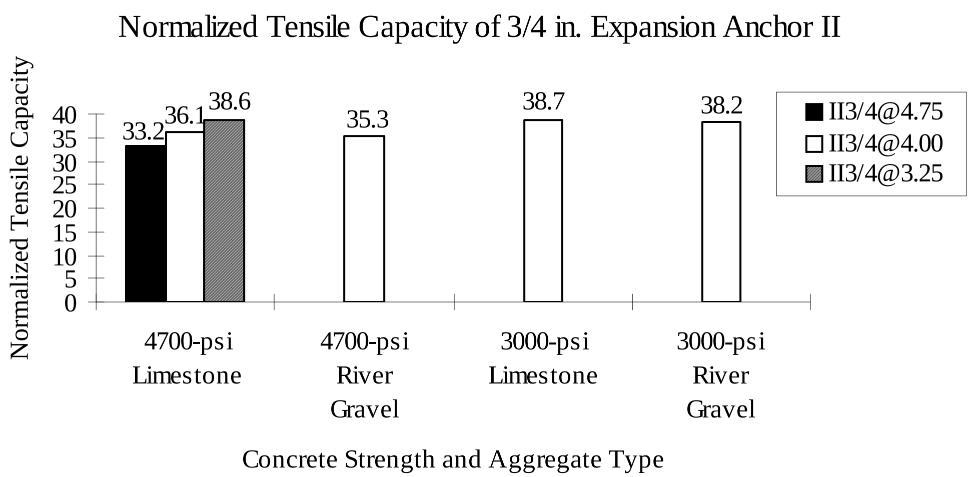


Figure 5.8 Effect of embedment depth, concrete strength, and aggregate type on cone breakout capacity of Expansion Anchor II

embedments, anchor capacity (not normalized) increases, and the anchor is more prone to pull-through and pull-out. Such anchors slip until the embedment depth is small enough to produce a cone breakout, at an embedment depth considerably smaller than the original value. Because capacity is normalized using the original embedment, the normalized tensile capacity is artificially small. The graph also suggests that normalized tensile capacity is not significantly affected by concrete compressive strength or aggregate type. These points are discussed in more detail below.

5.5 Effect of Loading Rate (Static versus Dynamic) on Wedge-Type Expansion Anchors Tested in Series 1

Figure 5.9 shows the values of the normalizing constant, k, for the original Expansion Anchor and for Expansion Anchor II. The figure shows that the normalized tensile capacity of the original Expansion Anchor is reduced by about 10% under dynamic loading, while the normalized tensile capacity of the Expansion Anchor II remains about the same. Results are obtained from all concrete strengths, aggregate types, anchor diameters, and embedment depths.

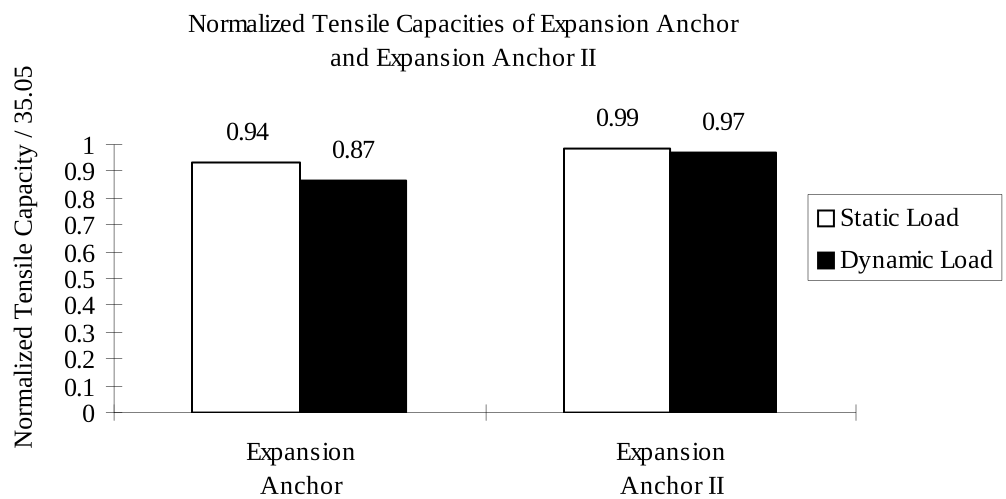


Figure 5.9 Effect of loading rate on normalized tensile capacity of Expansion Anchor and Expansion Anchor II

5.6 Effect of Loading Rate (Static versus Dynamic) on Failure Mode of Wedge-Type Expansion Anchors Tested in Series 1

Figure 5.10 shows the values of the normalizing constant, k, for Expansion Anchor and Expansion Anchor II, all 3/4-inch (19.1 mm) diameter, as a function of embedment depth. Nominal concrete strength was constant at 4700 psi (32.4 MPa), and limestone aggregate was used.

The graph shows that at an embedment depth of 4.75 inches (120.7 mm), the original Expansion Anchor fails by pull-through under static and dynamic loads. Dynamic capacity is less than static capacity. As the embedment depth is decreased to 3.25 inches (82.6 mm), the statically loaded anchor fails by cone breakout. While the capacity of the dynamically loaded anchor is about the same, the failure mode for some of the 5 replicates is pull-through. Expansion Anchor II has a greater tendency toward cone failure rather than pull-through. In general, the capacity of both expansion anchors is slightly less under dynamic load than under static load.

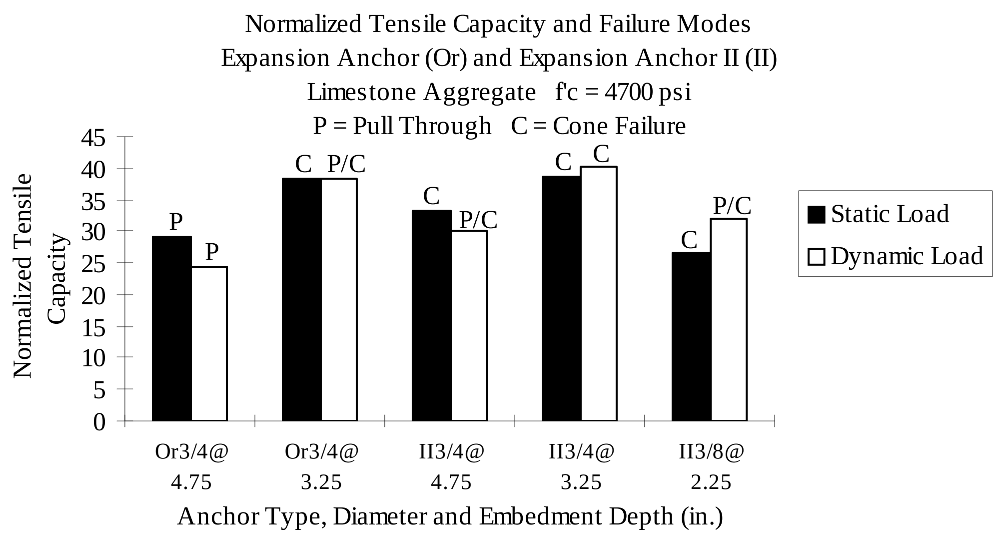


Figure 5.10 Effect of loading rate on failure mode of wedge-type anchors

5.7 Effect of Loading Rate (Static versus Dynamic) on Tensile Cone Breakout Capacity of Undercuts, Grouted and Sleeve Anchors Tested in Series 1

Figure 5.11 shows the effect of loading rate on the normalized tensile capacity, k, (as governed by concrete cone breakout) of the Undercut Anchor 1, Undercut Anchor 2, Sleeve Anchor and Grouted Anchor. Results show an increase in normalized tensile capacity of about 30% under dynamic load, as compared to static load.

5.8 Effect of Reinforcement

Figure 5.12 shows the effect of reinforcement on the normalized tensile capacity of anchors loaded statically. All anchors and all concrete strengths are included. Effects of reinforcement are seen to be negligible. This observation

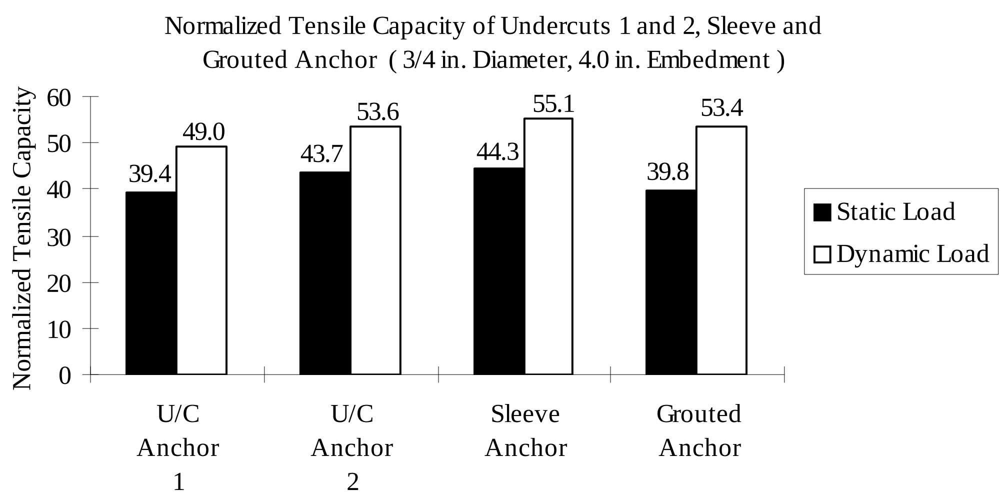


Figure 5.11 Effect of loading rate on normalized tensile capacity of Undercut Anchor 1, Undercut Anchor 2, Sleeve Anchor and Grouted Anchor

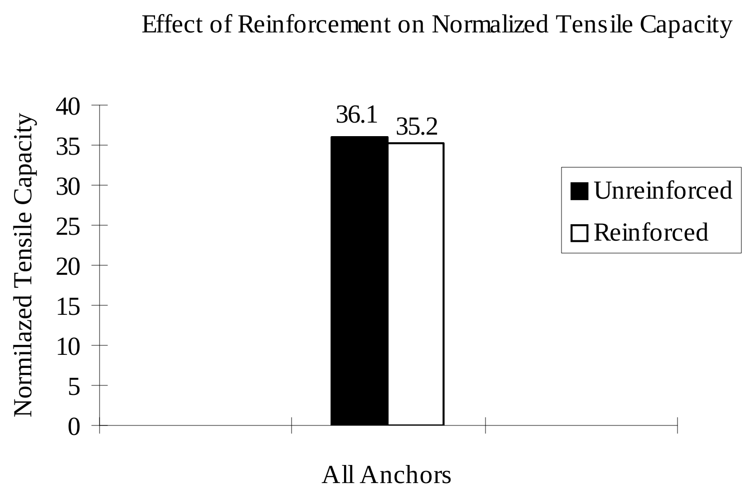


Figure 5.12 Effect of reinforcement on normalized tensile capacity

applies to reinforcement placed parallel to the free surface of the specimen, perpendicular to the axis of the anchor.

To affect the load-displacement curve, the reinforcement must lie within the breakout cone, and must be oriented parallel to the applied load. Because the reinforcement is not significantly stressed until cone breakout occurs, the reinforcement will affect only the descending branch of the load-displacement curve. Maximum capacity as governed by cone failure is reached when the inclined micro-crack has propagated about 40% of the embedment depth toward the surface [2,8]. Figure 5.13 illustrates how reinforcement can affect the cone breakout load. Unless the reinforcement lies within the zone of propagation of the inclined crack at maximum load, it does not significantly affect anchor behavior.

5.9 Effect of Aggregate Type

Figure 5.14 shows the effect of aggregate type on the normalized tensile capacity of all anchors. For both concrete strengths, changing from soft limestone aggregate to medium-hard river gravel aggregate has no significant effect on normalized tensile capacity.

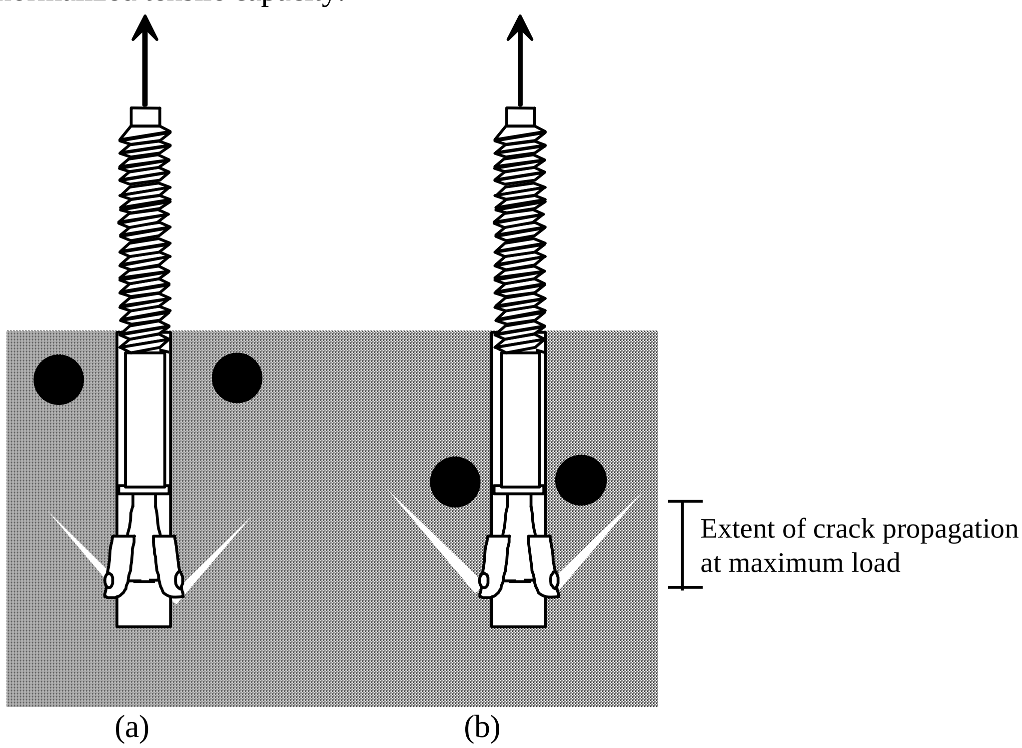


Figure 5.13 Effect of reinforcement position on cone breakout load
(a) Reinforcement above cracked zone at maximum load;
(b) Reinforcement within cracked zone at maximum load

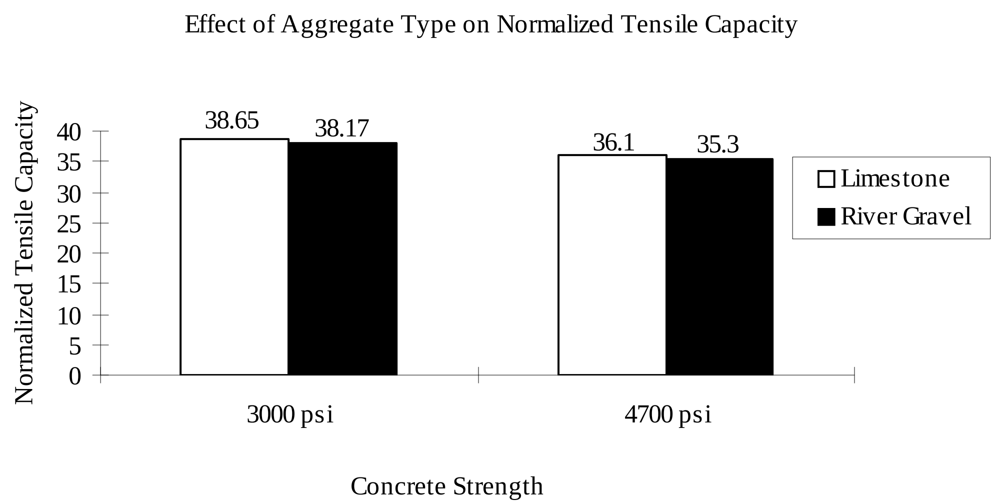


Figure 5.14 Effect of aggregate type on normalized tensile capacity of all anchors

Chapter 6

Summary, Conclusions and Recommendations

6.1 Summary

The overall objective of the U.S. Nuclear Regulatory Commission (NRC) sponsored test program is to assess the seismic performance of anchorages used to anchor mechanical and electrical equipment to the building concrete structure. To accomplish this objective, the NRC is sponsoring a multi-year testing program at The University of Texas at Austin. The research is to study the behavior of typical anchors used to anchor equipment under dynamic and static loading. The research includes the study of single and multiple anchors in tensile loading, and of near-edge anchors and multiple-anchor connections in tensile and shear loading.

This thesis which covers part of the NRC testing program. Test results are presented for single anchors under static and dynamic tensile loading. The effects of coarse aggregate, concrete compressive strength, type of anchor, and reinforcement were studied.

6.2 General Conclusions Regarding the Tensile Behavior of Anchors in Uncracked Concrete

1) Wedge-type expansion anchors have approximately the same tensile capacity under dynamic load, as under static load. However, this average is deceptive, because it is results from combining two distinct failure modes:

a) For wedge-type expansion anchors, if failure is by concrete cone breakout, dynamic capacity exceeds static capacity. Concrete cone breakout capacity under static loads is predicted with a coefficient of variation of about 10%, by the cone failure formula ($P = 35.05 \sqrt{f_c}\, h_e^{1.5}$). The multiplicative constant (ideally, 35.05) increases as the effective depth decreases. For wedge anchors, the effective embedment h_{eff} is measured from the free surface of the concrete to the point of the clip in contact with the concrete. Because of pull-through of the mandrel, estimation of the effective embedment when the cone is produced is difficult for wedge anchors.

b) For wedge-type expansion anchors, if failure is by pull-through, dynamic capacity is less than static capacity.

2) Dynamic loading worsens the performance of wedge-type expansion anchors. It increases the tendency for failure by pull-through and pull-out, rather than

by concrete cone failure. Evidently, dynamic loading decreases the coefficient of friction between the cone and the clip (steel to steel), and between the clip and the concrete (steel to concrete).

3) At embedments less than those required to produce steel failure, grouted anchors and undercuts anchors fail by concrete cone failure, without pullout. The concrete cone failure capacity of grouted anchors and of undercut anchors is predicted with a coefficient of variation of less than 10%, by the cone failure formula ($P = 40.24 \sqrt{f_c}\, h_e^{1.5}$).

4) Dynamic loading increases the capacity of grouted anchors, undercuts anchors, and sleeve anchors. Under dynamic loads, the concrete cone failure capacity of those anchors is about 30% greater than the capacity under static loads.

5) For all anchors tested so far, performance in concrete with limestone aggregate is not much different from performance in concrete with river gravel aggregate. Both those aggregates have identical hardness as measured by the LA Abrasion Loss Test [9] (28%). However, there is reason to believe that aggregate stiffness, not just hardness, may affect the performance of anchors with small bearing areas (and, consequently, high bearing stresses).

6) For all anchors tested so far, heavy reinforcement (#8 bars @ 8 inches {203.2 mm}, 1-1/2 inch {38.1 mm} cover) placed parallel to the surface of the concrete has no appreciable effect on performance. There are two primary reasons for this:

   a) That reinforcement did not pass through the failure cone. It is believed that reinforcement developed within the failure cone and also developed in the surrounding concrete, and oriented parallel to the direction of the applied load, will be effective in increasing anchor capacity.

   b) The reinforcement was shallow compared to the embedment depth. Maximum capacity as governed by cone failure is reached when the inclined crack has propagated about 40% of the embedment depth toward the surface. If the steel is above that point, it will not affect the maximum capacity as governed by cone failure.

6.3 Recommendations for Predicting the Tensile Capacity of Anchors in Uncracked Concrete under Dynamic and Static Loads

1) Procedures discussed here should be used for evaluating the tensile capacity of anchors under static and dynamic load.

2) For all anchors, tensile capacity as governed by steel failure should be predicted using the effective tensile stress area of the shank, multiplied by the tensile resistance of the steel. Depending on the purpose of the calculation, this resistance can be either the yield or the ultimate tensile strength. Those values should be increased as appropriate to reflect the effects of strain rates consistent with the seismic response of mounted equipment. Other researchers [2] have used increases of about 15% for this case.

3) For undercut anchors, the normalization constant for static tensile capacity as governed by cone breakout can be increased to 40.24, instead of the originally proposed value of 35.05. Limited data for sleeve anchors support the use of the higher value for those anchors as well.

4) For the undercut, sleeve and grouted anchors tested here, dynamic tensile capacity as governed by cone breakout can be computed using the static capacity multiplied by 1.24.

5) For the wedge-type anchors tested here, dynamic tensile capacity was essentially equal to the static capacity.

The conclusions presented are those of the author and are not to be considered as NRC recommendations or policy.