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16. Abstract

This report concerns the results of a study to investigate the tensile behavior of single anchors subjected to environmental exposure, and to compare the behavior of otherwise identical exposed and unexposed anchors.

Cast-in-place and retrofit anchors (adhesive, expansion, and undercut) were tested. Anchors were subjected to five environmental exposure conditions: (1) ultraviolet light; (2) freezing and thawing; (3) corrosion in a pH-neutral salt solution; (4) wetting and drying with an acid rain solution; and (5) combined freezing and thawing, corrosion in a pH-neutral salt solution, and wetting and drying.

Anchors were installed in concrete cylinders meeting TSDHPT specifications for Class C concrete. These concrete cylinders with installed anchors were then subjected to the above five environmental exposure conditions. After environmental exposure, the cylinders were cemented into a concrete block with an epoxy adhesive, and were tested in direct static tension to failure.

Effects of different environmental exposures on the subsequent tensile behavior of anchors are described.

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EFFECT OF ENVIRONMENTAL CYCLING ON THE STRENGTH OF SHORT RETROFIT ANCHOR BOLTS

by

C.C. HIGGINS AND R.E. KLINGNER

Research Report No. 1208-1F

Research Project 3-5-89/0-1208

"Effect of Environmental Cycling on the Strength
of Short Retrofit Anchor Bolts"

Conducted for

Texas
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In Cooperation with the
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by

CENTER FOR TRANSPORTATION RESEARCH
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PREFACE

The Texas State Department of Highways and Public Transportation (TSDHPT) uses cast-in-place and retrofit anchors in many structural applications such as attaching steel members to concrete, attaching guard rails to existing structures, and attaching fixtures to concrete. Cast-in-place anchors,as well as adhesive, expansion, and undercut retrofit anchors are used. Because little information is available regarding the effects of different environmental conditions on the behavior of these anchors, they are usually designed without consideration for environmental effects. Recent studies suggest that designs which do not include environmental factors could result in unsatisfactory behavior.

Texas Highway Department Project 1208, Strength of Retrofit Anchors Subjected to Environmental Exposure, was initiated to address this problem. The project's purpose is to document the effects of environmental exposure on the behavior of single retrofit anchors, and to develop rational design procedures for anchors exposed to such environmental exposure. The final result of this research is this report for the Texas SDHPT, describing the environmental exposure tests, tensile capacity tests, procedures used for environmental exposure, procedures used to evaluate tensile capacity, and a summary and discussion of the results.

SUMMARY

This report concerns the results of a study to investigate the tensile behavior of single anchors subjected to environmental exposure, and to compare the behavior of otherwise identical exposed and unexposed anchors.

Cast-in-place and retrofit anchors (adhesive, expansion, and undercut) were tested. Anchors were subjected to 5 environmental exposure conditions: 1) ultraviolet light; 2) freezing and thawing; 3) corrosion in a pH-neutral salt solution; wetting and drying with an acid rain solution; and 5) combined freezing and thawing, corrosion in a pH-neutral salt solution, and wetting and drying.

Anchors were installed in concrete cylinders meeting TSDHPT specifications for Class C concrete. These concrete cylinders with installed anchors were then subjected to environmental exposure. After environmental exposure, the cylinders were cemented into a concrete block with an epoxy adhesive, and were tested in direct static tension to failure.

Results of the tests presented in this report should be interpreted under the following conditions:

1) Results are strictly valid only for the anchors tested in this study and the conditions under which they were studied.

2) Results of these retrofit anchor tests could be modified as a result of changes in anchor specifications, concrete type, installation procedures, or testing environment.

3) Results should not be interpreted as applying to all anchors of a given type. That is, results should not be construed to imply that all anchors of a given type are better than all anchors of another type.

4) Results should not be construed as an endorsement of any particular anchor type or anchor brand.

The following general results were obtained. If a particular anchor type is not mentioned in connection with a particular environmental exposure, then that exposure did not significantly affect that anchor type:

Ultraviolet Light Exposure:

- No effects.

Freezing and Thawing Exposure:

- Reduces preload of torque-controlled expansion anchors.
- Reduces initial stiffness of some expansion anchors.

Salt (Corrosion) Exposure:

- No significant effects.

Acid Rain Wetting and Drying Exposure:

- No significant effects. However, incipient corrosion observed for some adhesive anchors.

Combination Exposure:

- Reduces the stiffness of some expansion anchors.

General:

- Water should be prevented from entering the drilled holes of anchors subjected to numerous cycles of freezing and thawing. If this is not possible, additional edge distance should be provided, or reinforcement should be placed between the drilled hole and the free surface of the concrete.
- Expansion anchors whose drilled holes are filled with standing water, and which are subjected to repeated cycles of freezing and thawing, can lose most or all of their preload. For such anchors, the manufacturer's recommended torque should be re-checked on a regular basis.

IMPLEMENTATION

This report address many aspects of the effects of environmental exposure on the performance of tensile anchors embedded in concrete. Its recommendations should be studied and included in General Notes pertaining to use of anchors by the Highway Department. Other factors being equal, anchors which are more resistant to the effects of environmental exposure should be specified for use in situations where environmental exposure is significant.

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CHAPTER 1. INTRODUCTION

1.1 General

The Texas State Department of Highways and Public Transportation (TSDHPT) uses cast-in-place and retrofit anchors in many structural applications, such as attaching steel members to concrete, attaching guard rails to existing structures, and attaching fixtures to concrete. Cast-in-place anchors, as well as adhesive, expansion, and undercut retrofit anchors are used. Because little information is available regarding the effect of different environmental conditions on the behavior of these anchors, they are usually designed without consideration for environmental effects. Recent studies suggest that designs which do not include environmental factors could result in unsatisfactory behavior [1,2].

1.2 Objectives and Scope

Texas Highway Department Project 1208, Strength of Retrofit Anchors Subjected to Environmental Exposure, was initiated to address this problem. The project's purpose is to document the effects of environmental exposure on the behavior of single retrofit anchors, and to develop rational design procedures for anchors exposed to such environmental exposure. The final result of this research is a report for the Texas SDHPT describing the environmental exposure tests, tensile capacity tests, procedures used for environmental exposure, procedures used to evaluate tensile capacity, and a summary and discussion of the results.

The specific objectives of this project are:

1) To evaluate the response of retrofit anchors subjected to various environmental exposure conditions.

2) To determine the static tensile load-deflection behavior of single anchors, following environmental exposure.

3) To compare behavior of environmentally exposed anchor bolts, with that of otherwise identical bolts not subjected to environmental exposure [3,4].

4) To recommend design procedures for retrofit anchors subjected to environmental exposure conditions.

The scope of this project comprises experimental testing, conducted in two phases:

1) Expose retrofit anchors to various environmental conditions.

2) Evaluate their tensile capacity and load-deformation characteristics.

CHAPTER 2. BACKGROUND

2.1 Introduction

Anchors in concrete can be classified as cast-in-place and retrofit. Cast-in-place anchors are installed in the formwork and concrete is then cast around them. Retrofit anchors are installed after the concrete has hardened. Increased use of anchors, particularly in the nuclear industry, has led to the development of ACI 349 Appendix B [5] and other design guides [6,7]. These guides give only limited assistance for the design of retrofit anchors, and no assistance for the design of anchors subjected to environmental exposure.

2.2 Design Philosophy of Retrofit Anchors

Current design codes such as ACI 349 Appendix B [5] and TVA DS-C1.7.1 [6], are based on a strength design approach, which requires that the steel yield and fracture prior to concrete failure.

The three basic types of retrofit anchors are: adhesive, expansion, and undercut.

Adhesive Anchors

An adhesive anchor is comprised of a steel rod which is placed in a drilled hole and bonded to the concrete with a chemical compound. Load is transferred from the anchor through the adhesive to the concrete along the entire embedment length. Load transfer depends on the adhesive-steel bond, the adhesive-concrete bond, the mechanical interlock at the adhesive-steel interface, and the mechanical interlock at the adhesive-concrete interface. Because bond between the adhesive and concrete is essential for load transfer, hole cleaning is very important [3]. No specific design standards now exist in the U.S. for adhesive anchors.

Of the many adhesives used for anchorage to concrete, the three major types are epoxy, vinylester, and polyester.

Epoxy adhesives are made by mixing an epoxy resin and a curing agent. An epoxy is a chemical group consisting of an oxygen atom bonded with two carbon atoms already united in some way. Epoxy resins are thermosetting plastics [9], requiring heat to cure. Epoxy adhesives are known to exhibit some sensitivity to environmental exposure, including the following: color instability and very slight strength loss from ultraviolet light exposure [9]; some moisture absorption (hydrolysis) which slightly affects physical properties but is completely reversible if the epoxy dries [9,10,11]. In addition to these sensitivities, epoxies exhibit slight shrinkage during cure [9].

Vinylester adhesives are made by mixing epoxy acrylate resin and a curing agent. Vinylesters also are thermosetting plastics. Vinylester adhesives are known to exhibit some sensitivity to environmental exposure, including the following: a short shelf life; a tendency to degrade under ultraviolet light; hydrolysis [10] and a tendency to polymerize at high temperatures without addition of a catalyst [2].

Polyester adhesives are thermosetting plastics made by mixing polyester resin and a catalyst. Polyester adhesives are known to exhibit some sensitivity to environmental exposure, including the following: degradation from ultraviolet light exposure [12]; shrinkage [9]; self-catalyzation at high temperatures [12]; and hydrolysis [10].

Adhesive anchors have three possible failure mechanisms [8]:

1) Yield and fracture of anchor steel

2) Formation of a concrete cone, accompanied by pullout of an adhesive core

3) Pullout of an adhesive core

Expansion Anchors

Load is transferred from the expansion anchor to the concrete by friction. When the anchor is installed, a torque is applied to the nut, the sleeve is forced over the expansion cone and expands against the sides of the hole. Applying the torque creates a prestressing force on the bolt which presses the attachment to the surface of the base material. If the applied tensile force exceeds the remaining prestressing force, the cone is drawn further into the sleeve, increasing the expansion force. Additional expansion is possible only if the friction between the cone and sleeve is less than the friction between the sleeve and the surface of the drilled hole [13]. ACI 349 Appendix B requires testing for verification of ductile behavior, in addition to meeting the requirements for cast-in-place anchors [5].

Torque controlled expansion anchors have three possible failure mechanisms [8]:

1) Yield and fracture of anchor steel

2) Formation of a concrete cone

3) Failure by pullout

Undercut Anchors

As with cast-in-place anchors, load is transferred from the anchor to the concrete by bearing on the undercut portion of the hole. ACI Appendix B has no specific design requirements for undercut anchors.

Undercut anchors have two possible failure mechanisms [8]:

1) Yield and fracture of anchor steel

2) Formation of a concrete cone

2.3 Current Knowledge of the Effects of Environmental Exposure on Retrofit Anchors

Little systematic research has been conducted on the effects of environmental exposure on the performance of retrofit anchors. Limited research has been performed on the creep of adhesive anchors subjected to salt in the concrete, standing water on the foundation, and outdoor environments [14]. Tensile strength of exposed anchors was not addressed in that reference.

2.4 Current Design Requirements for Anchors Subjected to Environmental Exposure

Current U.S. anchor design codes contain no provisions addressing the effects of environmental exposure.

CHAPTER 3. EXPERIMENTAL PROGRAM

3.1 Introduction

This investigation involved two separate phases of tests on retrofit anchor bolts:

1) Environmental exposure tests

2) Direct tensile tests

One hundred-twenty tests were performed on anchor bolts, including retrofit anchors involving various manufacturers, materials, and installation methods.

In the first phase, environmental test specimens (anchor bolts installed vertically in a concrete cylinder), were exposed to 5 different environmental conditions. In the second phase, following environmental exposure, these specimens were cemented into a reaction block and tested in direct tension to failure. After each phase, experimental results were collected and evaluated. In this chapter, these two separate phases are described in more detail.

3.2 Basic Testing Concept Used In This Project

Experimental investigations of the effects of environmental exposure involve either controlled or uncontrolled exposure. Controlled environmental exposure takes place in an environment where temperature, humidity, length of exposure, and other factors are carefully controlled. Uncontrolled environmental exposure takes place in situ, and involves exposing the test specimen to the natural elements. Each type of exposure has its advantages and disadvantages. Controlled environmental exposure allows consistent and repeatable exposure conditions, but the specimen size is limited because of the size of the environmental chamber used. Uncontrolled exposure does not restrict the size of the specimen, but the environmental exposure conditions are not consistent or repeatable.

In planning this test program, it was decided to use controlled environmental exposure. This would place severe restrictions on the specimen size. The large test blocks used in similar research could not fit into conventional environmental chambers.

To solve this problem, the following concept was proposed (Fig. 3.1):

1) Install anchors in concrete cylinder specimens.

2) Subject the concrete cylinders to environmental exposure.

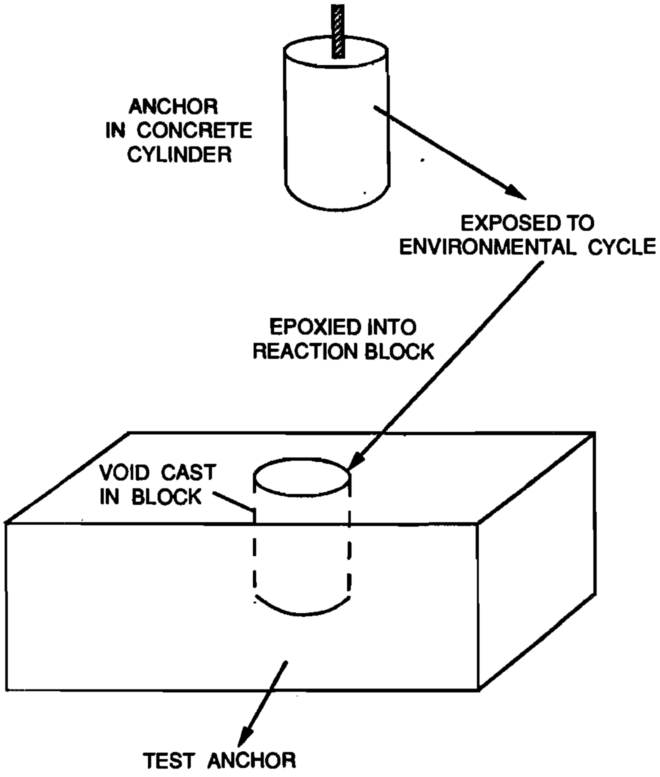


Figure 3.1 Proposed environmental and tensile testing procedure.

3) Attach the cylinders to large concrete blocks using an epoxy adhesive.

4) Test the anchors in tension.

Before proceeding with testing, it was considered necessary to evaluate the validity of this concept. The following questions were posed:

1) Was the cylinder approach valid? In other words, would unexposed anchors, installed in cylinders cemented into a concrete block, behave identically to anchors installed directly into a concrete block?

2) If the first question above was answered in the affirmative (validating the cylinder approach), what size cylinder would be appropriate?

Because all anchor bolts in this study were designed for a ductile steel failure [3], it was reasoned that there should be no concrete cone failures. Therefore, the glue line between the cylinder and the reaction block would not interfere with the anchor bolt behavior, and a cylinder of any size could be used from that viewpoint. Standard 6- x 12-inch cylinders were initially chosen because they were readily available, and easy to move. Also, the cylinder mold itself would protect all concrete surfaces except the top one, thereby duplicating the exposure conditions normally acting on an anchor in the field.

In deciding on the required cylinder size, consideration was also given to the possibility of damaging an excessively small cylinder under environmental cycling.

To answer the above questions, the Concept Verification Tests (series CVT) were carried out. Cast-in-place headed anchors of ASTM A325 grade steel were chosen for use in this test series because these anchors transfer force to the concrete without any anchor slip. The cast-in-place anchors were embedded 8 inches in concrete cylinders of two different sizes. Standard 6- x 12-inch cylinders were used, along with 12- x 12-inch cylinders, in the event that the smaller cylinders did not perform satisfactorily. The concrete mix used was Texas SDHPT Class C concrete with f'_c = 3700 psi, the same type and strength as used in previous anchor bolt studies at The University of Texas at Austin [3,4]. The cylinders and reaction blocks were field cured. After 28 days of curing, the cylinders with bolts were cemented into the reaction blocks with an epoxy adhesive, which was allowed to cure for 2 days before testing.

The bolts were loaded in direct static tension to failure, and the displacement of the concrete cylinder relative to the surrounding concrete block was measured. Results of the CVT test series were then compared to results of similar tests on identical anchors cast monolithically in a concrete block. Both the 6- and 12-inch diameter specimens failed by bolt fracture without the formation of a concrete cone. Thus, the failure mechanisms for the bolts in cylinders were identical to the failure mechanisms of bolts in a monolithic block. Failure loads of the 6- and 12-inch cylinders were similar to the failure loads of anchors in a monolithic block. Both the 6- and 12-inch cylinders showed no significant relative displacement with respect to the concrete block (Fig. 3.2).

Therefore, it was determined that there was no difference between the behavior of ductile anchors placed in a cylinder epoxied into a block, and the same anchors cast in a monolithic block. It was decided to use 6- x 12-inch cylinders. As will be discussed later, some 6- x 12-inch cylinder specimens showed splitting cracks under freeze-thaw cycling; those tests were repeated using 12- x 12-inch cylinders.

3.3 Scope of Test Program

3.3.1 Anchor Types. The following types of anchor bolts were used in this study:

1) Retrofit Anchors

    a) Adhesive anchors

    b) Expansion anchors

    c) Undercut anchors

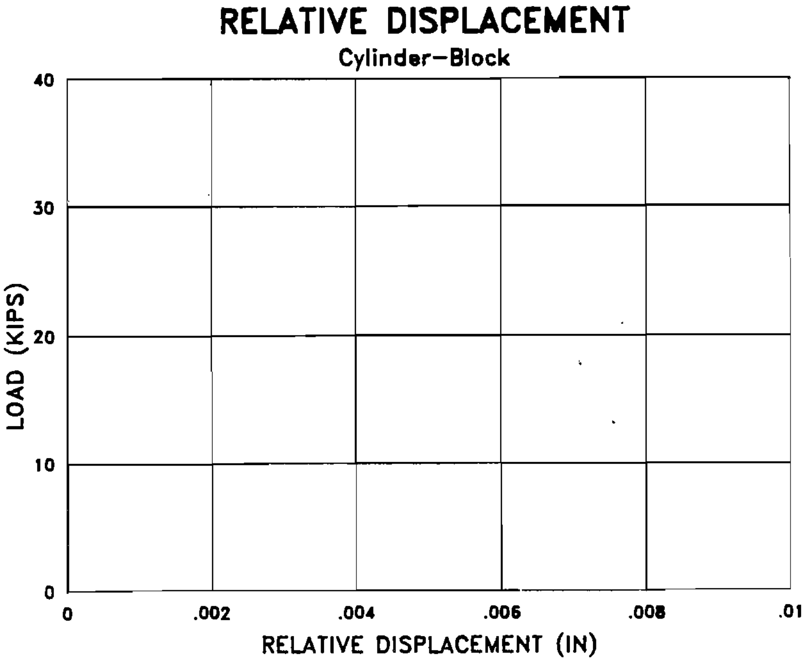


Figure 3.2 Relative movement between block and cylinder.

2) Cast-in-place anchors (for comparison only)

3.3.2 Anchor Diameter. Most anchors were 5/8-inch nominal diameter. Expansion anchors were 16 mm in diameter. One undercut anchor was 1/2-inch nominal diameter. Specific dimensions for each test specimen are given in Table 3.1. The test designations used in the table are explained in subsection 3.3.6.

3.3.3 Anchor Steel. All adhesive anchors used threaded rod meeting ASTM A193-B7 ($f_{ut}=150$ ksi). One adhesive anchor used a coarse, coil-threaded rod along the embedded length, while all other adhesive anchors used a standard threaded rod along the embedded length. The cast-in-place anchors met ASTM A325 ($f_{ut}=120$ ksi). Expansion and undercut anchors used steel of various types and strengths, as provided by their manufacturers (Table 3.1).

3.3.4 Embedment Length. Based on the results of Reference 4, an 8-inch embedment length was used for all adhesive and cast-in-place anchors. Embedment lengths for expansion and undercut anchors were set by each manufacturer (Table 3.1). All embedment lengths were intended to be sufficient to ensure yield and fracture of anchor steel.

3.3.5 Environmental Effects. After installation, anchors were subjected to 5 different environmental exposure conditions:

1) Ultraviolet light

Table 3.1 Anchor Parameters

Test Number	Anchor Type	Bolt Diameter (in.)	Anchor Steel	Anchor Strength (ksi)	Embedment Length (in.)
CVT K	CIP	5/8	HH	120	8.0
ECT A	Adhesive	5/8	TR	150	8.0
ECT B	Adhesive	5/8	TR	150	8.0
ECT C	Adhesive	5/8	TR	150	8.0
ECT D	Adhesive	5/8	CR	150	8.0
ECT E	Adhesive	5/8	TR	150	8.0
ECT F	Adhesive	5/8	CR	150	8.0
ECT G	Expansion	16 mm	SS	101	105 mm
ECT H	Expansion	16 mm	ZR	110	126 mm
ECT I	Undercut	1/2	PS	150	6.75
ECT J	Undercut	5/8	ZR	100	7.5
ECT K	CIP	5/8	HH	120	8.0
PLT G	Expansion	16 mm	SS	101	105 mm
PLT H	Expansion	16 mm	ZR	110	126 mm
PLT I	Undercut	1/2	PS	160	6.75
PLT J	Undercut	5/8	ZR	100	7.5

Notes:

1. TR : ASTM 193-B7 All Thread Rod
   CR : ASTM 193-B7 Coil Rod
   HH : ASTM A325 Hex Head Bolt
   SS : Stainless Steel AISI 316 Rod
   ZR : Zinc Electroplated ASTM 193-B7 Threaded Rod
   PS : ASTM 193-B7 Stud No Treatment

2. Minimum Specified Ultimate Tensile Strength

2) Freezing and thawing

3) Corrosion in a pH-neutral salt solution

4) Wetting and drying with an acid rain solution

5) Combined freezing and thawing, corrosion in a pH-neutral salt solution, and wetting and drying

These environmental conditions are discussed in detail in Chapter 5.

3.3.6 Specimen Designation. Each specimen (and its corresponding test) is identified, as shown in Figure 3.3, by the following designation:

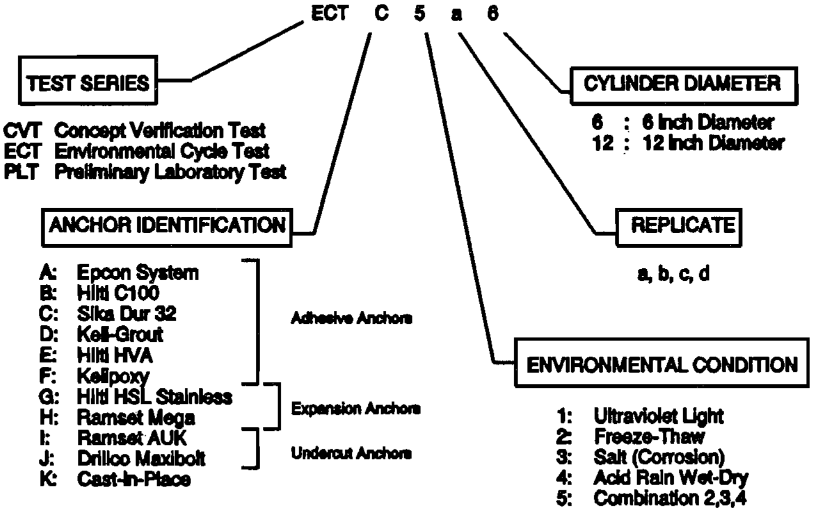


Figure 3.3 Test designations.

1) Three letters corresponding to the test series
2) A single letter identifying the bolt type and manufacturer
3) A number identifying the environmental condition
4) A lower case letter which describes the replicate
5) A number identifying the cylinder size

Test designation numbers for the experimental program are itemized in Table 3.2.

3.3.7 Test Matrix. Test variables included anchor bolt type, environmental exposure conditions, replicate number, and cylinder size. The complete test matrix is shown in Table 3.3.

3.4 Environmental Exposure Test Specimens

3.4.1 Description. Each environmental test specimen consisted of an anchor installed in a concrete cylinder. After casting, each cylinder was left in its mold. A typical test specimen is shown in Fig. 3.4. As shown in Fig. 3.5, a rim was built around the top of each cylinder with duct tape, and silicone caulk was used to seal between the top edge of the concrete and cylinder mold.

Table 3.2 Test Designations

Test Designation Number	Test Series #	Anchor Type *	Environmental Exposure Condition †	Replicates	Cylinder Diameter (in.)‡
CVT K 6	CON	CIP	None	a, b, c, d	6
CVT K 12	CON	CIP	None	a, b, c, d	12
ECT A 1 6	ENV	Adhesive	UV	a, b, c, d	6
ECT A 4 6	ENV	Adhesive	Acid Rn	a, b, c, d	6
ECT B 1 6	ENV	Adhesive	UV	a, b, c, d	6
ECT B 4 6	ENV	Adhesive	Acid Rn	a, b, c, d	6
ECT C 1 6	ENV	Adhesive	UV	a, b, c, d	6
ECT C 4 6	ENV	Adhesive	Acid Rn	a, b, c, d	6
ECT D 1 6	ENV	Adhesive	UV	a, b, c, d	6
ECT D 4 6	ENV	Adhesive	Acid Rn	a, b, c, d	6
ECT E 1 6	ENV	Adhesive	UV	a, b, c, d	6
ECT E 4 6	ENV	Adhesive	Acid Rn	a, b, c, d	6
ECT F 1 6	ENV	Adhesive	UV	a, b, c, d	6
ECT F 4 6	ENV	Adhesive	Acid Rn	a, b, c, d	6
ECT G 2 6	ENV	Expansion	F-T	a, b, c, d	6
ECT G 2 12	ENV	Expansion	F-T	a, b, c, d	12
ECT G 3 6	ENV	Expansion	Salt	a, b, c, d	6
ECT G 4 6	ENV	Expansion	Acid Rn	a, b, c, d	6
ECT G 5 6	ENV	Expansion	Combo	a, b, c, d	6
ECT H 2 6	ENV	Expansion	F-T	a, b, c, d	6
ECT H 2 12	ENV	Expansion	F-T	a, b, c, d	12
ECT H 3 6	ENV	Expansion	Salt	a, b, c, d	6
ECT H 4 6	ENV	Expansion	Acid Rn	a, b, c, d	6
ECT H 5 6	ENV	Expansion	Combo	a, b, c, d	6
ECT I 5 6	ENV	Undercut	Combo	a, b, c, d	6
ECT J 5 6	ENV	Undercut	Combo	a, b, c, d	6
ECT K 5 6	ENV	CIP	Combo	a, b, c, d	6
PLT G	PRE	Expansion	None	a, b, c, d	Block
PLT G 6	PRE	Expansion	None	e, f	6
PLT H	PRE	Expansion	None	a, b	Block
PLT H 6	PRE	Expansion	None	c,d	6
PLT I	PRE	Undercut	None	a, b	Block
PLT J	PRE	Undercut	None	a, b	Block

Notes:

\# CON : Concept Verification Test Series
ENV : Environmental Cycling Test Series
PRE : Preliminary Laboratory Test Series
* CIP : Cast-in-Place
† None : No Environmental Exposure
UV : Ultraviolet Light
F-T : Freeze-Thaw
Salt : Salt (Corrosion)
Acid Rn : Acid rain wetting and drying
Combo : Combination
‡ 6 : 6-inch diameter concrete cylinder
12 : 12-inch diameter concrete cylinder

Table 3.3 Test Matrix

Experimental Exposure Type	CIP 1 Type	Adhesive 6 Type	Expansion 2 Types	Undercut 2 Types	Total Tests
CONCEPT VERIFICATION TEST SERIES					
6 inch ϕ	x	–	–	–	4
12 inch ϕ	x	–	–	–	4
	8	0	0	0	8
ENVIRONMENTAL CYCLING TEST SERIES					
Ultraviolet	–	x	–	–	24
Freeze-Thaw 6 in. ϕ	–	–	x	–	8
Freeze-Thaw 12 in ϕ	–	–	x	–	8
Salt (Corrosion)	–	–	x	–	8
Acid Rain	–	x	x	–	32
Combination	x	–	x	x	20
	4	48	40	8	100
PRELIMINARY LABORATORY TEST SERIES					
6 in. Cylinder	–	–	x	–	4
Block	–	–	x	x	8
	0	0	8	4	12
				TOTAL NUMBER OF TESTS	120

NOTES: 1. Each x represents 4 replicate tests

3.4.2 Construction. All environmental test specimens initially used in the ECT and PLT test series were 6- x 12-inch cylinders, cast indoors using a single batch of ready-mix concrete meeting Texas SDHPT specification for Class C concrete. To make the cylinders more representative of typical field concrete, they were not cast in three lifts with each lift rodded 25 times as required by the ASTM specification for standard cylinders. Instead, the cylinders were poured in a single lift, vibrated, troweled and field cured. As discussed later, ECT tests with expansion anchors subjected to freeze-thaw required the use of 12-inch diameter cylinders. These were cast under the same conditions as the 6-inch cylinders. All concrete strengths were as shown in Table 3.4. After 28 days of field curing, the anchors were installed in the cylinders.

3.5 Reaction Blocks

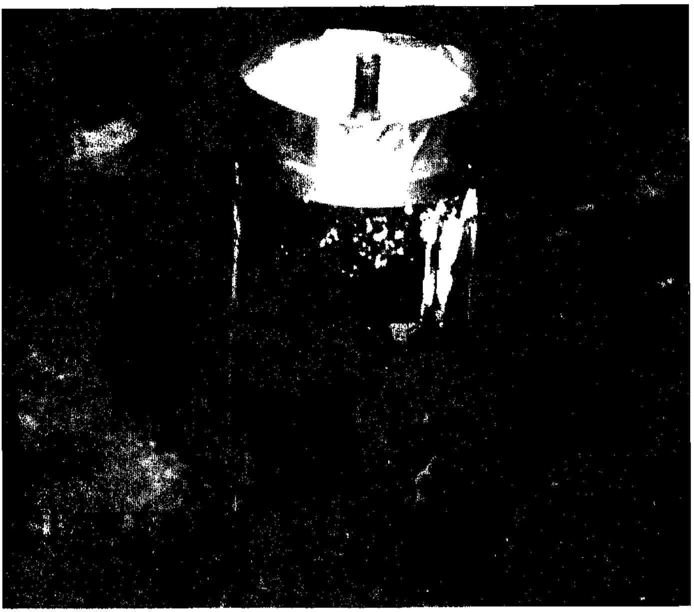


Figure 3.4 Typical test specimen.

3.5.1 Description. As shown in Figs. 3.6a and 3.6b, the concrete cylinders with anchor bolts were epoxied into cast cylindrical voids in 72- x 18- x 30-inch concrete reaction blocks. The reaction blocks for the CVT test series contained only 4 cylindrical voids (Fig. 3.7). Reaction blocks for all PLT and ECT tests contained 8 cylindrical voids each (Fig. 3.8). The void configuration was chosen in order to maximize the number of tests possible from each reaction block, while providing spacing sufficient so as not to alter the load-deformation behavior of the test specimens. The ECT tests of expansion anchors subjected to freeze-thaw, involving 12-inch cylinders, used reaction blocks with 4 voids, due to the spacing requirements of the larger diameter cylinders. Concrete compressive strengths for each block are shown in Table 3.4.

3.5.2 Construction. Two sets of formwork were constructed so that two blocks could be cast at once. The cylindrical voids were cast by attaching 6- x 12-inch plastic cylinder molds, filled with styrofoam, to the base of the formwork (Fig. 3.9). The styrofoam was placed in the molds to prevent the hydrostatic pressure of the fresh concrete from deforming them.

To prevent cracking of the blocks during handling in the lab, each block was reinforced with three #6 bars. The reinforcement was placed near the top of the reaction block with 1.75 inches of concrete cover (Fig. 3.10).

All blocks were cast indoors using different mixes of ready-mix concrete (Fig. 3.11). The concrete was placed in three lifts, and each lift was vibrated. The blocks were then covered with plastic to aid curing. The sides of the formwork were typically removed after 3 days. At about 5 days, the blocks were turned over, so that the reinforcement was now at the bottom of the specimen and the voids were at the top. When the blocks were rotated, they were externally reinforced (Fig. 3.12) to prevent any cracking and as a safety precaution. The blocks were used when their compressive strength reached at least 3500 psi. Compressive strengths at the time of testing for each block are shown in Table 3.4.

Table 3.4 Concrete Strengths

Test Specimen	Strength (psi)
CVT Block # 0	4390
CVT 6 in. ϕ cylinders	4390
CVT 12 in. ϕ cylinders	4390
ECT Block # 1	4740
ECT Block # 2	4900
ECT Block # 3	5020
ECT Block # 4	6220
ECT Block # 5	6780
ECT Block # 6	8960
ECT Block # 7	5430
ECT 6 in. ϕ cylinders	4790
ECT 12 in. ϕ cylinders	4900
PLT Block # 0	4390
PLT 6 in. ϕ cylinders	4790

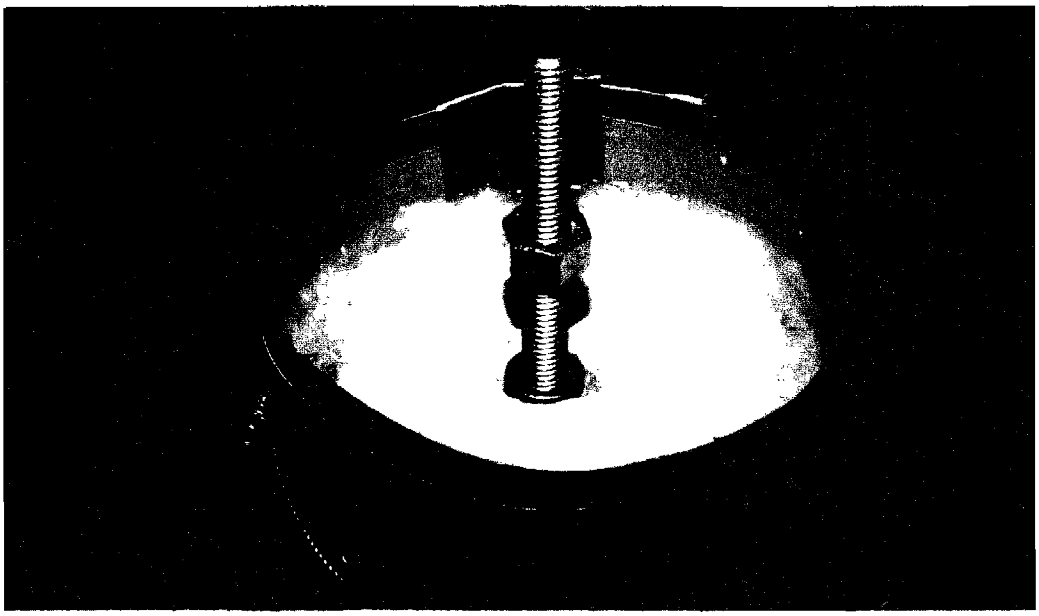


Figure 3.5 Rim of test specimen.

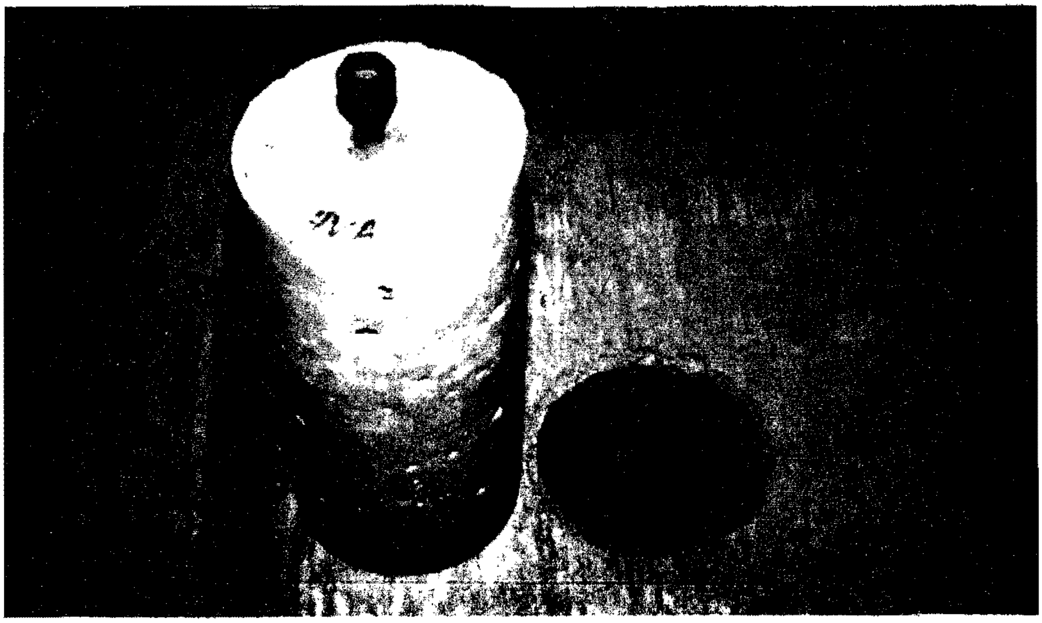


Figure 3.6a Specimen before being epoxied into reaction block.

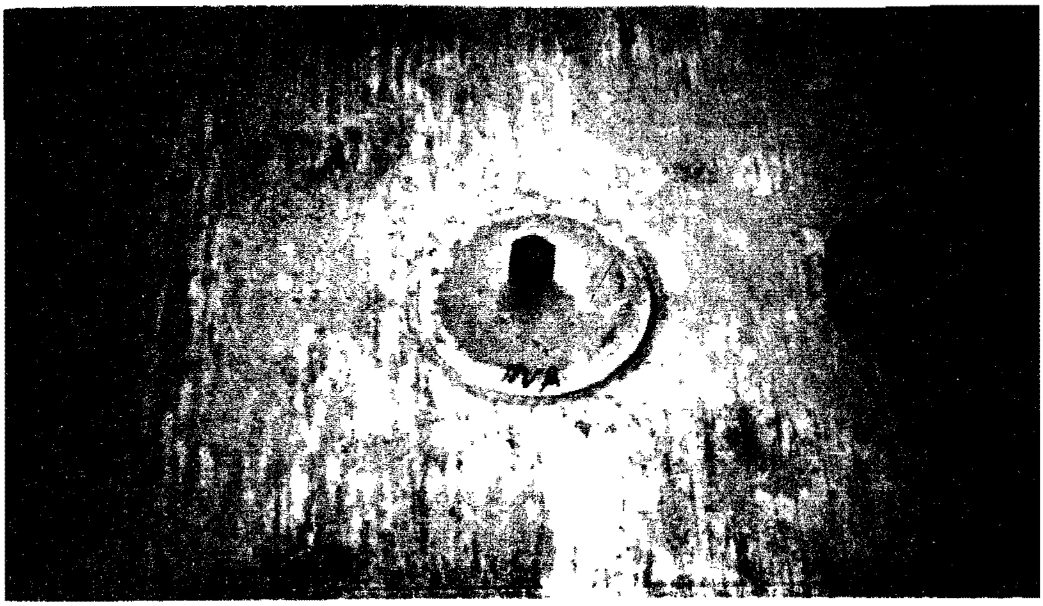


Figure 3.6b Specimen after being epoxied into reaction block.

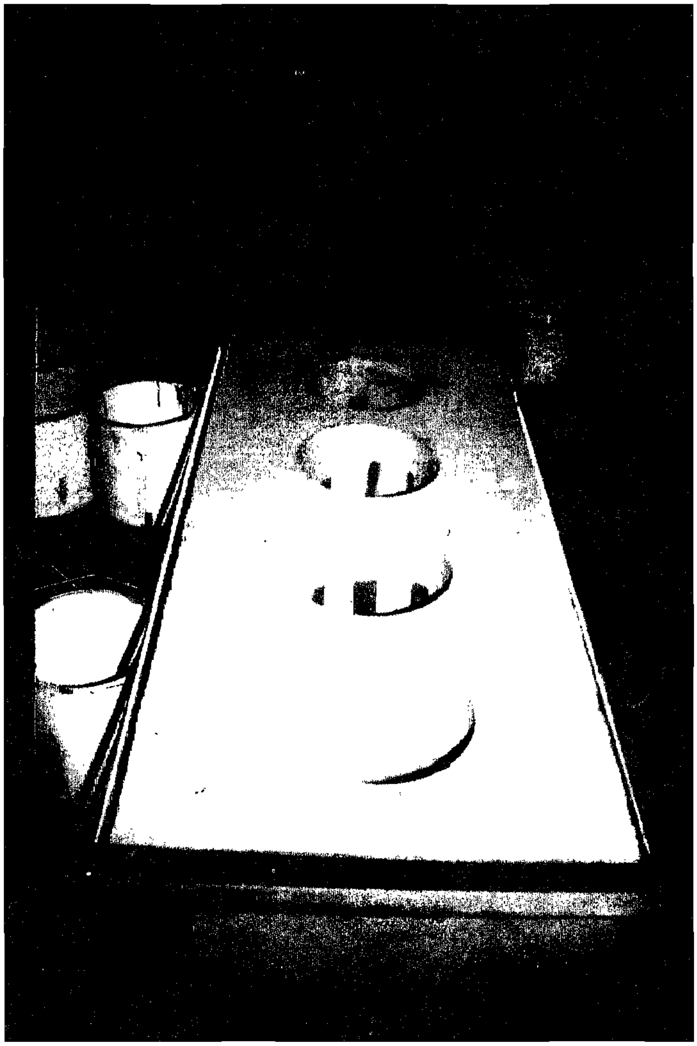


Figure 3.7 Reaction block with four 12-inch diameter cylindrical voids.

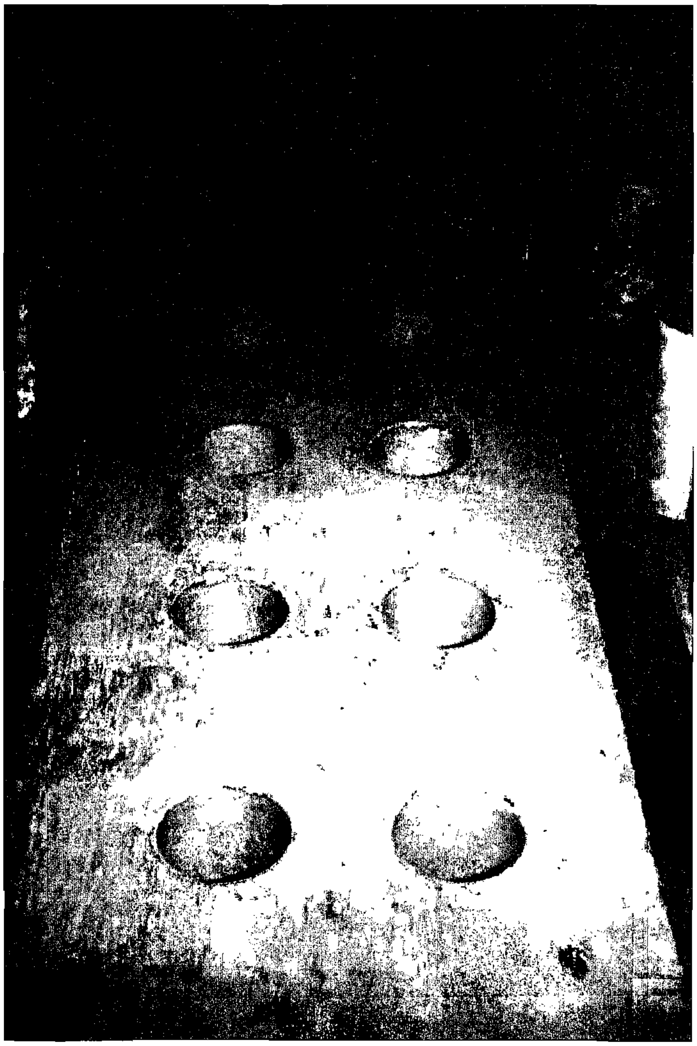


Figure 3.8 Reaction block with eight 6-inch diameter cylindrical voids.

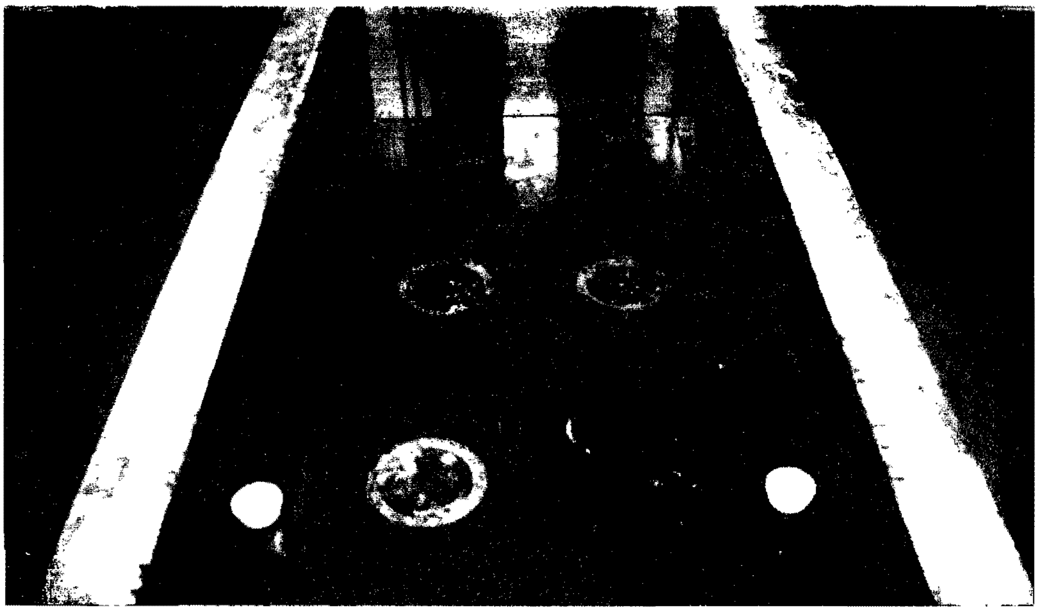


Figure 3.9 Cylindrical voids attached to formwork.

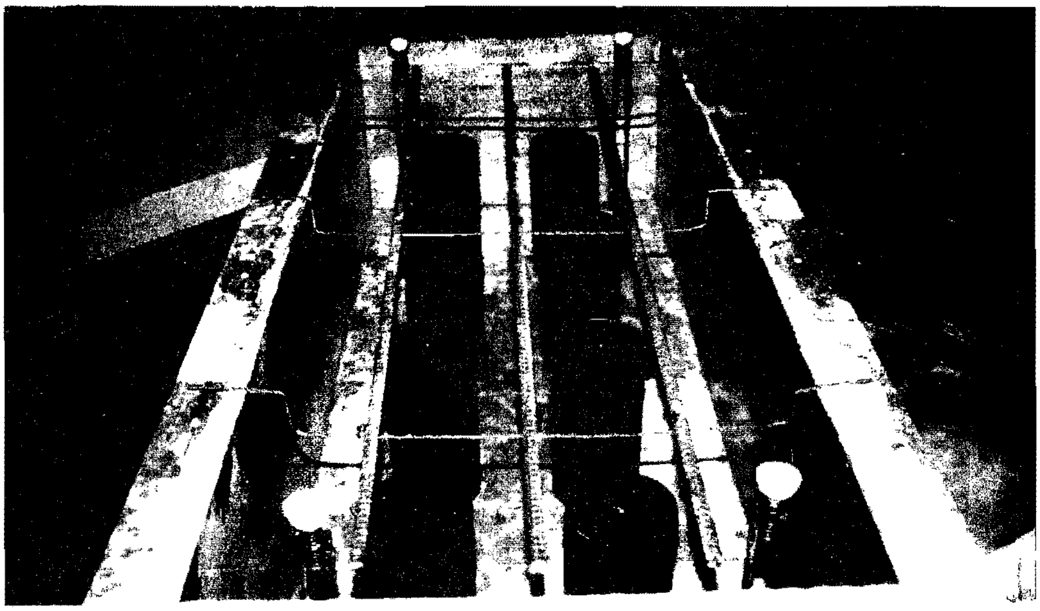


Figure 3.10 Reinforcing details.

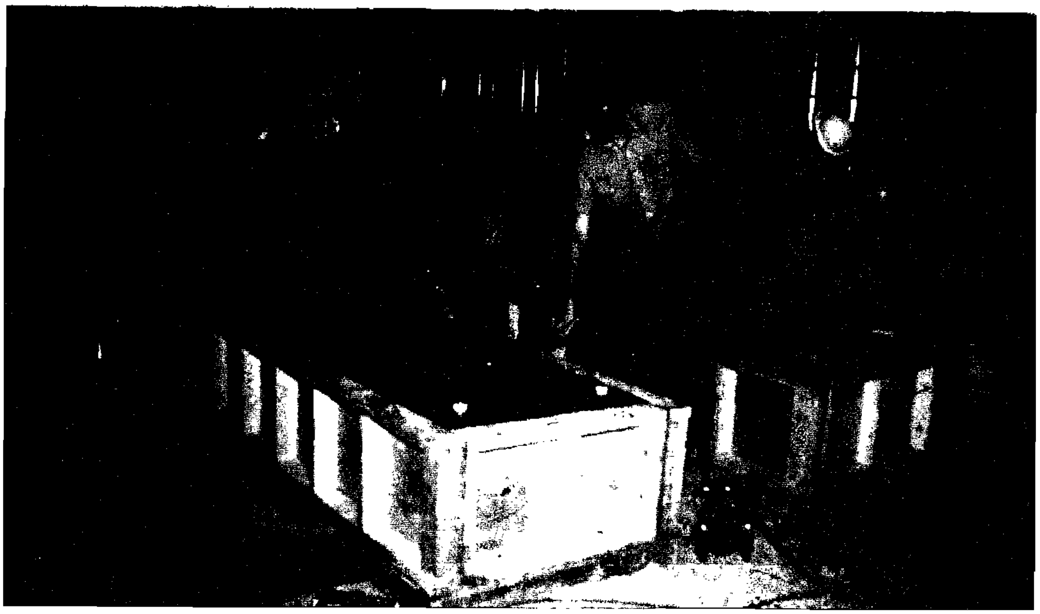


Figure 3.11 Casting reaction blocks.

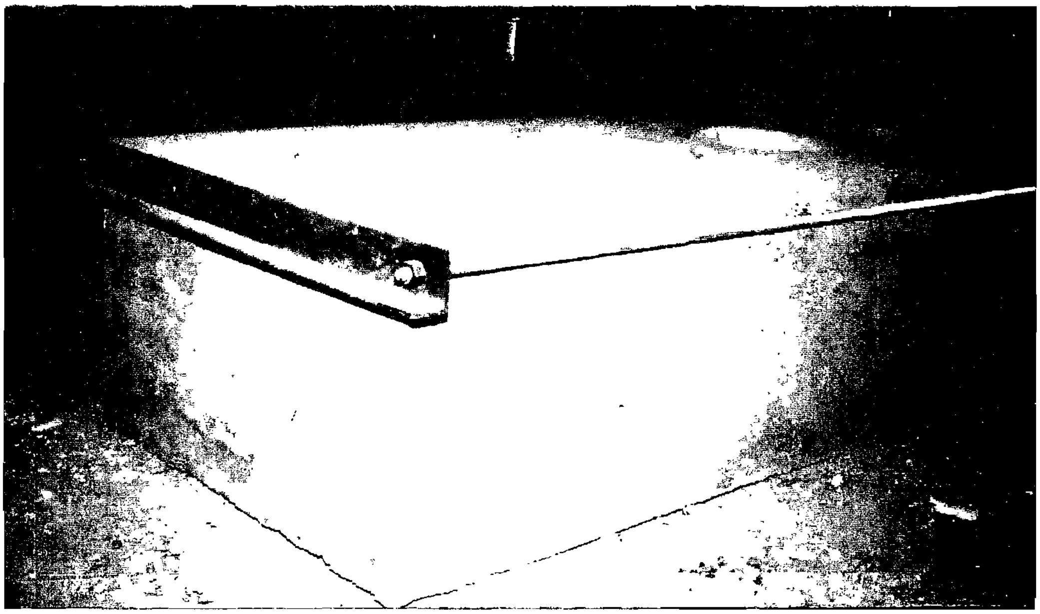


Figure 3.12 External reinforcing details.

CHAPTER 4. ANCHOR INSTALLATION

4.1 Introduction

Each anchor was installed in a concrete cylinder, left in its original mold. Some cylinders were cast in steel molds, while others were cast in plastic molds. During installation, the concrete cylinders with plastic molds were encased in steel collars which provided confinement and held them securely during the drilling operation, as shown in Figures 4.1 and 4.2.

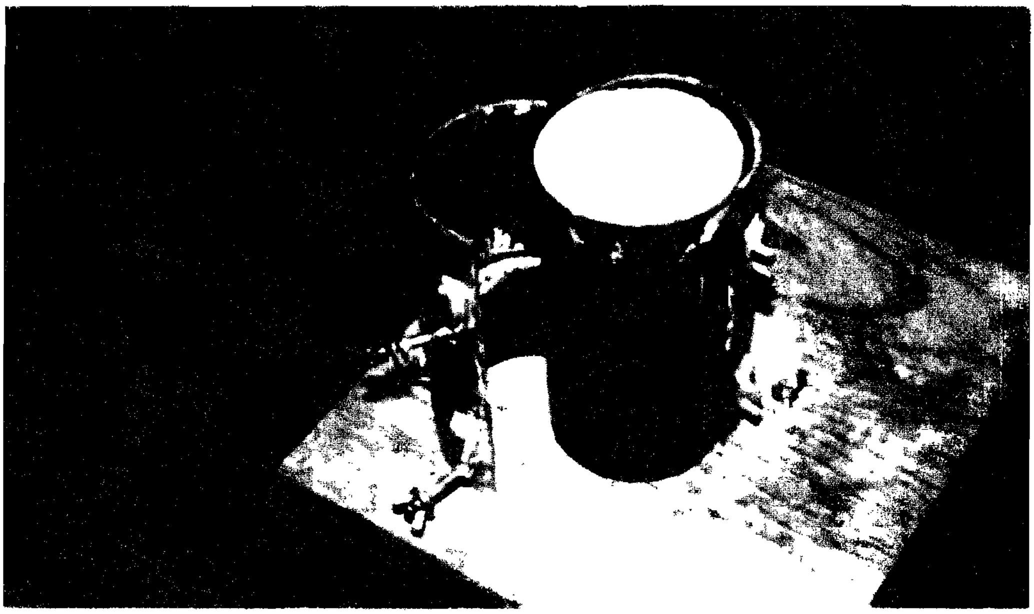


Figure 4.1 Steel collar used during drilling operation (open).

4.2 Cast-in-Place Anchors

Cast-in-place anchors were held in the cylinder molds during the casting operation by 1/2- x 1-inch wooden boards, allowing an 8-inch embedment length.

4.3 Adhesive Anchors

4.3.1 Hole Diameter. Holes for all adhesive anchors were drilled using a rotary hammer drill or an air drill, as recommended by each manufacturer (Figures 4.3 and 4.4). Unless specified by the manufacturer, all holes were drilled with a 3/4-inch bit. Table 4.1 summarizes the hole diameters and drill types used for each adhesive anchor.

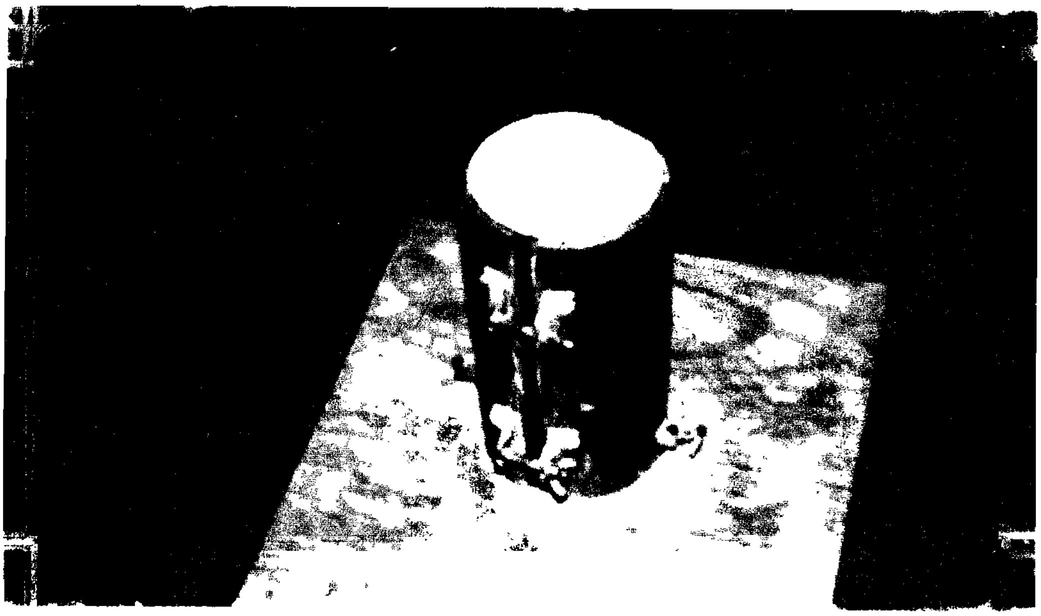


Figure 4.2 Steel collar used during drilling operation (closed).

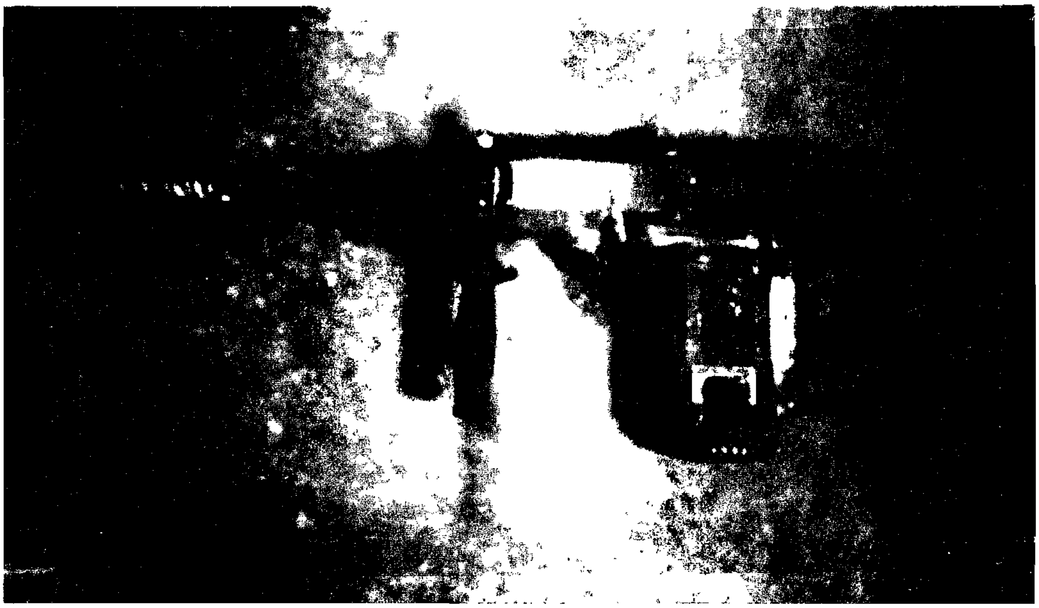


Figure 4.3 Rotary hammer drill.

Table 4.1 Installation Parameters

Test Number	Anchor Type	Hole Diameter (in.)	Drill Type #
CVT K	CIP	None	None
ECT A	Adhesive	7/8	RHD
ECT B	Adhesive	11/16	RHD
ECT C	Adhesive	7/8	RHD
ECT D	Adhesive	7/8	AIR
ECT E	Adhesive	11/16	RHD
ECT F	Adhesive	7/8	AIR
ECT G	Expansion	24 mm	RHD
ECT H	Expansion	24 mm	RHD
ECT I	Undercut	7/8	RHD
ECT J	Undercut	3/4	RHD
ECT K	CIP	None	None
PLT G	Expansion	24 mm	RHD
PLT H	Expansion	24 mm	RHD
PLT I	Undercut	7/8	RHD
PLT J	Undercut	3/4	RHD

Note: #. RHD: Rotary Hammer Drill
AIR: Air Drill

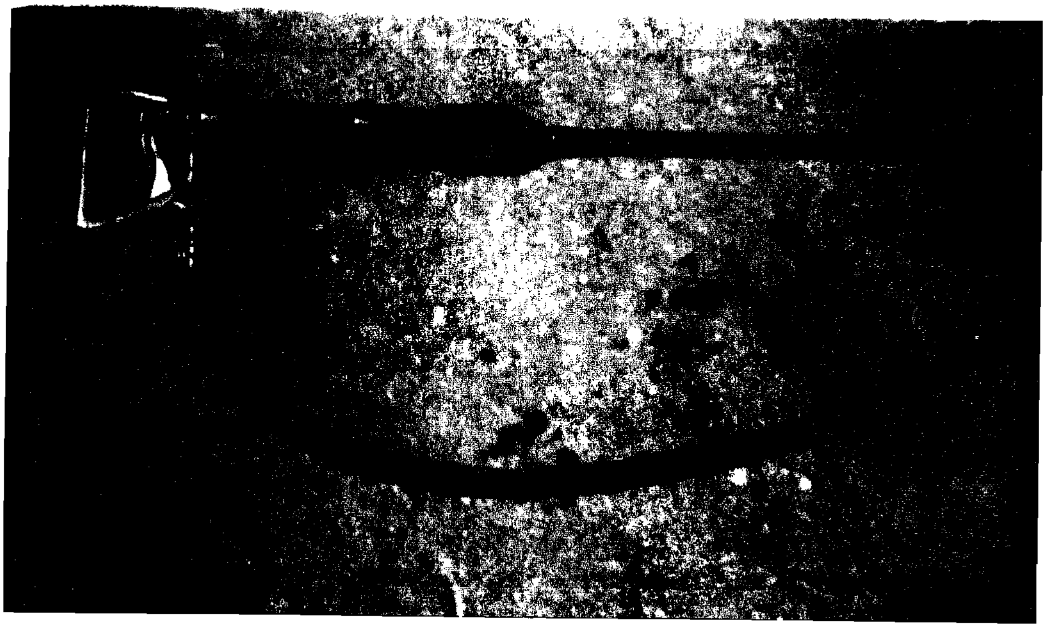


Figure 4.4 Air drill.

4.3.2 Hole Preparation. After the holes were drilled to the required depth, they were cleaned using a stiff bottle brush (Fig. 4.5), oil-free compressed air, and a vacuum cleaner as recommended by previous research [3]. After the holes had been brushed to remove as much concrete dust as possible, compressed air was then blown into the hole to remove more dust, the holes were again brushed, and finally were vacuumed to remove the remaining concrete dust.

4.3.3 Anchor Preparation. Threaded rods and coil rods were cut to the required length, wire-brushed to remove any rust, and finally immersed in a methyl-ethyl-ketone solution to remove any oily residue.

4.3.4 Preparation and Placement of Hand-Mixed Polyester. Polyester adhesive was supplied as a two-component resin and powder catalyst system. Prior to mixing, the two components were kept in an air-conditioned room below 75° F. The catalyst came in a pre-measured container, and was mixed with a pre-measured can of resin. As recommended by the manufacturer, the adhesive was stirred for 3 to 4 minutes to ensure proper mixing. The adhesive was placed in the hole, and the coil rod was turned while being pushed into the hole, to ensure that the rod was well coated with adhesive.

4.3.5 Preparation and Placement of Hand-Mixed Epoxy. Epoxy systems which required hand mixing came as a two-component resin and hardener system. The two components were proportioned by volume in plastic cups and combined in a 6- x 12-inch plastic cylinder mold. The adhesive was mixed with an electric drill and a paint stirrer for

Figure 4.5 Cleaning holes with bottle brush.

3 to 4 minutes, until the epoxy showed a uniform color. The adhesive was placed in the hole and the threaded rod was rotated while being pushed into the hole to ensure that the rod was well coated with adhesive.

4.3.6 Preparation and Placement of Two-Component Cartridge . Some adhesives were supplied in a prepackaged cartridge as shown in Fig 4.6. The cartridge is placed into the injector "gun" and the two components mix in the nozzle as the injector is pumped, thereby requiring no hand proportioning or mixing. Adhesive from the injector was discarded until it showed a uniform color and texture. To avoid trapping air in the hole, the adhesive was placed from the bottom upward. The threaded rod was rotated while being pushed into the adhesive-filled hole to ensure that the rod was well coated with adhesive.

4.3.7 Preparation and Placement of Glass Capsule. One adhesive was provided in a glass capsule as shown in Fig. 4.7. Glass capsules were placed in the hole and broken with an angle-tipped threaded rod which was hammer-drilled into the hole to crush the glass and mix the adhesive. The adhesive is mixed correctly when the threaded rod reaches the bottom of the hole.

4.3.8 Curing of Adhesives. All adhesives were cured at ambient temperatures (75 to 95 degrees F.) for a minimum of 5 days before the cylinders were moved. This curing satisfied manufacturer's recommendations, which vary among adhesives.

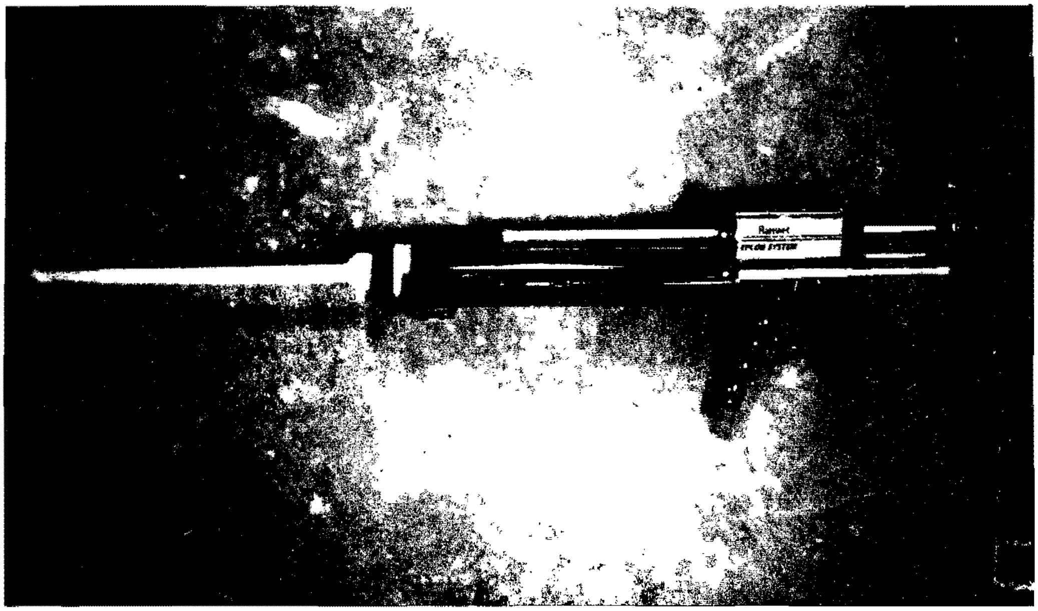


Figure 4.6 Two-component cartridge in applicator.

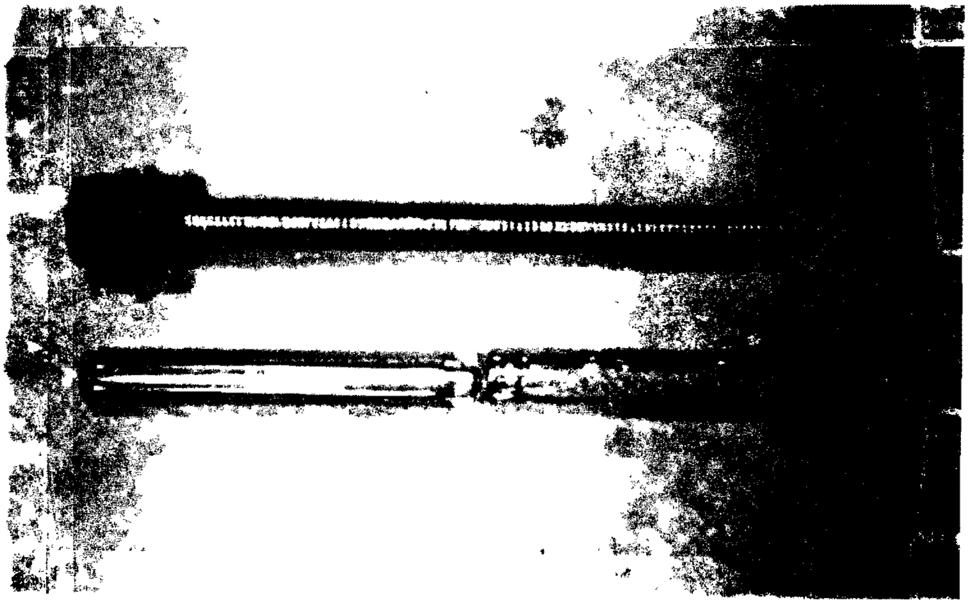


Figure 4.7 Glass capsules and threaded rod.

4.4 Expansion Anchors

4.4.1 Hole Diameter. All holes drilled for the expansion anchors were 24-mm in diameter, as shown in Table 4.1.

4.4.2 Hole Preparation. All holes were cleaned as described in subsection 4.3.2.

4.4.3 Placement of Anchors. Expansion anchors were hammered into place in the drilled holes. Each anchor was expanded in the hole by pre-loading the bolt according to the manufacturer's specification, using a torque wrench set at the required torque.

4.5 Undercut Anchors

4.5.1 Hole Diameter. The straight hole diameters used with undercut anchors are shown in Table 4.1. The ECT J test anchors required an additional drilling operation using an undercutting bit (Fig. 4.8) to cut a bell at the base of the previously drilled straight hole (Fig. 4.9).

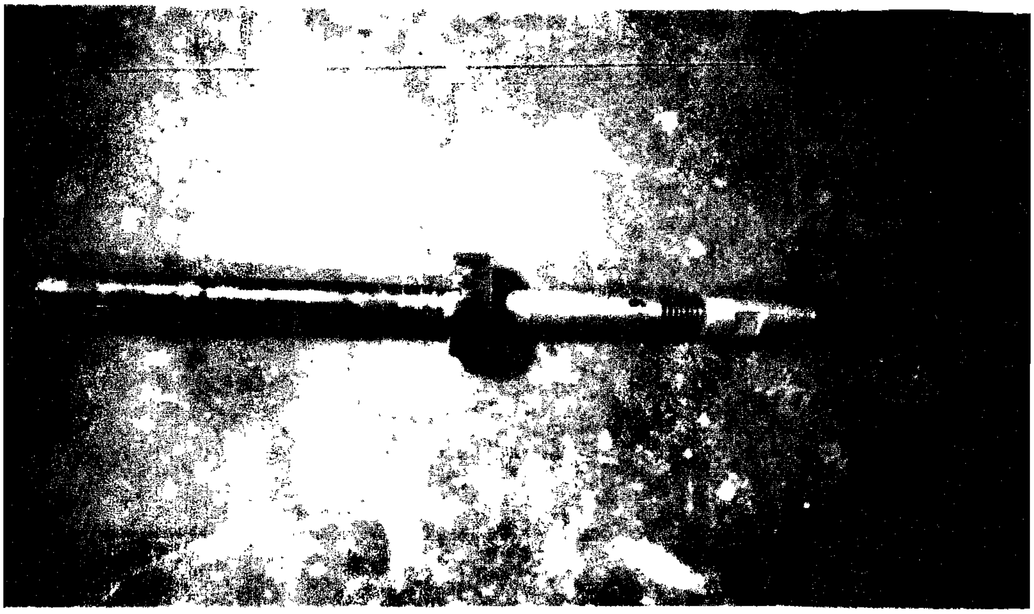


Figure 4.8 Undercutting drill bit.

4.5.2 Hole Preparation. All holes were cleaned as described in subsection 4.3.2.

4.5.3 Placement of Anchors. ECT I and PLT I test anchors were placed in the holes, and the undercutting mechanism was engaged by hammer drilling the collar of the anchor

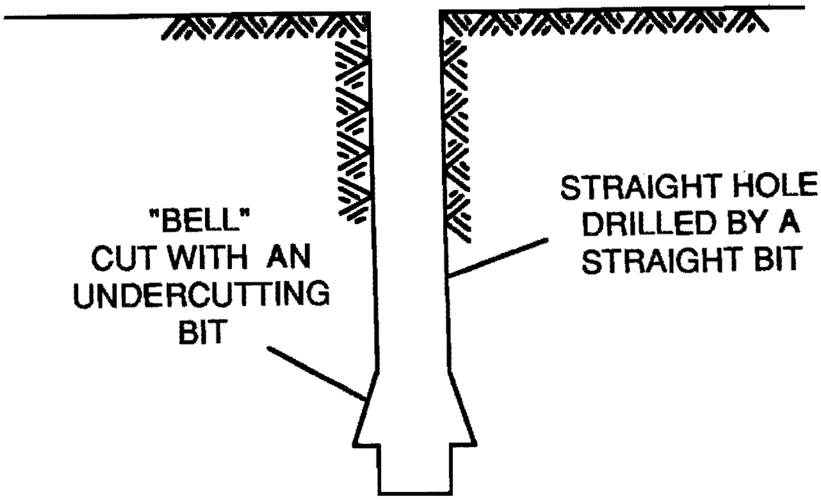


Figure 4.9 Schematic of hole cut by undercutting bit.

into the concrete with a special setting tool provided by the manufacturer. The ECT J and PLT J test anchors were placed in the holes and set with a hydraulic actuator.

CHAPTER 5. ENVIRONMENTAL EXPOSURE TESTING

5.1 Introduction

Anchors in this study were subjected to one of five different environmental conditions, chosen in an attempt to represent actual field exposure conditions:

1) Ultraviolet light
2) Freezing and thawing
3) Salt (corrosion)
4) Acid rain wetting and drying
5) Combination of these exposures

Currently, there are no ASTM specifications for the exposure of anchors to environmental conditions. Therefore, the environmental exposure program developed in this study was developed based on standard specifications for environmental exposure of other materials.

Each type of anchor in this study was not exposed to every environmental condition. Anchors were only subjected to environments which were reasoned would effect anchor performance. Adhesive anchors were not exposed to the salt, freezing and thawing, or combination exposures. It was reasoned that these three exposures would only affect the exposed part of the anchor above the concrete because the adhesive would prevent the water or salt solution from entering the drilled hole. Likewise, expansion anchors were not subjected to ultraviolet light, which has no effect on metals. Undercut anchors were only subjected to the combination exposure; because if they showed no change in behavior under this exposure, then any single exposure would not have an effect on their behavior. After the environmental exposure program, freezing and thawing as a single exposure was found to be a very severe environment which could be more detrimental than the combination exposure. Cast-in-place anchors were only subjected to the combination exposure.

5.2 Ultraviolet Light Exposure

This exposure condition, used to predict the effects of ultraviolet light exposure on adhesive anchors, is shown schematically in Fig. 5.1. The installed adhesive anchors were placed in a reflective aluminum cabinet as recommended by ASTM Designation C 718-72 (Fig 5.2). Three Philips TLK 40W/10R UV-A sun lamps on adjustable mountings were used in the cabinet. The distance between the test anchors and the lamps was adjusted to maintain the exposure temperature below 140° F. The anchors were placed under the sun lamps for a period of 8 hours. The lamps were then turned off for 16 hours. Each cycle took 24 hours, and was repeated 30 times.

According to Philips, 30 minutes of exposure under those conditions is equivalent to two hours of severe summer exposure; that is, the box is about four times as severe as natural UV exposure. The box involved a total of 8 hours/day x 30 days x 4 (factor), or the equivalent of 960 hours of intense UV exposure. Assuming the equivalent of four hours/day of intense exposure, one month in the box would be equivalent to about 240 days of normal exposure.

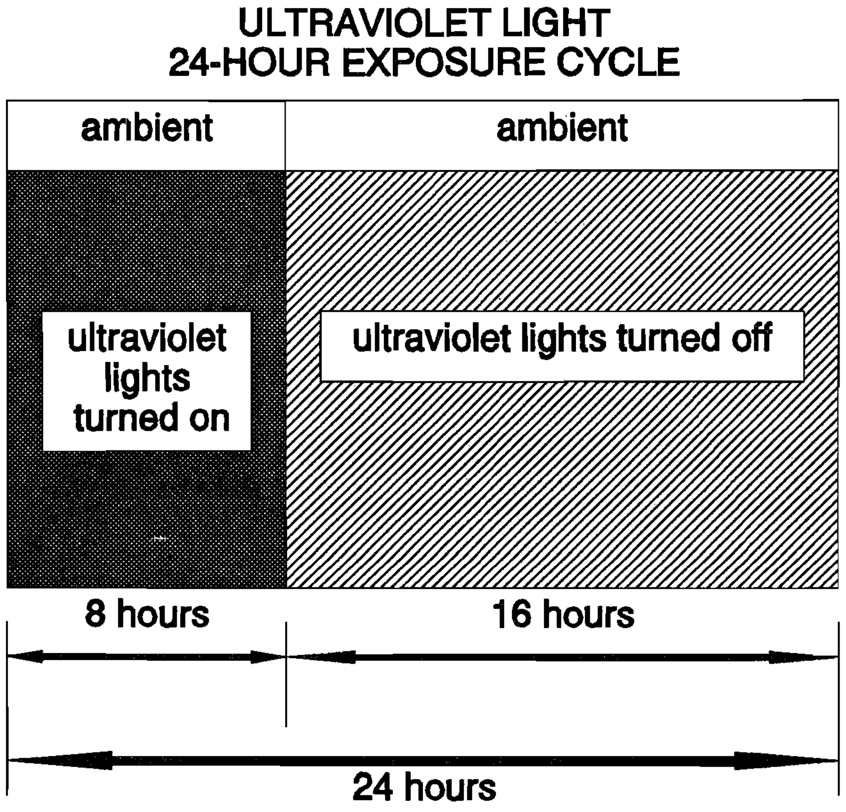


Figure 5.1 Schematic of ultraviolet light exposure.

5.3 Freezing and Thawing Exposure

This exposure was used to predict the effects of freezing and thawing on expansion anchors. A rim was put on the top of each environmental test specimen to allow water to pond on the surface of the specimen. Specimens were placed in an environmental chamber (CM Lingle Company Model 400) (Fig. 5.3), and water was ponded on the surface of each

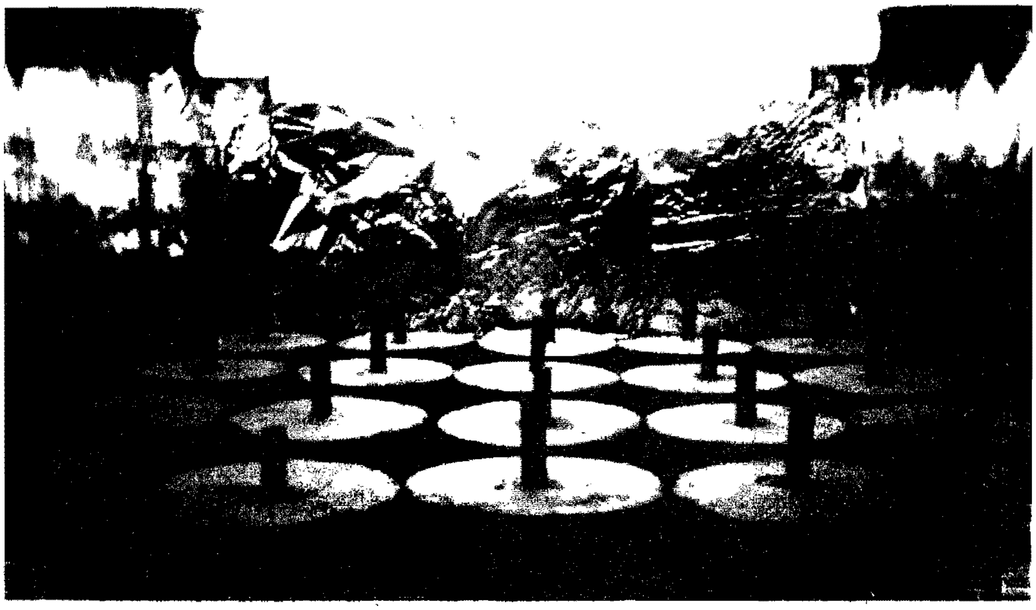


Figure 5.2 Reflective aluminum ultraviolet light exposure cabinet.

Figure 5.3 Environmental chamber.

specimen. Tap water with an adjusted pH of 7.02 was used during this test. As shown schematically in Fig. 5.4, the environmental chamber was set for one cycle of freezing and thawing in each 24-hour period. The chamber reached a low temperature of -20° F and remained there for 6 hours. The high temperature was +60° F and remained at +60° F for 6 hours. These temperature settings allowed the test anchors to freeze and thaw completely without experiencing radical temperature gradients. Each cycle took 24 hours, and was repeated 50 times.

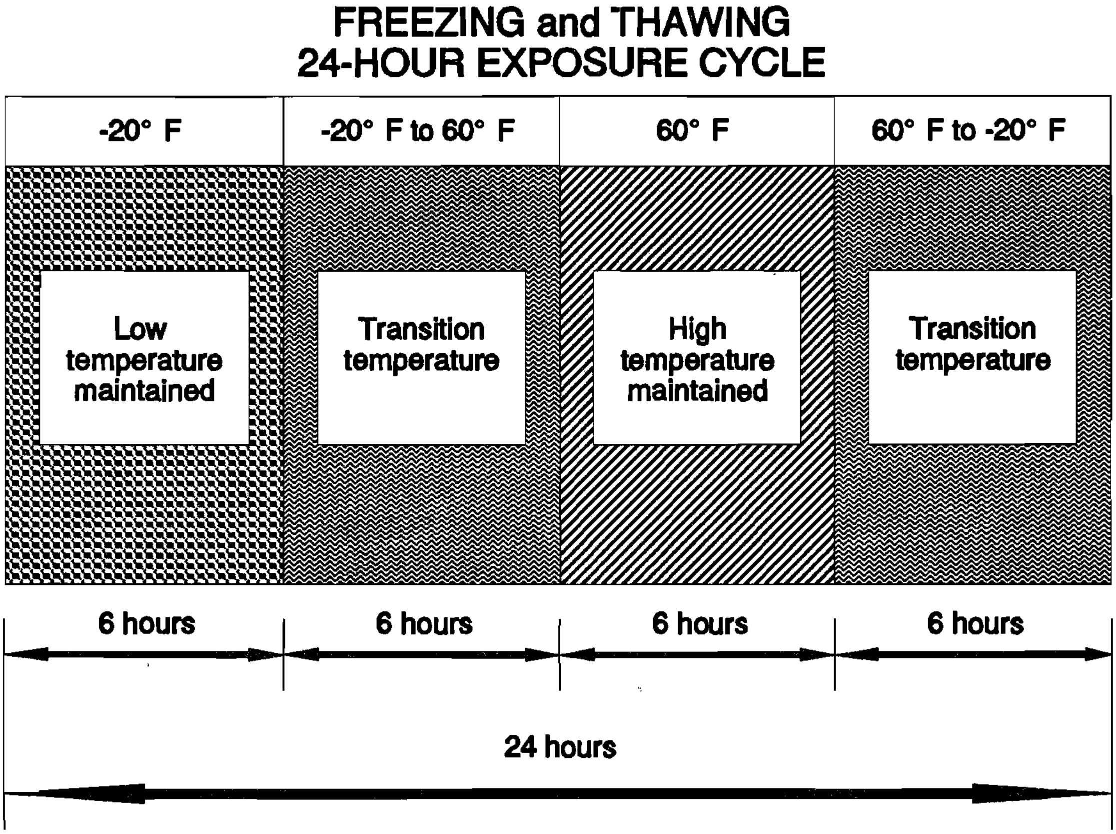


Figure 5.4 Schematic of freezing and thawing exposure.

5.4 Salt (Corrosion) Exposure

This exposure was used to predict the effects of de-icing salt exposure on expansion anchors. A rim was put around the top of each specimen to allow the salt solution to pond on the surface of the specimen. The salt solution was prepared by dissolving 5 parts sodium chloride (NaCl) by weight in 95 parts water, as recommended by ASTM Designation B117-85. The pH of the salt solution was adjusted to 7.0 as measured by an Altex Model 3500 Digital pH Meter. Salt used in this test was laboratory quality Baker Analyzed Sodium Chloride, lot C10703. A hydrometer reading taken of the salt solution measured 1.028 at 75° F. Throughout the test program, the solution was monitored and adjusted to maintain the initial salt concentration.

As shown schematically in Fig. 5.5, the salt solution was ponded on the test specimens for a period of 5 hours at ambient temperature. The solution was then drained off, and the specimens were placed in an environmental chamber at 100% humidity and 70° F for 16 hours. At the end of 16 hours of humidity exposure, the test specimens were allowed to dry for 3 hours at ambient temperature. Each cycle took 24 hours, and was repeated 50 times.

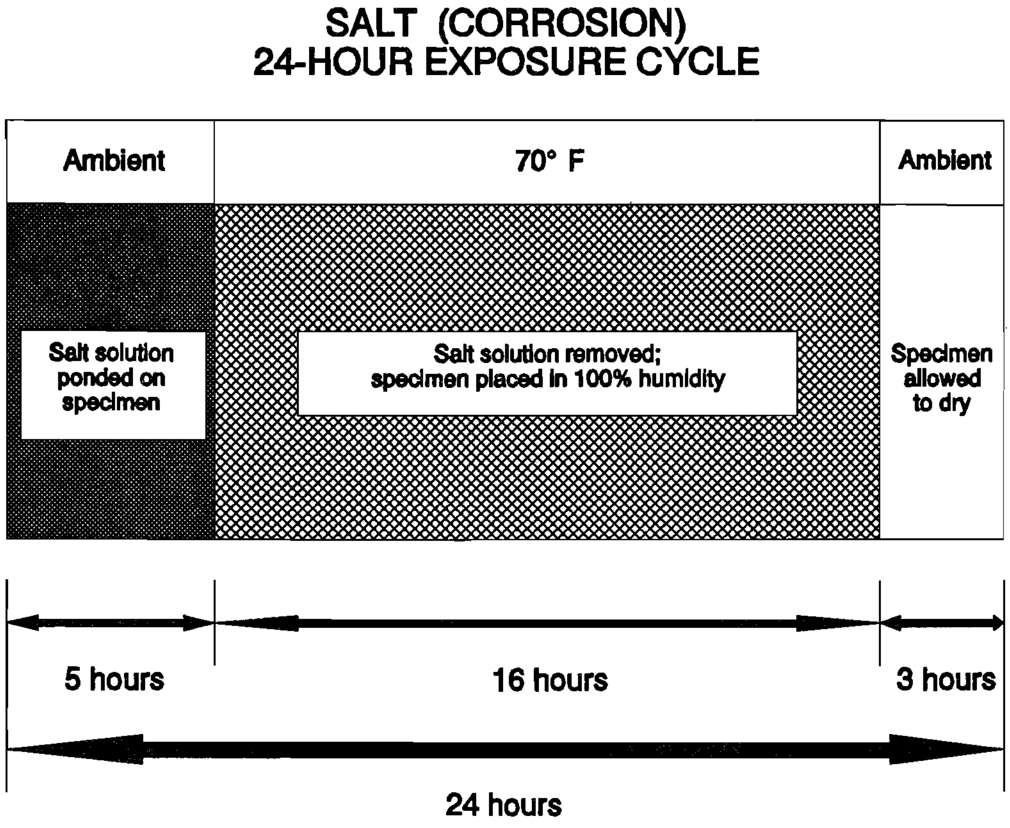


Figure 5.5 Schematic of salt (corrosion) exposure.

5.5 Acid Rain Wetting and Drying Exposure

This exposure was used to predict the effect of acid rain, combined with alternating cycles of wetting and drying on adhesive and expansion anchors. A rim was put around the top of each environmental test specimen to allow the acid rain to pond on the surface of the specimen. The solution used was a laboratory simulation of typical east coast acid rain, which was recommended by the Acid Rain Division of the Environmental Protection Agency [15]. This solution was prepared by mixing 1 part nitric acid with 2 parts sulfuric acid by volume, and then diluting the acid mixture with water to achieve a pH between 4.0 and 4.3. The actual solution used had a pH of 4.07 as measured with an Altex Model 3500 Digital pH Meter.

As shown schematically in Fig. 5.6, the solution was ponded on the test specimens for a period of 10 hours at ambient temperature. At the end of the 10 hours, the solution was poured off and the test specimen was allowed to dry for 14 hours at ambient temperature. Each wetting and drying cycle took 24 hours, and was repeated 50 times.

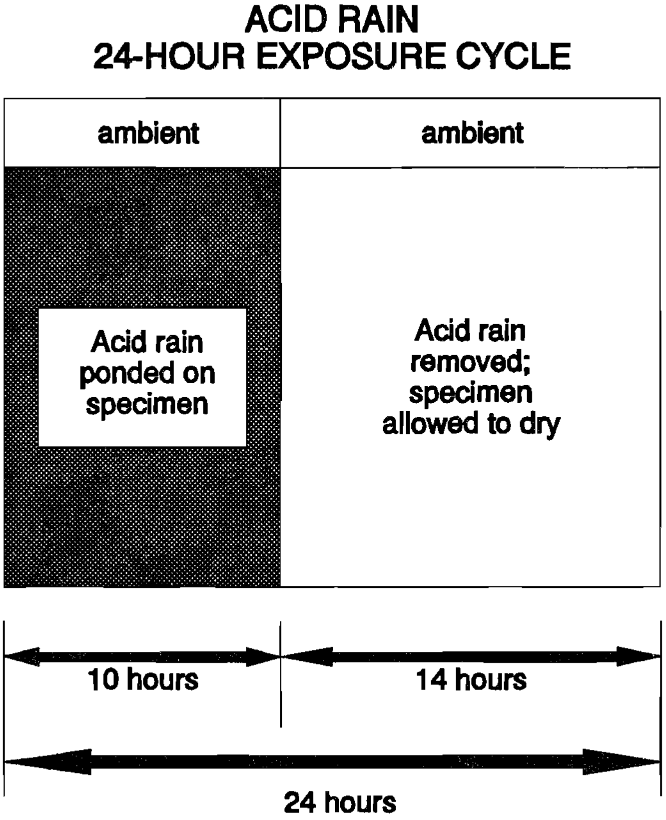


Figure 5.6 Schematic of acid rain wetting and drying exposure.

5.6 Combination Exposure

This exposure was used to predict the effects of wetting and drying, freezing and thawing, and salt exposure on expansion, undercut, and cast-in-place anchors. A rim was put around the top of each environmental test specimen to allow a salt solution to pond on the surface of the specimens. The solution used in this test is the same as that described in Section 5.4.

As shown schematically in Fig. 5.7, the salt solution was ponded on the surface of the test specimens for 5 hours at ambient temperature. It was then poured off, and the specimens were allowed to dry for 3 hours at ambient temperature. The specimens were then moved to the environmental chamber at 100% humidity and 70° F for 6 hours. Finally, the specimens were placed in a freezer at -20° F, and the salt solution was ponded on them for 10 hours. The temperature in the freezer was low enough to freeze the salt solution completely. Each cycle took 24 hours, and was repeated 50 times.

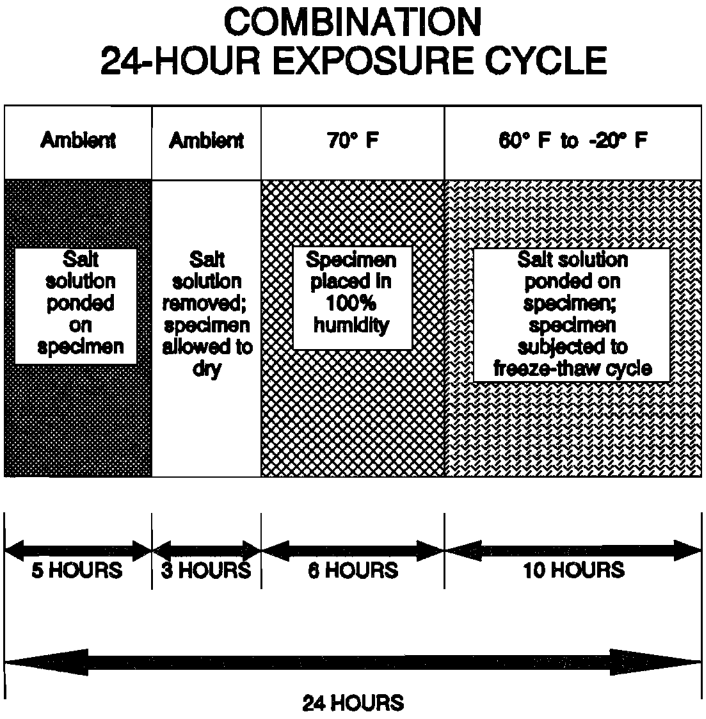


Figure 5.7 Schematic of combination exposure.

CHAPTER 6. TENSILE TESTING

6.1 Introduction

After environmental exposure, the test specimens were cemented into reaction blocks with a structural epoxy. Anchors were then loaded in tension to failure. Before tensile testing of expansion and undercut anchors, the preload was removed to attach the loading system.

6.2 Tensile Test Setup

6.2.1 Loading System. Load was applied to each anchor by a 100-ton, center-hole hydraulic ram as shown in Figs. 6.1 and 6.2. The ram was connected to a 27-inch diameter steel ring which reacted against the concrete block. The ring applied the reaction far enough away from the test anchor so that the load-deflection behavior and mode of failure would not be significantly altered by local bearing stresses.

Load was transferred to the anchor bolt through a 1-inch diameter, high-strength threaded steel rod, passing through the load cell, hydraulic ram, and connecting to a load shoe. Two different shoes were used in this experimental program. As shown in Fig. 6.3, the load shoe used in most tests is a 3/4-inch thick hardened steel plate with a 3/4-inch hole in the base. This shoe was placed over the threaded portion of each test anchor and secured with a washer and hex nut. A second load shoe was used for the Hilti HSL expansion anchors (test designation G) because the threaded portion on those anchors was too short to use the steel plate, washer, and hex nut. The second load shoe, shown in Fig. 6.4, consists of a 2-inch diameter high strength steel double connector with 1-inch threads on one side and 16-mm threads on the other. This was screwed directly onto the threaded portion of the test anchor.

All tests were conducted under displacement control. Hydraulic fluid was supplied to the ram by a MTS 6-gpm 3000 psi (Model 506.02) hydraulic supply, a MTS 290 hydraulic service manifold, and a Moog servovalve. The servovalve was controlled by an MTS 458.1 Microconsole servocontroller.

6.3 Instrumentation

6.3.1 Load Measurement. Load applied to the test anchor was measured with an Interface 100-kip load cell. As shown in Fig. 6.1, the load cell was placed between the nut of the threaded rod connected to the load shoe, and the top of the hydraulic ram.

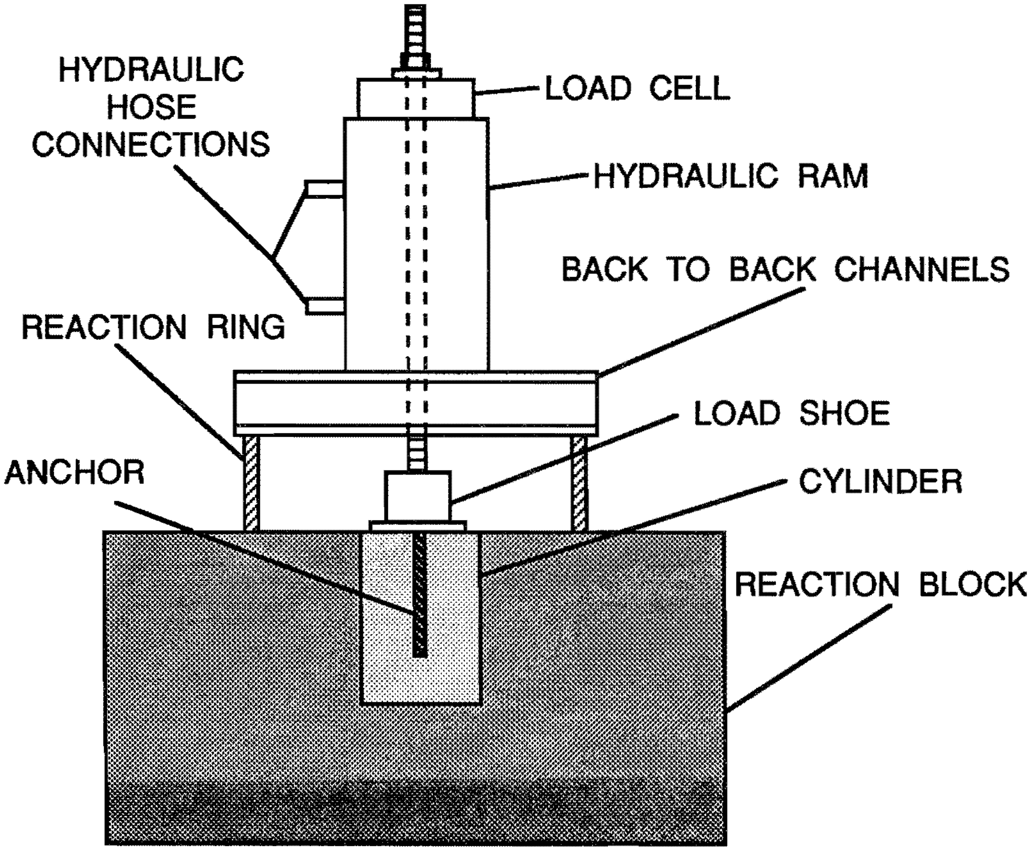


Figure 6.1 Schematic of loading system.

6.3.2 Displacement Measurements. As shown in Fig. 6.5, displacements were recorded at two locations:

1) The loaded end of the anchor

2) The interface between the cylinder and the reaction block

Displacements were measured using 2-inch linear potentiometers. The first displacement measurement gave the total movement of the loaded end of the anchor, including axial deformation of the anchor, concrete deformation, and slip between the anchor and the surrounding concrete. The second displacement measurement gave the relative movement between the cylinder and the reaction block.

6.3.3 Data Acquisition. Load and displacement measurements were recorded using a Hewlett-Packard 7090A data acquisition system. The measurements were converted to engineering units, stored on a microcomputer, and reduced and plotted using spreadsheet programs.

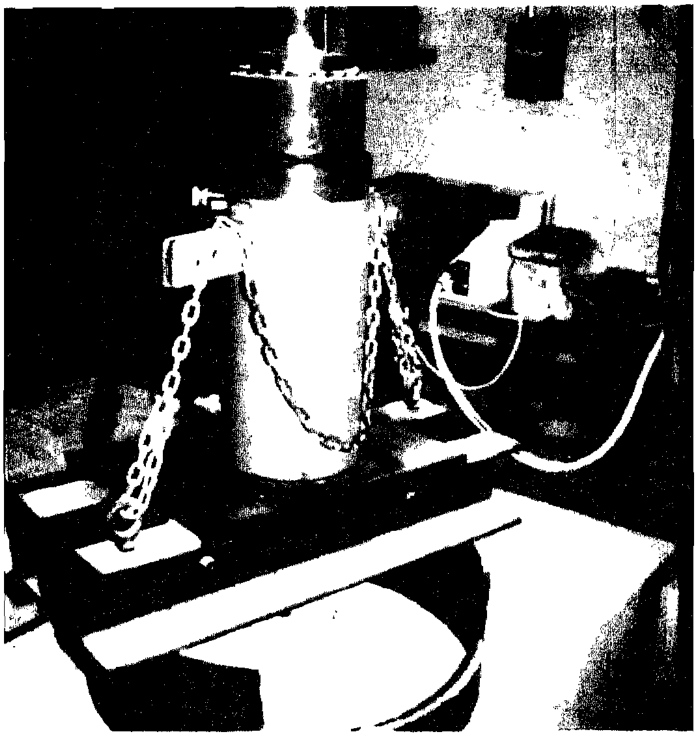


Figure 6.2 Loading system.

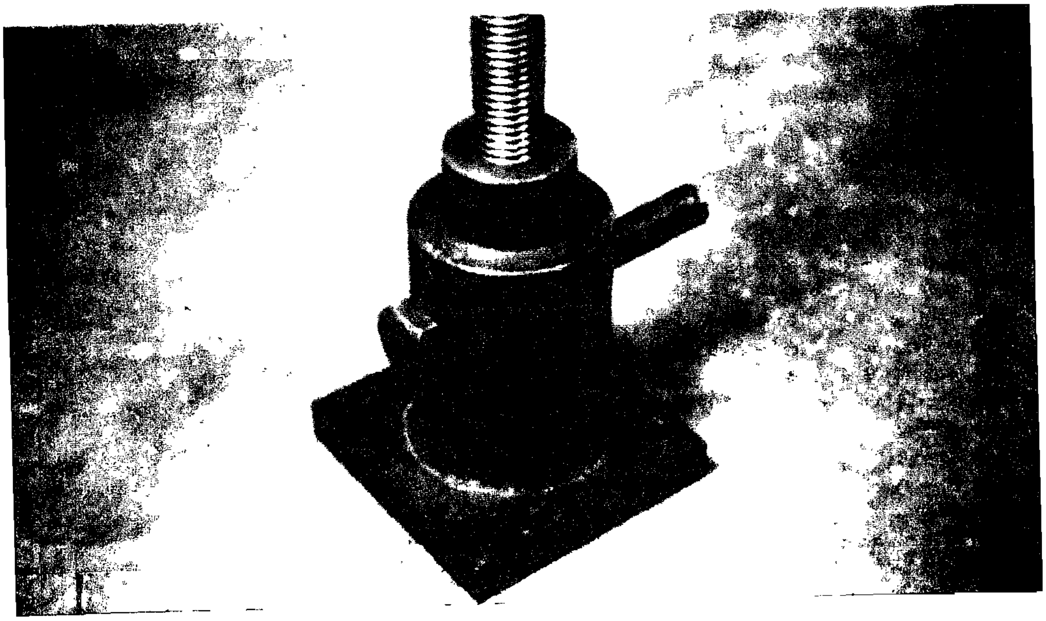


Figure 6.3 Load shoe.

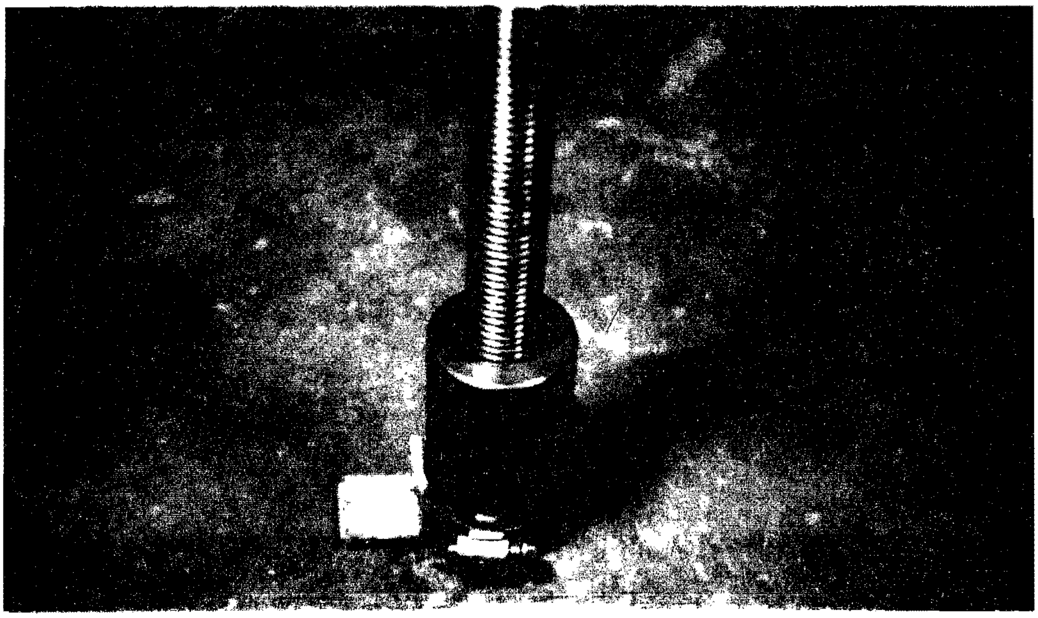


Figure 6.4 Internally threaded connector.

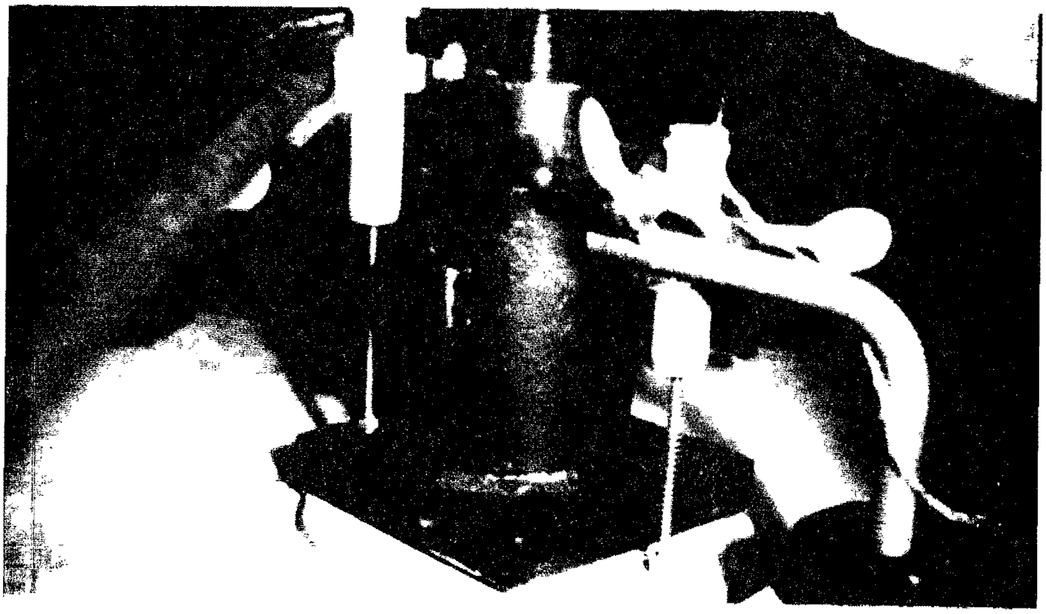


Figure 6.5 Location of displacement measurements.

6.4 Test Procedure

Each anchor was loaded to failure under displacement control. Load and displacement readings were taken continuously over the duration of a preset time window, set at 5 minutes. From start to finish of each test, measurements were taken 3.4 times per second.

CHAPTER 7. TEST RESULTS

7.1 Introduction

This chapter summarizes the results of both the environmental exposure tests and the tensile tests for the anchor bolts described in Chapter 3. Complete results are presented in Appendix A. The results of the environmental exposure tests are organized according to the particular environmental exposure test. Observations reported here reflect the overall response of the four replicates of particular anchors in each environment. Results of the tensile tests are organized according to anchor type. Results of the environmental exposure tests are qualitative, and are based on subjective visual observation. Pictures and schematics are presented here and in Appendix A to illustrate changes in appearance.

Results of the tests presented in this report should be interpreted under the following conditions:

1) Results are strictly valid only for the anchors tested in this study and the conditions under which they were studied.

2) Results of these retrofit anchor tests could be affected by anchor specifications, concrete type, installation procedures, or testing environment.

3) Results should not be construed to imply that all anchors of a given type are better than all anchors of another type.

4) Results should not be construed as an endorsement of any particular anchor type or brand.

7.2 Environmental Exposure Results

7.2.1 Ultraviolet Light Exposure. This exposure test was performed on all six adhesive anchors for 30 cycles (one cycle per day). Observations were made on the test specimens every 10 days to check for any color change, surface charring, or change in appearance of the adhesives. Figures A.1a and A.1b through A.6a and A.6b demonstrate the conditions of the test specimens at the end of 30 cycles.

From one observation to the next, there were no apparent changes of any kind on any of the adhesives. Adhesives did not undergo radical color changes or surface charring, nor did they break down (Figs. A.7 and A.8). However, after tensile testing, the adhesive surrounding each anchor could be examined across its section, as shown in Fig. 7.1, allowing a comparison between the surface of the adhesive exposed to ultraviolet light and the adhesive below the surface. In some of the adhesives (Table 7.1), this comparison showed a subtle color difference between the two surfaces.

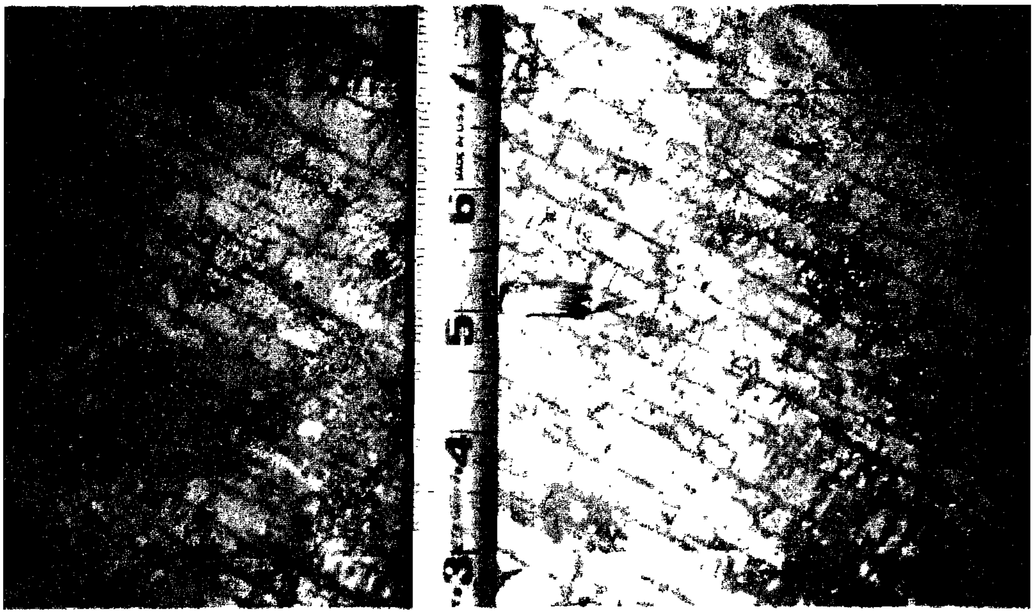


Figure 7.1 Adhesive surrounding the threaded rod, examined after tensile testing.

Table 7.1 Color change of adhesive anchors.

Test Identification	Replicates	Color Change After 30 Cycles #
ECT A 1	a,b,c,d	YES
ECT B 1	a,b,c,d	NO
ECT C 1	a,b,c,d	YES
ECT D 1	a,b,c,d	YES
ECT E 1	a,b,c,d	NO
ECT F 1	a,b,c,d	NO

NOTES, # YES: There was a color difference between the surface of the adhesive and the adhesive below the surface.

NO: There was no color change.

7.2.2 Freezing and Thawing Exposure. This exposure test was performed on expansion anchors for 50 cycles (one cycle per day). Figures A.9a, A.9b, A.10a, and A.10b demonstrate the condition of the test specimens at the end of 50 cycles of freezing and thawing. Test specimens were monitored every 7 days. Results are summarized in Table 7.2, and are discussed below.

Table 7.2 Summary of Freeze-Thaw Exposure Results

Anchor	Response to Exposure	Freeze-Thaw Cycles						
		7	14	21	28	35	42	50
ECT G	Small flakes			X	X	X	X	X
	Flakes near hole							
	Top cracks						X	
	Complete cracks							X
	Nuts loose						X	X
ECT H	Small flakes			X	X	X	X	
	Flakes near hole				X	X	X	
	Top cracks							
	Complete cracks							X
	Nuts loose							

The first series of this environmental test was carried out on expansion anchors installed in 6-inch diameter concrete cylinders. The following observations were made:

<u>7 Cycles</u>

Specimen ECT G-H: No change.

<u>14 Cycles</u>

Specimen ECT G-H: No change.

<u>21 Cycles</u>

Specimen ECT G-H: Appearance of a few random, very small flakes of concrete on both the ECT G and H specimens.

28 Cycles

Specimen ECT G: Some additional random, very small flakes of concrete on the specimens.

Specimen ECT H: Some additional random, very small flakes of concrete on the specimens. Flaking was more concentrated near the hole on these specimens.

35 Cycles

Specimen ECT G: No additional random flaking.

Specimen ECT H: No additional random flaking. Slight additional flaking, progressing outward, of the concrete near the hole.

42 Cycles

Specimen ECT G: Two specimens exhibited large cracks across the top of the concrete cylinder (Fig. A.11). There was no visible cracking on any other specimens. A little additional random flaking occurred on the surface of the concrete. The nut on one of the uncracked ECT G specimens was loose.

Specimen ECT H: Slight additional random flaking occurred on the surface of the concrete. Flaking concentrated near the hole.

50 Cycles

Specimens were removed from the environmental chamber and the cylinder molds were removed. All test specimens were cracked (Fig. A.12). All 4 ECT H specimens were cracked horizontally and vertically on the sides of the cylinders at the level of the expansion mechanism. The 2 ECT G specimens, which had no visible top cracks at the end of 42 cycles, did have horizontal and vertical cracking patterns on their sides at the level of the expansion mechanism. Surface flaking did not significantly increase from 42 cycles. Finally, the nut on one additional ECT G specimen was loose. Typical random surface flaking for the specimens is shown in Figs. A.9a and A.10a.

These freezing and thawing cycles were repeated with expansion anchors installed in 12-inch diameter concrete cylinders. The same random surface flaking pattern was observed as with the 6-inch test specimens. Again, the flaking appeared concentrated near the hole on the ECT H test specimens. At 50 cycles, two of the ECT H test specimens showed cracks along the sides of the concrete cylinders (Fig. A.13). Other specimens showed no cracks. The nuts on 3 of the ECT G expansion anchors were loose at the end of 50 cycles.

7.2.3 Salt (Corrosion) Exposure. This exposure test was conducted for 50 cycles (one cycle per day) on both the ECT G and ECT H expansion anchors. Figures A.14a, A.14b, A.15a, and A.15b demonstrate the condition of the test specimens after 50 cycles of salt exposure. Observations were made every 7 days. Results are summarized in Table 7.3 and discussed below. Further details are given in Appendix A. The following observations were made:

Table 7.3 Summary of Salt (Corrosion) Exposure Results

Anchor	Response to Exposure	Salt Exposure Cycles						
		7	14	21	28	35	42	50
ECT G	Salt build-up		X	X	X	X	X	X
	Nut at nut-washer interface						X	X
	Rust on anchor top						X	X
	Rust on sleeves							
ECT H	Salt build-up	X						
	Nut at nut-washer interface		X	X	X	X	X	X
	Rust on anchor top		X	X	X	X	X	X
	Rust on sleeves				X	X	X	X

7 Cycles

Specimen ECT G: No change.

Specimen ECT H: Salt was building up on the anchor.

14 Cycles

Specimen ECT G: Two anchors showed small rust spots on the washer at the nut-washer interface.

Specimen ECT H: Anchors showed rust, starting at the top of the threaded rod and extending to the nut and washer.

21 Cycles

Specimen ECT G: All anchors showed small rust spots on the washer at the nut-washer interface.

Specimen ECT H: The tops of the anchors were completely covered with rust.

28 Cycles

Specimen ECT G: The rust spots on the anchors had slightly increased in size.

Specimen ECT H: All anchors were beginning to rust at the top of the sleeve.

35 Cycles

Specimen ECT G: New small rust spots appeared on the anchors at the nut-washer interface.

Specimen ECT H: The sleeves of the anchors had additional rust, starting at the top, and progressing down.

42 Cycles

Specimen ECT G: New rust spots were visible on top of the threaded rod of the ECT G test anchors, and the previous rust spots were slightly larger.

Specimen ECT H: The tops of the anchors were heavily rusted, and the sleeve continued to rust along its entire length.

50 Cycles

Specimen ECT G: The rust spots on all specimens were slightly larger.

Specimen ECT H: The portion of the anchor above the surface of the concrete was completely rusted, with the top of the threaded rod being heavily rusted.

7.2.4 Acid Rain Wetting and Drying Exposure. This exposure test was performed on both expansion and adhesive anchors for 50 cycles. Figures A.16a and A.16b through A.23a and A.23b demonstrate the condition of the specimens after 50 cycles of exposure. Test specimens were monitored every 7 days. The results are summarized in Table 7.4 and discussed below. The following observations were made:

Table 7.4 Summary of Acid Rain Wetting & Drying Exposure Results

Anchor	Response to Exposure	Exposure Cycles						
		7	14	21	28	35	42	50
ECT AF	Rust on exposed rod	X	X	X	X	X	X	X
	White build-up on sleeve							
ECT G	Rust on exposed rod							
	White build-up on sleeve							
ECT H	Rust on exposed rod							
	White build-up on sleeve			X	X	X	X	X

<u>7 Cycles</u>

Specimen ECT A-F:	Rust was found on the threaded rod exposed above the surface of the concrete on all adhesive anchors.
Specimen ECT G:	No change.
Specimen ECT H:	No change.

<u>14 Cycles</u>

Specimen ECT A-F:	The threaded rods of all adhesive anchors showed additional rust.
Specimen ECT G:	No change.
Specimen ECT H:	No change.

21 Cycles

Specimen ECT A-F: The threaded rod on all adhesive anchors showed additional rust.

Specimen ECT G: No change.

Specimen ECT H: The base of the sleeve exhibited a buildup of white material.

28 Cycles

Specimen ECT A-F: No change from 21 cycles.

Specimen ECT G: No change.

Specimen ECT H: No change from 21 cycles.

35 Cycles

Specimen ECT A-F: The threaded rods of all adhesive anchors were becoming heavily rusted.

Specimen ECT G: No change.

Specimen ECT H: Specimens showed a small additional buildup of white material.

42 Cycles

Specimen ECT A-F: Heavy rust on the threaded rod on all adhesive anchors.

Specimen ECT G: No change.

Specimen ECT H: Specimens showed some small additional buildup of the white material on the anchor sleeve.

50 Cycles

Specimen ECT A-F: Threaded rod was heavily rusted.

Specimen ECT G: No change from 0 cycles.

Specimen ECT H: No change from 42 cycles.

Acid rain wetting and drying cycles had no apparent effect on any of the adhesives. After tensile testing, the threaded rod below the surface of the concrete and adhesive surrounding the threaded rod could be examined (Fig. 7.2). This investigation showed that the threaded rod used with some adhesives had rusted below the surface of the concrete (Fig. 7.3). The length of threaded rod which was rusted below the surface of the concrete for each adhesive is listed in Table 7.5.

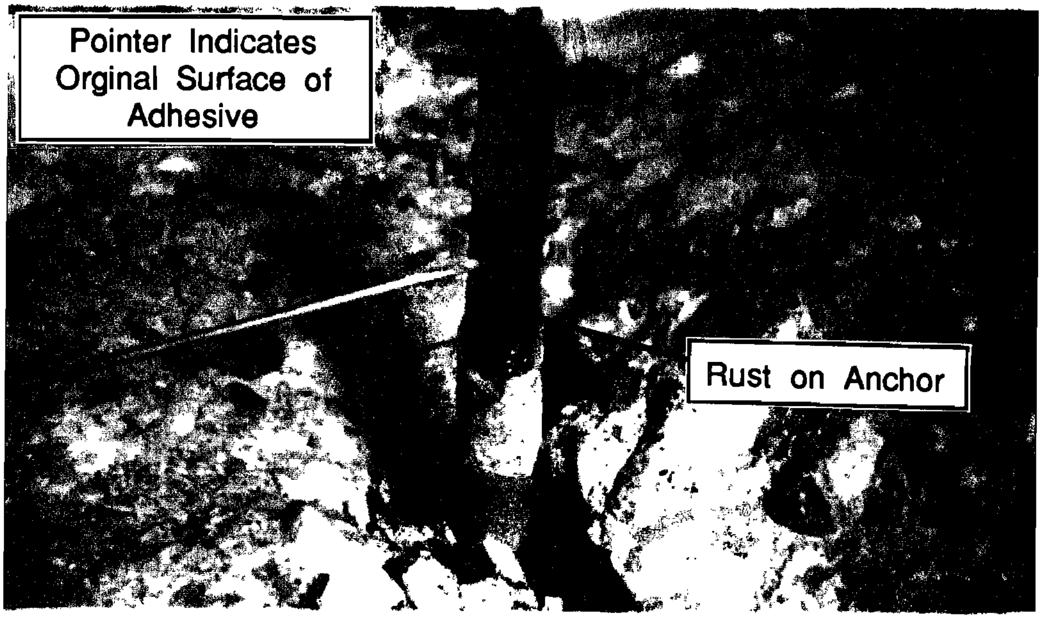


Figure 7.2 Adhesive exhibiting rust penetration below surface.

7.2.5 Combination Exposure. This exposure was performed on undercut, expansion, and cast-in-place anchors for 50 cycles. Figures A.24a and A.24b through A.28a and A.28b demonstrate the conditions of the specimens after 50 cycles of combination exposure. Observations were made every 7 days. The results are summarized in Table 7.6 and discussed below. The following observations were made:

7 Cycles

Specimen ECT G: No change.

Specimen ECT H: Salt buildup on the bolt.

Specimen ECT I: Salt buildup on the bolt.

Specimen ECT J: Small amount of salt buildup on the bolt.

Specimen ECT K: Rust on the threaded rod.

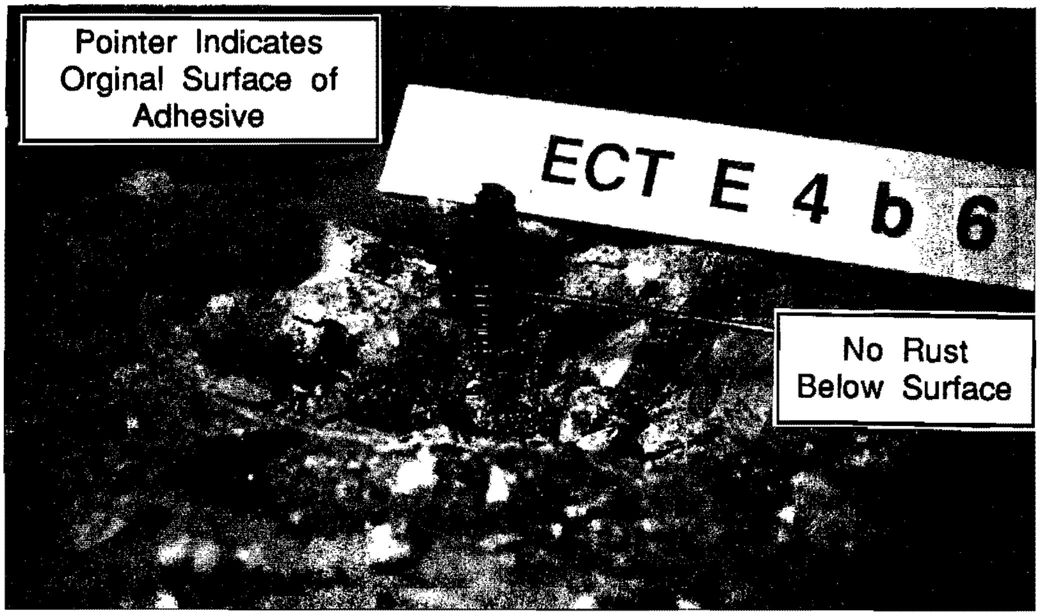


Figure 7.3 Adhesive exhibiting no rust penetration below surface.

Table 7.5 Depth of penetration of rust on adhesive anchors subjected to acid rain wetting and drying

Test Identification	Replicates	Depth of Rust from Surface (in.) #
ECT A 4	a,b,c,d	0
ECT B 4	a,b,c,d	1.125
ECT C 4	a,b,c,d	0
ECT D 4	a,b,c,d	.3125
ECT E 4	a,b,c,d	.3125
ECT F 4	a,b,c,d	0

Notes: # Measurement of the length of threaded rod which is rusted below the surface of the adhesive.

Table 7.6 Summary of Combination Exposure Results

Anchor	Response to Exposure	Exposure Cycles						
		7	14	21	28	35	42	50
ECT G	Small flakes		X	X	X	X	X	X
	Salt build-up							
	Rust on rod				X	X	X	X
	Flaking near hole							
ECT H	Small flakes		X	X	X	X	X	X
	Salt build-up	X	X					
	Rust on rod			X	X	X	X	X
	Flaking near hole			X	X	X	X	X
ECT I	Small flakes		X	X	X	X	X	X
	Salt build-up	X						
	Rust on rod		X	X	X	X	X	X
	Flaking near hole			X	X	X	X	X
ECT J	Small flakes		X	X	X	X	X	X
	Salt build-up	X	X	X	X	X	X	X
	Rust on rod							
	Flaking near hole			X	X	X	X	X
ECT K	Small flakes							X
	Salt build-up	X	X	X	X	X	X	X
	Rust on rod							
	Flaking near hole							

14 Cycles

Specimen ECT G:	No change on bolt. A few random flakes of concrete.
Specimen ECT H:	Considerable salt buildup on the bolt. A few random flakes of concrete.
Specimen ECT I:	Rust on the threaded rod. A few random flakes of concrete.
Specimen ECT J:	Small amount of salt buildup on bolt. A few random flakes of concrete.
Specimen ECT K:	Rust on the threaded rod. No change in concrete.

21 Cycles

Specimen ECT G:	A few rust spots on the washer. Random flaking on the concrete.
Specimen ECT H:	Rust on the bolt at the top. Flaking concentrated at the hole. Random flaking away from the hole.
Specimen ECT I:	Rust along the entire bolt. Flaking concentrated at the hole. Random flaking away from the hole.
Specimen ECT J:	Small amount of salt buildup, but no rust. Flaking concentrated at the hole. Random flaking away from the hole.
Specimen ECT K:	Rust on the threaded rod. No change in concrete.

28 Cycles

Specimen ECT G:	A few new rust spots on the washer. Some random flaking on the concrete.
Specimen ECT H:	Rust on the nut, washer, and bolt. Flaking concentrated at the hole, working outward. Random flaking of concrete across the surface.
Specimen ECT I:	Top of bolt well rusted. Flaking concentrated at the hole, working outward. Significant amount of random flaking of concrete away from the hole.

Specimen ECT J: Small amount of salt buildup, but no rust. Flaking concentrated at the hole, working outward. Random flaking of concrete across the surface.

Specimen ECT K: Rust on the threaded rod. No concrete flaking.

35 Cycles

Specimen ECT G: No new rust spots on the washer.

Specimen ECT H: Rust covering the nut, washer, bolt, and at top of collar. Flaking concentrated at the hole. Random flaking across the surface.

Specimen ECT I: Top of bolt well rusted. Flaking concentrated at the hole. Random flaking across the surface.

Specimen ECT J: Small amount of salt buildup, but no rust. Concrete flaking concentrated at hole. Random flaking across the surface.

Specimen ECT K: Considerable rust on the threaded rod. No concrete flaking.

42 Cycles

Specimen ECT G: Rust spots on the washer and nut. Random flaking on the concrete.

Specimen ECT H: Rust on the nut, washer, bolt and collar. Flaking of concrete concentrated at the hole. Considerable amount of random flaking on the concrete surface.

Specimen ECT I: Top of bolt well rusted. Flaking concentrated at the hole. Considerable amount of random flaking on the concrete surface.

Specimen ECT J: Small amount of salt buildup, but no rust. Flaking concentrated at the hole. Considerable amount of random flaking on the concrete surface.

Specimen ECT K: Heavy rust on the threaded rod. No concrete flaking.

50 Cycles

Specimen ECT G: Rust spots on the washer and nut. Random flaking on the concrete.

Specimen ECT H: Bolt is completely rusted. Flaking of concrete concentrated at the hole. Concrete badly spalled on the entire surface.

Specimen ECT I: Top of bolt heavily rusted. Flaking concentrated at the hole. Concrete badly spalled on the entire surface.

Specimen ECT J: Small amount of salt buildup, but no rust. Flaking concentrated at the hole. Concrete badly spalled on the entire surface.

Specimen ECT K: Threaded rod is very heavily rusted. A few random flakes of concrete on the surface.

7.3 Preliminary Laboratory Test Results

7.3.1 Adhesive Anchors. Two tests were run on test designation F adhesive, as no data was available for these anchors. No preliminary laboratory tests were conducted for any of the other adhesives. The anchors tested exhibited one failure mode:

1) Yield and fracture of anchor steel (Fig. 7.4a)

7.3.2 Expansion Anchors. Expansion anchors which were not subjected to any environmental exposure condition were loaded in tension to failure. These anchors exhibited two failure modes:

1) Failure by yield and fracture of anchor steel (Fig 7.5a)

2) Failure by anchor pullout (Fig. 7.5b)

Nine of the 10 tests conducted on expansion anchors failed by yield and fracture of the anchor steel. Typical load-deflection plots are shown in Figs. 7.6a and 7.6b. One PLT H anchor pulled out of the concrete (Fig. 7.7). The anchor pullout load-deflection plot is shown in Fig. 7.8.

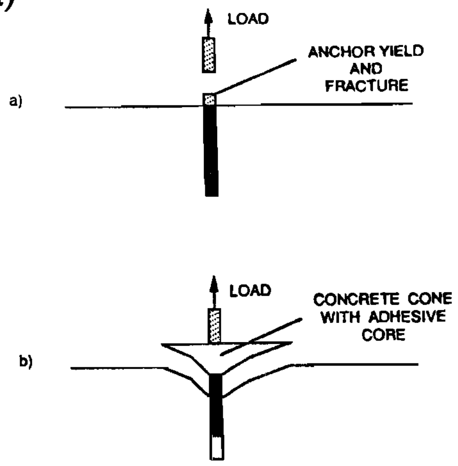


Figure 7.4 Failure modes for adhesive anchors.

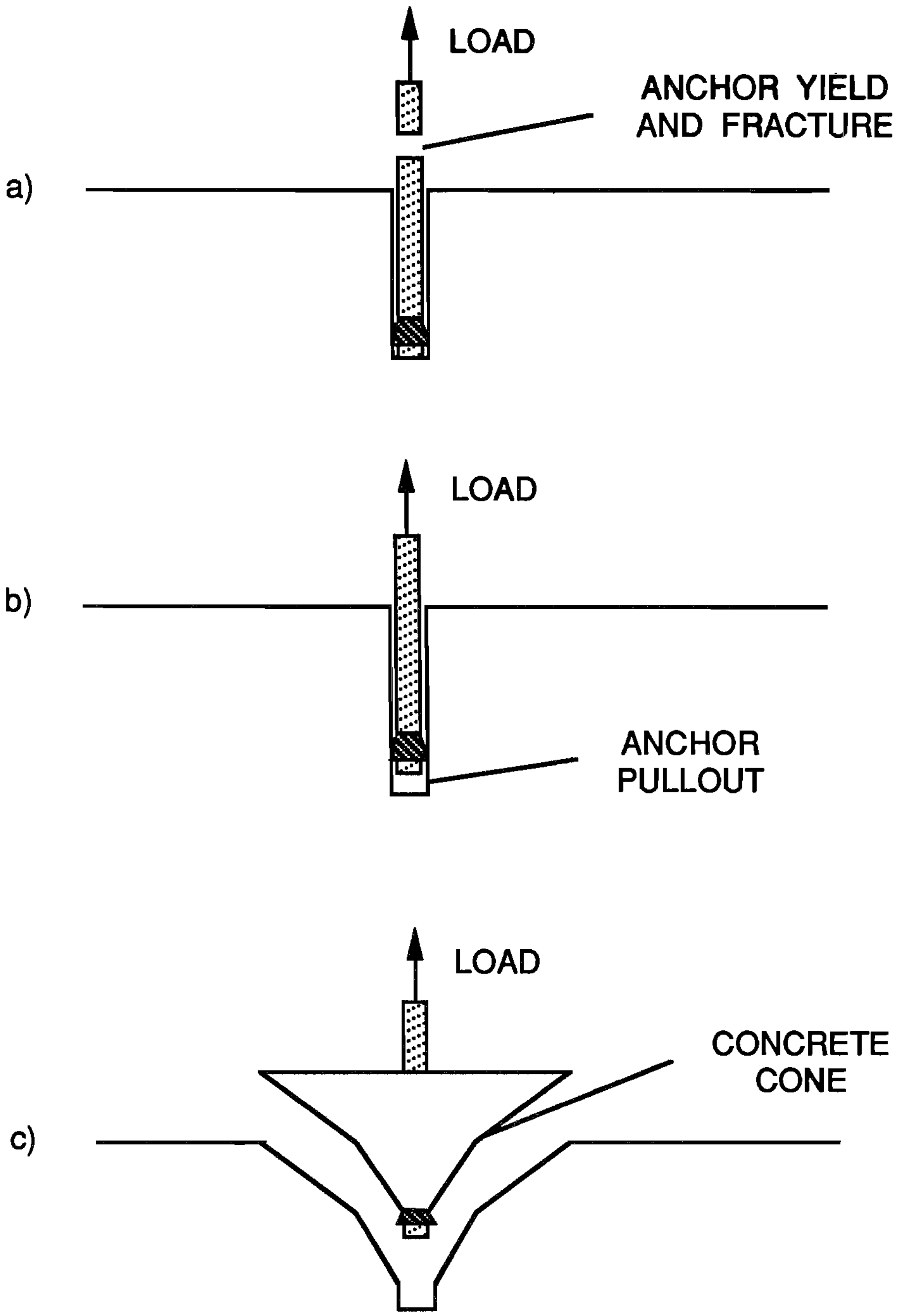


Figure 7.5 Failure modes for expansion anchors

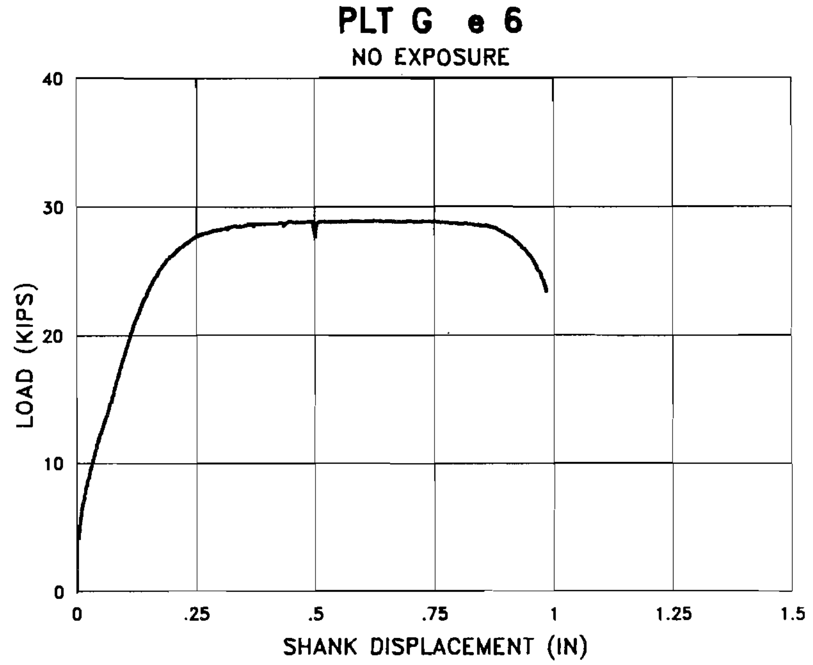


Figure 7.6a Typical load-deflection plot for PLT G anchors.

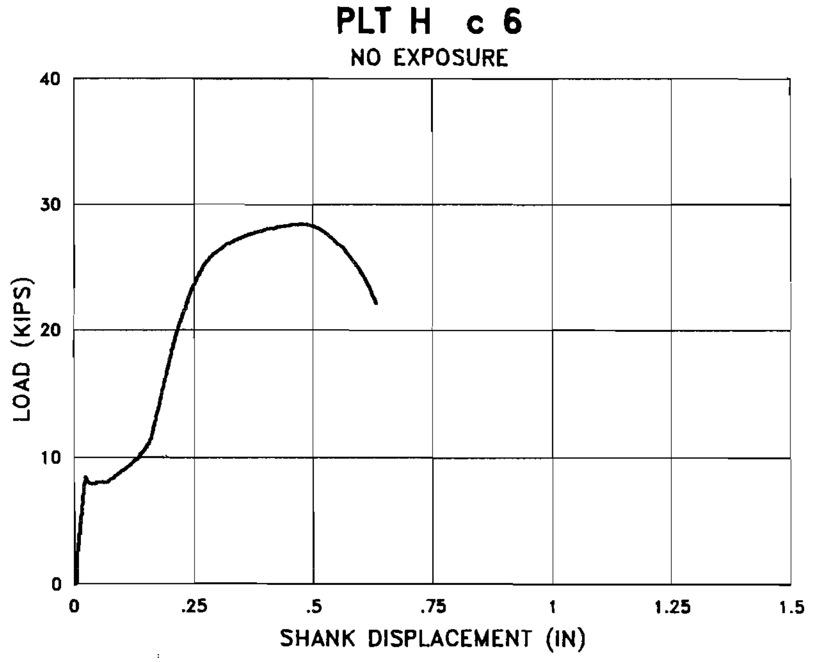


Figure 7.6b Typical load-deflection plot for PLT H anchors.

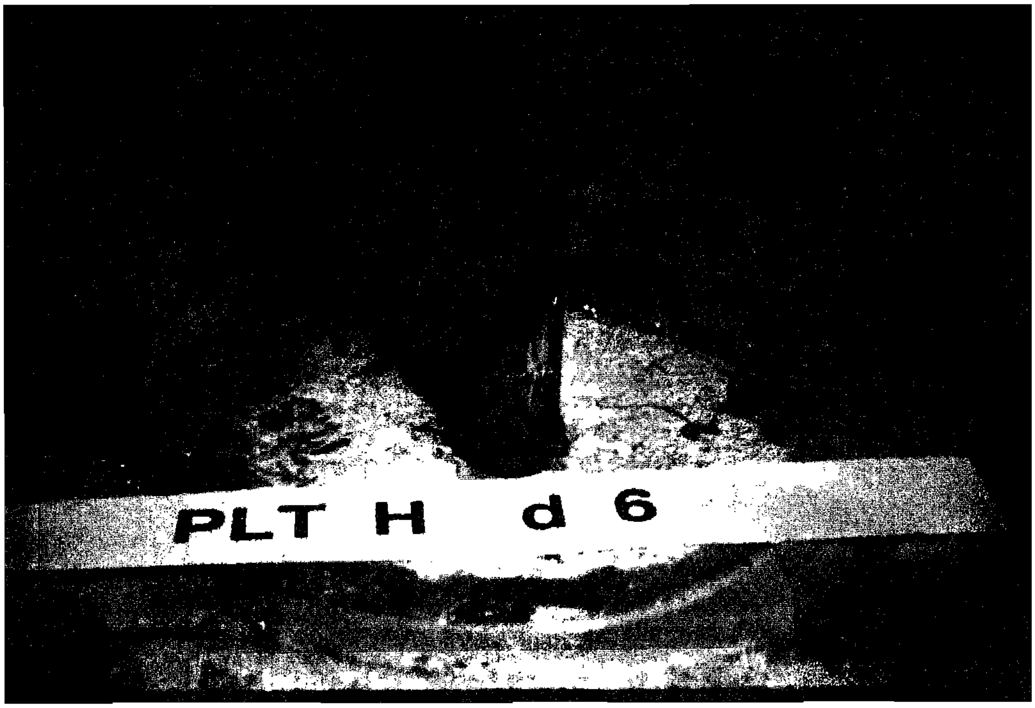


Figure 7.7 Pullout failure of PLT H anchor.

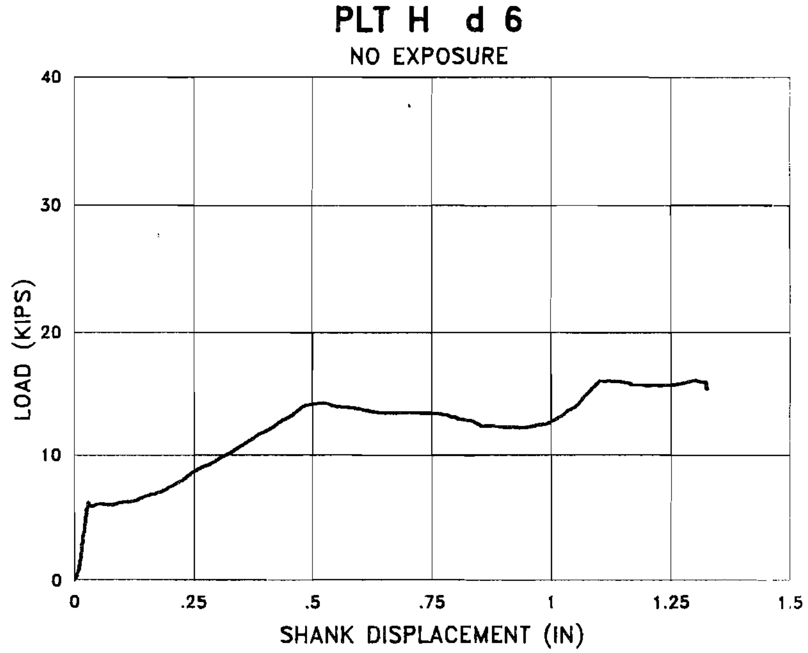


Figure 7.8 Load-deflection plot for pullout of PLT H anchor.

7.3.3 Undercut Anchors. Undercut anchors which were not subjected to any environmental exposure condition were loaded in tension to failure. These anchors exhibited one failure mode:

1) Failure by yield and fracture of anchor steel (Fig. 7.9a)

All 4 tests on undercut anchors failed by yield and fracture of anchor steel. Typical load-deflection plots are shown in Figs. 7.10a and 7.10b.

7.4 Environmental Cycling Tensile Test Results

7.4.1 Adhesive Anchors. Adhesive anchors were loaded in tension to failure after being exposed to cycles of ultraviolet light or acid rain wetting and drying. Adhesive anchors exhibited two failure modes:

1) Failure by yield and fracture of adhesive steel (Fig. 7.5a)
2) Failure by concrete cone with adhesive core (Fig. 7.5b)

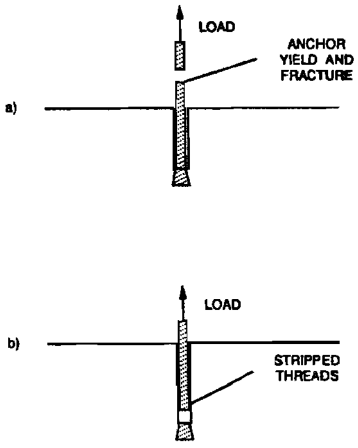


Figure 7.9 Failure modes for undercut anchors.

Ultraviolet Light Exposure Tensile Test Results

Twenty of the 24 tests on adhesive anchors subjected to ultraviolet light failed by yield and fracture of anchor steel. Typical load-deflection behavior for this failure mode is shown in Fig. 7.11. The other 4 anchors failed after formation of a single concrete cone with a depth of between 1 and 2-inches, after which, the adhesive core around the anchor pulled out of the concrete (Fig. 7.12). Concrete cone diameters varied from 8 to 12-inches. Cone depth, and diameters are contained in Table 7.7. Typical load-deflection behavior for this failure mode is shown in Fig. 7.13. Anchors, their failure modes and loads are listed in Table 7.8a.

Acid Rain Wetting and Drying Exposure Tensile Test Results

Twenty-one of the 24 tests on adhesive anchors subjected to acid rain wetting and drying failed by yield and fracture of anchor steel. Typical load-deflection behavior for this failure mode is shown in Fig. 7.14. The other 3 anchors failed after formation of a single concrete cone with a depth of between 1 and 3-inches, after which, the adhesive core around the anchor pulled out of the concrete (Fig. 7.15). Typical load-deflection behavior for this failure mode is shown in Fig. 7.16. Concrete cone diameters varied from 4.5 to 19-inches (Table 7.7). The adhesive anchors, their failure modes and loads are listed in Table 7.8b.

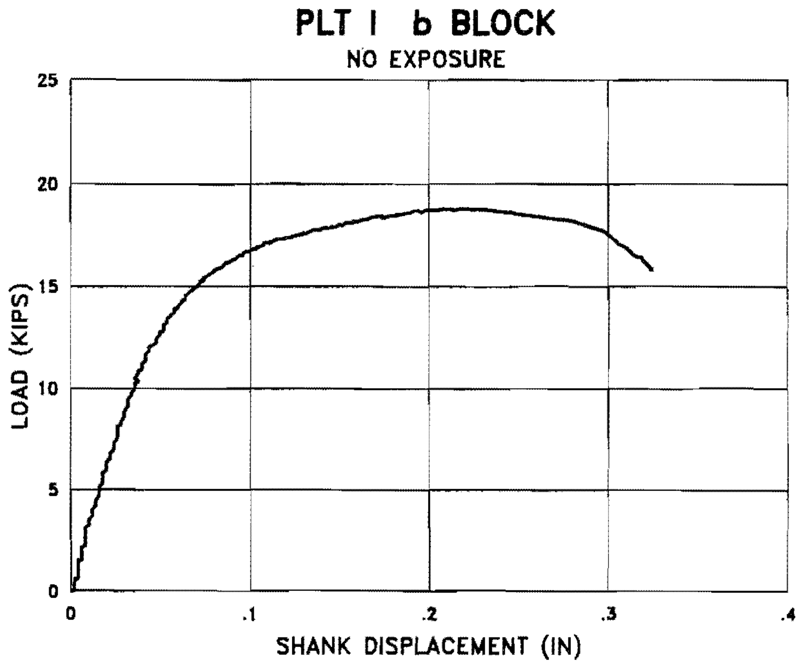


Figure 7.10a Typical load-deflection plot for PLT I anchors.

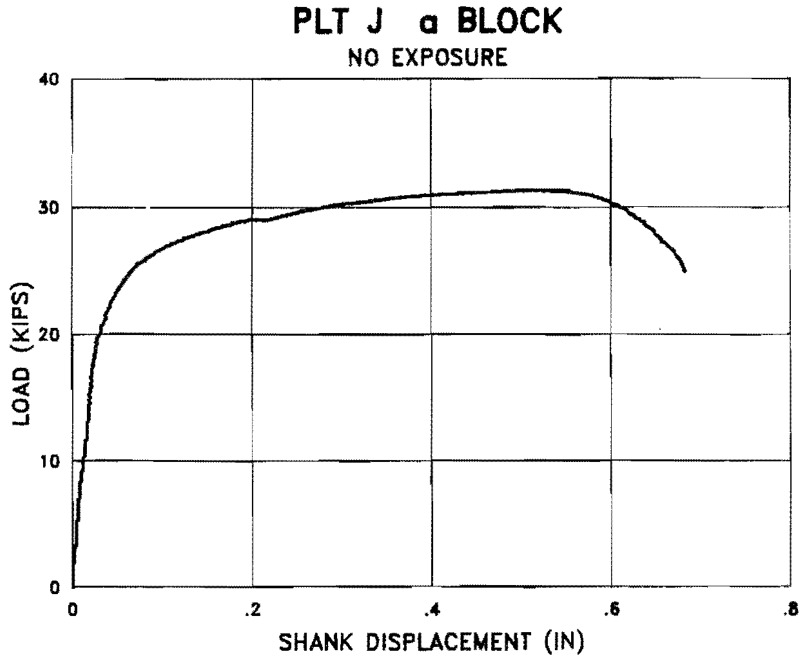


Figure 7.10b Typical load-deflection plot for PLT J anchors.

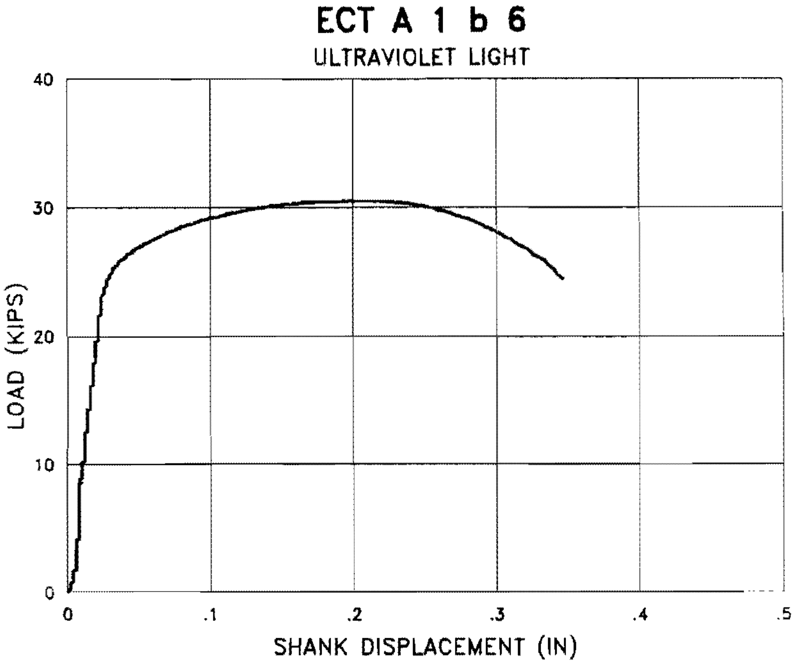


Figure 7.11 Typical load-deflection plot for adhesive anchor subjected to ultraviolet light exposure.

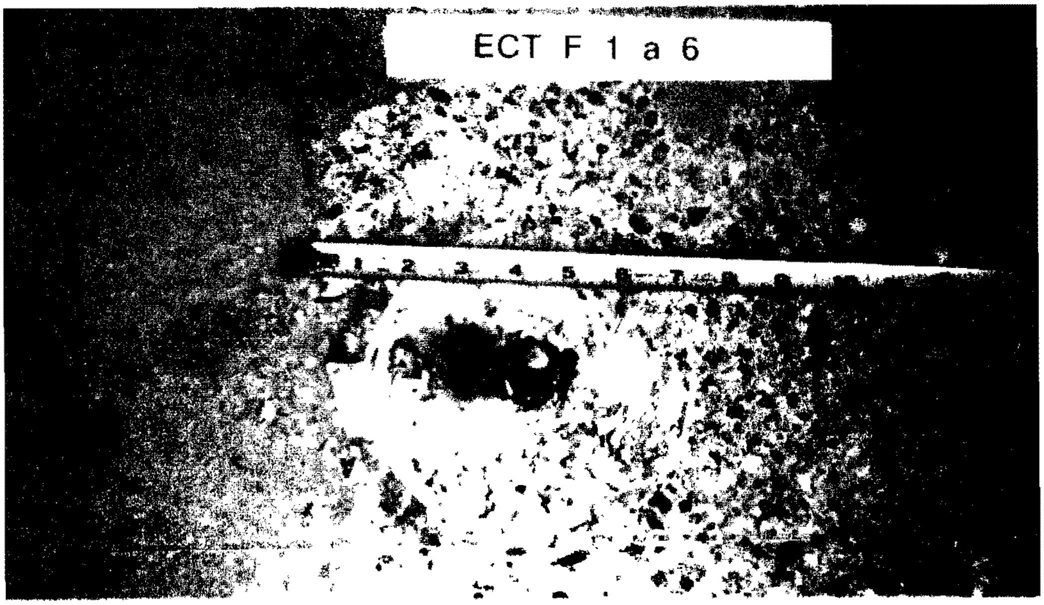


Figure 7.12 Cone failure of adhesive anchor subjected to ultraviolet light exposure.

Table 7.7 Concrete cone data			
Test Identification	Environmental Exposure Condition	Depth of Concrete Cone (in.)	Diameter of Concrete Cone (in.)
ECT B 1 a 6	Ultraviolet	1.5	8
ECT B 1 c 6	Ultraviolet	1.375	8
ECT B 4 b 6	Acid Rain	1	9
ECT B 4 c 6	Acid Rain	2.75	19
ECT F 1 a 6	Ultraviolet	1.25	8.5
ECT F 1 d 6	Ultraviolet	1.75	12
ECT F 4 a 6	Acid Rain	1	4.5
*ECT H 2 a 12	Freeze-Thaw	3.25	19
ECT H 2 d 12	Freeze-Thaw	3	18.5
Notes: * Test ECT H 2 a 12 was cracked before tensile testing.			

Table 7.8a Tensile test data for adhesive anchors subjected to ultraviolet light exposure

Test Identification	Initial Stiffness	Secant Stiffness to 90% Max	Maximum Load (kips)	Maximum Displacement (in.)	Failure Mode #
ECT A 1 a 6	313.1	422.27	30.65	.410	STEEL
ECT A 1 b 6	437.3	458.75	30.55	.346	STEEL
ECT A 1 c 6	50.9	254.32	31.08	.416	STEEL
ECT A 1 d 6	103.2	233.59	33.23	.406	STEEL
ECT B 1 a 6	86.2	144.33	34.00	.596	CONE
ECT B 1 b 6	584.6	286.79	33.72	.478	STEEL
ECT B 1 c 6	770.1	197.17	32.73	1.236	CONE
ECT B 1 d 6	1,332.8	345.45	33.83	.396	STEEL
ECT C 1 a 6	309.8	288.76	31.00	.396	STEEL
ECT C 1 b 6	1,441.3	538.94	31.68	.470	STEEL
ECT C 1 c 6	130.4	338.99	31.40	.462	STEEL
ECT C 1 d 6	1,831.9	583.85	31.48	.412	STEEL
ECT D 1 a 6	1,727.3	245.38	32.69	.414	STEEL
ECT D 1 b 6	1,477.7	325.22	32.61	.366	STEEL
ECT D 1 c 6	1,904.1	353.49	33.82	.360	STEEL
ECT D 1 d 6	1,372.7	559.98	32.56	.328	STEEL
ECT E 1 a 6	345.7	529.46	32.90	.280	STEEL
ECT E 1 b 6	370.5	526.72	33.98	.262	STEEL
ECT E 1 c 6	719.4	375.00	30.85	.306	STEEL
ECT E 1 d 6	231.8	528.88	34.15	.314	STEEL
ECT F 1 a 6	85.5	317.68	31.73	1.430	CONE
ECT F 1 b 6	1,574.2	719.80	32.00	.282	STEEL
ECT F 1 c 6	1,900.0	546.22	32.76	.318	STEEL
ECT F 1 d 6	771.1	436.72	32.89	.882	CONE

Notes: # STEEL : Failure by yield and fracture of anchor steel
CONE : Failure by formation of a concrete cone followed by pullout of adhesive core

Table 7.8b Tensile test data for adhesive anchors subjected to acid rain wetting and drying.

Test Identification	Initial Stiffness	Secant Stiffness to 90% Max	Maximum Load (kips)	Maximum Displacement (in.)	Failure Mode #
ECT A 4 a 6	779.3	666.67	31.15	.315	STEEL
ECT A 4 b 6	735.7	467.50	31.13	.325	STEEL
ECT A 4 c 6	1,020.3	404.17	32.13	.344	STEEL
ECT A 4 d 6	546.3	497.32	30.93	.338	STEEL
ECT B 4 a 6	101.0	270.76	33.70	.394	STEEL
ECT B 4 b 6	361.1	137.15	32.65	1.328	CONE
ECT B 4 c 6	673.8	521.50	28.85	.768	CONE
ECT B 4 d 6	313.9	230.49	33.80	.432	STEEL
ECT C 4 a 6	418.8	461.67	30.85	.344	STEEL
ECT C 4 b 6	114.8	210.61	30.90	.488	STEEL
ECT C 4 c 6	753.4	400.35	32.13	.384	STEEL
ECT C 4 d 6	260.2	327.67	30.58	.364	STEEL
ECT D 4 a 6	1,189.1	195.04	32.94	.412	STEEL
ECT D 4 b 6	1,900.0	278.53	32.16	.372	STEEL
ECT D 4 c 6	348.1	451.49	34.14	.286	STEEL
ECT D 4 d 6	1,329.2	307.51	32.81	.354	STEEL
ECT E 4 a 6	461.4	452.21	34.15	.274	STEEL
ECT E 4 b 6	365.5	557.87	33.45	.266	STEEL
ECT E 4 c 6	377.8	542.41	33.78	.262	STEEL
ECT E 4 d 6	194.5	636.98	33.95	.286	STEEL
ECT F 4 a 6	1,685.1	803.97	30.53	1.238	CONE
ECT F 4 b 6	1,900.0	489.92	32.71	.328	STEEL
ECT F 4 c 6	1,759.4	553.66	33.21	.340	STEEL
ECT F 4 d 6	1,649.3	494.78	34.14	.320	STEEL

NOTES: # STEEL : Failure by yield and fracture of anchor steel
CONE : Failure by formation of a concrete cone followed by pullout of adhesive core.

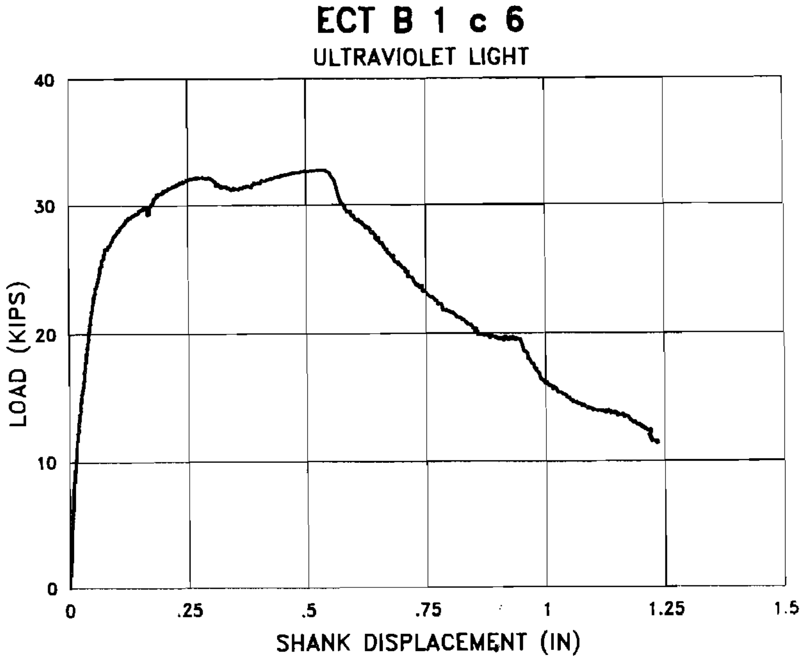


Figure 7.13 Load-deflection plot of cone failure for adhesive anchor subjected to ultraviolet light.

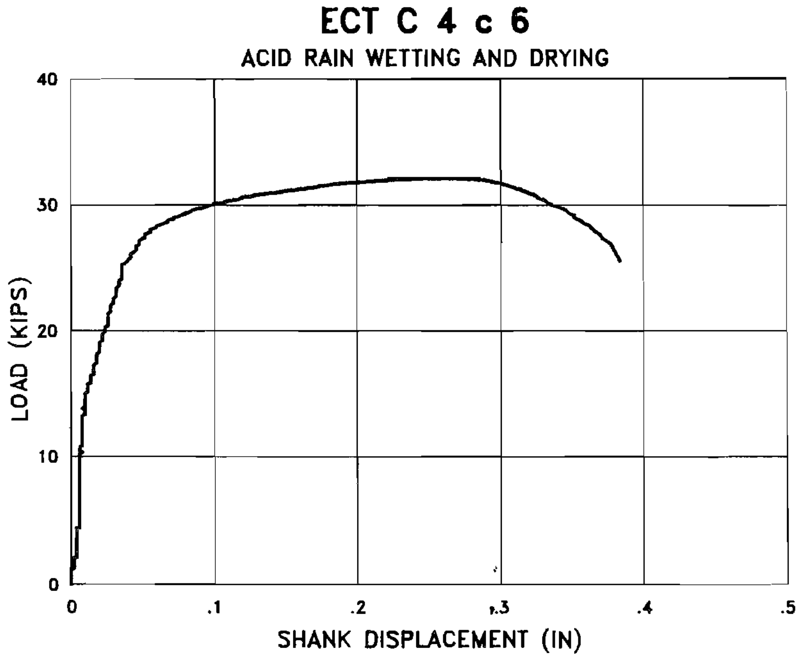


Figure 7.14 Typical load-deflection plot for adhesive anchor subjected to acid rain wetting and drying.

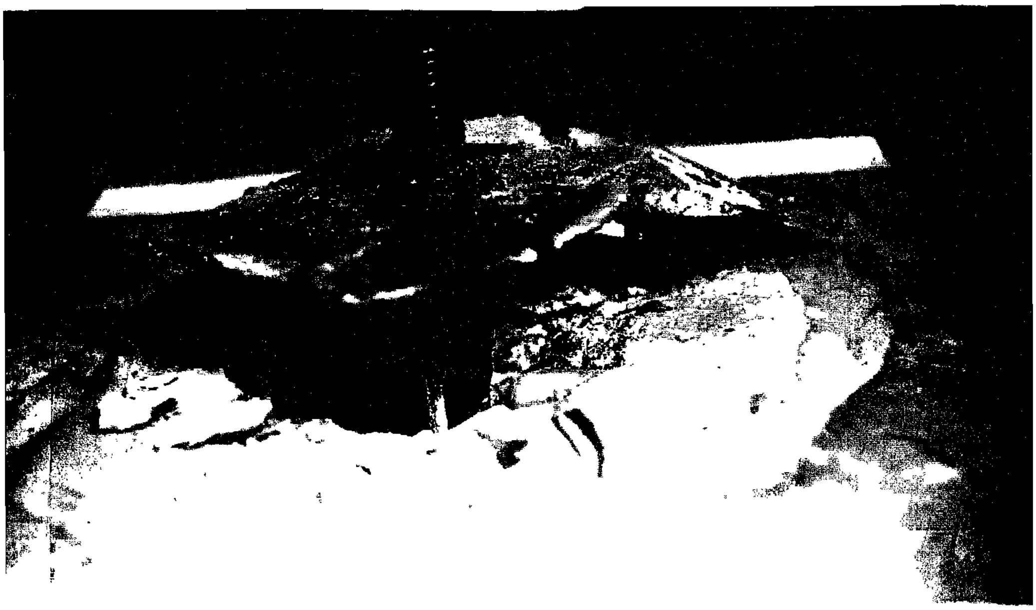


Figure 7.15 Cone failure of adhesive anchor subjected to acid rain wetting and drying exposure.

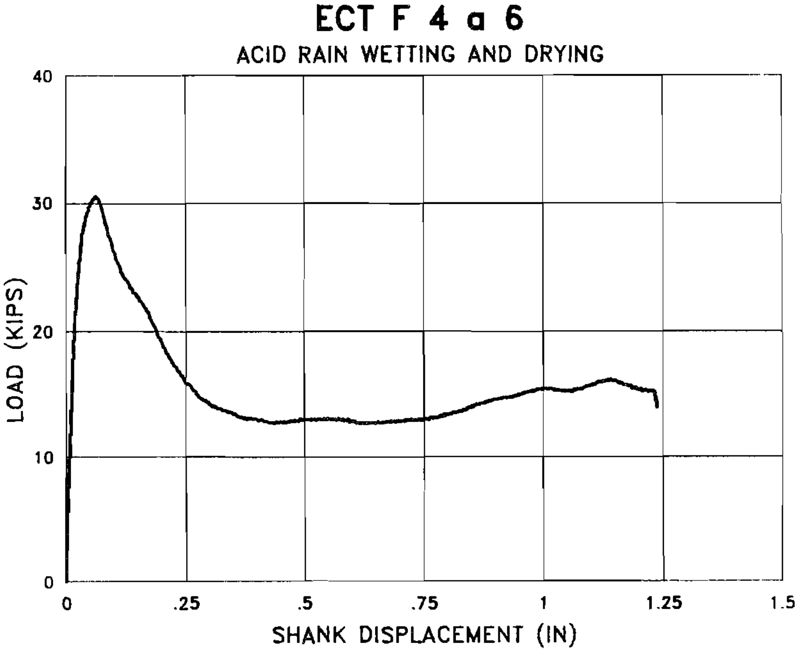


Figure 7.16 Load-deflection plot of cone failure for adhesive anchor subjected to acid rain wetting and drying.

7.4.2 Expansion Anchors. Expansion anchors were loaded in tension to failure after being subjected to cycles of freeze-thaw, salt (corrosion), acid rain wetting and drying, or combination exposure. These anchors exhibited three failure modes:

1) Failure by yield and fracture of anchor steel (Fig 7.5a)
2) Failure by anchor pullout (Fig 7.5b)
3) Failure by concrete cone formation. (Fig. 7.5c)

Freeze-Thaw Exposure Tensile Test Results

Six of the 8 tests conducted on expansion anchors subjected to freezing and thawing failed by yield and fracture of anchor steel. Almost all anchors slipped during loading. This slip was accompanied by a loud "popping" noise. Slip was also detectable because the collar of the anchor had displaced some distance from the surface of the concrete. Typical load-deflection curves are shown in Figs. 7.17a and 7.17b for both ECT G and ECT H anchors. Two ECT H anchors failed by formation of a concrete cone (Fig. 7.18). Typical load-deflection behavior for this failure mode is shown if Fig. 7.19. Before formation of the concrete cone, the anchors experienced significant slip. One anchor which formed a concrete cone was previously cracked due to freeze-thaw exposure. Tensile test data are contained in Table 7.7.

Salt (Corrosion) Exposure Tensile Test Results

All 8 tests conducted on expansion anchors subjected to salt (corrosion) exposure failed by yield and fracture of anchor steel. Typical load-deflection plots for both ECT G and ECT H anchors are shown in Figs. 7.20a and 7.20b. Tensile test data are contained in Table 7.7.

Acid Rain Wetting and Drying Exposure Tensile Test Results

Seven of the 8 tests conducted on expansion anchors subjected to acid rain wetting and drying failed by yield and fracture of anchor steel. Typical load-deflection curves are shown in Figs. 7.21a and 7.21b for both ECT G and ECT H anchors. One ECT H anchor failed by anchor pullout. The load-deflection plot for this failure mode is shown in Fig 7.22. Tensile test data are contained in Table 7.9.

Combination Exposure Tensile Test Results

All 8 tests conducted on expansion anchors subjected to combination exposure failed by yield and fracture of anchor steel. Almost all anchors slipped during loading. This slip was accompanied by a loud "popping" noise. Slip was also detectable because the collar of the anchor had displaced some distance from the surface of the concrete. Typical load-deflection curves are shown in Figs. 7.23a and 7.23b for both ECT G and ECT H anchors. Tensile test data are contained in Table 7.9.

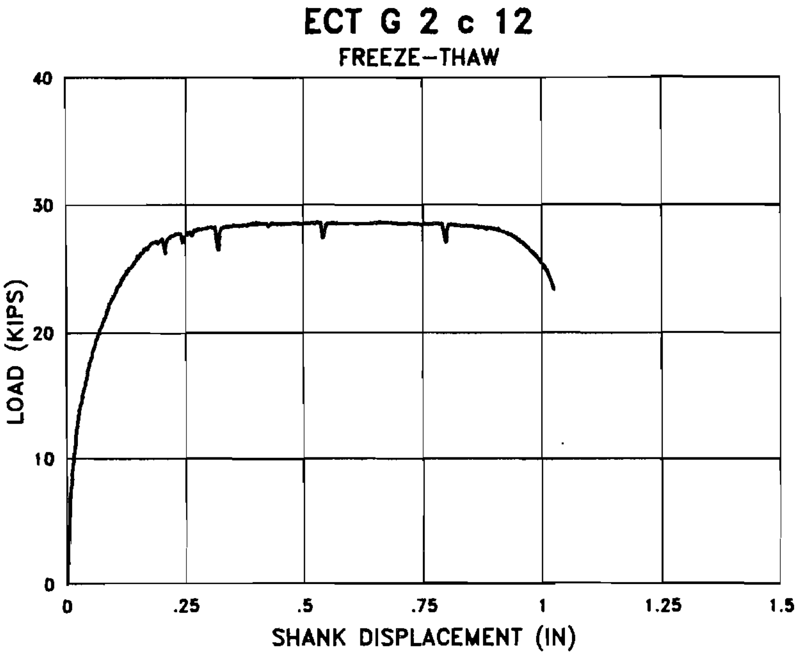


Figure 7.17a Typical load-deflection plot for Designation G anchors subjected to freezing and thawing.

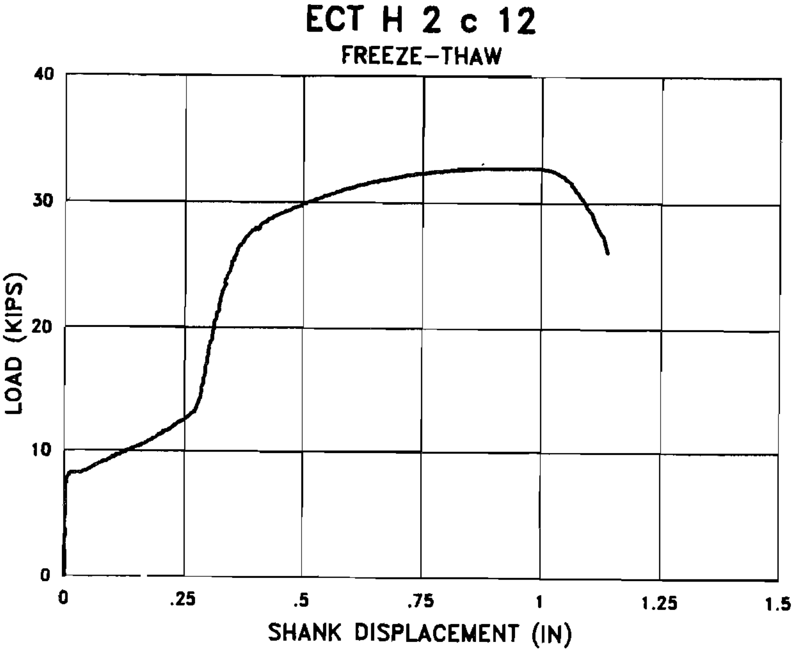


Figure 7.17b Typical load-deflection plot for Designation H anchors subjected to freezing and thawing.

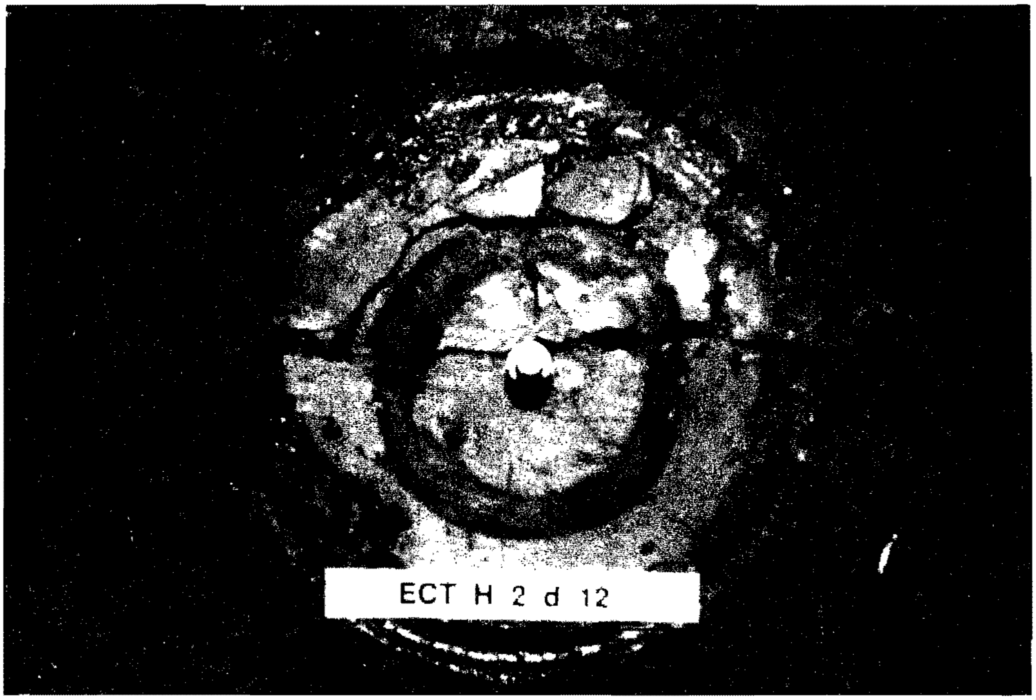


Figure 7.18 Cone failure of ECT H specimen subjected to freezing and thawing (concrete uncracked before testing)

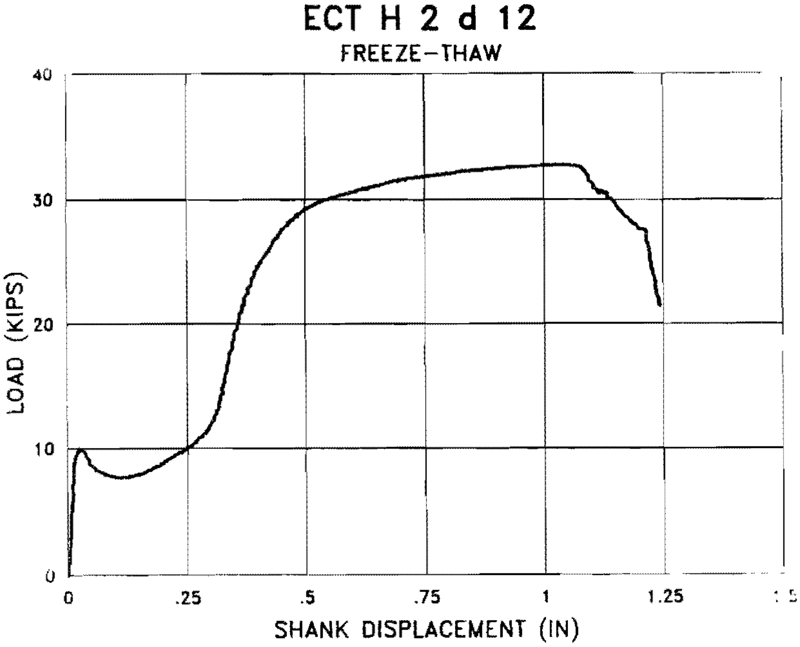


Figure 7.19 Load-deflection plot of cone failure for Designation H subjected to freezing and thawing

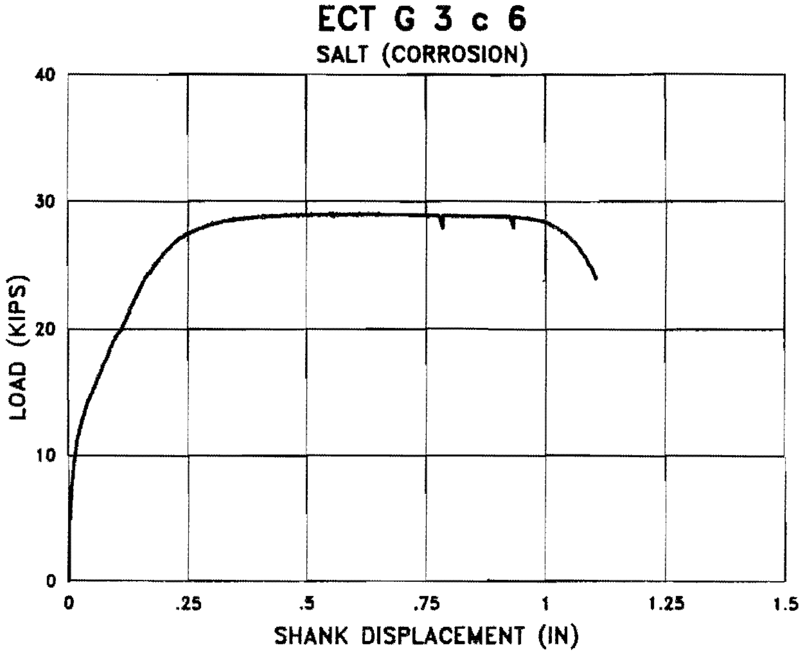


Figure 7.20a Typical load-deflection plot for designation G anchors subjected to salt (corrosion) exposure.

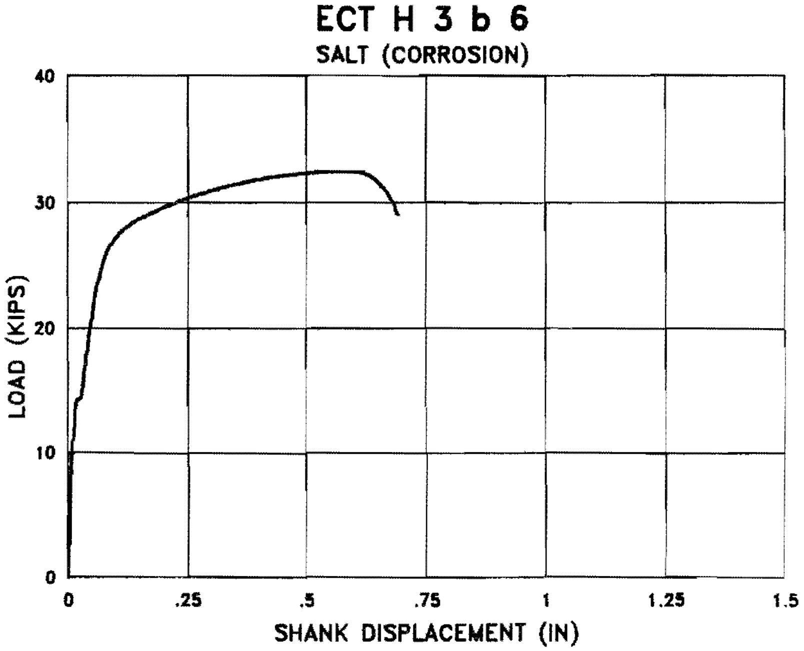


Figure 7.20b Typical load-deflection plot for Designation H anchors subjected to salt (corrosion) exposure.

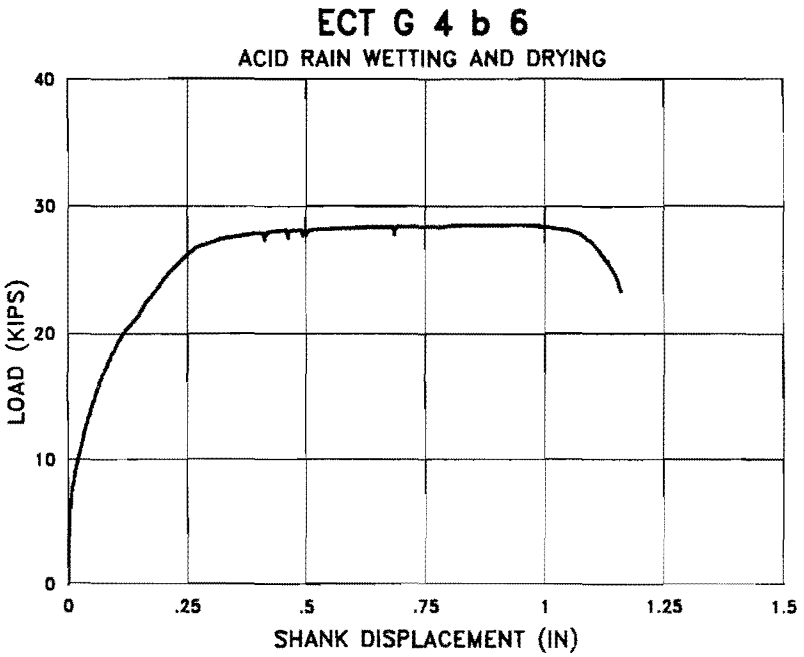


Figure 7.21a Typical load-deflection plot for Designation G anchors subjected to acid rain wetting and drying.

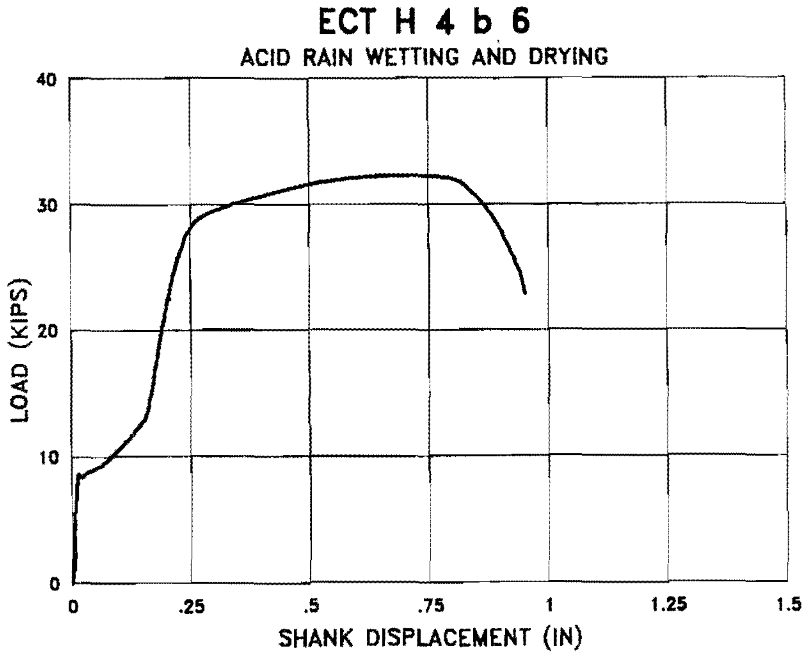


Figure 7.21b Typical load-deflection plot for Designation H anchors subjected to acid rain wetting and drying.

Table 7.9 Tensile Test Data for Expansion Anchor

Test Identification	Initial Stiffness	Secant Stiffness to 90% Max	Maximum Load (kips)	Maximum Displacement (in.)	Failure Mode #
PLT G a BLOCK	450.0	82.19	29.52	1.300	STEEL
PLT G b BLOCK	450.0	83.90	29.09	1.336	STEEL
PLT G c BLOCK	364.3	109.45	24.59	1.434	STEEL
PLT G d BLOCK	319.6	104.75	28.79	1.098	STEEL
PLT G e 6	450.0	134.27	28.93	.986	STEEL
PLT G f 6	447.5	124.40	29.03	1.096	STEEL
ECT G 2 a 12	377.8	117.05	28.58	1.086	STEEL
ECT G 2 b 12	381.9	146.95	27.88	1.234	STEEL
ECT G 2 c 12	327.3	169.90	28.73	1.026	STEEL
ECT G 2 d 12	335.4	109.80	28.38	1.164	STEEL
ECT G 3 a 6	450.0	115.77	28.57	1.092	STEEL
ECT G 3 b 6	405.1	146.28	29.27	1.160	STEEL
ECT G 3 c 6	450.0	126.58	29.10	1.106	STEEL
ECT G 3 d 6	450.0	86.52	29.04	1.242	STEEL
ECT G 4 a 6	303.1	140.66	28.45	1.200	STEEL
ECT G 4 b 6	450.0	109.11	28.63	1.160	STEEL
ECT G 4 c 6	345.8	78.56	28.80	1.212	STEEL
ECT G 4 d 6	80.9	102.72	28.38	1.104	STEEL
ECT G 5 a 6	101.5	119.09	29.10	1.112	STEEL
ECT G 5 b 6	151.5	129.59	28.24	1.072	STEEL
ECT G 5 c 6	450.0	147.96	28.29	1.142	STEEL
ECT G 5 d 6	253.8	113.60	29.24	1.098	STEEL
PLT H a BLOCK	433.9	78.53	26.53	.680	STEEL
PLT H b BLOCK	135.4	99.81	28.58	.614	STEEL
PLT H c 6	385.4	90.96	28.50	.632	STEEL
PLT H d 6	87.9	13.67	16.15	1.326	PULLOUT
ECT H 2 a 12*	–.–	–.–	–.–	–.–	—
ECT H 2 b 12	468.8	181.32	32.58	.820	STEEL
ECT H 2 c 12*	251.0	62.03	32.78	1.138	STEEL
ECT H 2 d 12	171.1	57.27	32.80	1.244	CONE
ECT H 3 a 6	187.9	190.20	32.94	.624	STEEL
ECT H 3 b 6	477.4	159.07	32.51	.692	STEEL
ECT H 3 c 6^	209.1	–.–	–.–	–.–	—
ECT H 3 d 6	477.0	86.25	32.30	.634	STEEL
ECT H 4 a 6	303.9	83.35	32.40	.686	STEEL
ECT H 4 b 6	408.9	104.95	32.06	.871	STEEL
ECT H 4 c 6	340.5	75.38	32.33	.952	STEEL
ECT H 4 d 6	405.0	21.81	27.73	1.239	PULLOUT
ECT H 5 a 6	361.8	50.47	33.14	1.122	STEEL
ECT H 5 b 6	203.6	185.60	33.01	.608	STEEL
ECT H 5 c 6	477.3	112.86	31.68	.724	STEEL
ECT H 5 d 6	285.5	79.99	32.41	.828	STEEL

NOTES:

\# CONE : Failure by concrete cone formation
PULLOUT : Failure by anchor pullout of concrete
STEEL : Failure by yield and fracture of anchor steel
* Specimen was cracked from freezing and thawing before tensile testing.
^ Cylinder improperly installed in reaction block.

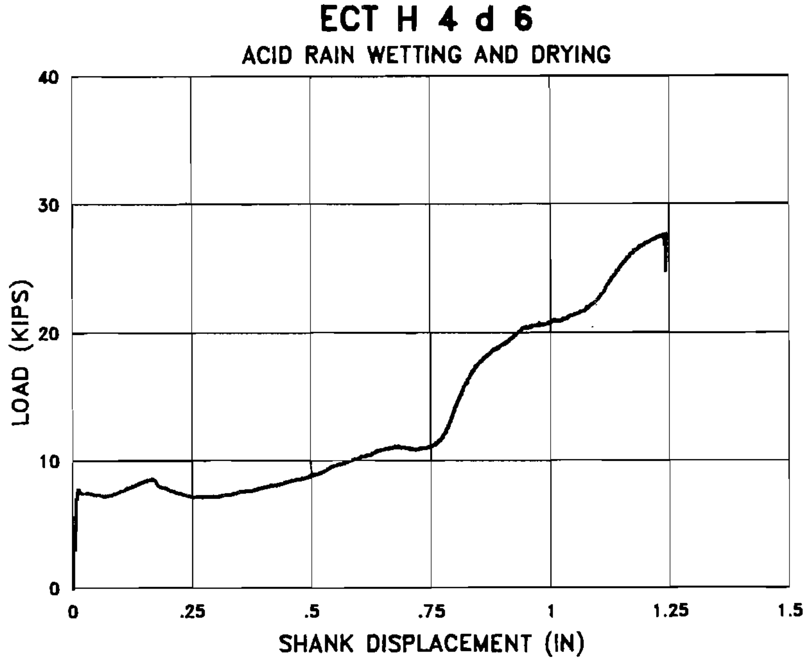


Figure 7.22 Load-deflection plots of pullout failure for Designation H anchors subjected to acid rain wetting and drying.

7.4.3 Undercut Anchors. Undercut anchors were loaded in tension to failure after being subjected to cycles of combination exposure. These anchors exhibited two failure modes:

1) Failure by yield and fracture of anchor steel (Fig 7.20a)

2) Failure by stripped threads at the bottom of the anchor bolt (Fig. 7.20b)

Combination Exposure Tensile Test Results

Seven of 8 tests on undercut anchors subjected to combination exposure failed by yield and fracture of anchor steel. Typical load-deflection plots for undercut anchors exposed to combination exposure are shown in Figs. 7.24a, and 7.24b. One undercut anchor failed because the threads which secure the bolt to the undercutting mechanism were stripped before the bolt yielded and fractured (Fig 7.25). The load-deflection plot for this failure is shown in Fig. 7.26. Failure loads and modes are shown in Table 7.10.

7.4.4 Cast-In-Place Anchors. Cast-in-place anchors were loaded in tension to failure after being subjected to cycles of combination exposure. These anchors exhibited one type of failure mode:

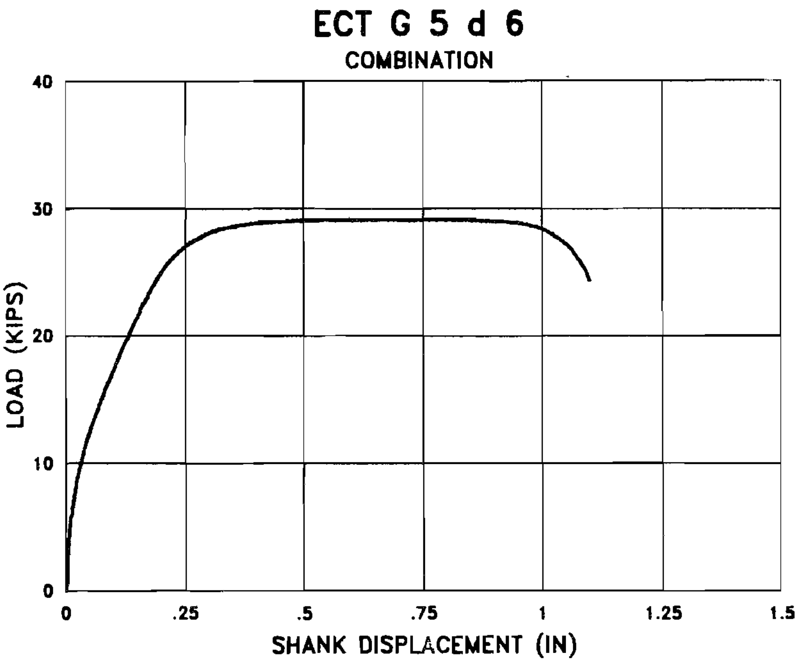


Figure 7.23a Typical load-deflection plot for Designation G anchors subjected to combination exposure.

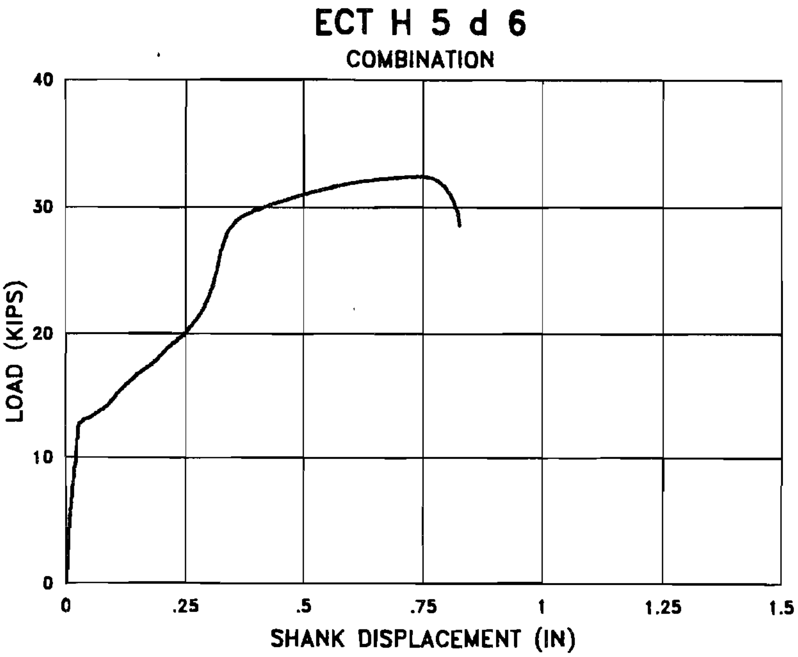


Figure 7.23b Typical load-deflection plot for Designation H anchors subjected to combination exposure.

1) Failure by yield and fracture of anchor steel (Fig 7.27)

Combination Exposure Tensile Test Results

All 4 anchors failed by yield and fracture of anchor steel. Typical load-deflection plots for cast-in-place anchors exposed to combination exposure are shown in Fig 7.28. Failure loads are listed in Table 7.8.

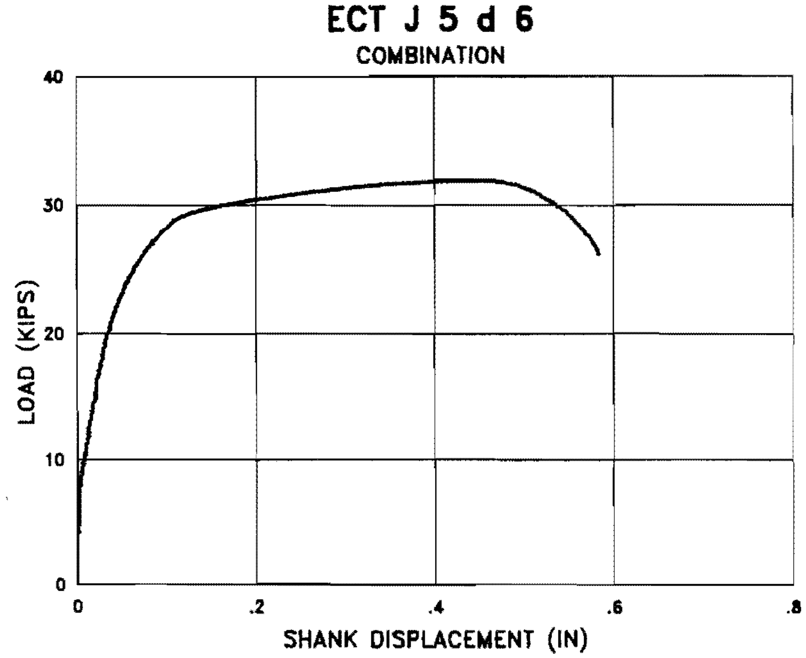


Figure 7.24a Typical load-deflection plot for Designation I anchors subjected to combination exposure.

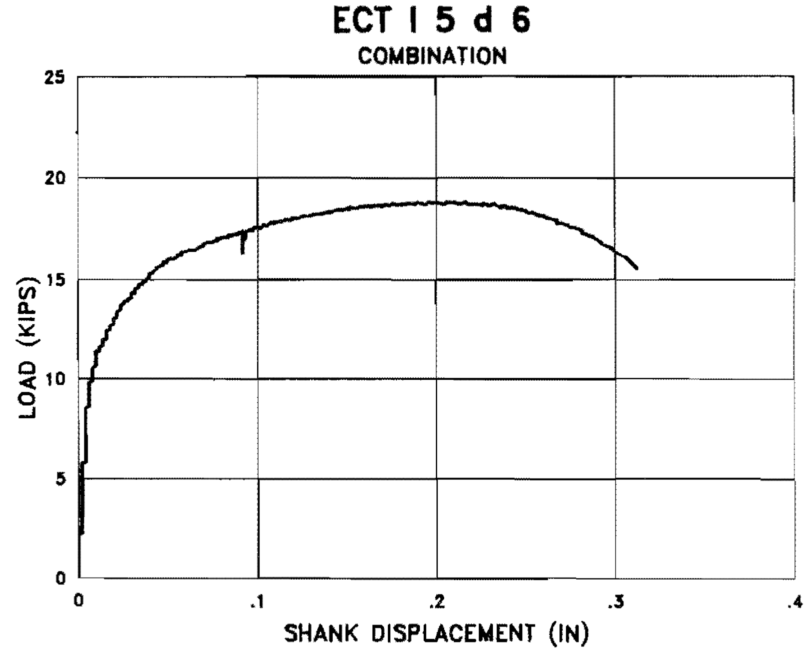


Figure 7.24b Typical load-deflection plot for Designation J anchors subjected to combination exposure.

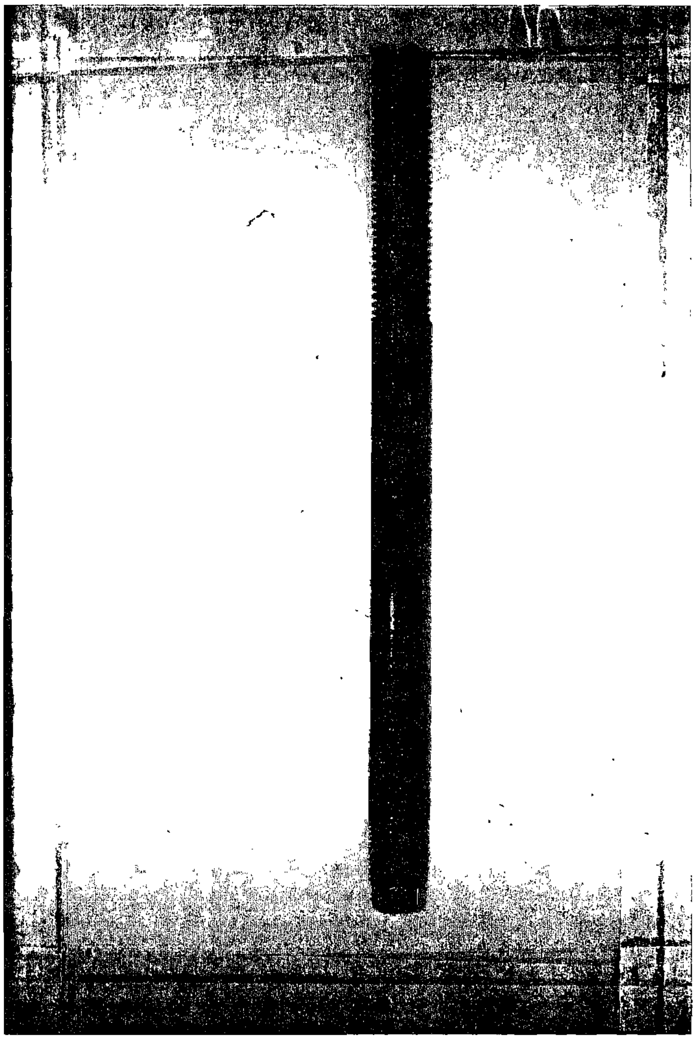


Figure 7.25 Stripped lower threads of Designation I anchor.

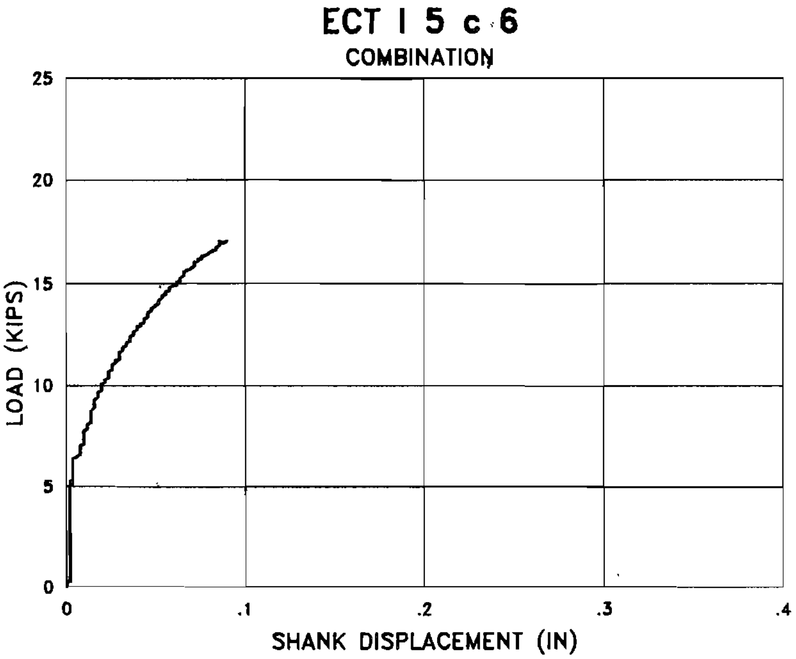


Figure 7.26 Load-deflection plot for Designation I anchor which failed by stripped lower threads.

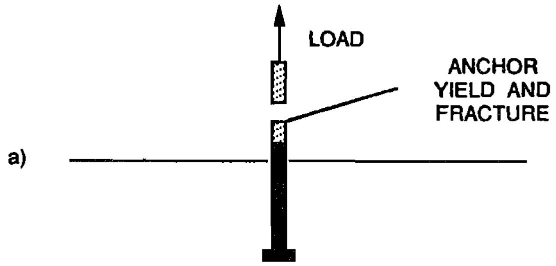


Figure 7.27 Failure mode for cast-in-place anchors.

Table 7.10 Tensile Test Data for Undercut and Cast-In-Place Anchors

Test Identification	Initial Stiffness	Secant Stiffness to 90% Max	Maximum Load (kips)	Maximum Displacement (in.)	Failure Mode #
PLT I a BLOCK	335.6	172.36	17.58	.347	STEEL
PLT I b BLOCK	309.7	163.22	18.80	.324	STEEL
ECT I 5 a 6	1,754.3	293.38	20.22	.282	STEEL
ECT I 5 b 6	1,209.4	193.28	18.92	.314	STEEL
ECT I 5 c 6	1,186.8	235.60	17.06	.090	THREADS
ECT I 5 d 6	1,839.2	217.42	18.84	.312	STEEL
PLT J a BLOCK	1,100.1	183.54	31.43	.682	STEEL
PLT J b BLOCK	772.3	113.36	31.76	.990	STEEL
ECT J 5 a 6	843.9	307.22	31.41	.504	STEEL
ECT J 5 b 6	721.3	605.20	32.28	.632	STEEL
ECT J 5 c 6	417.8	270.57	31.73	.498	STEEL
ECT J 5 d 6	2,226.6	266.13	31.93	.584	STEEL
ECT K 5 a 6	157.4	272.34	30.10	.244	STEEL
ECT K 5 b 6	109.3	241.96	30.08	.278	STEEL
ECT K 5 c 6	136.7	300.56	30.03	.252	STEEL
ECT K 5 d 6	97.8	293.47	30.05	.244	STEEL

6Notes: # STEEL : Failure by yield and fracture of anchor steel.
THREADS : Failure by stripped threads at the base of the anchor rod.

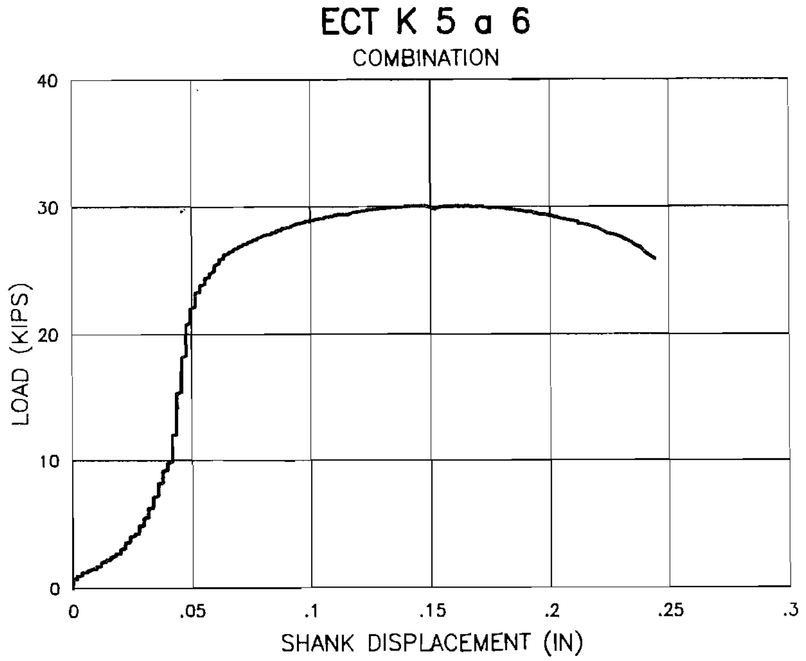


Figure 7.28 Typical load-deflection plot for designation K anchors subjected to combination exposure.

CHAPTER 8.
DISCUSSION OF ENVIRONMENTAL EXPOSURE TEST RESULTS

8.1 Introduction

Environmental exposure results are discussed in this chapter. This discussion is organized according to environmental exposure, and further by anchor type.

8.2 Ultraviolet Light Exposure

8.2.1 Adhesive Anchors. Two observations were made regarding adhesive anchors exposed to ultraviolet light:

1) Color change of the adhesive

2) Depth of penetration of color change in the adhesive

Three of the 6 adhesives tested underwent a color change after 30 cycles of ultraviolet light exposure. This color change was undetectable from one observation to the next, and was only noticeable after comparison of the adhesive below the surface as described in Chapter 7.

Of the 3 adhesives which showed some color change, the depth of penetration of color change in the adhesive was very small and therefore, the color change appeared to be only cosmetic.

8.3 Freezing and Thawing Exposure

8.3.1 Expansion Anchors in 6-Inch Diameter Cylinders. Three observations were made regarding expansion anchors in 6-inch diameter cylinders exposed to freezing and thawing:

1) Surface flaking of the concrete

2) Cracking of the concrete

3) Loosening of the nut on the anchor

The amount of concrete surface flaking was limited in both the size and number of flakes. Surface flaking was cosmetic, and did no structural damage to the concrete.

All of the 8 specimens tested showed large cracks along the sides of the concrete cylinders after 50 cycles of freeze-thaw exposure. Two of the ECT G specimens exhibited large splitting cracks down the center of the cylinder at 42 cycles. Cracks were generally located at the level of the expansion mechanism. The tensile capacity of the concrete was exceeded by the expansion force of the ice, in addition to the expansion force exerted by the anchor. Because of their extensive damage, none of the 6-inch cylinders was subjected to tensile testing.

Three of the 4 ECT G specimens exhibited loosened nuts on the anchors, indicating complete loss of preload after 50 cycles of freeze-thaw exposure.

8.3.2 Expansion Anchors in 12-Inch Diameter Cylinders. Three observations were made regarding expansion anchors in 12-inch diameter cylinders exposed to freezing and thawing:

1) Surface flaking of the concrete

2) Cracking of the concrete

3) Loosening of the nut on the anchor

The amount of concrete surface flaking was limited in both the size and number of flakes. Surface flaking was cosmetic and did no structural damage to the concrete. Surface flaking due only to freezing and thawing was not as severe as the surface flaking due to combination exposure which includes freezing and thawing.

Two of the 8 specimens tested showed large cracks along the sides of the concrete cylinders after 50 cycles of freeze-thaw exposure. Cracks were located at the level of the expansion mechanism on two of the ECT H specimens. The tensile capacity of the concrete was exceeded by the expansion force of the ice, in addition to the expansion force exerted by the anchor, on these two specimens. These two specimens were not subjected to tensile testing. The remaining 12-inch specimens were tested.

Three of the 4 ECT G specimens (all uncracked) exhibited loosened nuts on the anchors, indicating complete loss of preload after 50 cycles of freeze-thaw exposure. Nuts on all ECT H specimens were still tight after the exposure, demonstrating retention of some preload.

8.4 Salt (Corrosion) Exposure

8.4.1 Expansion Anchors. Two observations were made regarding expansion anchors exposed to salt (corrosion):

1) Salt buildup on the anchor

2) Rust on the anchor

Stainless steel anchors (ECT G specimens) showed no salt buildup and almost no rusting. Zinc electroplated anchors (ECT H specimens) showed salt buildup and significant rusting on the anchor above and below the surface of the concrete.

8.5 Acid Rain Wetting and Drying Exposure

8.5.1 Adhesive Anchors. Three observations were made regarding adhesive anchors exposed to acid rain wetting and drying:

1) Rust on the threaded rod above the surface of the adhesive

2) Rust on the threaded rod below the surface of the adhesive

3) No change of the adhesive

Rust formed on the threaded rod above the surface of the concrete with all adhesives by the end of 7 cycles. There was no change in or breakdown of the adhesives after 50 cycles of exposure.

After tensile testing, the threaded rod and adhesive below the surface of the concrete was examined. This examination showed that the threaded rods of the ECT B and ECT D specimens were rusted below the surface of the adhesive. All threaded rods were rust free when installed. Presence of rust below the surface of the adhesive shows that the acid rain solution was able to penetrate between the adhesive and the threaded rod. There was no way to tell if acid rain solution was able to penetrate between the concrete-adhesive interface.

8.5.2 Expansion Anchors. Two observations were made regarding expansion anchors exposed to acid rain wetting and drying:

1) No change of anchor

2) Buildup of white material on anchor

Stainless steel anchors (ECT G specimens) showed no change in appearance after 50 cycles. ECT H specimens showed a buildup of white material on the collar of the anchor at the level where the acid rain solution was allowed to pond. No rust appeared on either type of specimen.

8.6 Combination Exposure

8.6.1 Expansion Anchors. Three observations were made regarding expansion anchors subjected to combination exposure:

1) Surface flaking of the concrete

2) Salt buildup on the anchor

3) Rust on the anchor

Concrete surface flaking was observed on both ECT G and ECT H specimens. The size and amount of random flaking was equal on both specimens. ECT H specimens showed more flaking, concentrated near the hole, than ECT G specimens. There was less flaking on ECT G specimens because the concrete around the hole was confined by the washer of the anchor. Concrete around the hole of the ECT H specimens was unconfined. The damage occurring at the hole appears to be due to the drilling operation during installation of the anchor. A control test specimen identical to the ECT specimens was exposed to the same environment, but with a cast hole instead of a drilled hole (Fig 8.1).

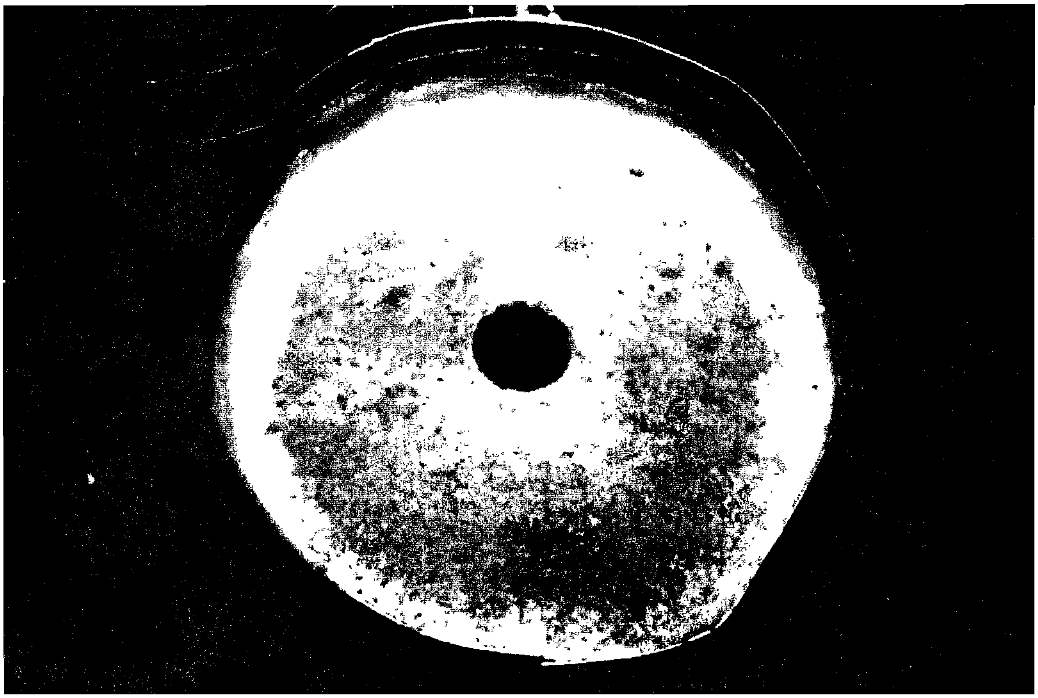


Figure 8.1 Control specimen with cast hole.

This control specimen exhibited less random flaking than observed on the ECT G and ECT H specimens. In addition, there was no concentrated damage at the surface of the cast hole. All surface flaking appeared cosmetic and did no structural damage to the concrete.

Stainless steel anchors (ECT G specimens) showed no salt buildup and almost no rusting. Zinc electroplated anchors (ECT H specimens) showed salt buildup and significant rusting on the anchor above and below the surface of the concrete.

These specimens did not show any cracking of the concrete, even though the combination exposure included 50 cycles of freezing and thawing. Possible reasons for the difference between expansion anchors in combination exposure and expansion anchors in freeze-thaw exposure include:

1) Drying period in the combination exposure cycle: Freeze-thaw only specimens were wet continuously during the thaw period, so that water in any formed cracks would be able to fill air voids at the edge of the crack. Upon freezing, the water would expand and the crack could grow. Specimens in the combination exposure were allowed to dry out for 3 hours during every cycle.

2) Salt solution used in the combination exposure: The salt solution used in the combination exposure did freeze completely during the freezing stage of the combination exposure, but did not freeze as solidly as the plain water solution used in the freezing and thawing exposure. There was some "glaze" on the ice which formed from the salt solution.

8.6.2 Undercut Anchors. Three observations were made regarding expansion anchors subjected to combination exposure:

1) Surface flaking of the concrete
2) Salt buildup on the anchor
3) Rust on the anchor

Concrete surface flaking was observed on both ECT I and ECT J specimens. The size and amount of random flaking was equal on both specimens. Both specimens showed flaking concentrated near the hole. The concrete around the hole on both the specimens was unconfined. Damage occurring at hole appeared to be due to drilling during installation of the anchor, as discussed in subsection 8.6.1. All surface flaking appeared cosmetic and did no structural damage to the concrete.

Anchors with electroplated zinc coating (ECT J specimens) showed salt buildup but no rusting. ECT I specimens, which were plain steel anchors, showed significant rusting on the anchor above and below the surface of the concrete.

Because water is able to penetrate the hole, undercut anchors subjected to freezing and thawing exposure with plain water (ECT 2 exposure) would probably exhibit the same concrete damage observed with expansion anchors.

8.6.3 Cast-In-Place Anchors. Two observations were made regarding cast-in-place anchors subjected to combination exposure:

1) Surface flaking of the concrete

2) Rust on the anchor

Very minor random concrete surface flaking was observed on ECT K specimens. The surface flaking was consistent with that observed on the control specimen described in subsection 8.6.1. This surface flaking was limited because no drilling was done on the concrete.

The exposed threaded rod (plain steel) was rusted at the end of 7 cycles.

CHAPTER 9. DISCUSSION OF TENSILE TEST RESULTS

9.1 Introduction

Tensile test results from the Preliminary Laboratory Tests (PLT) and Environmental Cycling Tests (ECT) are discussed in this chapter. Preliminary Laboratory tensile tests are discussed first. The remainder of the chapter is organized according to anchor type and exposure condition.

Six characteristics were used for evaluation of tensile behavior of all anchors:

1) Best-fit linear regression of initial stiffness

2) Failure mode

3) Maximum load

4) Maximum displacement

5) Secant stiffness to 90% of maximum load

6) Load-deflection characteristics

In each case the anchor characteristic, after environmental cycling, was compared with the same characteristic in anchors not subjected to environmental exposure. Significant changes in characteristics were taken to indicated changes in tensile behavior as a result of environmental cycling.

9.2 Preliminary Laboratory Tensile Tests (PLT)

9.2.1 Adhesive Anchors. Two PLT tests were conducted on type F anchors because no previous data were available for these anchors. Data for other unexposed adhesive anchors were taken from previous research [3,4].

9.2.2 Expansion Anchors. PLT tensile test results for expansion anchors were used as a basis for comparison with otherwise identical expansion anchors subjected to environmental exposure.

PLT tensile tests were performed on expansion anchors installed in concrete cylinders and monolithic blocks. Expansion anchors installed in concrete cylinders behaved like otherwise identical anchors installed in monolithic blocks, with respect to best-fit initial stiffness, failure mode, maximum load, maximum displacement, secant stiffness to 90% of maximum load, and load-deflection characteristics (Fig 9.1).

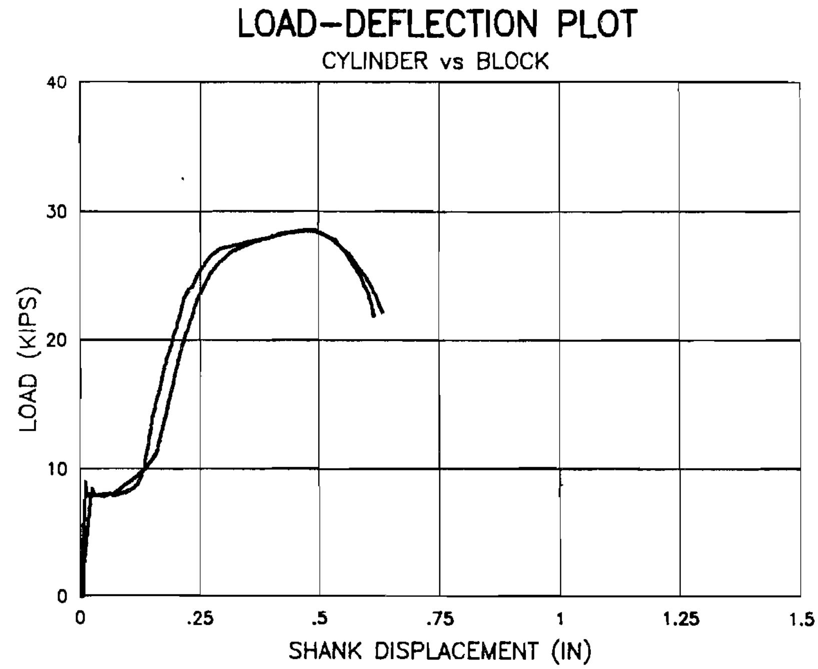


Figure 9.1 Comparison load-deflection plot of expansion anchors installed in blocks and in cylinders.

9.2.3 Undercut Anchors. PLT tensile test results for undercut anchors were used as a basis for comparison with otherwise identical undercut anchors subjected to the combination exposure.

9.3 Adhesive Anchor Tensile Tests

9.3.1 Ultraviolet Light Exposure. Each type of adhesive anchor is treated separately.

ECT A Specimens

ECT A specimens exposed to ultraviolet light behaved like otherwise identical unexposed anchors, according to the criteria of Section 9.1. The initial stiffness of the exposed specimens was slightly lower than that of the unexposed specimens. This lower initial stiffness is not thought to have been caused by the exposure, because the adhesive suffered little or no visible damage (subsection 8.2.1).

ECT B Specimens

ECT B specimens exposed to ultraviolet light behaved like otherwise identical unexposed anchors, according to the criteria of Section 9.1. Two of the exposed anchors failed by formation of a concrete cone, accompanied by pullout of an adhesive core. The two anchors exhibiting this failure mode had maximum capacities very close to those of anchors failing by yield and fracture of the steel. Because the adhesive showed no damage or color change after ultraviolet light exposure, and because this failure mode was also observed with unexposed anchors [2], it was concluded that ultraviolet light exposure did not produce the change in failure mode.

ECT C Specimens

ECT C specimens exposed to ultraviolet light behaved like otherwise identical unexposed anchors, according to the criteria of Section 9.1.

ECT D Specimens

ECT D specimens exposed to ultraviolet light behaved like otherwise identical unexposed anchors, according to the criteria of Section 9.1.

ECT E Specimens

ECT E specimens exposed to ultraviolet light behaved like otherwise identical unexposed anchors, according to the criteria of Section 9.1.

ECT F Specimens

ECT F specimens exposed to ultraviolet light behaved like otherwise identical unexposed anchors, according to the criteria of Section 9.1. Two specimens failed by formation of a concrete cone accompanied by pullout of the adhesive core. Because no damage or color change was observed on these specimens after ultraviolet exposure, this failure mode (though not observed with unexposed anchors) is not believed to have been caused by the ultraviolet light exposure.

This failure mode is more likely linked to the viscosity of the type F adhesive, which is very thick when mixed. When the coil rod was inserted into the adhesive-filled hole, large air bubbles were trapped in the adhesive. After tensile testing, these trapped air bubbles were visible in the adhesive core surrounding the coil rod. They probably reduced the overall strength of the adhesive.

9.3.2 Acid Rain Wetting and Drying Exposure. Each type of adhesive anchor is treated separately.

ECT A Specimens

ECT A specimens exposed to acid rain wetting and drying behaved like otherwise identical unexposed anchors, according to the criteria of Section 9.1.

ECT B Specimens

ECT B specimens exposed to acid rain wetting and drying behaved like otherwise identical unexposed anchors, according to the criteria of Section 9.1. Two of the exposed anchors failed by formation of a concrete cone, accompanied by pullout of the adhesive core. The two anchors exhibiting this failure mode had maximum loads close to those of anchors failing by yield and fracture of the steel. Although the cone failure mode was also observed with unexposed anchors [2], acid rain wetting and drying may have contributed to it. As noted in subsection 8.5.1, the acid rain solution was able to penetrate between the adhesive and the threaded rod, and may also have penetrated between the concrete and the adhesive, weakening the bond. Because the exposed specimens were dried for two months before tensile testing, and because the effects of hydrolysis are reversible (Section 2.2), hydrolysis is not believed to have contributed to this failure mode.

ECT C Specimens

ECT C specimens exposed to acid rain wetting and drying behaved like otherwise identical unexposed anchors, according to the criteria of Section 9.1.

ECT D Specimens

ECT D specimens exposed to acid rain wetting and drying behaved like otherwise identical unexposed anchors, according to the criteria of Section 9.1. As noted in subsection 8.5.1, the acid rain solution was able to penetrate between the adhesive and the threaded rod, and may have also penetrated between the concrete and the adhesive, weakening the bond. Although acid rain solution was able to penetrate between the adhesive and coil rod, there was no change in behavior of the anchor.

ECT E Specimens

ECT E specimens exposed to acid rain wetting and drying behaved like otherwise identical unexposed anchors, according to the criteria of Section 9.1.

ECT F Specimens

ECT F specimens exposed to acid rain wetting and drying behaved like otherwise identical unexposed anchors, according to the criteria of Section 9.1. One specimen failed by formation of a concrete cone with adhesive core. This failure mode, although not observed with unexposed anchors, is not believed to have been caused by the acid rain exposure. Below the surface of the adhesive, no damage or rust was observed on these specimens after exposure. The cone failure was probably caused by trapped air bubbles, as discussed in subsection 9.3.1.

9.4 Expansion Anchor Tensile Tests

9.4.1 Freezing and Thawing Exposure. Each type of expansion anchor is treated separately.

ECT G Specimens

ECT G anchors exposed to freezing and thawing behaved like otherwise identical unexposed anchors with respect to maximum load, maximum displacement, failure mode, and the secant stiffness at 90% of maximum load.

Three major differences exist between exposed and unexposed ECT G anchors:

1) Anchors exposed to freezing and thawing show lower stiffness at low loads (below 2 kips) than unexposed anchors.

2) As shown by comparing Figs. 9.2 and 7.6a, load-deflection characteristics of exposed anchors show significantly more slip (accompanied by load reductions) than for unexposed anchors.

3) Exposed anchors showed complete loss of preload after 50 cycles of freezing and thawing (subsection 8.3.2).

These differences are believed due to enlargement of the hole, and to weakening of the concrete on the inside of the hole from repeated cycles of freezing and thawing.

ECT H Specimens

As discussed in subsection 8.3.2, two specimens (ECT H 2 a 12 and ECT H 2 c 12) were cracked due to freezing and thawing exposure. One cracked specimen (ECT H 2 a 12) performed badly in tensile tests, and is not included in the data set. ECT H specimens subjected to freeze-thaw cycles behaved like otherwise identical unexposed anchors with respect to maximum load, and failure mechanism. The initial stiffness is slightly lower for exposed anchors than for unexposed PLT H specimens. One ECT H anchor failed by formation of a concrete cone; however, the maximum load achieved before the formation of that cone was larger than the maximum loads of other anchors failing by steel fracture.

Two differences exist between the behavior of exposed and unexposed ECT H anchors:

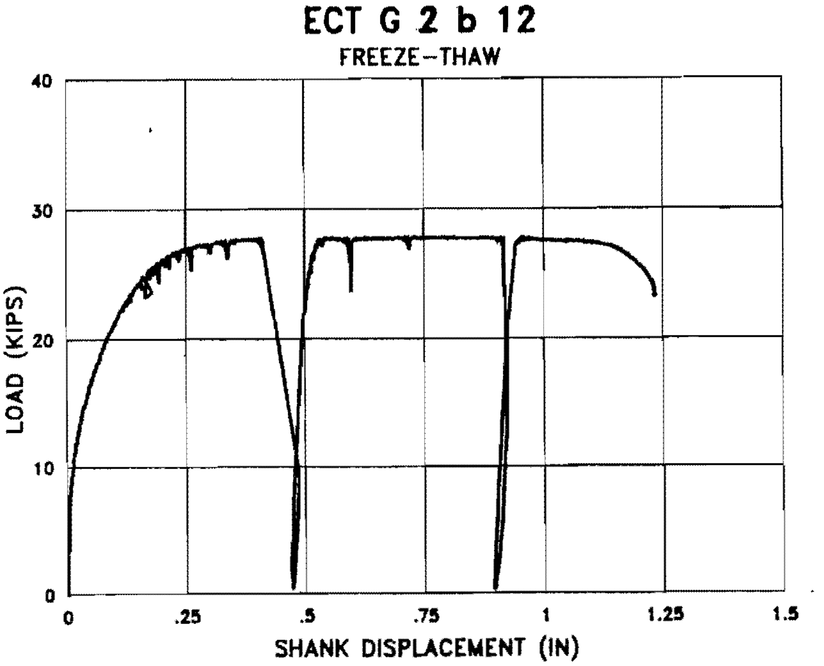


Figure 9.2 Load-deflection characteristics for exposed anchor demonstrating more slip than unexposed anchor.

1) Secant modulus at 90% of maximum load is significantly less for exposed anchors than for unexposed anchors.

2) Anchors subjected to freeze-thaw exposure exhibited larger total displacement at failure than unexposed anchors. This additional displacement, which occurs due to freezing and thawing, contributed to the cone failure exhibited by one anchor. As the anchor was pulled up in the hole by the applied load, its effective embedment length became shallow enough to cause the formation of a concrete cone.

9.4.2 Salt (Corrosion) Exposure. Each type of expansion anchor is treated separately.

ECT G Specimens

ECT G specimens exposed to salt (corrosion) behaved like otherwise identical unexposed anchors with respect to initial stiffness, maximum load, maximum displacement, failure mode, secant stiffness and load-deformation characteristics.

ECT H Specimens

Test data for ECT H 3 c 6 are not included in the data set; because the cylinder pulled out of the reaction block during loading, due to improper installation. ECT H anchors exposed to salt (corrosion) behaved like otherwise identical unexposed anchors with respect to failure mode, similar maximum load, and maximum displacement.

Three differences exist between exposed and unexposed ECT H anchors:

1) Exposed anchors showed slightly higher initial stiffness and significantly higher secant stiffness at 90% maximum load, than did unexposed anchors.

2) Exposed anchors showed much less slip than unexposed anchors. The higher initial stiffness of the exposed anchors may have been caused by the buildup of rust and salt between the expansion sleeve and concrete. This is believed to have increased the coefficient of friction between the concrete and the expansion mechanism.

9.4.3 Acid Rain Wetting and Drying Exposure. Each type of expansion anchor is treated separately.

ECT G Specimens

ECT G anchors exposed to acid rain wetting and drying behaved like otherwise identical unexposed anchors with respect to initial stiffness, maximum load, maximum displacement, failure mode, secant stiffness, and load-deflection characteristics.

ECT H Specimens

ECT H anchors exposed to acid rain wetting and drying behaved like otherwise identical unexposed anchors with respect to initial stiffness, maximum load, maximum displacement, failure mode, secant stiffness, and load-deflection characteristics. The maximum displacement for exposed anchors was larger than for unexposed anchors.

9.4.4 Combination Exposure. Each type of expansion anchor is treated separately.

ECT G Specimens

ECT G anchors exposed to combination exposure behaved like otherwise identical unexposed anchors with respect to failure mode, maximum load, maximum displacement, secant stiffness, and load-deflection characteristics.

One major difference exists between exposed and unexposed ECT G anchors:

1) Exposed anchors were significantly less stiff initially than unexposed anchors. This reduced initial stiffness may be due to weakened concrete in the drilled hole. Concrete along the surface of the drilled hole may be damaged from the drilling operation (subsection 8.6.1). Repeated cycles of freeze-thaw combined with salt penetration could spall and weaken the drill-damaged concrete in the hole (subsection 8.6.1). The anchor will slip until the additional lateral force caused by the applied load becomes sufficient to crush the weakened concrete.

ECT H Specimens

ECT H anchors exposed to combination exposure behaved like otherwise identical unexposed anchors with respect to maximum load, and failure mode.

Three differences exist between exposed and unexposed ECT H anchors:

1) Initial stiffness for exposed anchors is slightly lower than that of unexposed anchors.

2) Secant stiffness for exposed anchors is much lower than that of unexposed anchors.

3) Maximum displacement for exposed anchors is significantly higher than that of unexposed anchors.

Possible reasons for the differences between the exposed and unexposed anchors are discussed above.

9.5 Undercut Anchor Tensile Tests

9.5.1 Combination Exposure. Each undercut anchor is treated separately.

ECT I Specimens

ECT I anchors exposed to combination exposure behaved like otherwise identical unexposed anchors with respect to failure mode, maximum load, maximum displacement, secant stiffness at 90%, maximum load, and load-deflection characteristics. The initial stiffness for exposed anchors was significantly higher than the unexposed anchors, due to a buildup of rust and salt between the undercutting cone and sleeve as discussed in subsection 9.4.2. The buildup is believed to have caused some frictional resistance in addition to the bearing produced in the undercut region. Because most of the resistance comes from direct bearing on the concrete by the undercutting mechanism, the capacity would not be adversely affected by the freeze-thaw deterioration of the sides hole. The capacity may be significantly reduced if the is a large amount of concrete cracking from freezing and thawing exposure.

One ECT I anchor failed before yield and fracture of the steel because the threads at the bottom of the anchor stripped. Visual inspection could not determine whether the bolt had been completely screwed into the base cone (Figure 9.3).

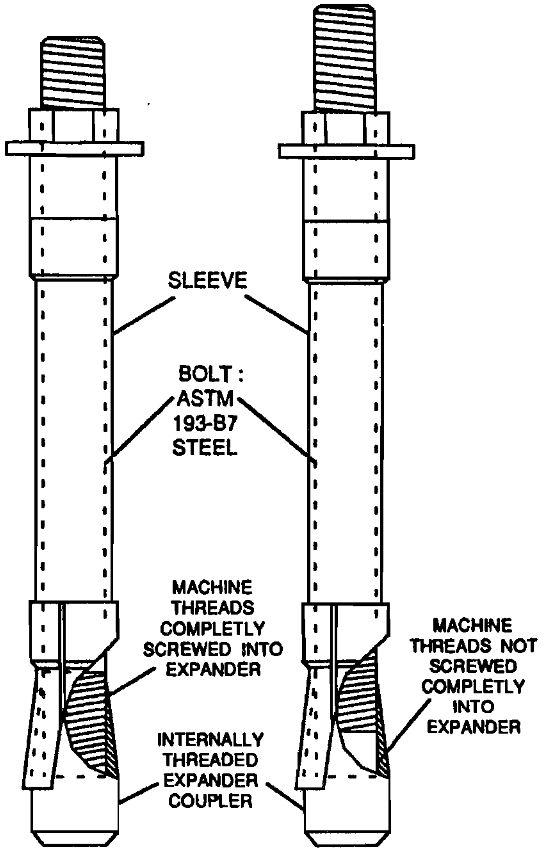


Figure 9.3 Undercut anchor with internal threads at base of anchor stud.

ECT J Specimens

ECT J anchors exposed to combination exposure behaved like otherwise identical unexposed anchors.with respect to failure modes, maximum loads, maximum displacements, load-deflection characteristics, and the initial and secant stiffnesses.

9.6 Cast-In-Place Anchor Tensile Tests

9.6.1 Combination Exposure. Cast-in-place anchors (ECT K specimens) exposed to combination exposure behaved like otherwise identical unexposed anchors with respect to failure modes, initial stiffness, maximum load, maximum displacement, and load-deflection characteristics.

CHAPTER 10.
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

10.1 Summary

The purpose of this study was to investigate the response of anchors to various environmental exposure conditions, to evaluate the tensile behavior of single anchors subjected to environmental exposure, and compare the behavior of otherwise identical exposed and unexposed anchors. The following anchor types were tested:

1) Retrofit Anchors
    a) Adhesive anchors
    b) Expansion anchors
    c) Undercut anchors
2) Cast-in-place anchors (for comparison only)

This study involves anchors subjected to 5 environmental exposure conditions:

1) Ultraviolet light
2) Freezing and thawing
3) Corrosion in a pH-neutral salt solution
4) Wetting and drying with an acid rain solution
5) Combined freezing and thawing, corrosion in a pH-neutral salt solution, and wetting and drying

Anchors were installed in concrete cylinders meeting TSDHPT specification for Class C concrete. These concrete cylinders with installed anchors were then subjected to 5 environmental exposure conditions. After environmental exposure, the cylinders were cemented into a concrete block with an epoxy adhesive and tested in direct static tension to failure.

Although the concrete used in these tests did undergo some damage during the freeze-thaw tests, damage to concrete was not the focus of this research. Such damage is independent of the type of anchor used.

Results of tests presented in this report should be interpreted under the following conditions:

1) Results are strictly valid only for the anchors tested in this study and the conditions under which they were studied.

2) Results of these retrofit anchor tests could be affected by anchor specifications, concrete type, installation procedures, or testing environment.

3) Results should not be construed to imply that all anchors of a given type are better than all anchors of another type.

4) Results should not be construed as an endorsement of any particular anchor type or brand.

The following responses were observed for anchors in each environment:

Ultraviolet Light Exposure

1) Adhesive Anchors: Very slight color change with some adhesives.

Freezing and Thawing Exposure

1) Expansion Anchors (6-Inch Diameter Cylinders): Cracking of the concrete at the level of the expansion mechanism after 42 cycles of exposure. Cosmetic flaking on concrete at the surface. Complete loss of preload after 50 cycles of exposure (three of 8 tests).

2) Expansion Anchors (12-Inch Diameter Cylinders): Cracking of the concrete after 50 cycles of exposure (two of 8 tests). Cosmetic flaking on concrete at the surface. Complete loss of preload after 50 cycles of exposure (four of 8 tests).

Salt (Corrosion) Exposure

1) Expansion Anchors: Limited rusting of stainless steel anchor. Significant rusting of zinc electroplated anchors.

Acid Rain Wetting and Drying Exposure

1) Adhesive Anchors: Significant rusting of threaded rod. Some types of adhesive exhibited rusting below the surface of the adhesive.

2) Expansion Anchors: No change in appearance other than buildup of white material on some anchors.

Combination Exposure

1) Expansion Anchors: Cosmetic flaking on the surface of the concrete. Rust on zinc electroplated anchor steel. Very little rusting of stainless steel anchors.

2) Undercut Anchors: Cosmetic flaking on the surface of the concrete. Significant rusting on untreated anchor steel. Salt buildup but no rust on zinc electroplated steel anchors.

3) Cast-In-Place Anchors: Mild cosmetic flaking on the surface of the concrete. Significant rusting on the untreated anchor steel.

The following static tensile loading behaviors were observed for anchors after environmental exposure:

Adhesive Anchors

1) Ultraviolet Light Exposure: Twenty of 24 tests failed by yield and fracture of anchor steel. Four anchors failed by formation of a concrete cone followed by pullout of an adhesive core. Ultraviolet light exposure was not believed to have caused the cone failures.

2) Acid Rain Wetting and Drying Exposure: Twenty-one of the 24 anchors tested failed by yield and fracture of anchor steel. Three anchors failed by formation of a concrete cone followed by pullout of an adhesive core. It could not be determined if the acid rain wetting and drying contributed to the cone failures.

Expansion Anchors

1) Freezing and Thawing Exposure: Six of 7 anchors tested failed by yield and fracture of anchor steel. One anchor failed by formation of a concrete cone

after significant slip. Some exposed anchors showed more slip and lower initial stiffness than unexposed anchors.

2) Salt (Corrosion) Exposure: All 8 anchors tested failed by yield and fracture of anchor steel. Some exposed anchors showed slightly higher initial stiffness and much less slip than unexposed anchors.

3) Acid Rain Wetting and Drying Exposure: Seven of the 8 anchors tested failed by yield and fracture of anchor steel. One anchor failed by pullout. There was no difference between exposed and unexposed anchors.

4) Combination Exposure: All 8 anchors tested failed by yield and fracture of anchor steel. Some exposed anchors showed significantly lower initial stiffness, lower secant stiffness, and more total displacement, than unexposed anchors.

Undercut Anchors

1) Combination Exposure: Seven of the 8 anchors tested failed by yield and fracture of anchor steel. One anchor failed because the threads at the bottom of the anchor stripped before yield and fracture could occur (subsection 9.5.1). There was no difference between exposed and unexposed anchors.

Cast-In-Place Anchors

1) Combination Exposure: All 4 anchors tested failed by yield and fracture of anchor steel. There was no difference between exposed and unexposed anchors.

10.2 Conclusions

Based on the test results reported in this study the conclusions are as follows:

Ultraviolet Light Exposure

1) Ultraviolet light does not affect the behavior of adhesive anchors.

Freezing and Thawing Exposure

2) Freezing and thawing significantly reduces the applied preload of torque-controlled expansion anchors. The manufacturer's recommended torque should be reapplied on a regular basis for anchors which are subjected to numerous cycles of freezing and thawing.

3) Freezing and thawing can damage the concrete and thereby affect the behavior of expansion anchors. To reduce the chance of damage to the concrete from numerous cycles of freezing and thawing, water should be prevented from entering the drilled hole, additional edge distance should be provided, or the anchor should be placed so that reinforcement lies between the drilled hole and free surface.

4) Freezing and thawing increases the amount of slip which takes place during loading and reduces the initial stiffness of some expansion anchors. Water should be prevented from entering the drilled hole for anchors which are subjected to numerous cycles of freezing and thawing. Reapplication of the initial torque for anchors subjected to numerous cycles of freezing and thawing is recommended if water is able to fill the drilled hole.

Salt (Corrosion) Exposure

5) Salt (Corrosion) exposure does not adversely affect the behavior of expansion anchors. That is, within the range of exposures tests, corrosion exposure did not adversely affect the behavior of the expansion anchors tested. For extended exposure and serious deterioration of the anchor, the behavior may change. Expansion anchors, like any other steel embedment, do corrode. If the corrosive exposure is severe enough to warrant special corrosion resistance for ordinary embedments (such as reinforcing dowels or cast-in-place bolts), then special corrosion resistance should be specified for expansion anchors as well.

Acid Rain Wetting and Drying Exposure

6) Acid rain wetting and drying does not significantly affect the behavior of adhesive anchors (tested when the adhesive is dry). As discussed in Section 2.2, hydrolysis can affect the physical properties of adhesives, but the effect is reversible if the adhesive dries. The behavior of adhesive anchors tested when wet is unknown. In some cases, acid rain was able to penetrate between the threaded rod and adhesive. For long term exposure, this could lead to serious detrimental results.

7) Acid rain wetting and drying does not significantly affect the behavior of expansion anchors.

Combination Exposure

8) Combination exposure reduces the stiffness of some expansion anchors. Water should be prevented from entering the drilled hole for anchors which are subjected to numerous cycles of freezing and thawing. Reapplication of the initial torque for anchors subjected to numerous cycles of freezing and thawing is recommended if water is able to fill the drilled hole.

9) Combination exposure does not adversely affect the behavior of undercut anchors.

10) Combination exposure does not affect the behavior of cast-in-place anchors.

General

11) Because of damage to the concrete from freezing and thawing (observed with expansion anchors), additional precautions should be taken for undercut anchors subjected to numerous cycles of freezing and thawing. Using sealant, water should be prevented from entering the drilled hole; additional edge distance should be provided; or reinforcement should be placed between the drilled hole and the free surface of the concrete.

12) Additional caution should be used before installation of anchors which can be unscrewed and taken apart. They should be checked to ensure all parts are properly connected or they should not be tampered with before installation.

10.3 Recommendations for Further Research

Based on the test results reported in this study, the following additional research is recommended:

1) Further investigate the effects of freezing and thawing on anchors where water can penetrate into the hole. Specifically, investigate the effect on loss of preload on expansion and undercut anchors.

2) Investigate the edge distances required for anchors subjected to freezing and thawing.

3) Investigate the effects of freezing and thawing on different concrete strengths.

4) Investigate the effects of salt (corrosion) on adhesive anchors.

5) Investigate the effects of long term exposure to acid rain wetting and drying on adhesive anchors.

6) Investigate the behavior of different anchor diameters and concrete strengths in the 5 environments.

7) Investigate the effects on anchor behavior of fatigue loads after environmental exposure.

8) Investigate the effects on anchor behavior of impact loads after environmental exposure.

9) Investigate the behavior of adhesive anchors subjected to environmental exposure while under load (stress corrosion effects on adhesives).

10) Investigate the relationship between results from synthetic laboratory environments and field exposure conditions so that laboratory data provide an indication of actual field exposure.

APPENDIX A

ENVIRONMENTAL EXPOSURE RESULTS

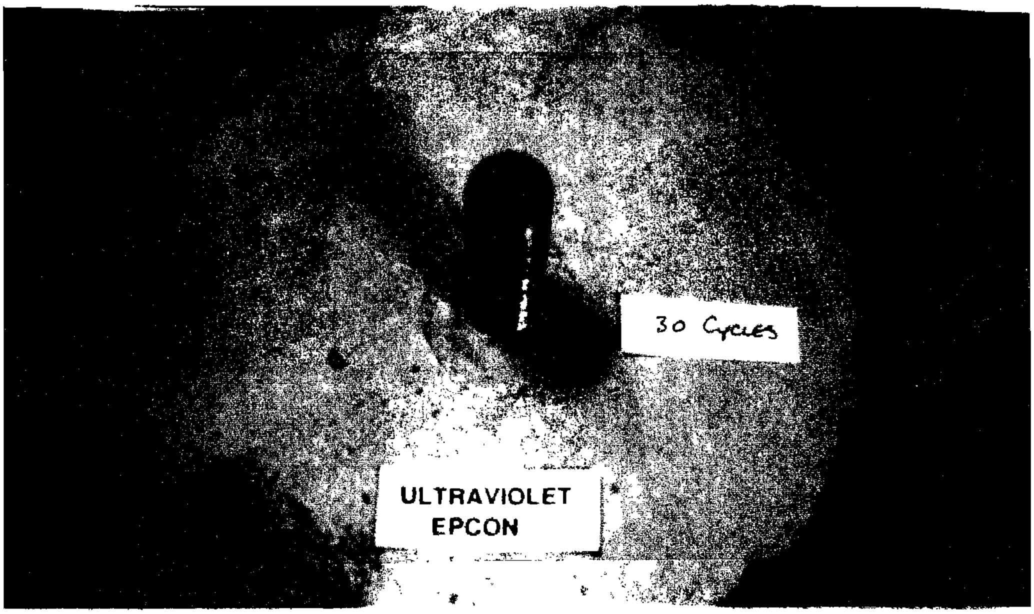


Figure A.1a Condition of Designation A anchors after 30 cycles of ultraviolet light exposure.

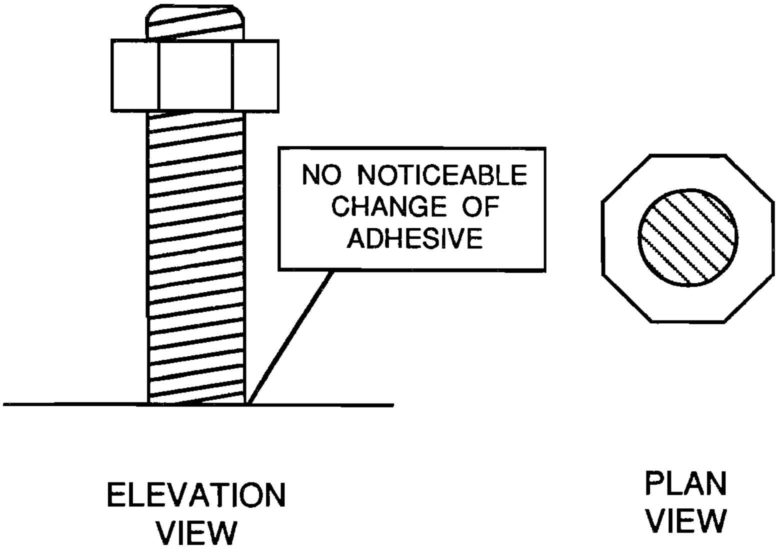


Figure A.1b Schematic of condition of Designation A anchors after 30 cycles of ultraviolet light exposure.

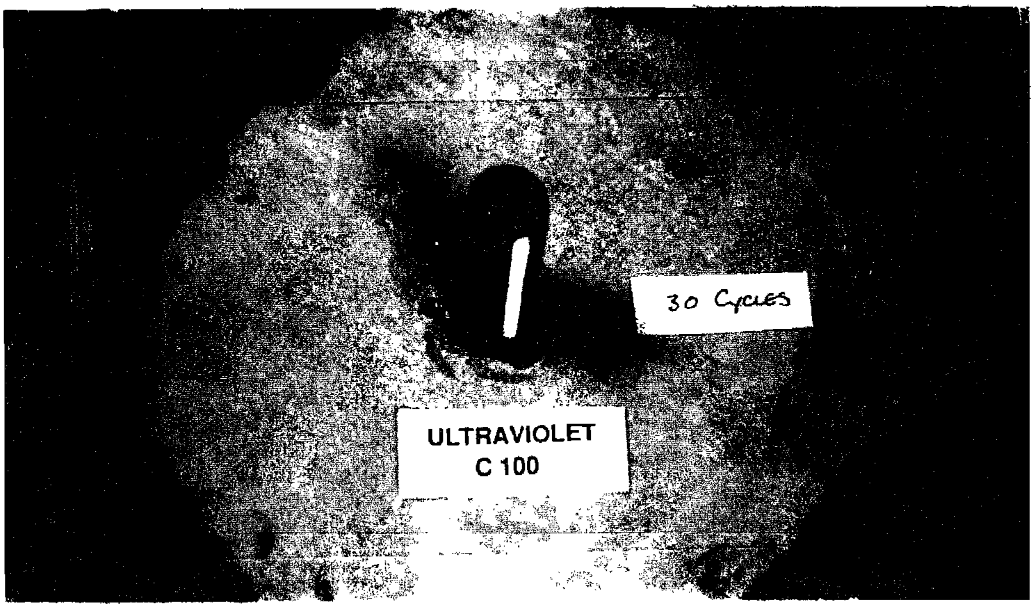


Figure A.2a Condition of Designation B anchors after 30 cycles of ultraviolet light exposure.

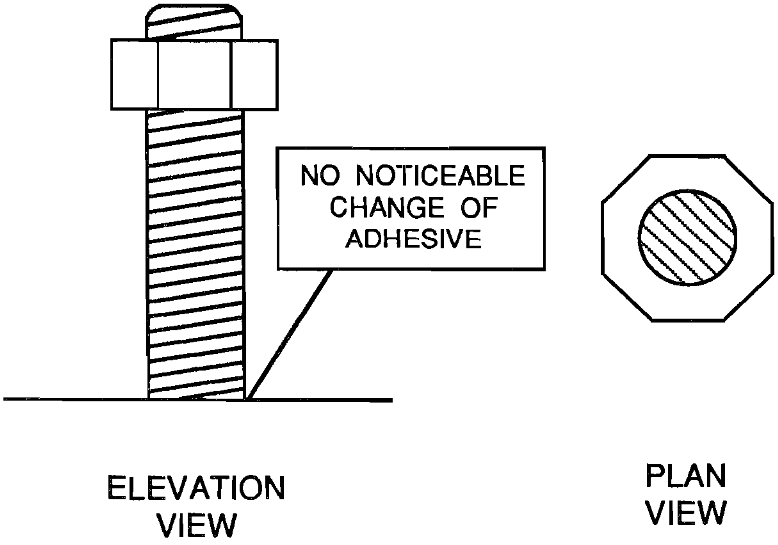


Figure A.2b Schematic of condition of Designation B anchors after 30 cycles of ultraviolet light exposure.

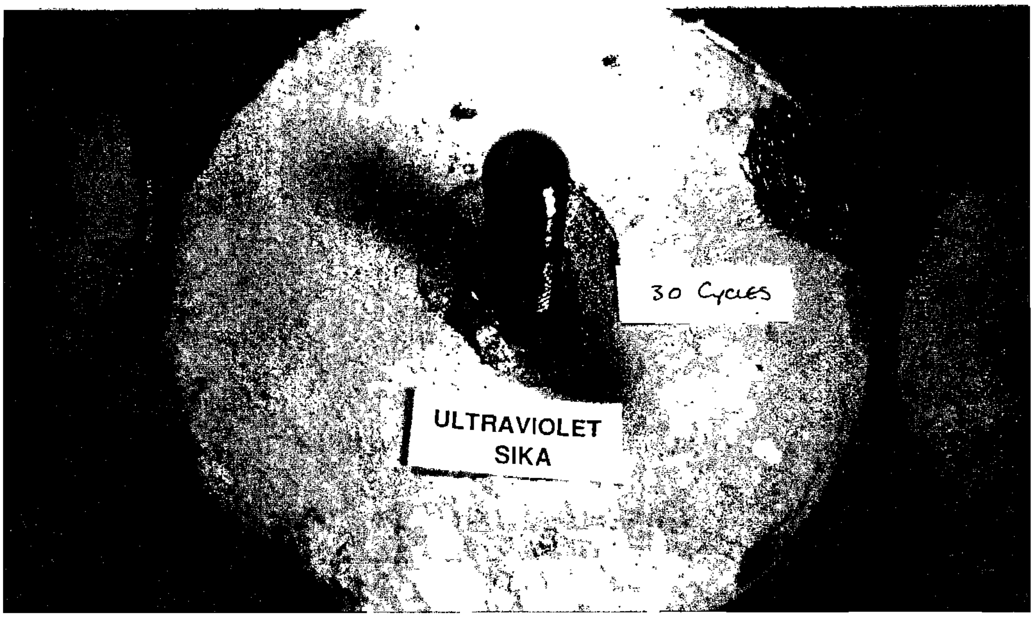


Figure A.3a Condition of Designation C anchors after 30 cycles of ultraviolet light exposure.

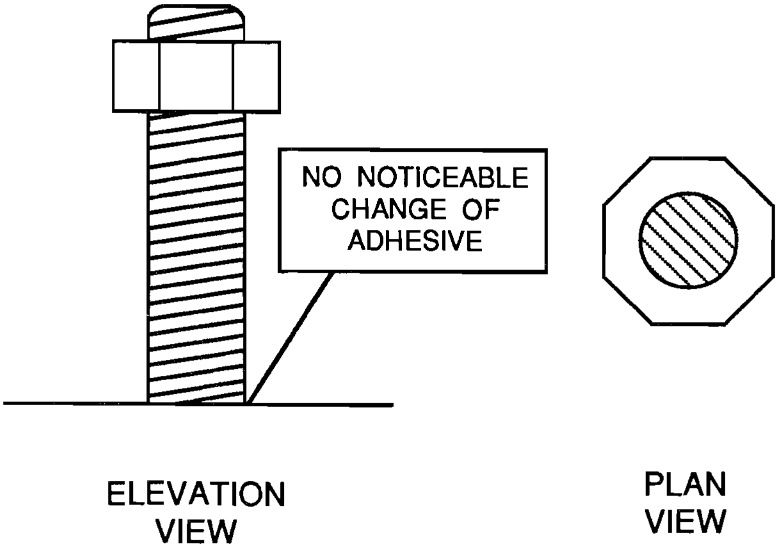


Figure A.3b Schematic of condition of Designation C anchors after 30 cycles of ultraviolet light exposure.

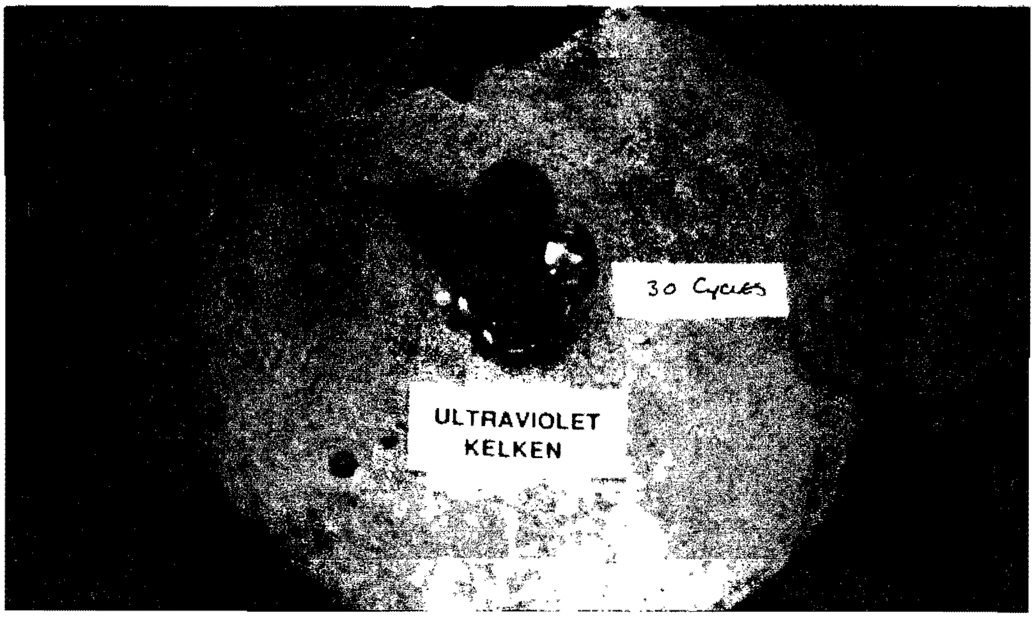


Figure A.4a Condition of Designation D anchors after 30 cycles of ultraviolet light exposure.

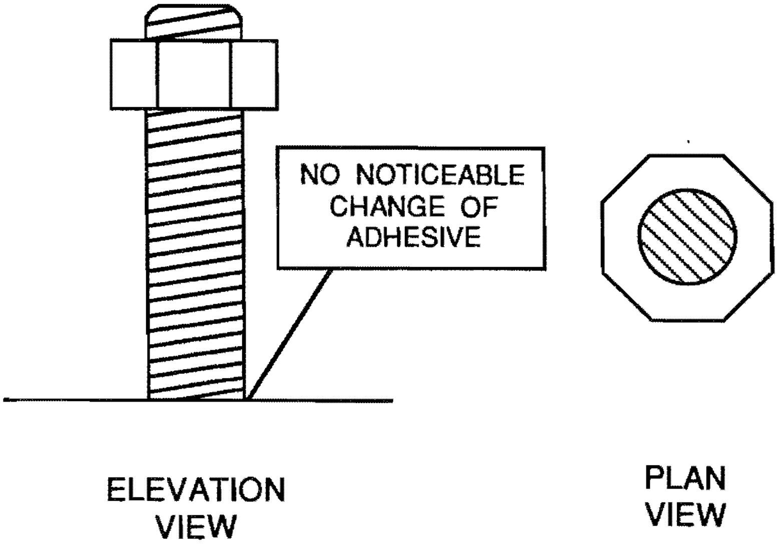


Figure A.4b Schematic of condition of Designation D anchors after 30 cycles of ultraviolet light exposure

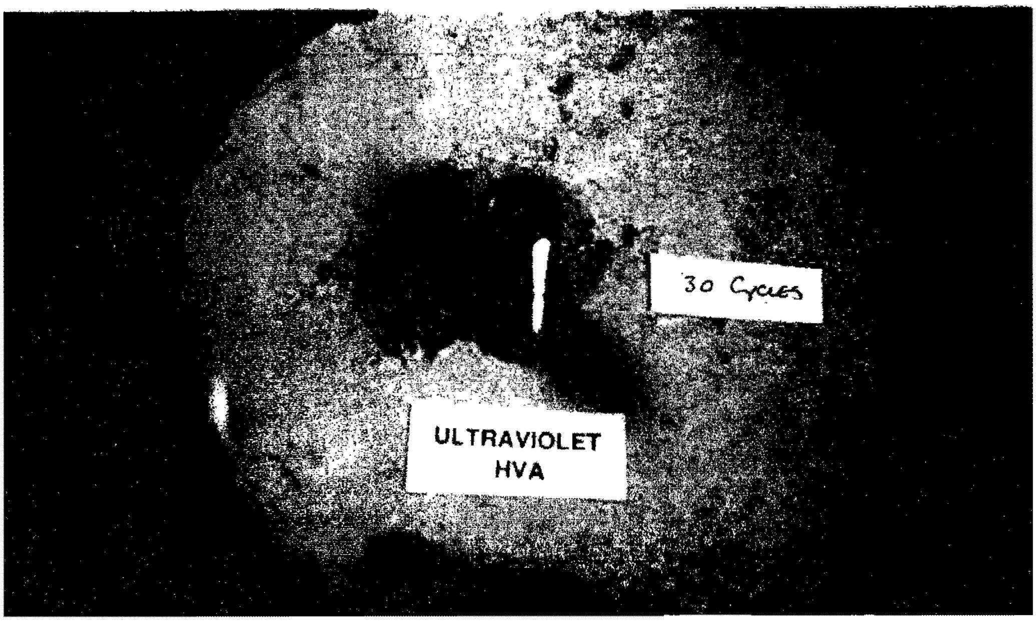


Figure A.5a Condition of Designation E anchors after 30 cycles of ultraviolet light exposure.

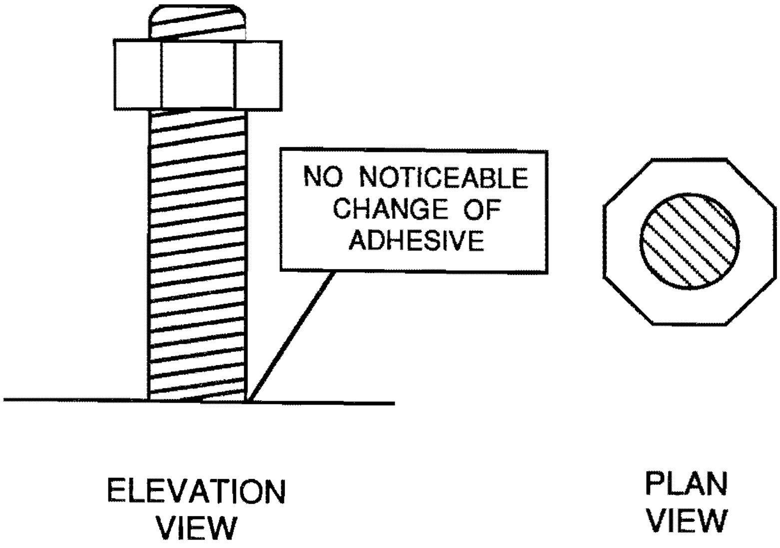


Figure A.5b Schematic of condition of Designation E anchors after 30 cycles of ultraviolet light exposure.

Figure A.6a Condition of Designation F anchors after 30 cycles of ultraviolet light exposure.

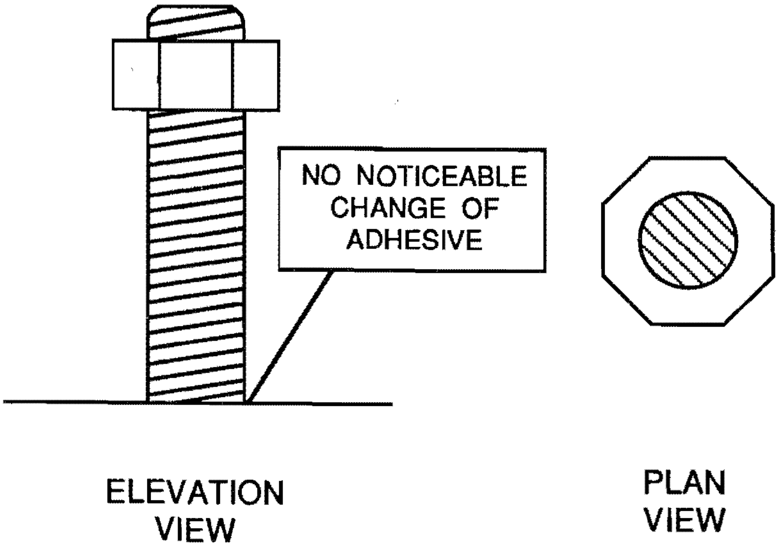


Figure A.6b Schematic of condition of Designation F anchors after 30 cycles of ultraviolet light exposure.

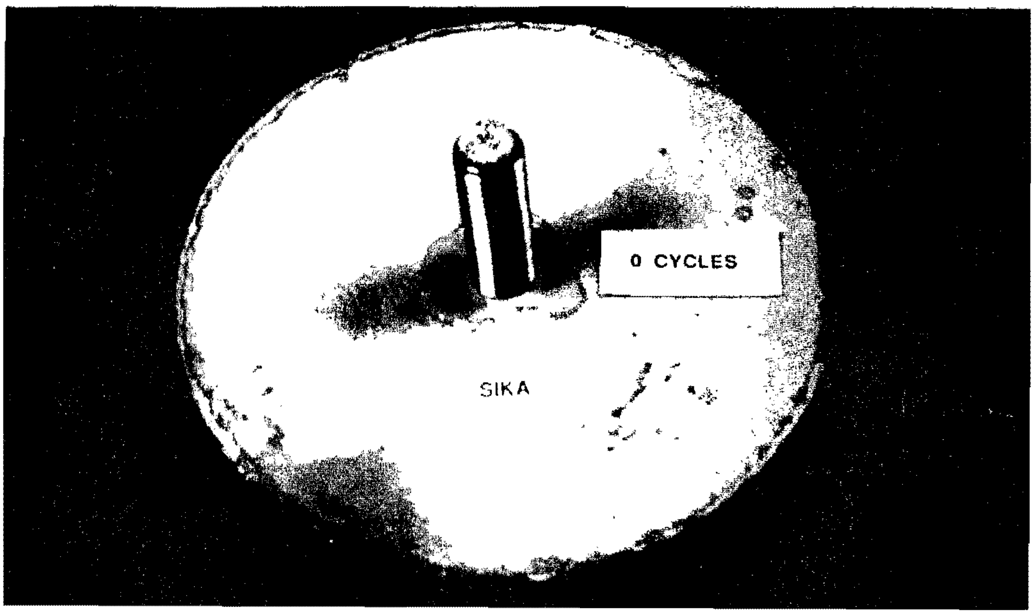


Figure A.7 Typical condition of adhesive anchor before ultraviolet light exposure.

Figure A.8 Typical condition of adhesive anchor after 30 cycles of ultraviolet light exposure.

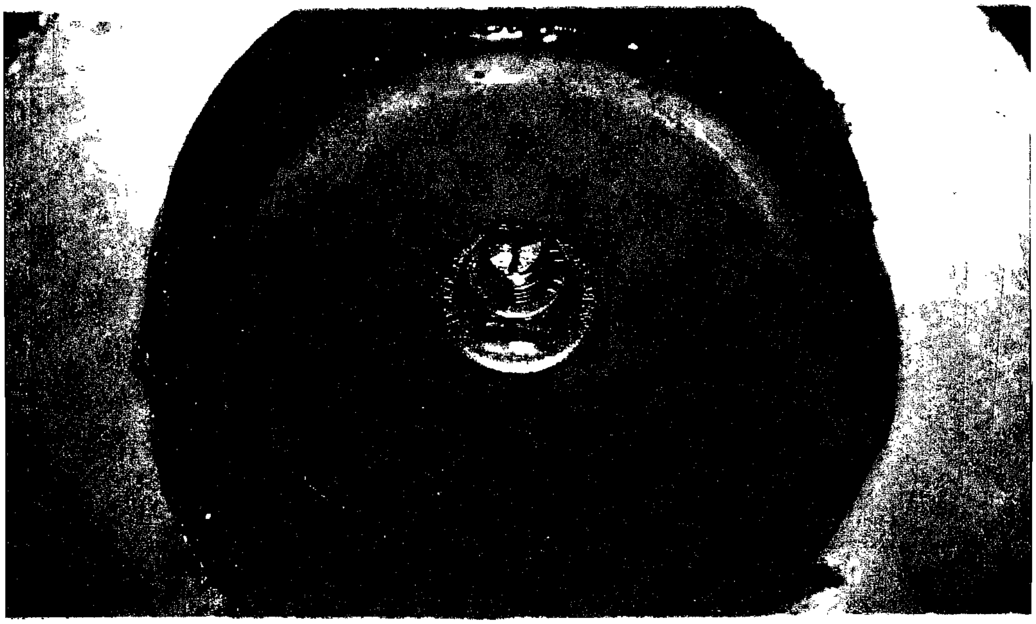


Figure A.9a Condition of Designation G anchors after 50 cycles of freeze and thaw exposure.

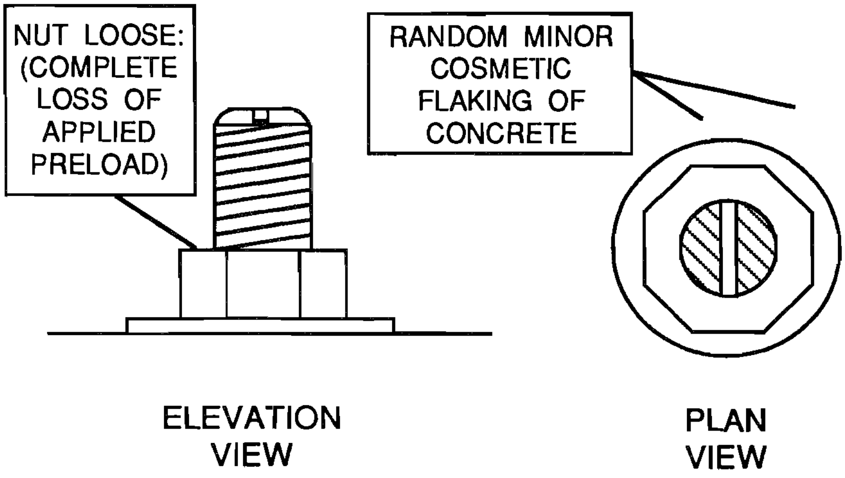


Figure A.9b Schematic of condition of Designation G anchors after 50 cycles of freeze and thaw exposure.

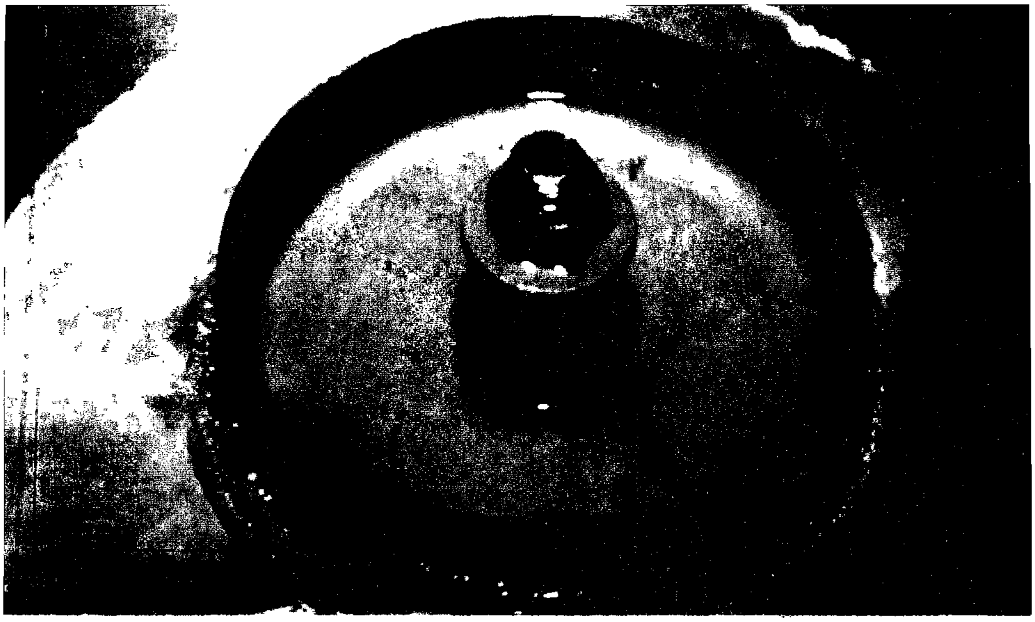


Figure A.10a Condition of Designation H anchors after 50 cycles of freeze and thaw exposure.

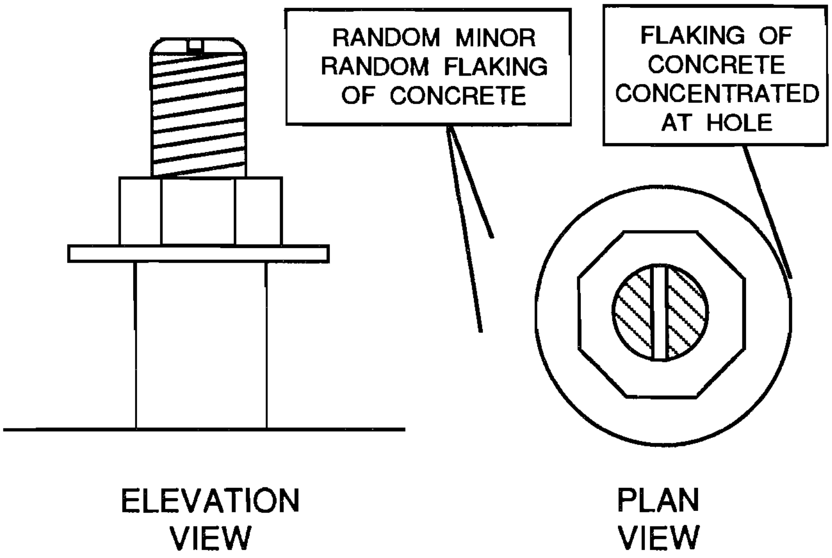


Figure A.10b Schematic of condition of Designation H anchors after 50 cycles of freeze and thaw exposure.

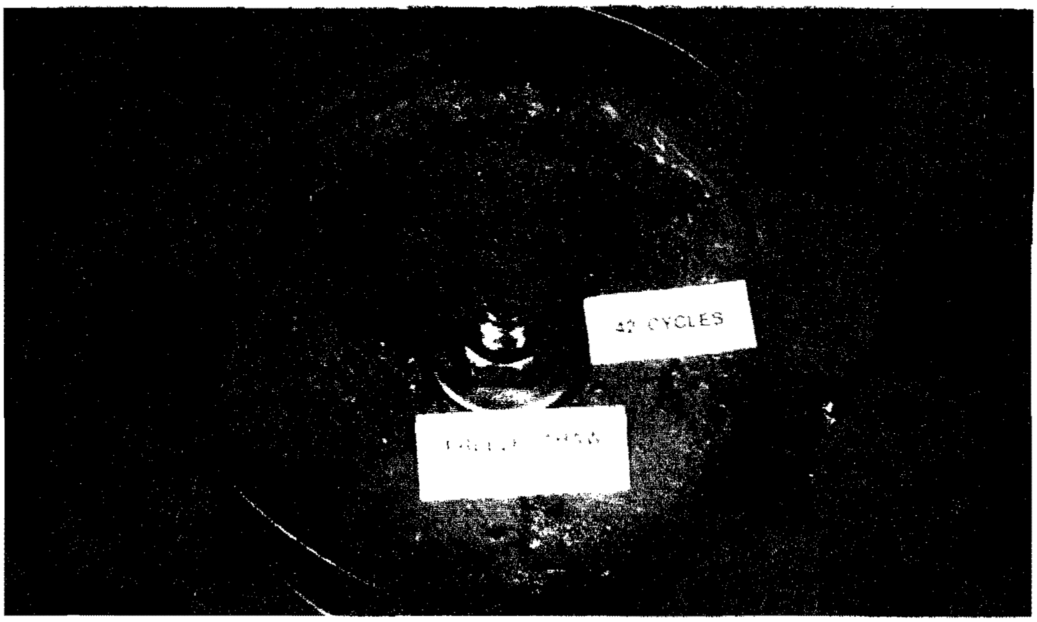


Figure A.11 ECT G specimen exhibiting cracks after 42 cycles of freezing and thawing exposure.

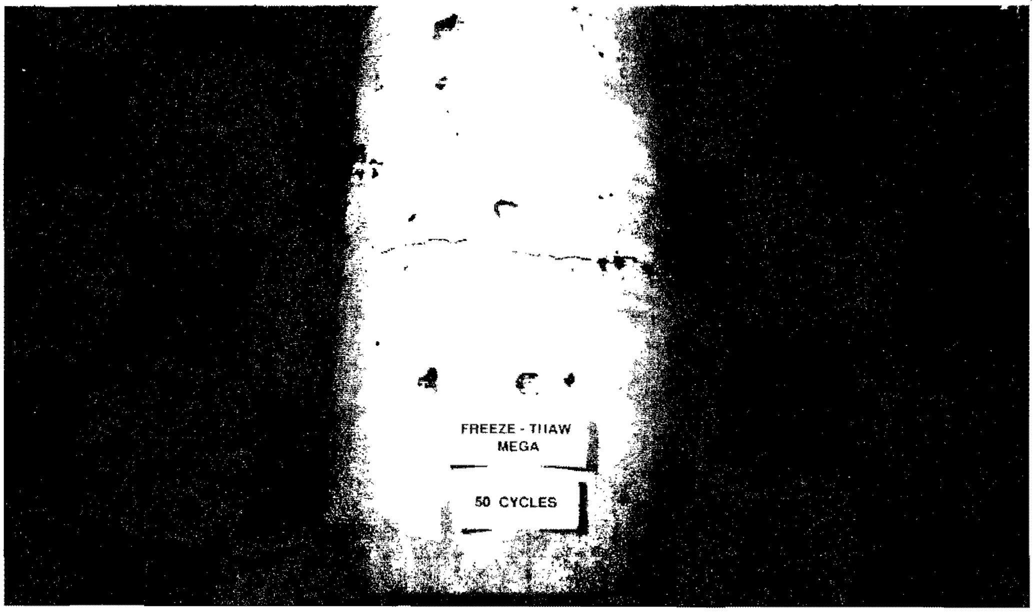


Figure A.12 ECT H specimen exhibiting cracks after 50 cycles of freezing and thawing exposure.

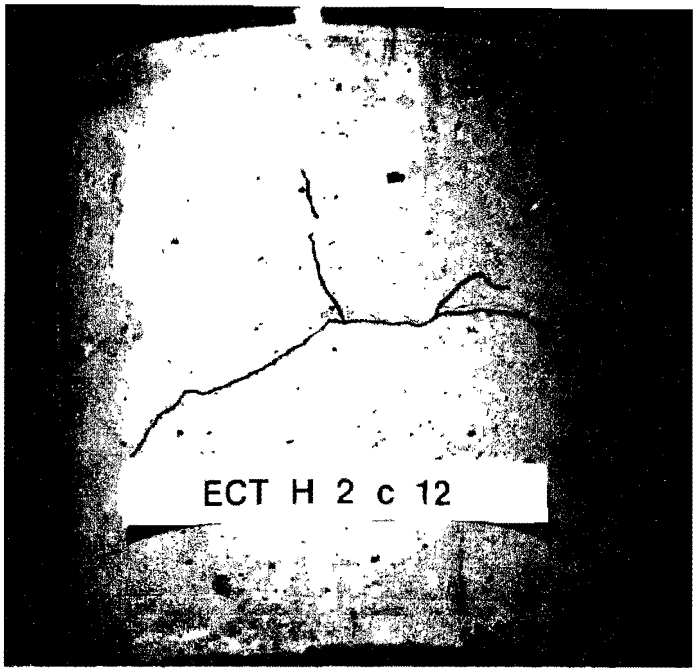


Figure A.13 Twelve-inch ECT H specimen exhibiting cracks after 50 cycles of freeze-thaw exposure.

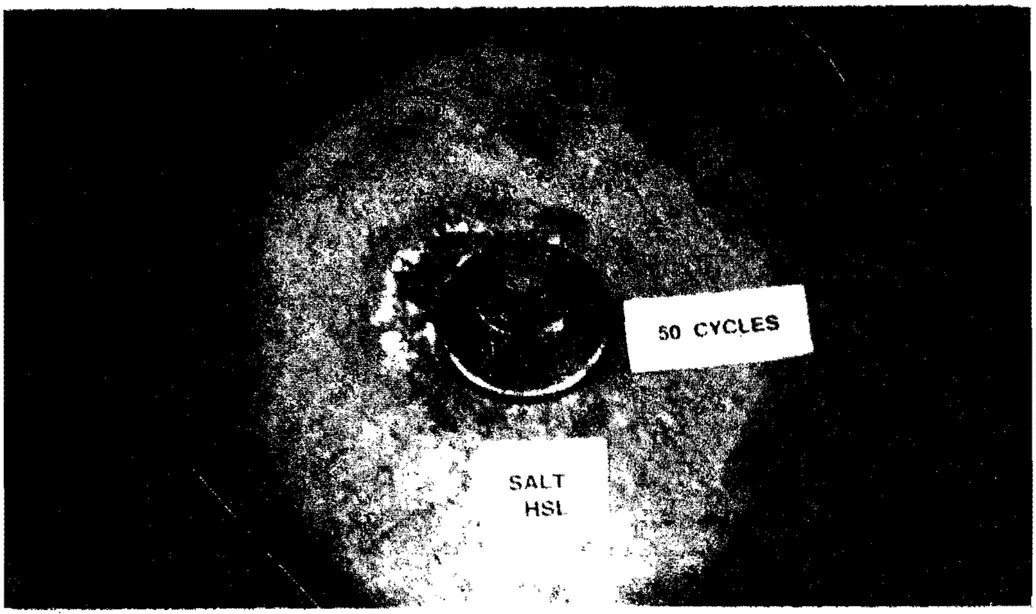


Figure A.14a Condition of Designation G anchors after 50 cycles of salt (corrosion exposure).

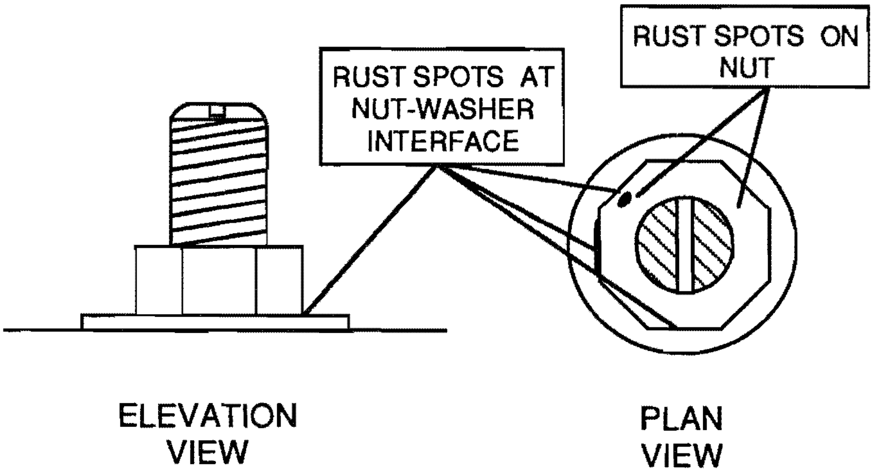


Figure A.14b Schematic of condition of Designation G anchors after 50 cycles of salt (corrosion) exposure.

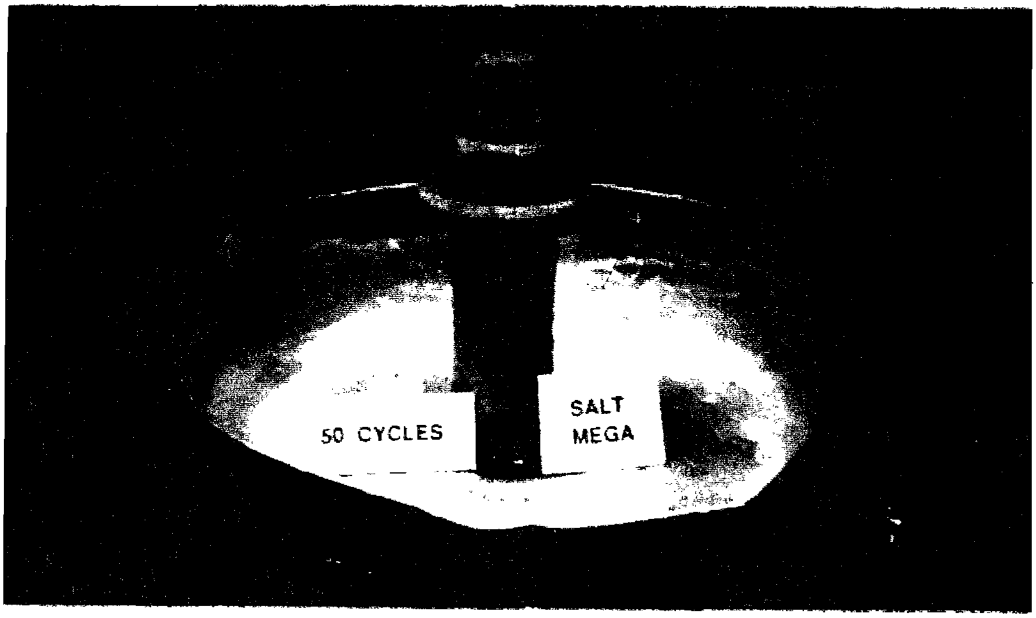


Figure A.15a Condition of Designation H anchors after 50 cycles of salt (corrosion) exposure.

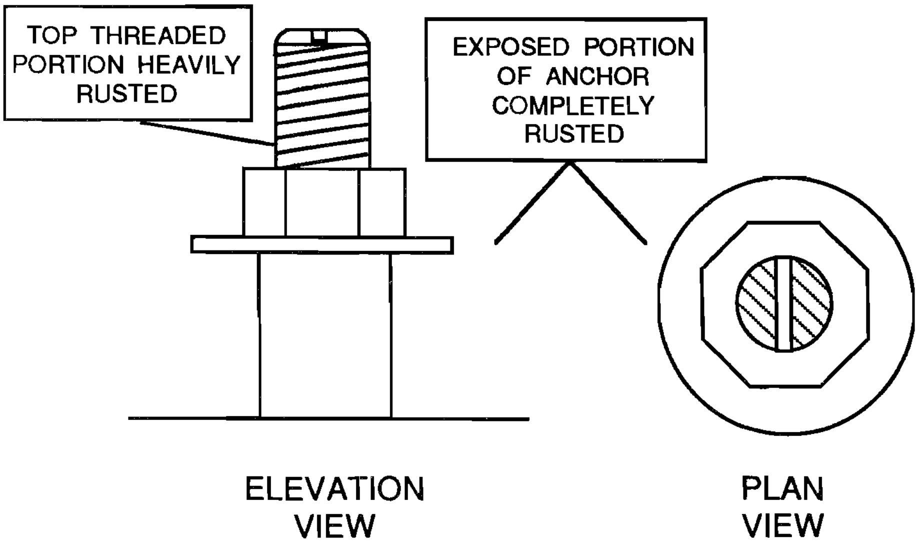


Figure A.15b Schematic of condition of Designation H anchors after 50 cycles of salt (corrosion) exposure.

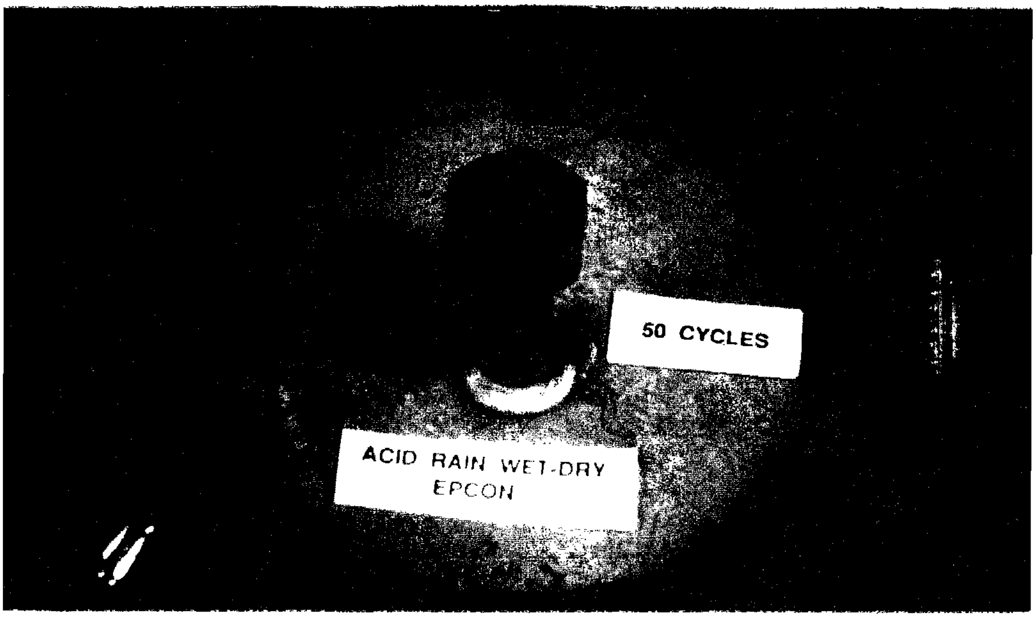


Figure A.16a Condition of Designation A anchors after 50 cycles of acid rain wetting and drying.

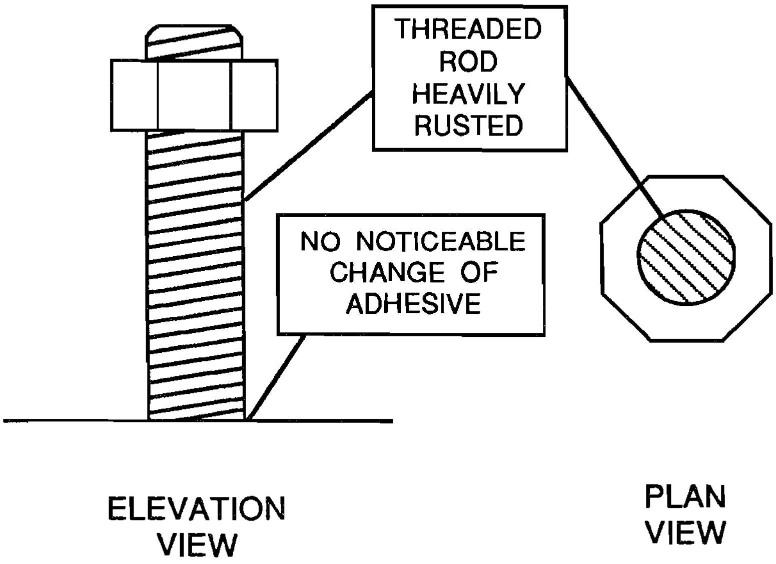


Figure A.16b Schematic of condition of Designation A anchors after 50 cycles of acid rain wetting and drying.

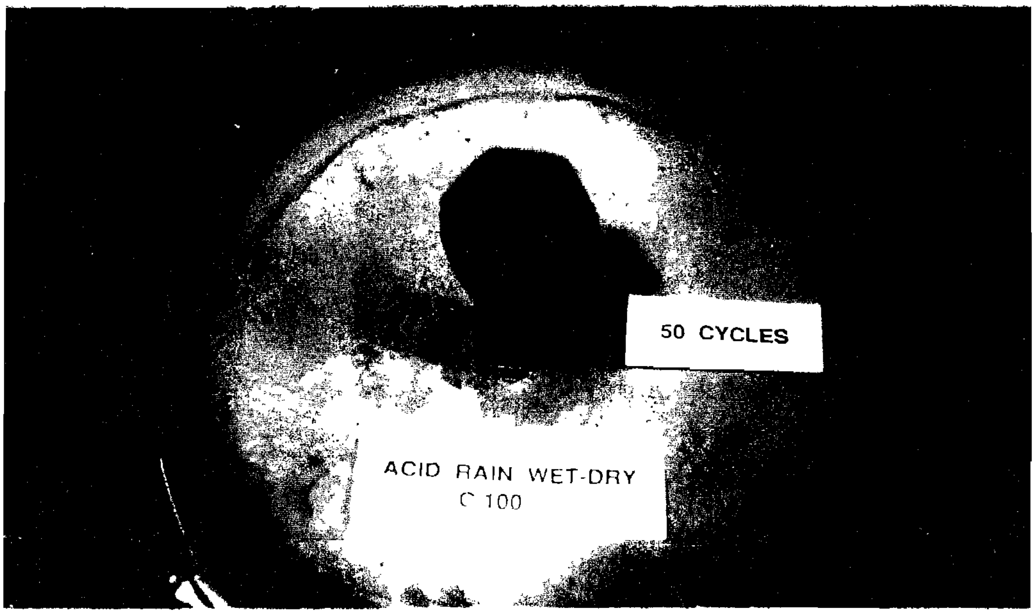


Figure A.17a Condition of Designation B anchors after 50 cycles of acid rain wetting and drying.

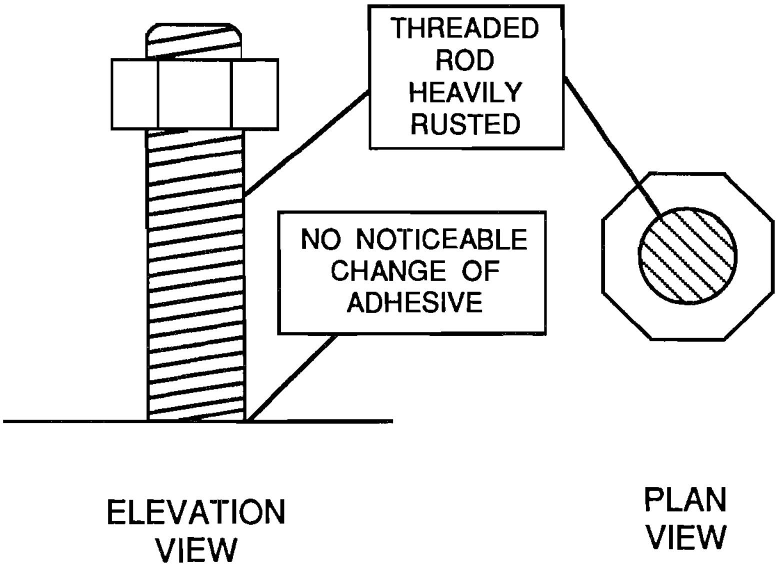


Figure A.17b Schematic of condition of Designation B anchors after 50 cycles of acid rain wetting and drying.

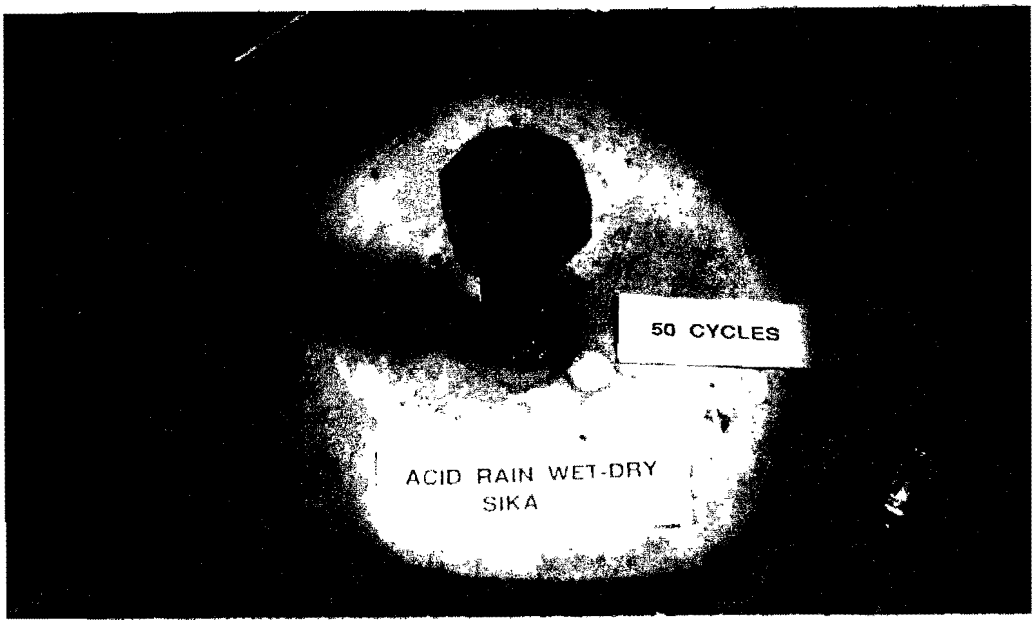


Figure A.18a Condition of Designation C anchors after 50 cycles of acid rain wetting and drying.

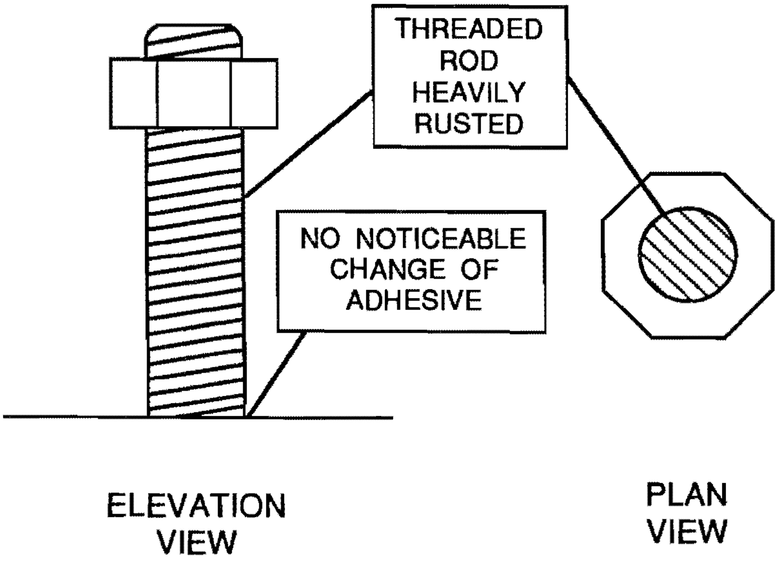


Figure A.18b Schematic of condition of Designation C after 50 cycles of acid rain wetting and drying.

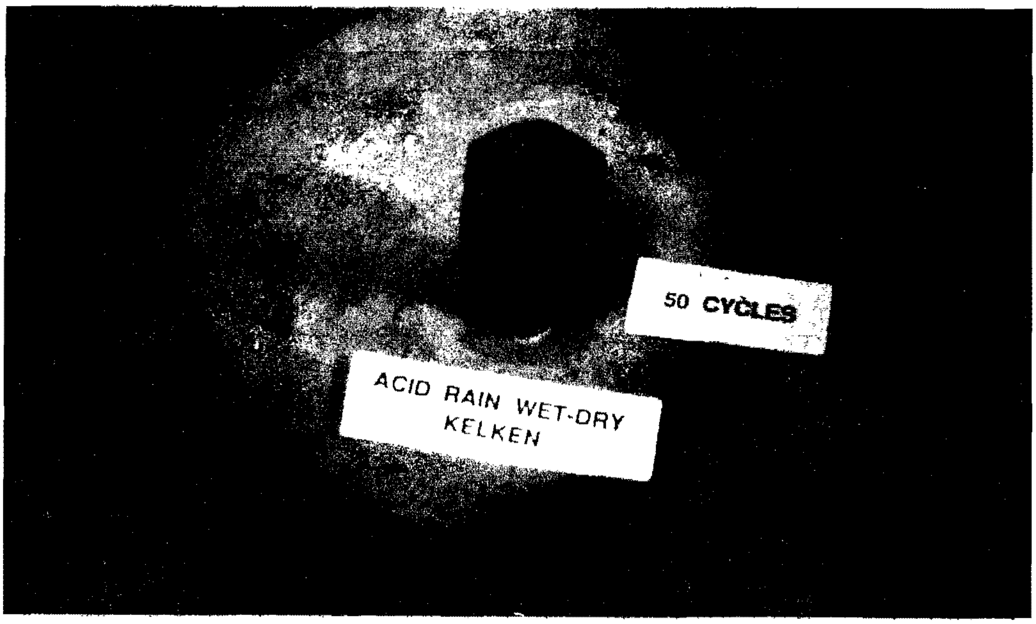


Figure A.19a Condition of Designation D anchors after 50 cycles of acid rain wetting and drying.

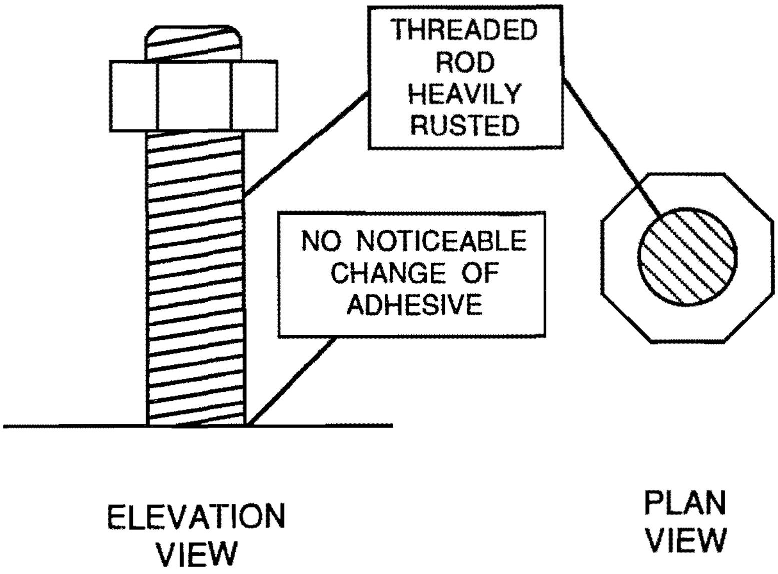


Figure A.19b Schematic of condition of Designation D anchors after 50 cycles of acid rain wetting and drying.

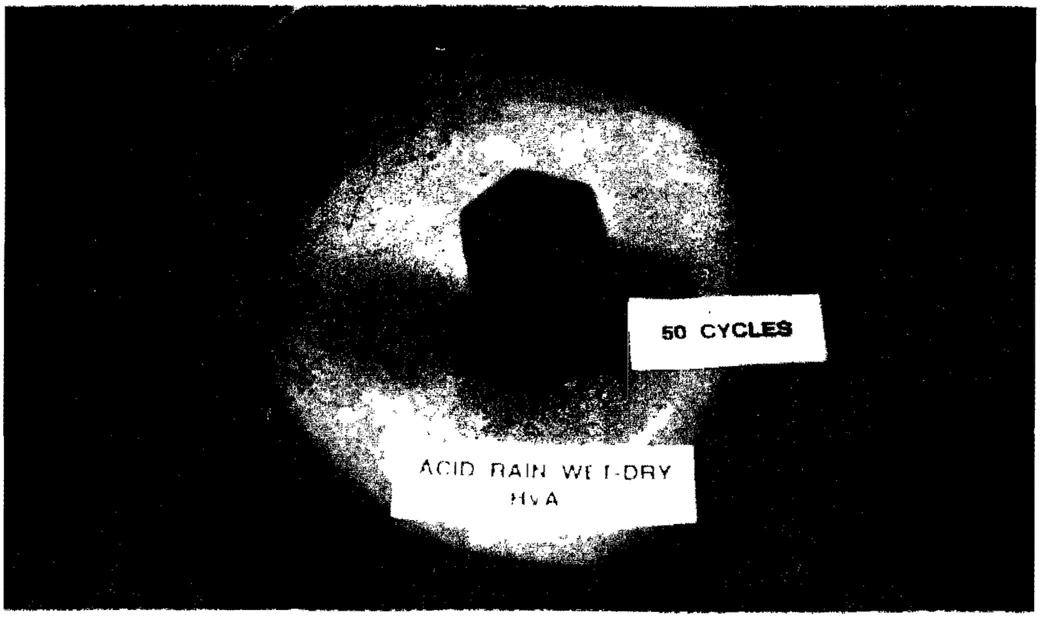


Figure A.20a Condition of Designation E anchors after 50 cycles of acid rain wetting and drying.

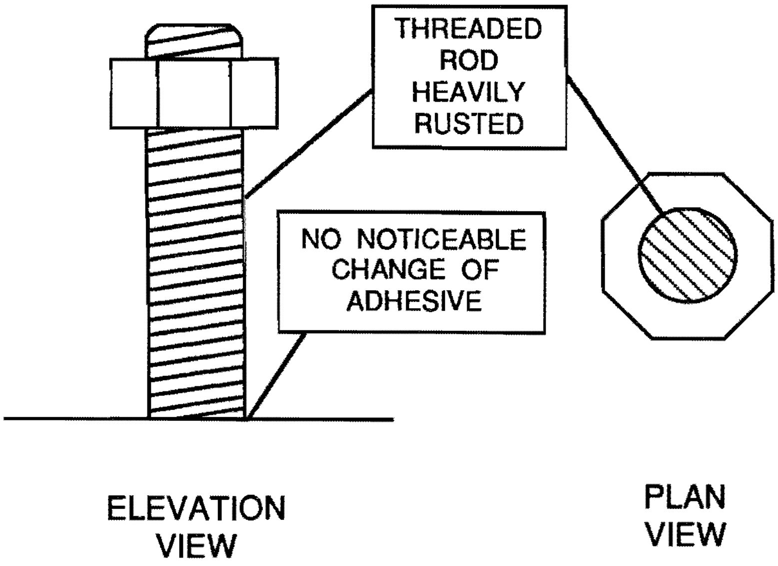


Figure A.20b Schematic of condition of Designation E anchors after 50 cycles of acid rain wetting and drying.

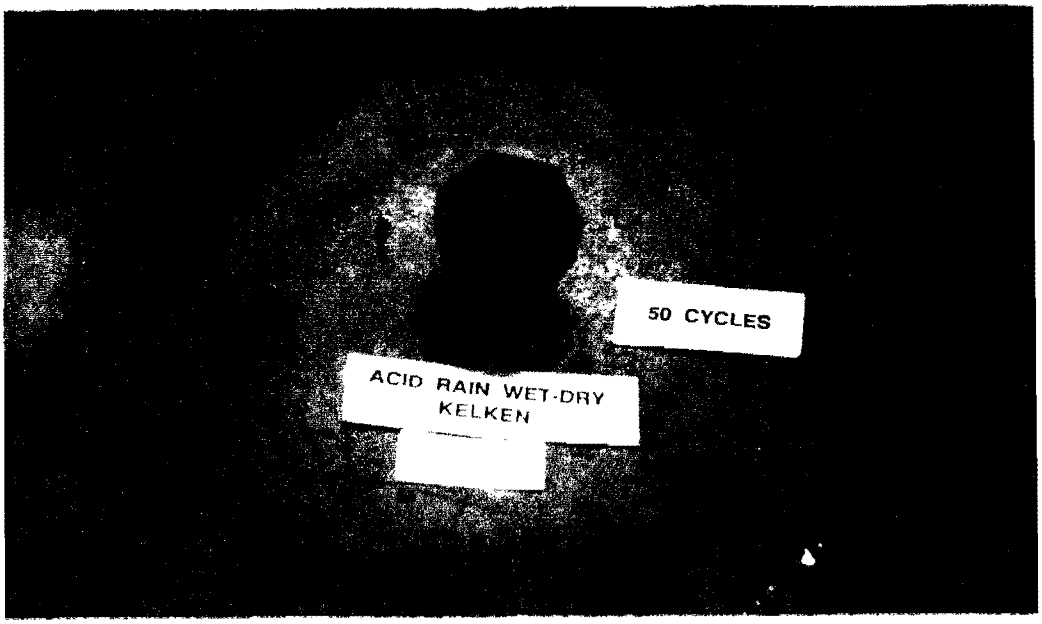


Figure A.21a Condition of Designation F anchors after 50 cycles of acid rain wetting and drying.

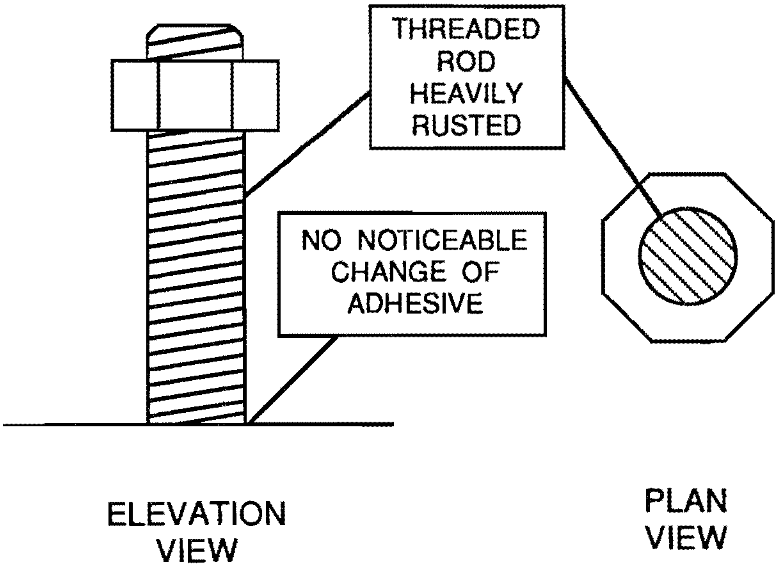


Figure A.21b Schematic of condition of Designation F anchors after 50 cycles of acid rain wetting and drying.

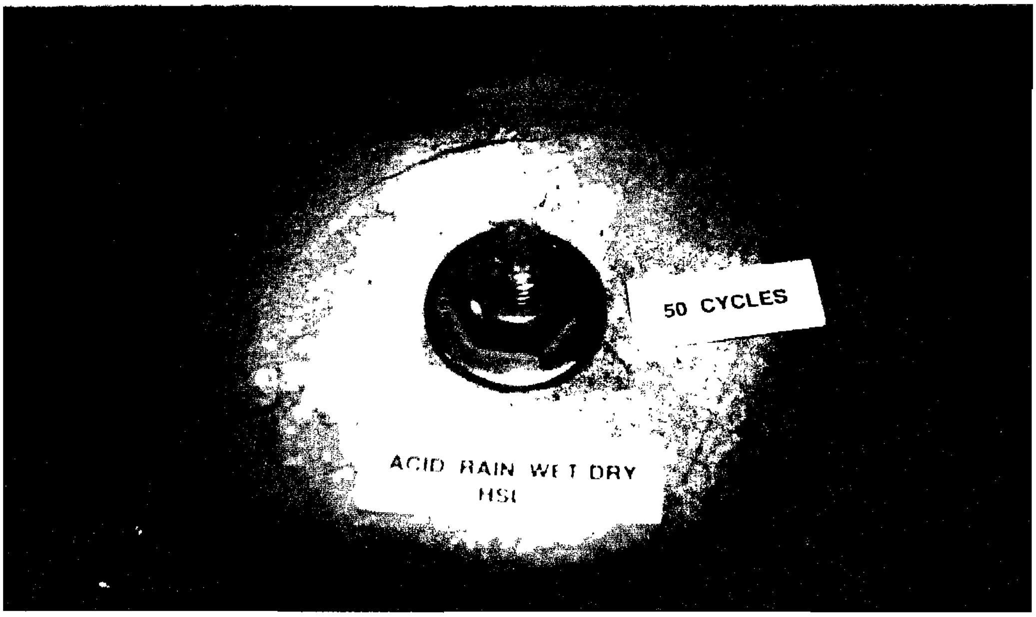


Figure A.22a Condition of Designation G anchors after 50 cycles of acid rain wetting and drying.

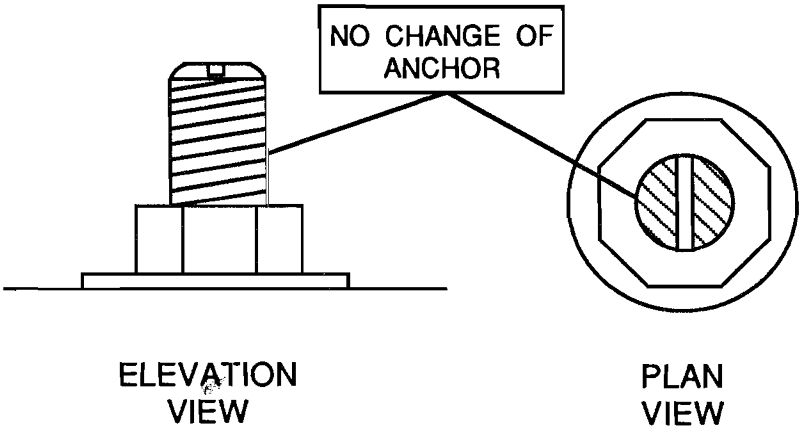


Figure A.22b Schematic of condition of Designation G anchors after 50 cycles of acid rain wetting and drying.

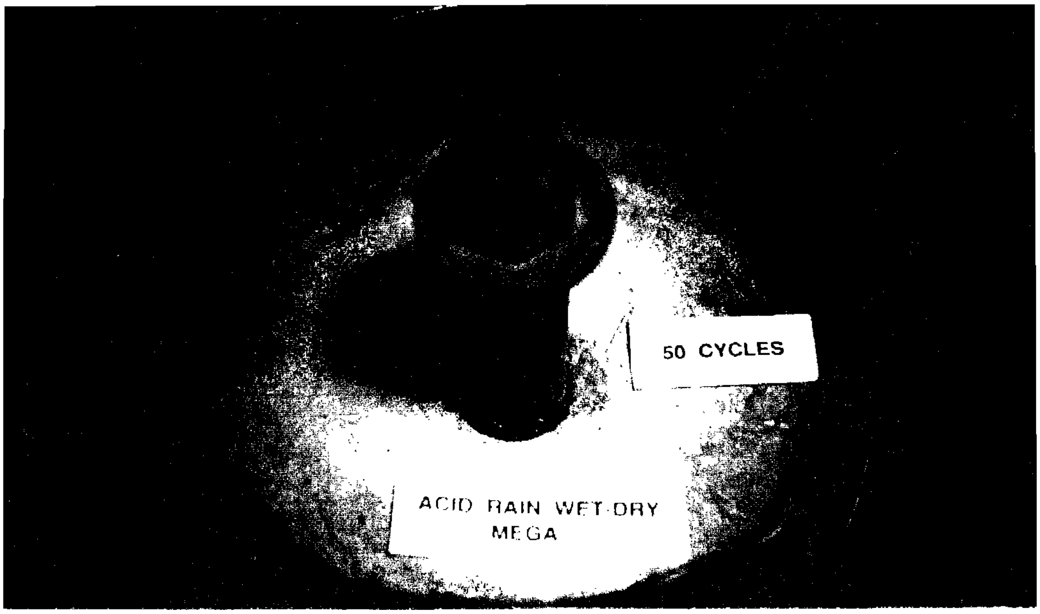


Figure A.23a Condition of Designation H anchors after 50 cycles of acid rain wetting an drying.

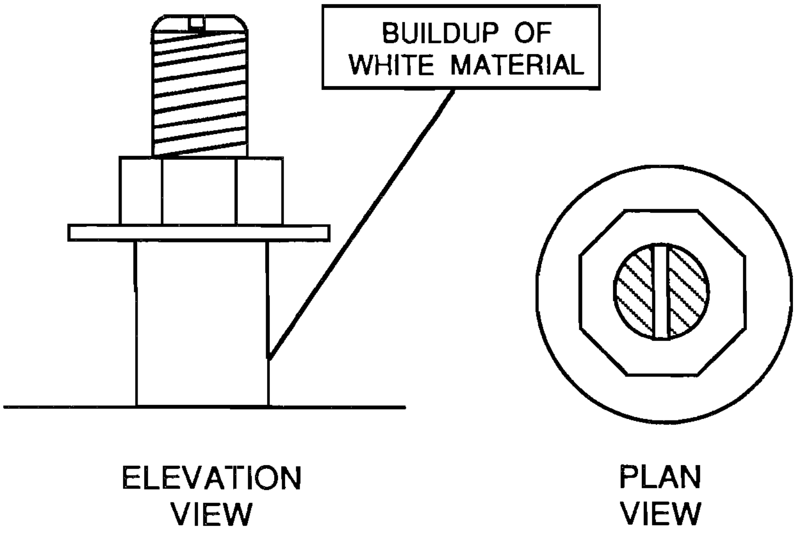


Figure A.23b Schematic of condition of Designation H anchors after 50 cycles of acid rain wetting and drying.

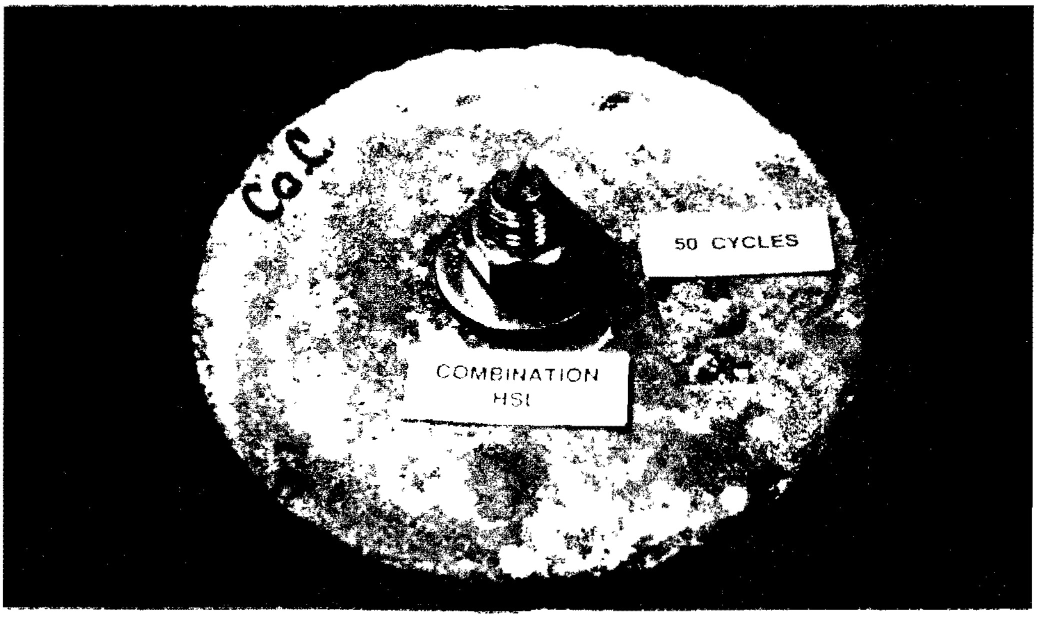


Figure A.24a Condition of Designation G anchors after 50 cycles of combination exposure.

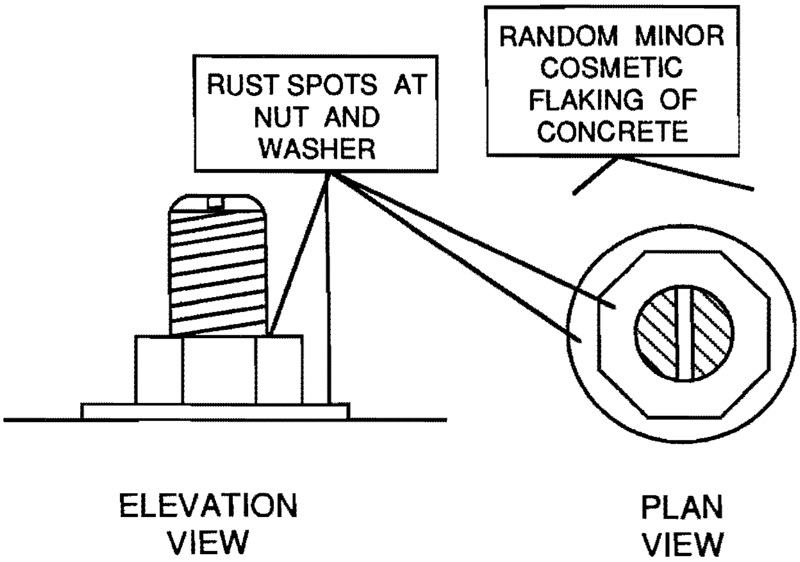


Figure A.24b Schematic of condition of Designation G anchors after 50 cycles of combination exposure.

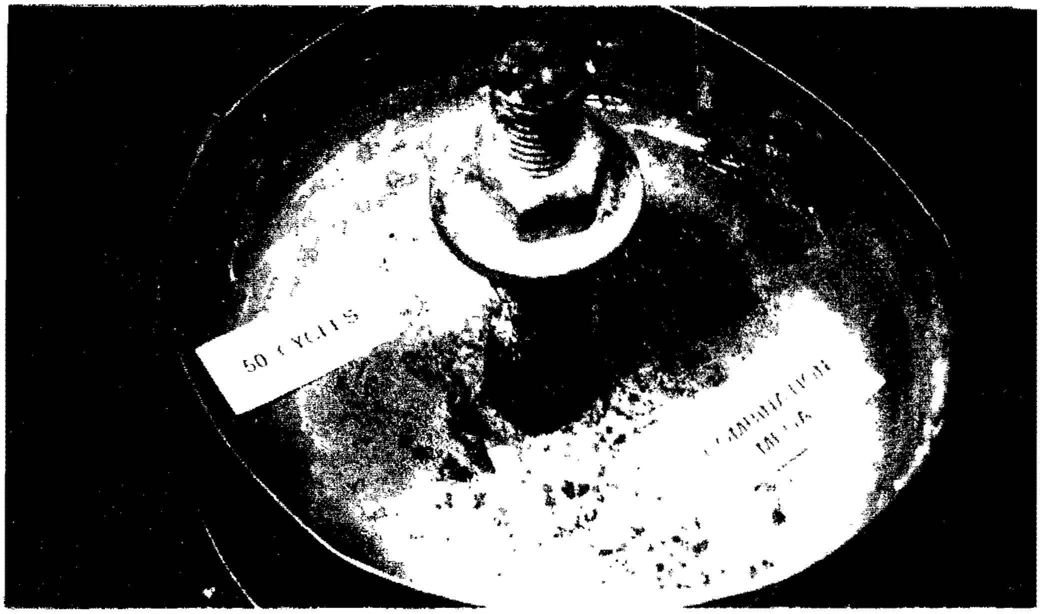


Figure A.25a Condition of Designation H anchors after 50 cycles of combination exposure.

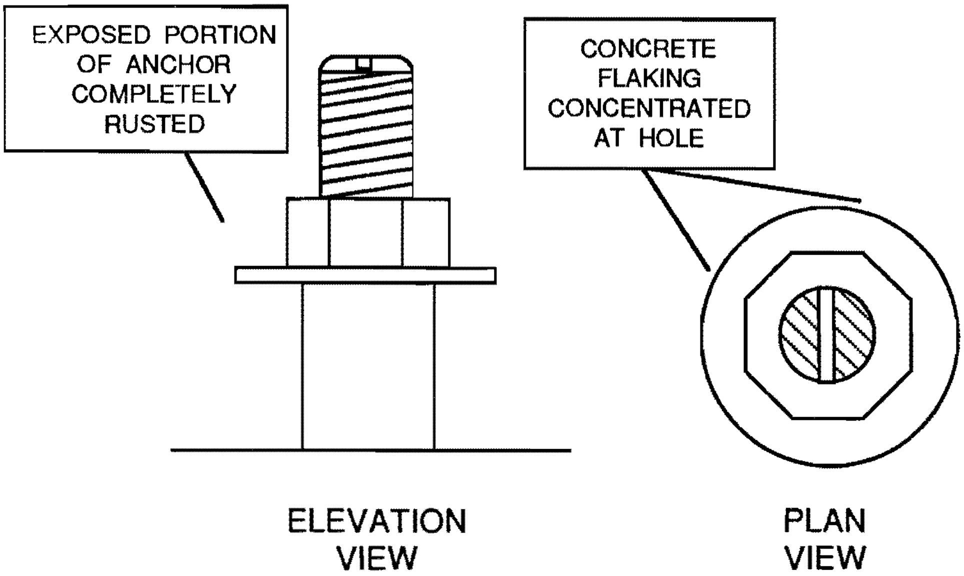


Figure A.25a Schematic of condition of Designation H anchors after 50 cycles of combination exposure.

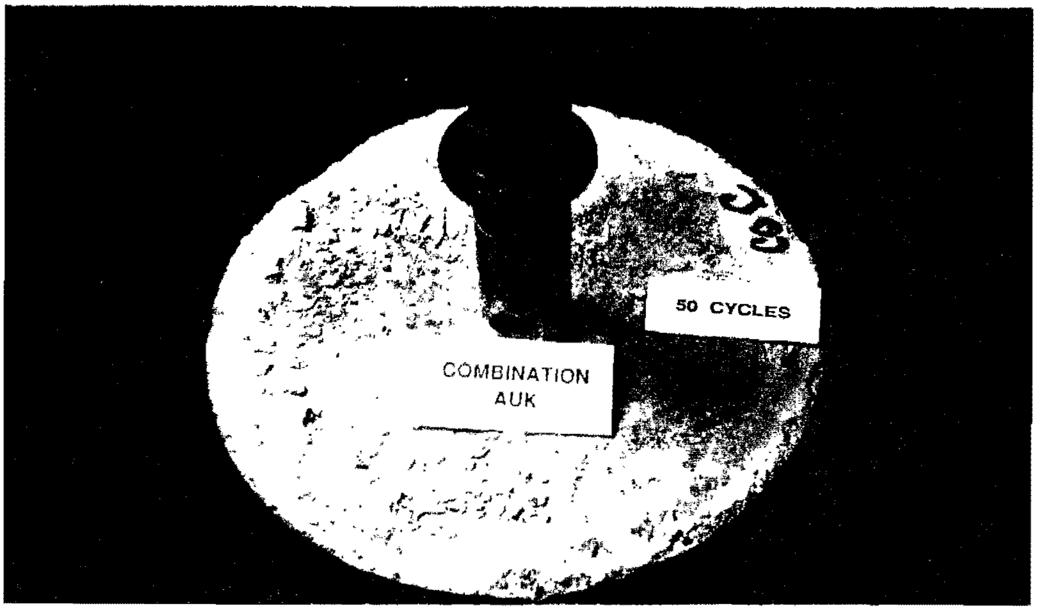


Figure A.26a Condition of Designation I anchors after 50 cycles of combination exposure.

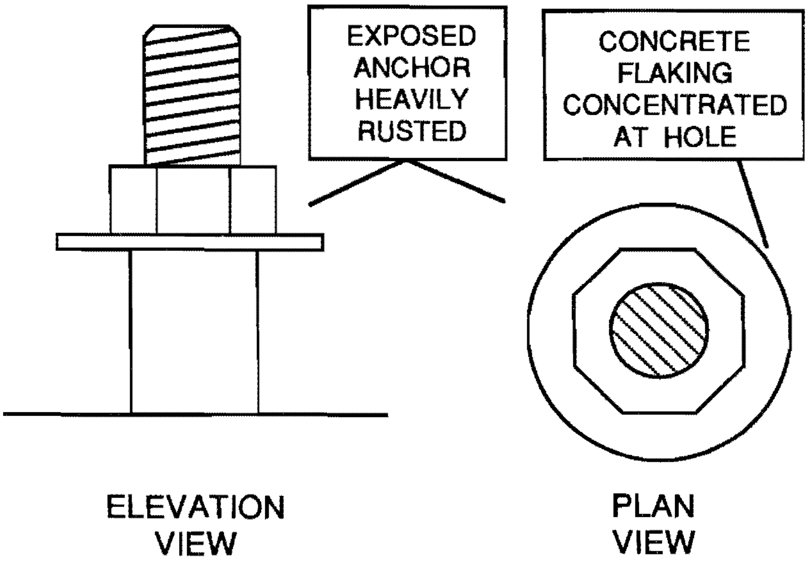


Figure A.26b Schematic of condition of Designation I anchors after 50 cycles of combination exposure.

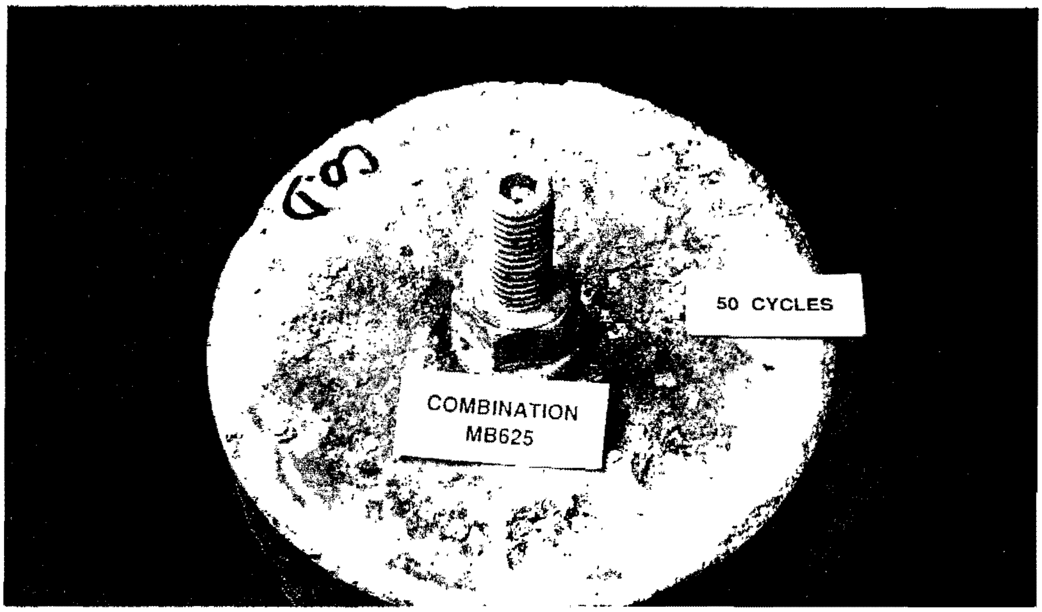


Figure A.27a Condition of Designation J anchors after 50 cycles of combination exposure.

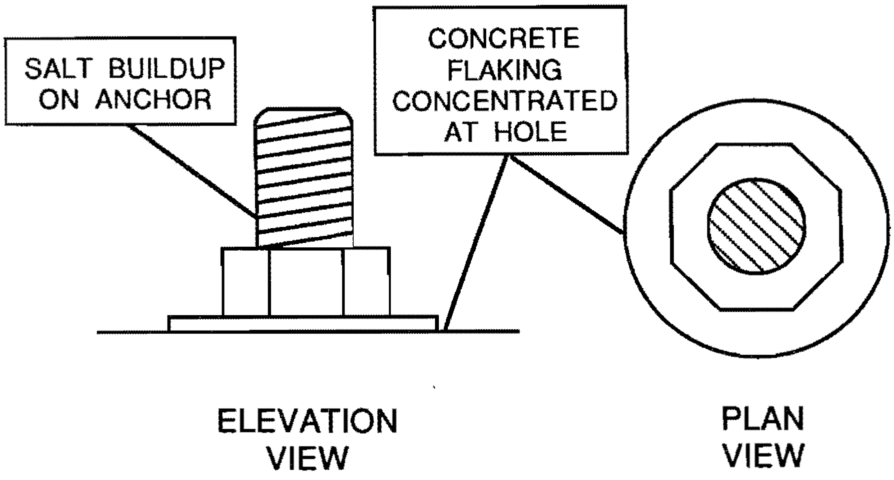


Figure A.27b Schematic of condition of Designation J anchors after 50 cycles of combination exposure.

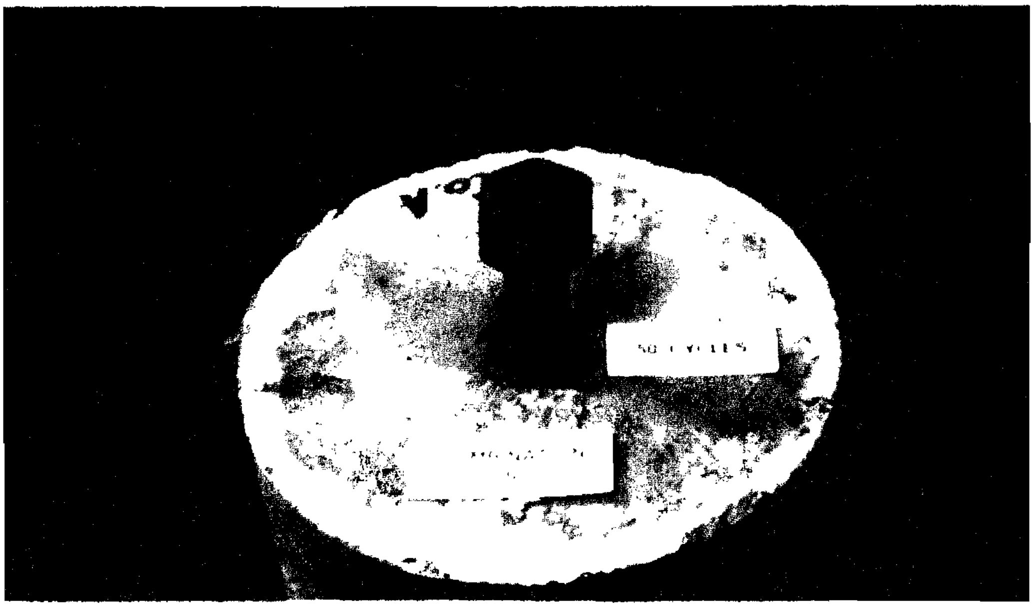


Figure A.28a Condition of Designation K anchors after 50 cycles of combination exposure.

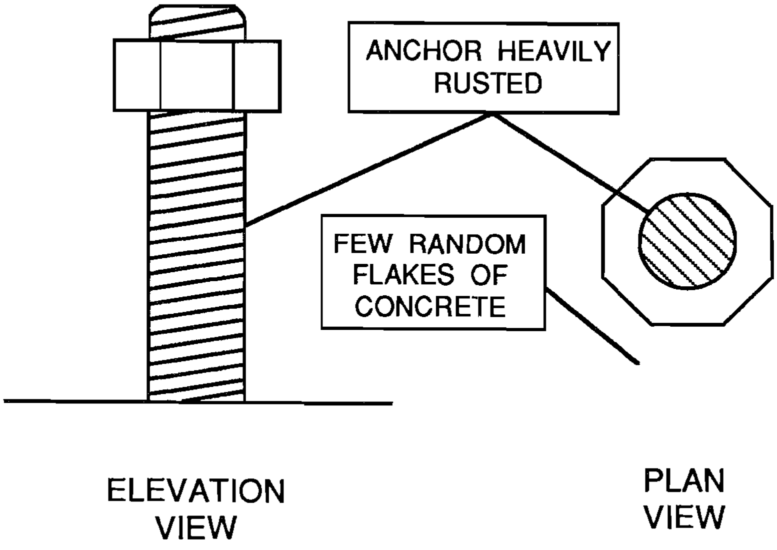
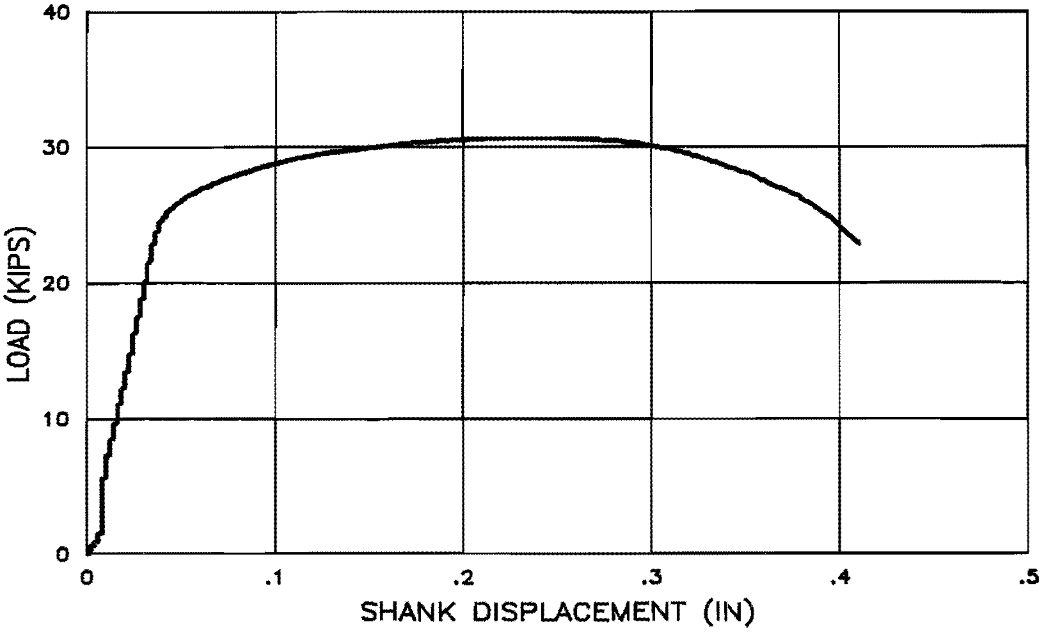


Figure A.28b Schematic of condition of Designation K anchors after 50 cycles of combination exposure.

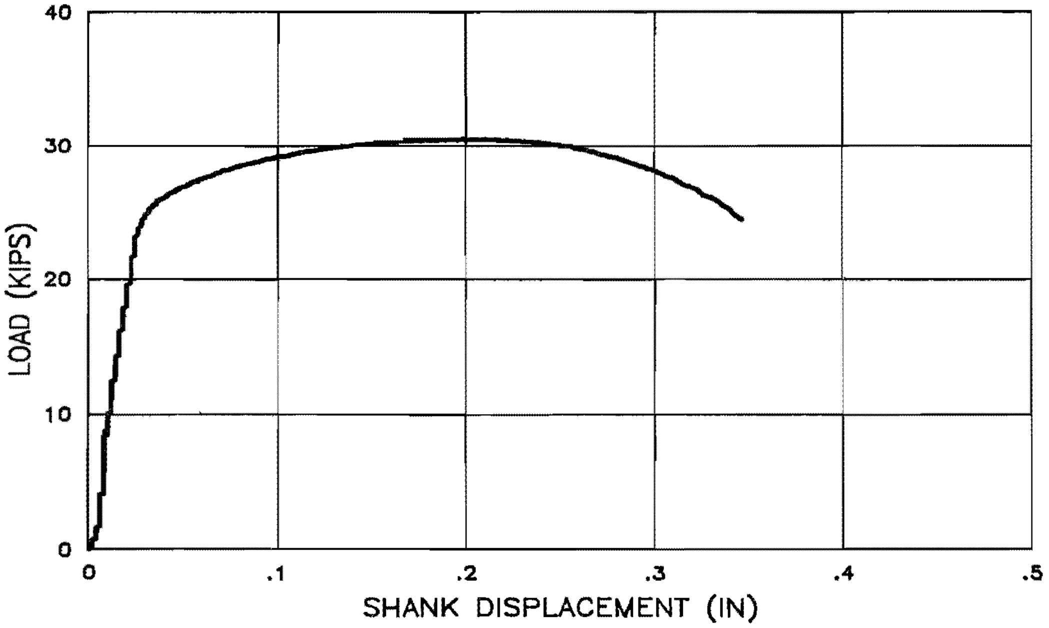
APPENDIX B

LOAD-DEFLECTION PLOTS



ECT A 1 a 6

ULTRAVIOLET LIGHT

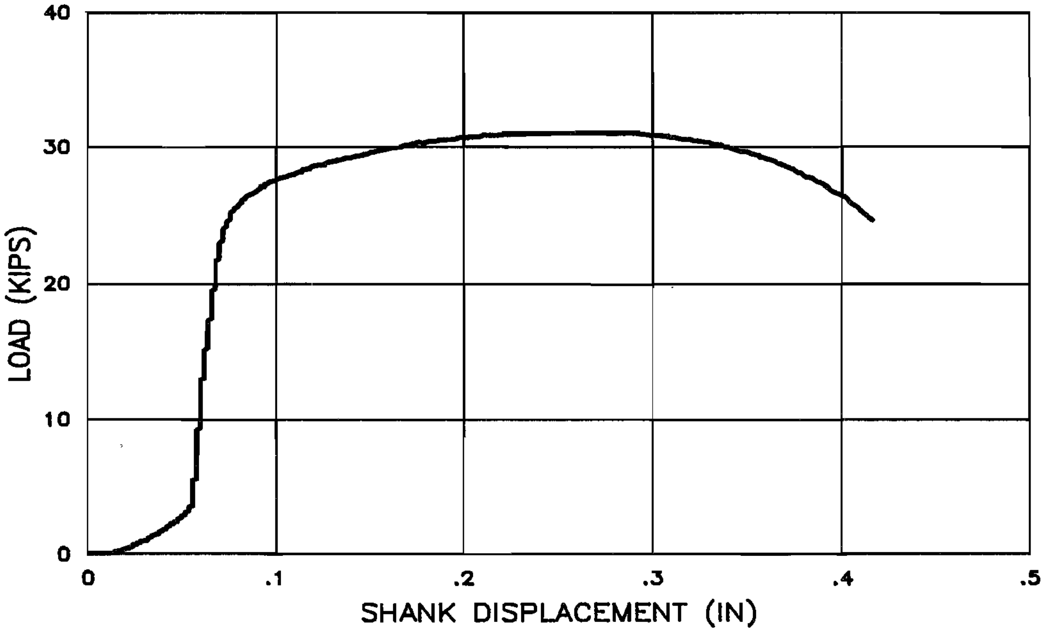


ECT A 1 b 6

ULTRAVIOLET LIGHT

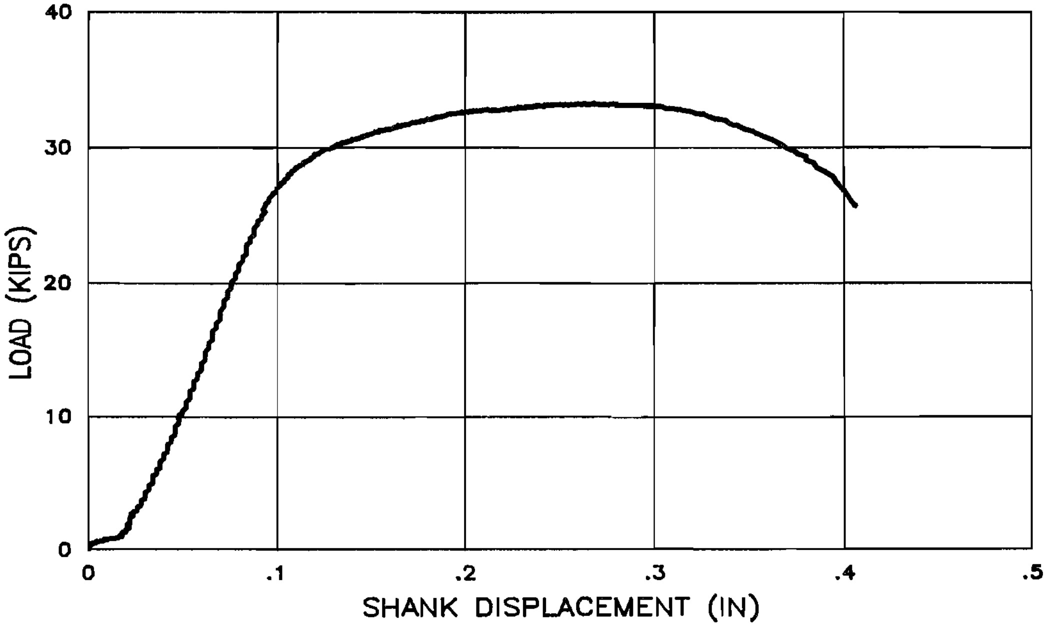
ECT A 1 c 6

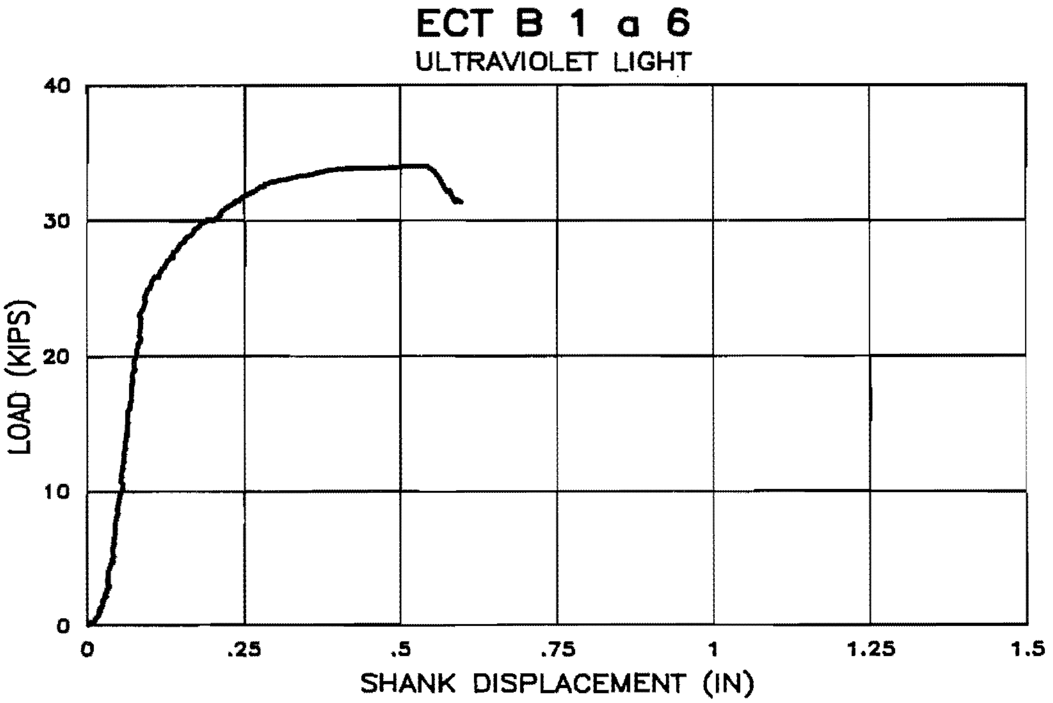
ULTRAVIOLET LIGHT

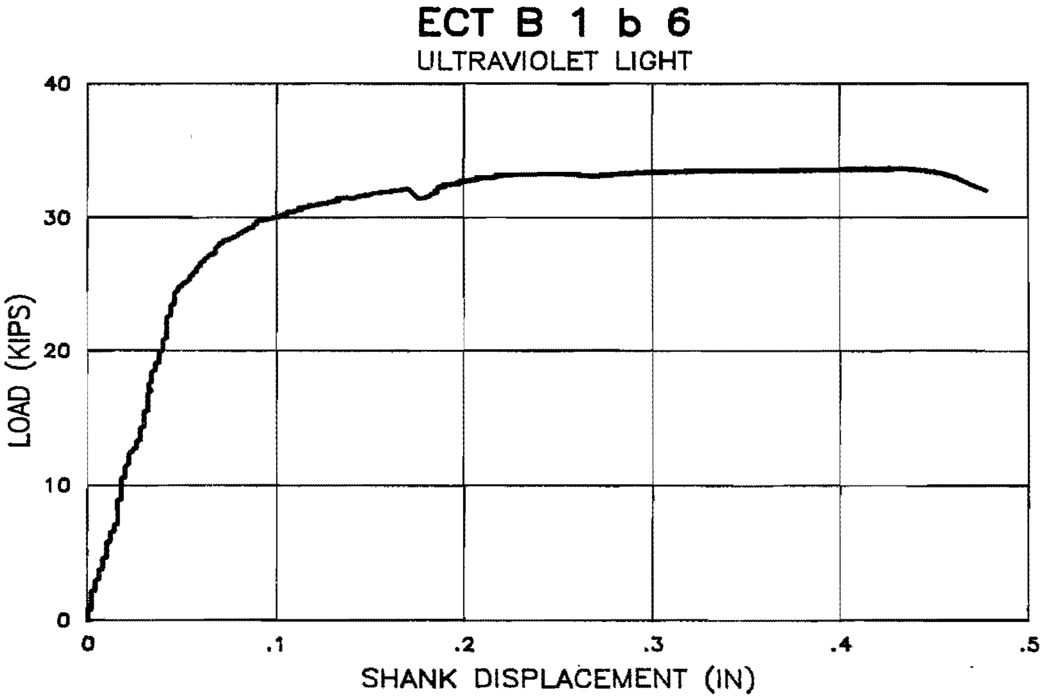


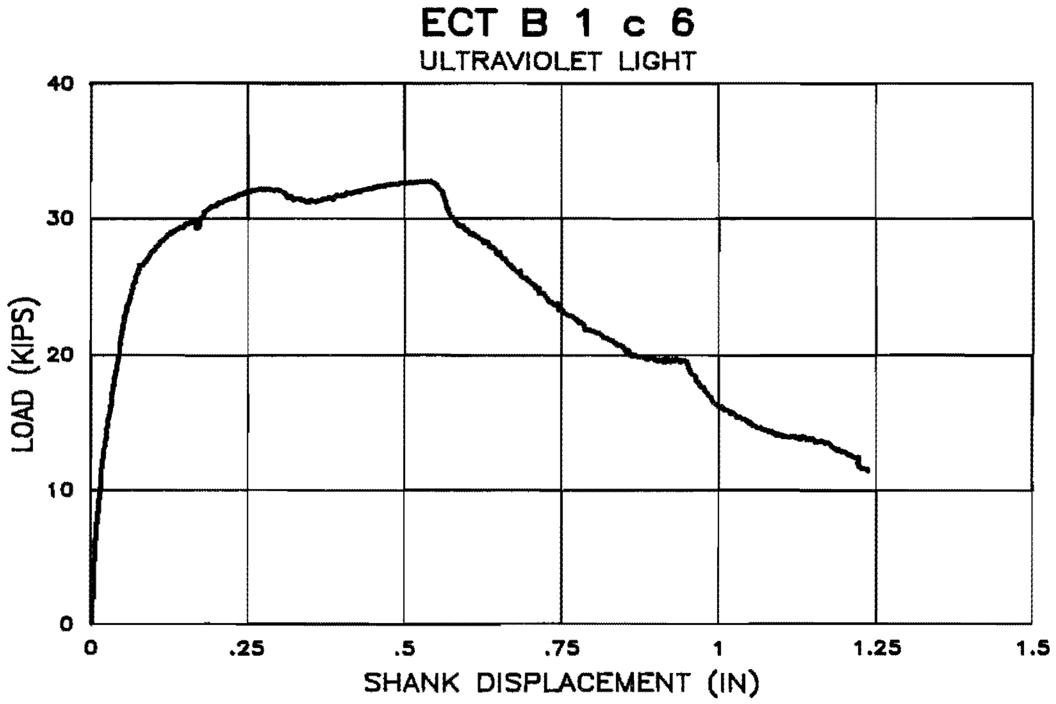
ECT A 1 d 6

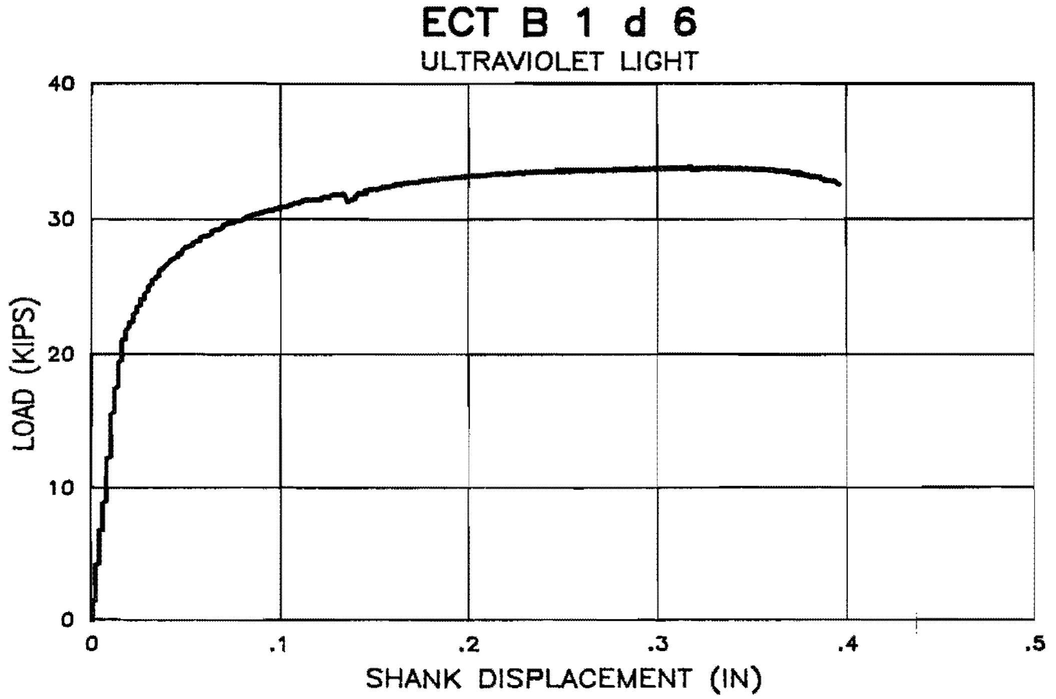
ULTRAVIOLET LIGHT

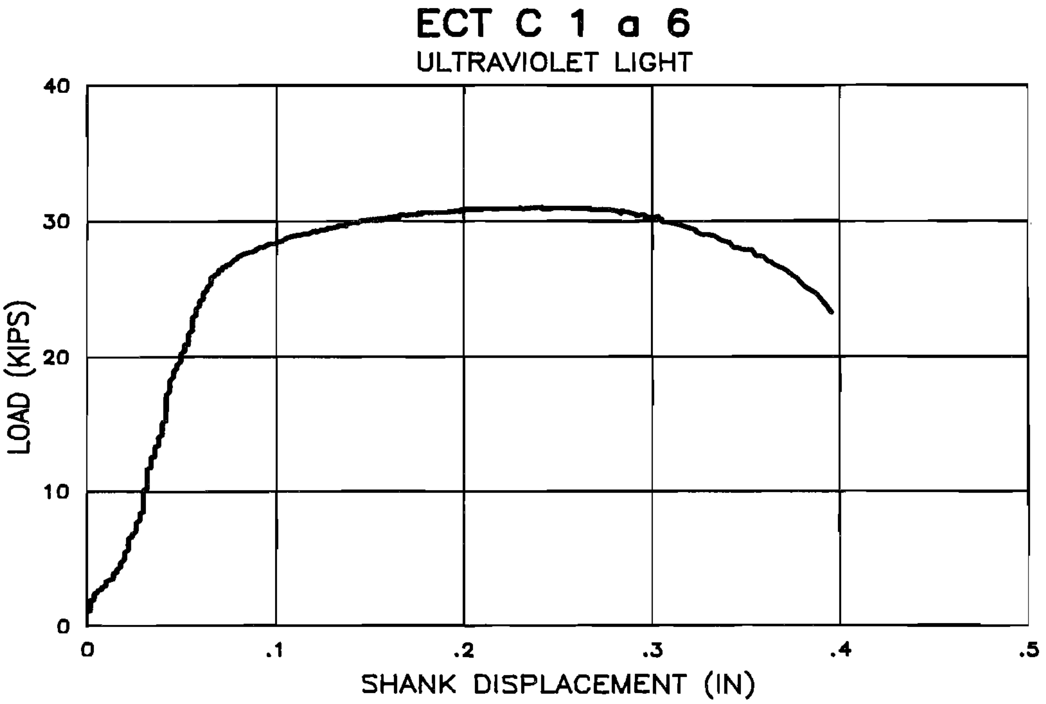



ECT B 1 a 6
ULTRAVIOLET LIGHT
LOAD (KIPS)
0
10
20
30
40
SHANK DISPLACEMENT (IN)
0
.25
.5
.75
1
1.25
1.5


ECT B 1 b 6
ULTRAVIOLET LIGHT
LOAD (KIPS)
0
10
20
30
40
SHANK DISPLACEMENT (IN)
0
.1
.2
.3
.4
.5

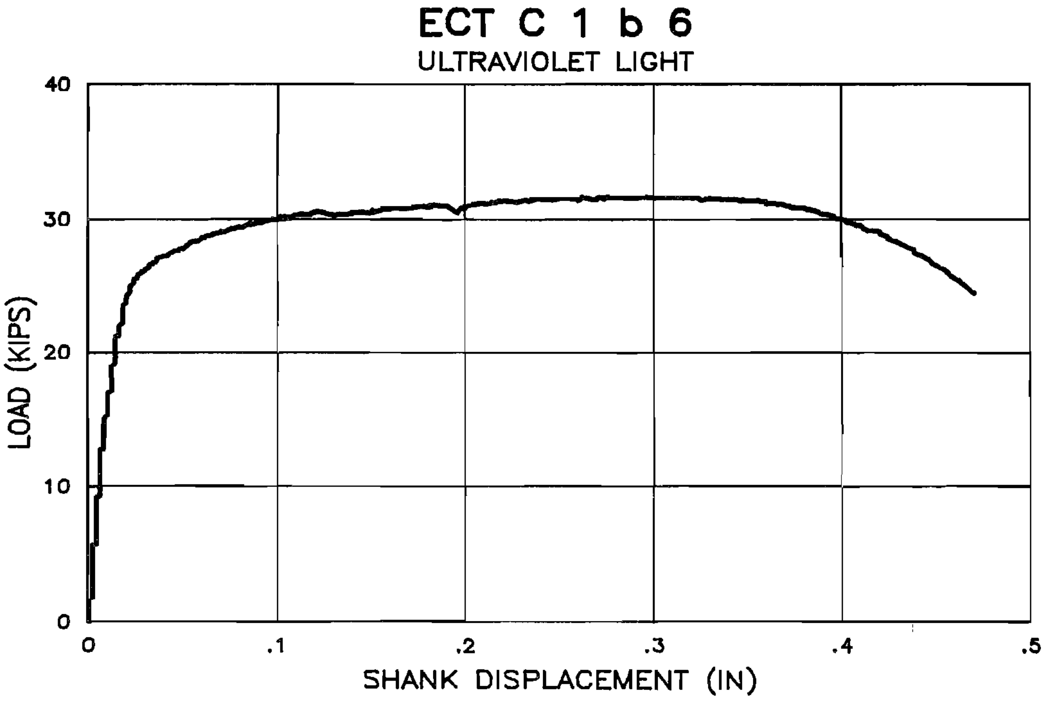

ECT B 1 c 6
ULTRAVIOLET LIGHT


ECT B 1 d 6
ULTRAVIOLET LIGHT



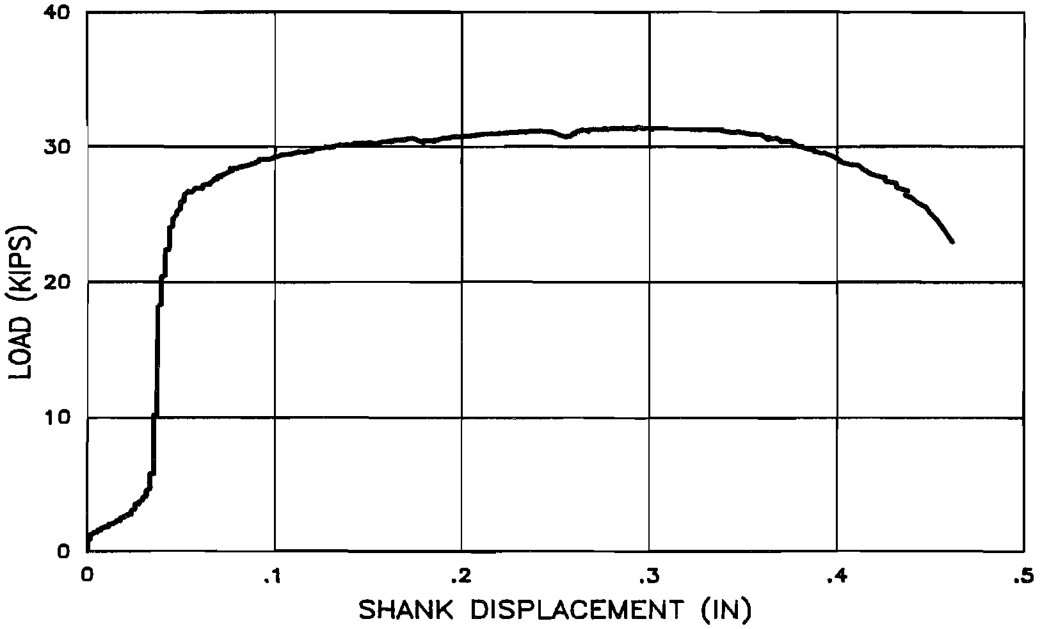
ECT C 1 a 6

ULTRAVIOLET LIGHT



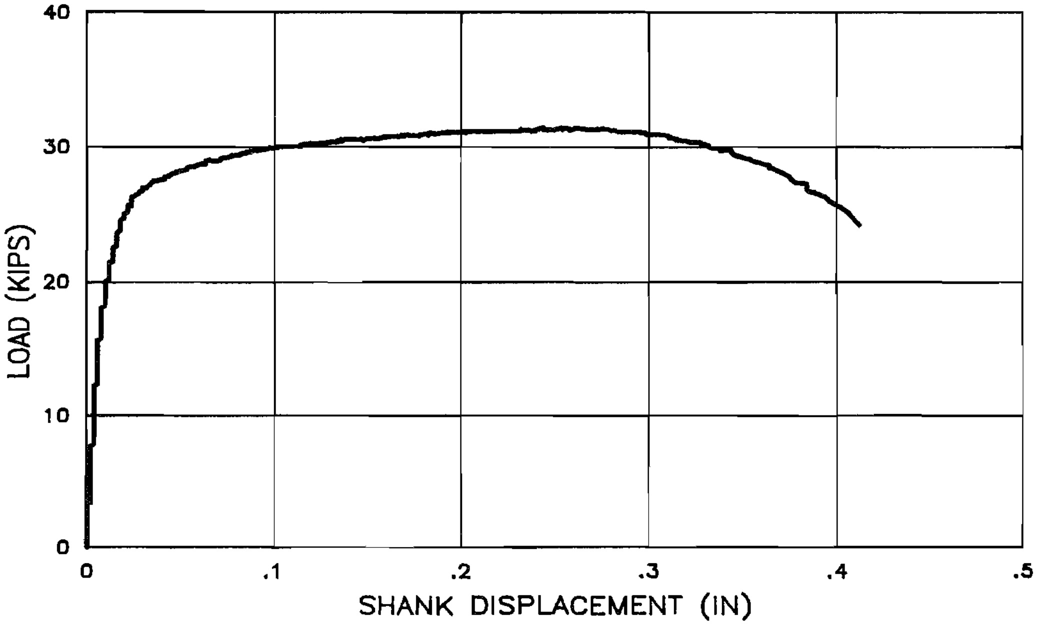
ECT C 1 b 6

ULTRAVIOLET LIGHT



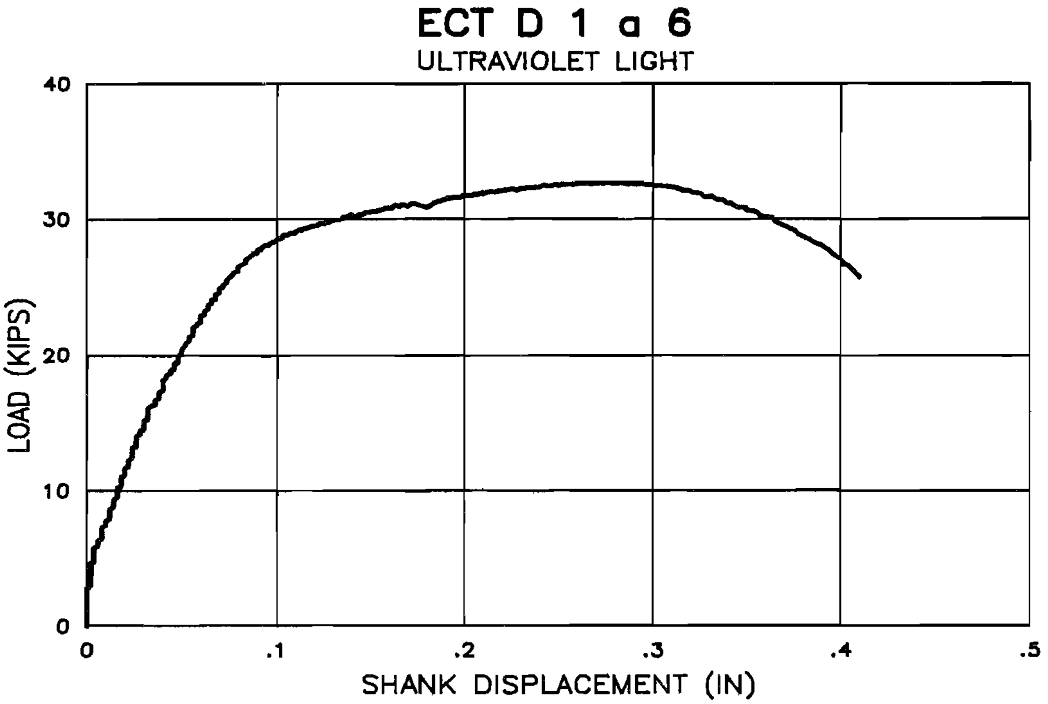
ECT C 1 c 6

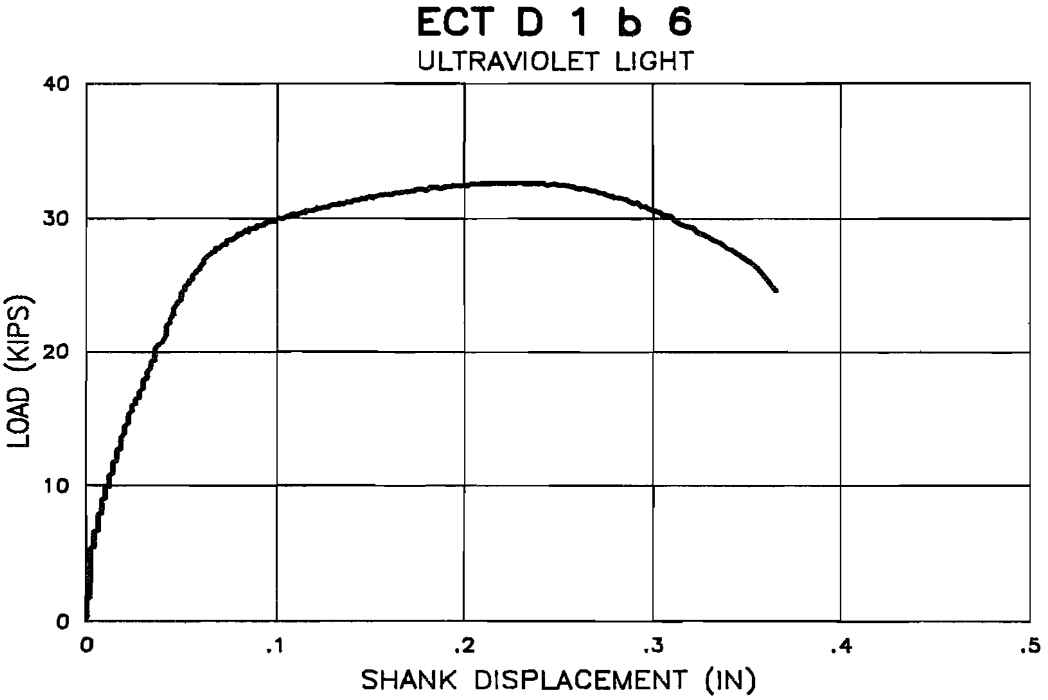
ULTRAVIOLET LIGHT



ECT C 1 d 6

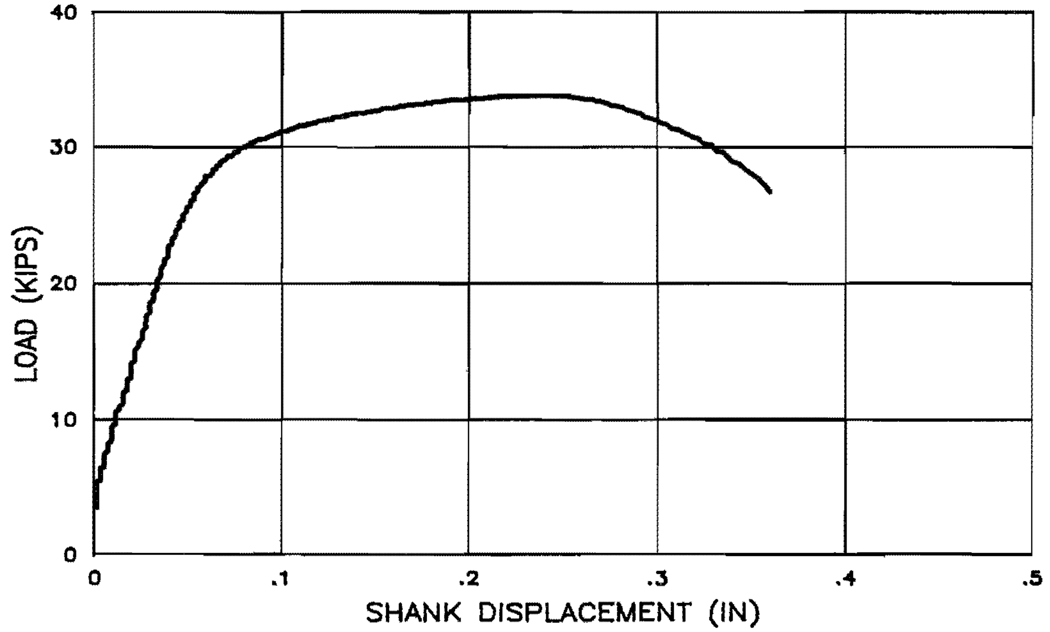
ULTRAVIOLET LIGHT


ECT D 1 a 6
ULTRAVIOLET LIGHT
LOAD (KIPS)
40
30
20
10
0
0
.1
.2
.3
.4
.5
SHANK DISPLACEMENT (IN)


ECT D 1 b 6
ULTRAVIOLET LIGHT
LOAD (KIPS)
40
30
20
10
0
0
.1
.2
.3
.4
.5
SHANK DISPLACEMENT (IN)

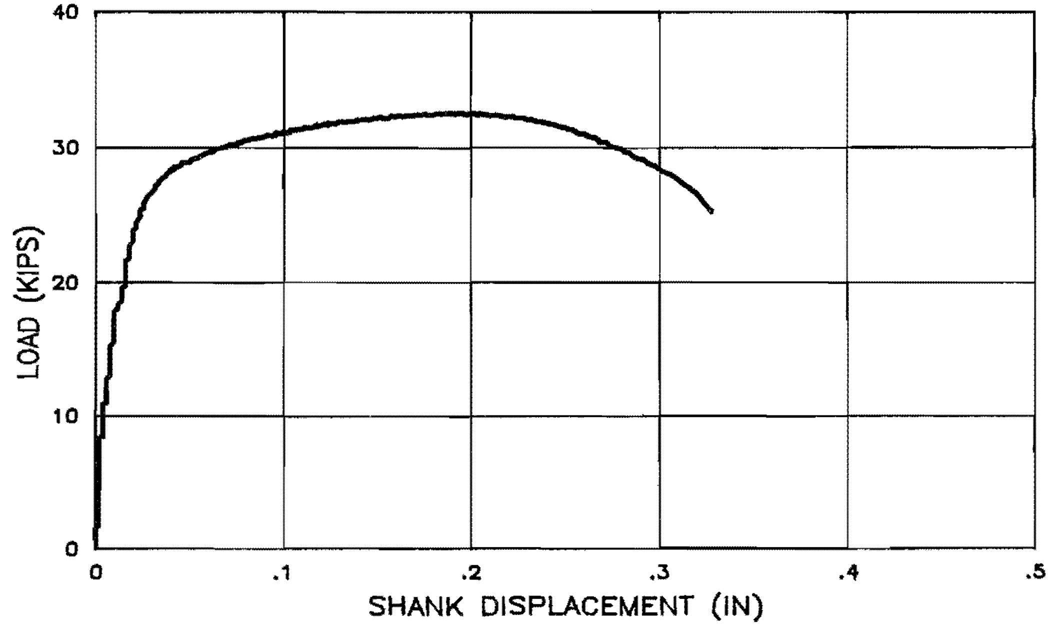
ECT D 1 c 6

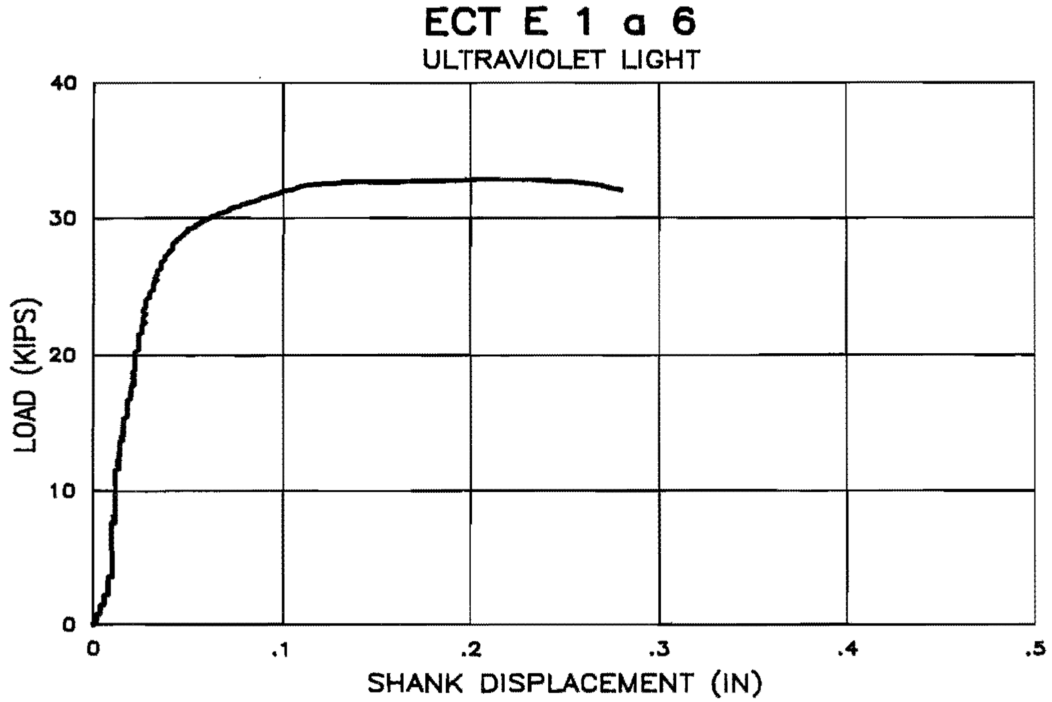
ULTRAVIOLET LIGHT

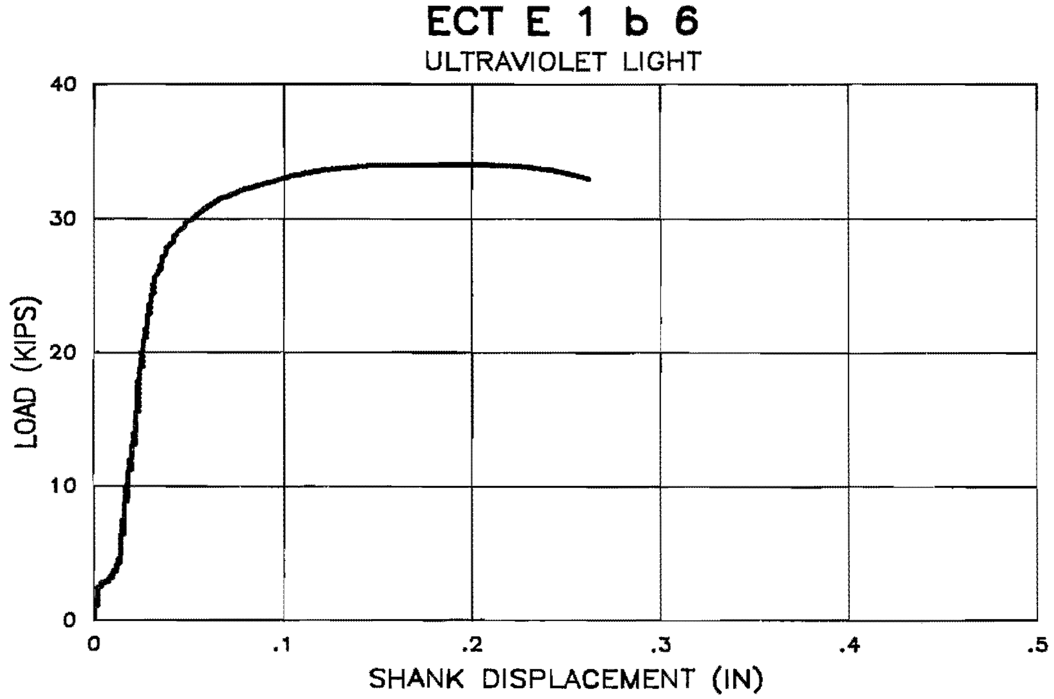


ECT D 1 d 6

ULTRAVIOLET LIGHT

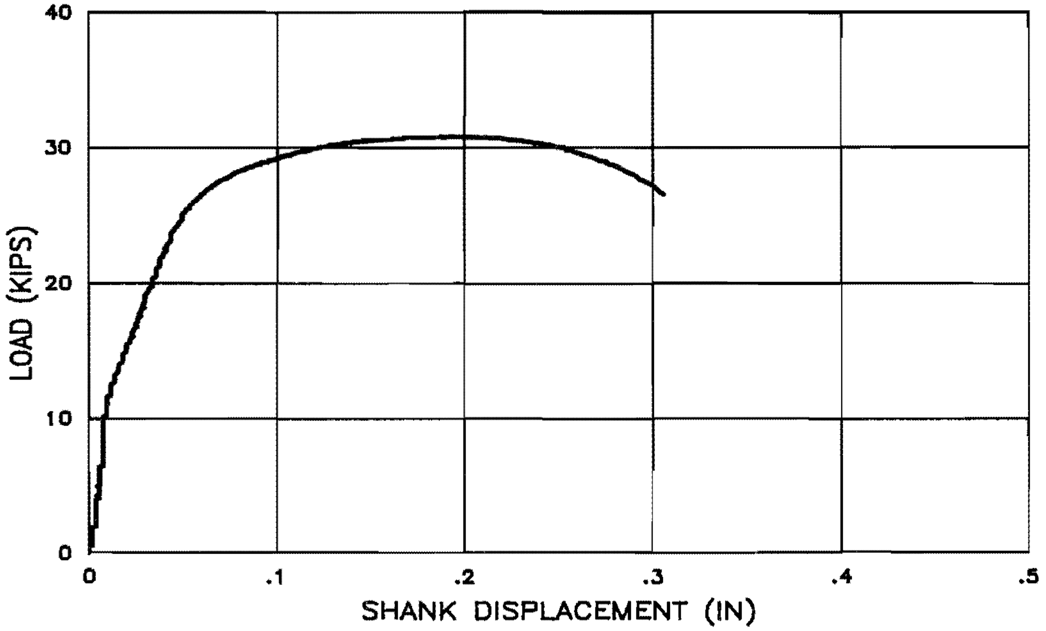



ECT E 1 a 6
ULTRAVIOLET LIGHT


ECT E 1 b 6
ULTRAVIOLET LIGHT

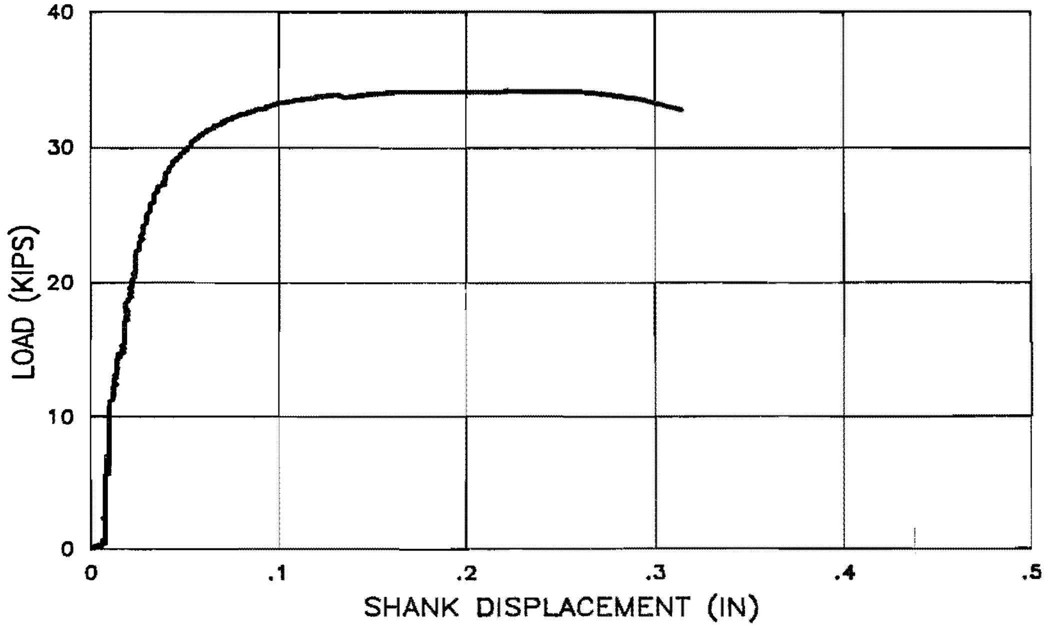
ECT E 1 c 6

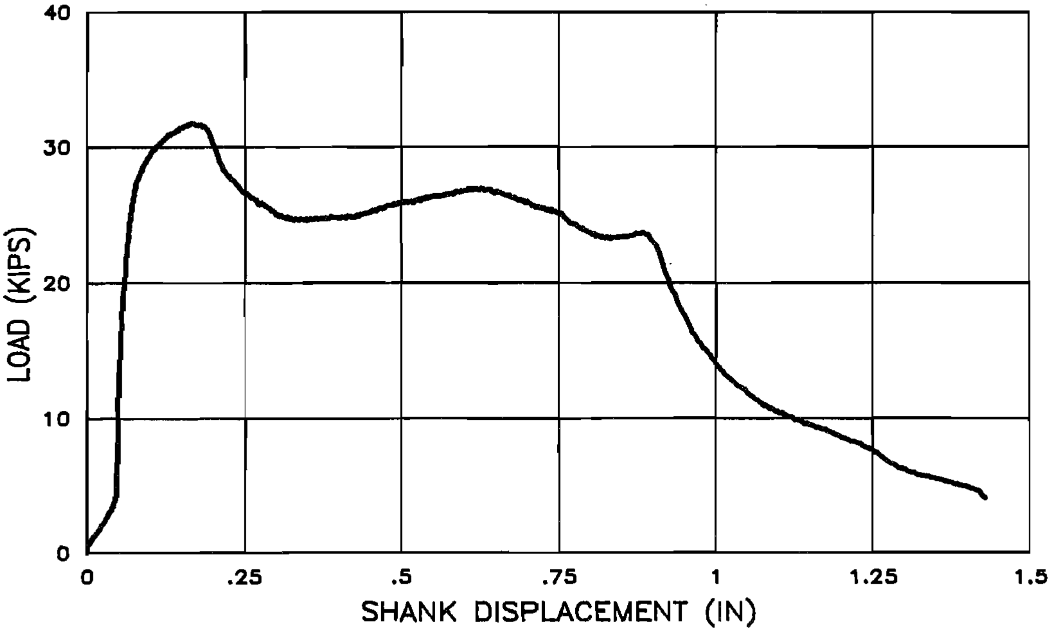
ULTRAVIOLET LIGHT



ECT E 1 d 6

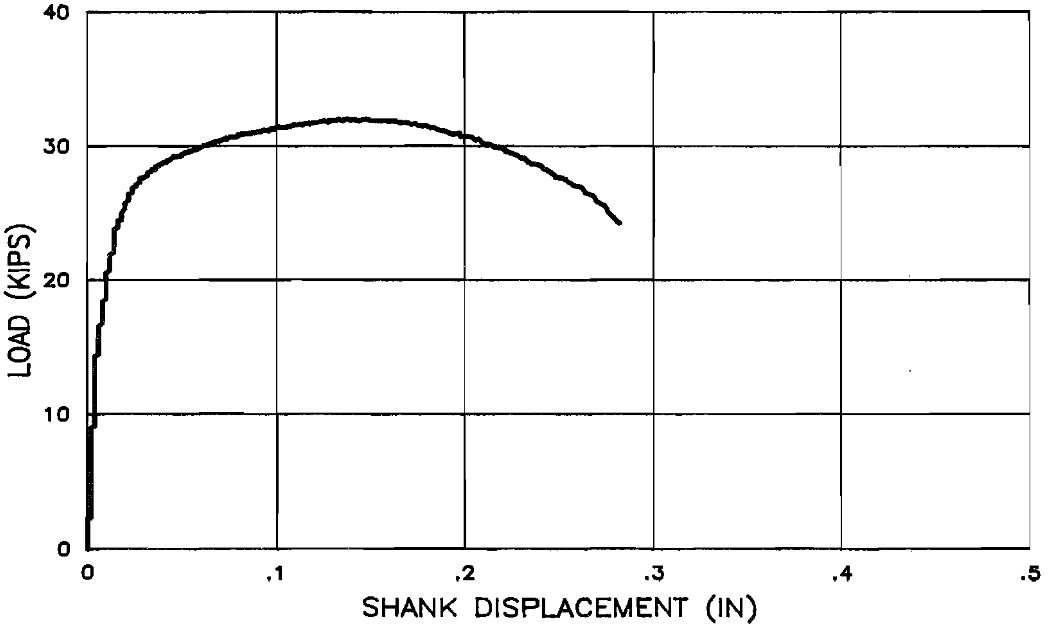
ULTRAVIOLET LIGHT





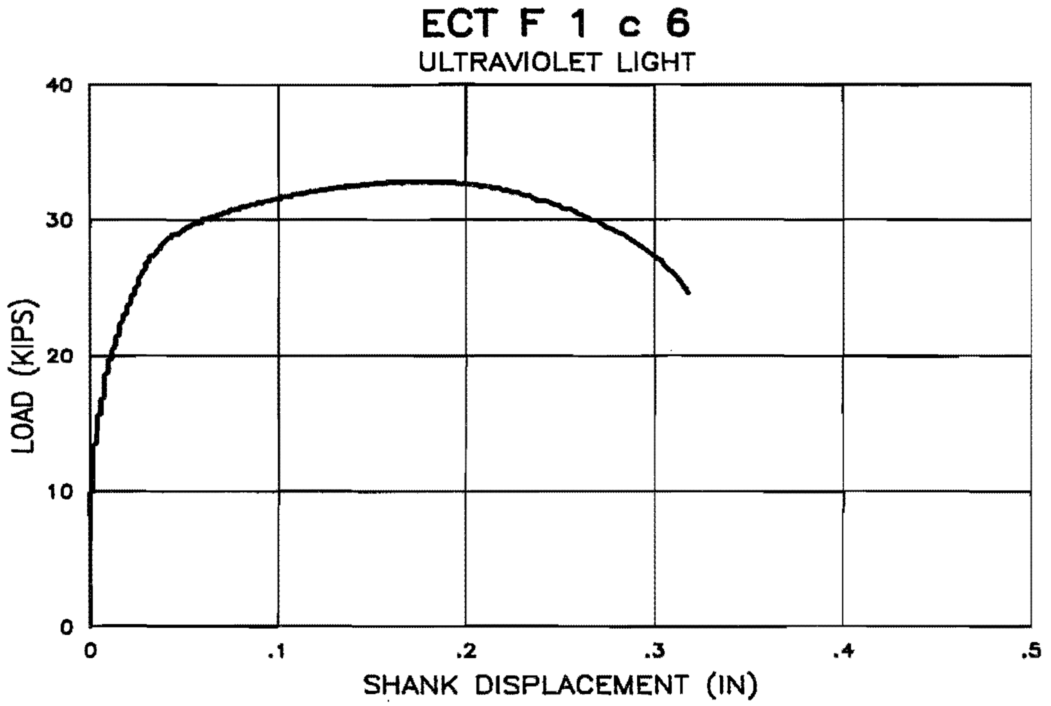
ECT F 1 a 6

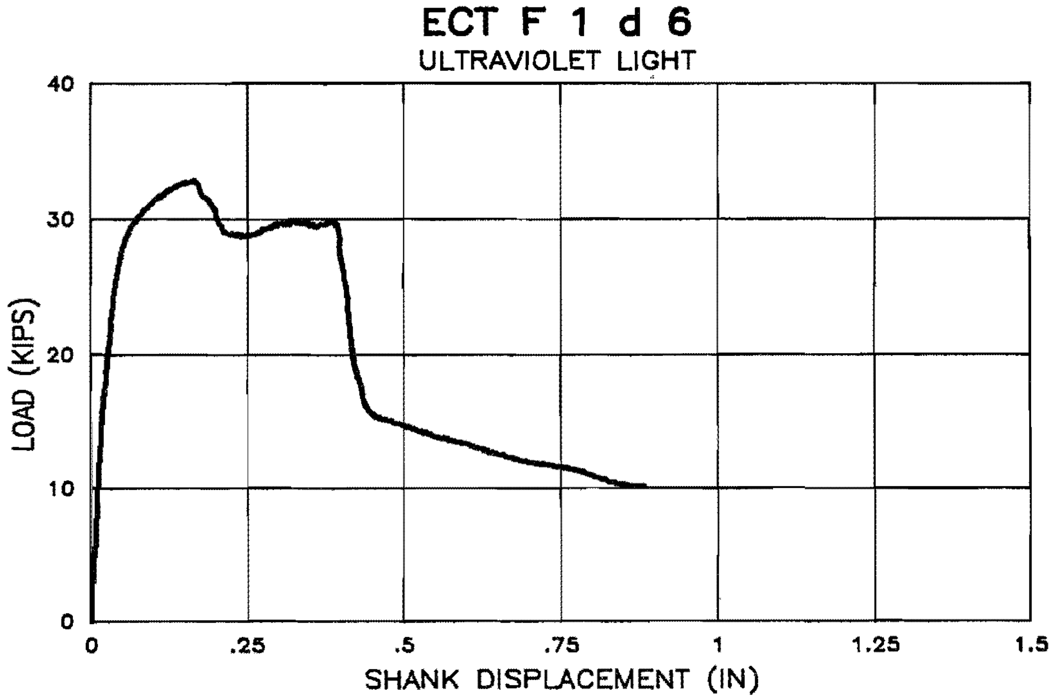
ULTRAVIOLET LIGHT

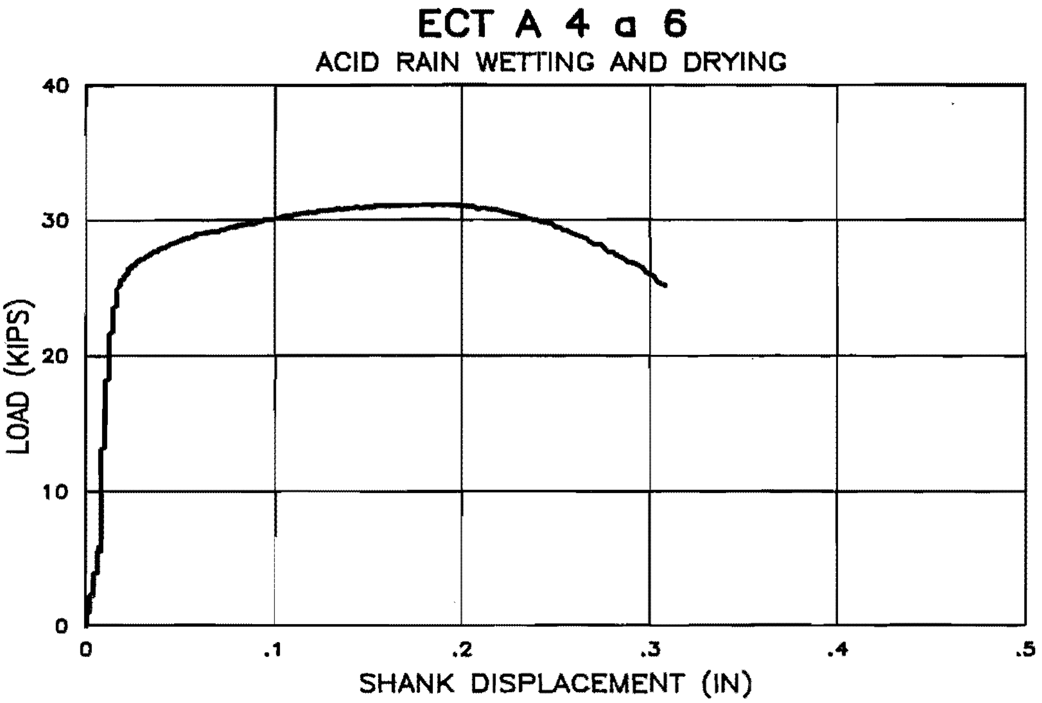


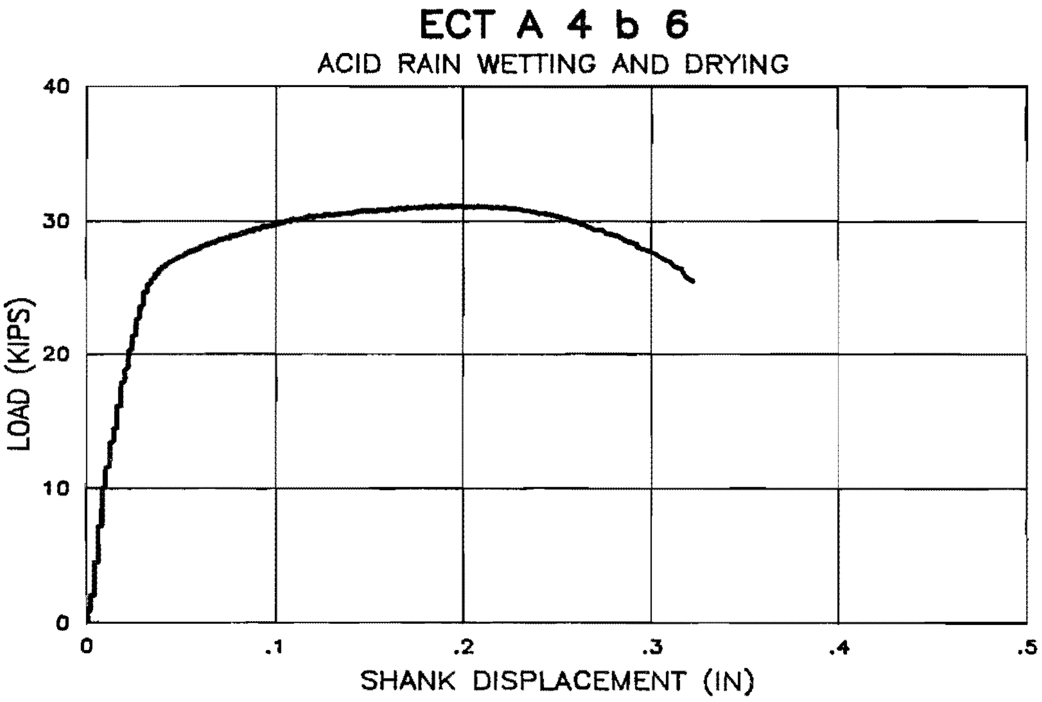
ECT F 1 b 6

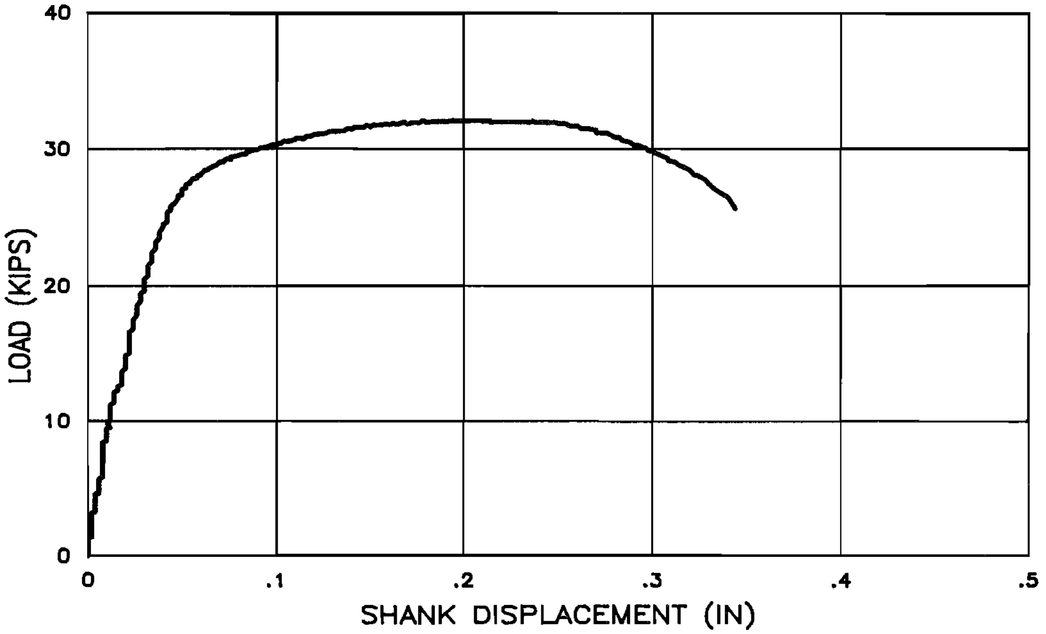
ULTRAVIOLET LIGHT


ECT F 1 c 6
ULTRAVIOLET LIGHT
LOAD (KIPS)
40
30
20
10
0
0
.1
.2
.3
.4
.5
SHANK DISPLACEMENT (IN)


ECT F 1 d 6
ULTRAVIOLET LIGHT
LOAD (KIPS)
40
30
20
10
0
0
.25
.5
.75
1
1.25
1.5
SHANK DISPLACEMENT (IN)

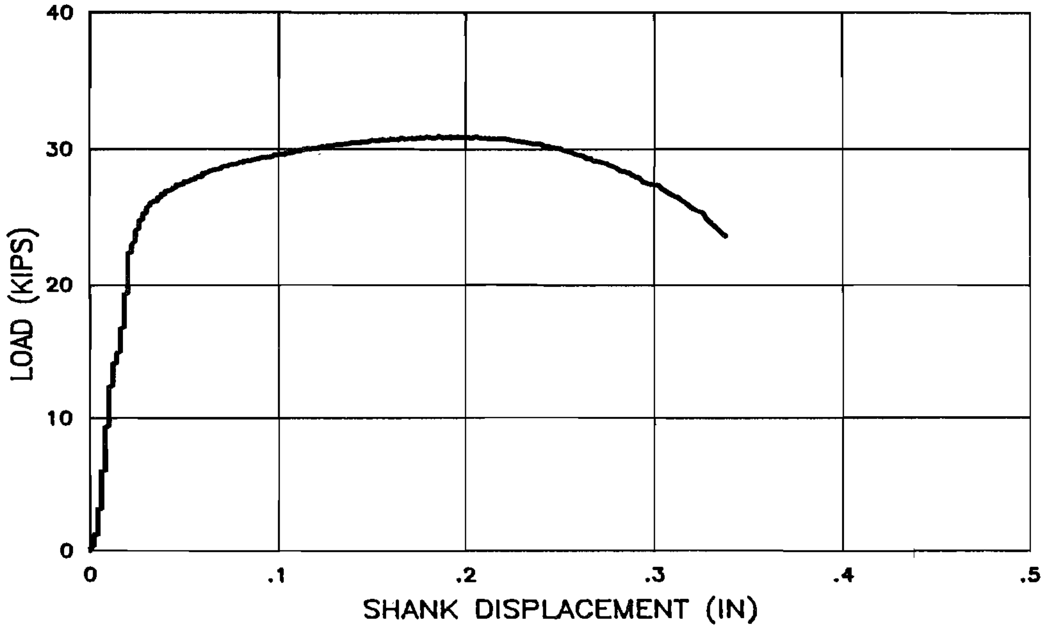

ECT A 4 a 6
ACID RAIN WETTING AND DRYING


ECT A 4 b 6
ACID RAIN WETTING AND DRYING



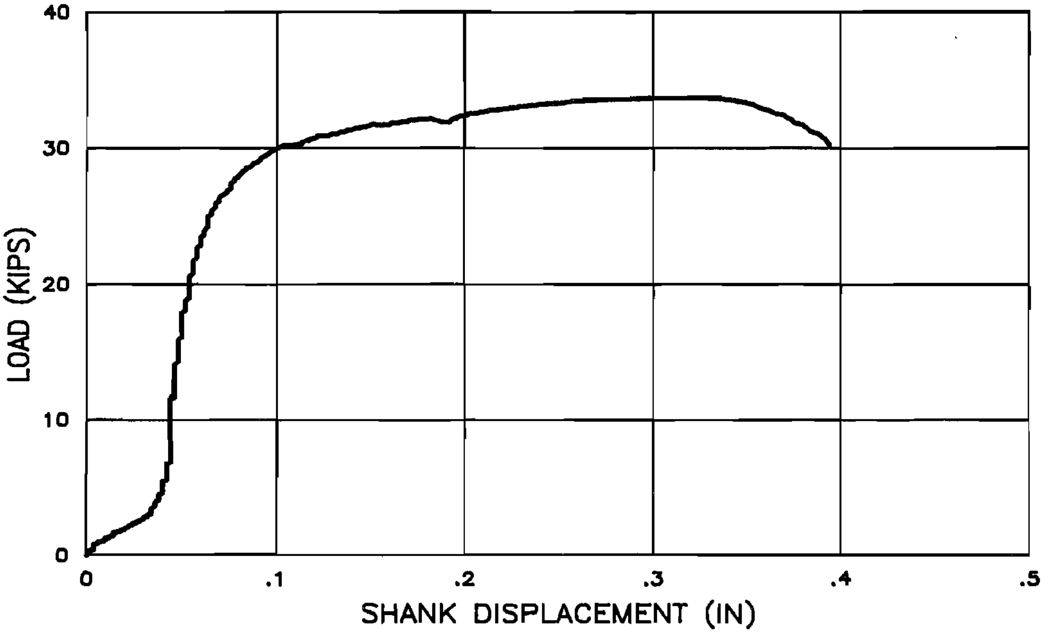
ECT A 4 c 6

ACID RAIN WETTING AND DRYING



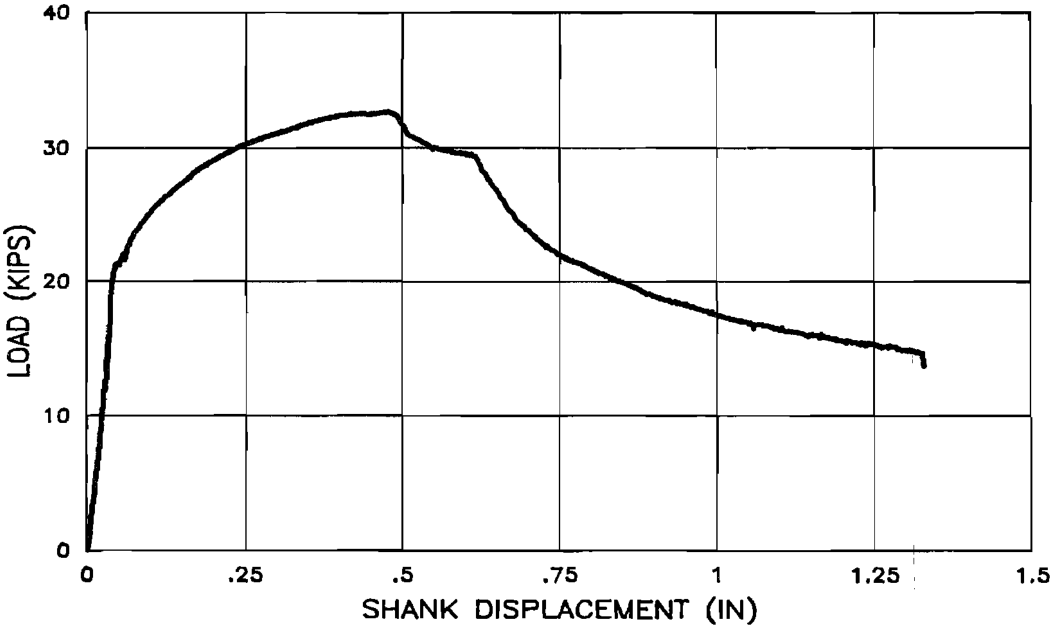
ECT A 4 d 6

ACID RAIN WETTING AND DRYING



ECT B 4 a 6

ACID RAIN WETTING AND DRYING

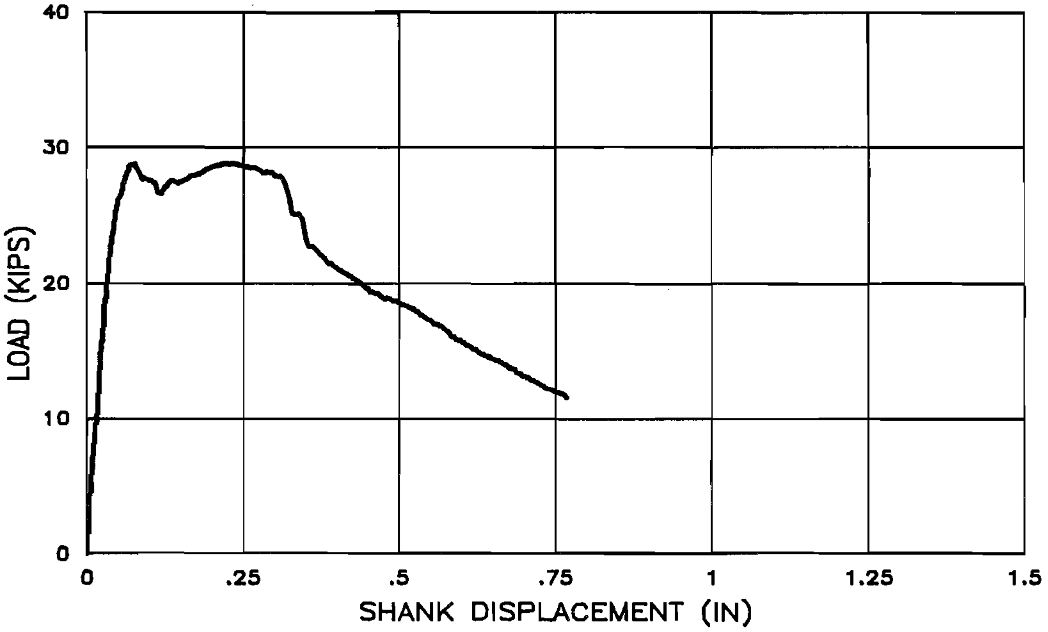


ECT B 4 b 6

ACID RAIN WETTING AND DRYING

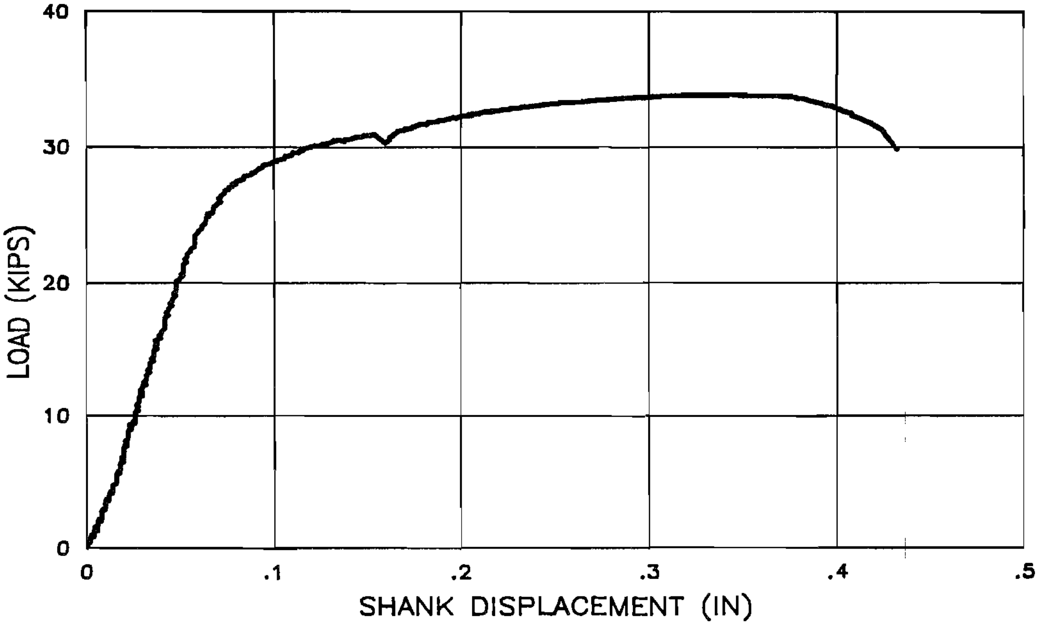
ECT B 4 c 6

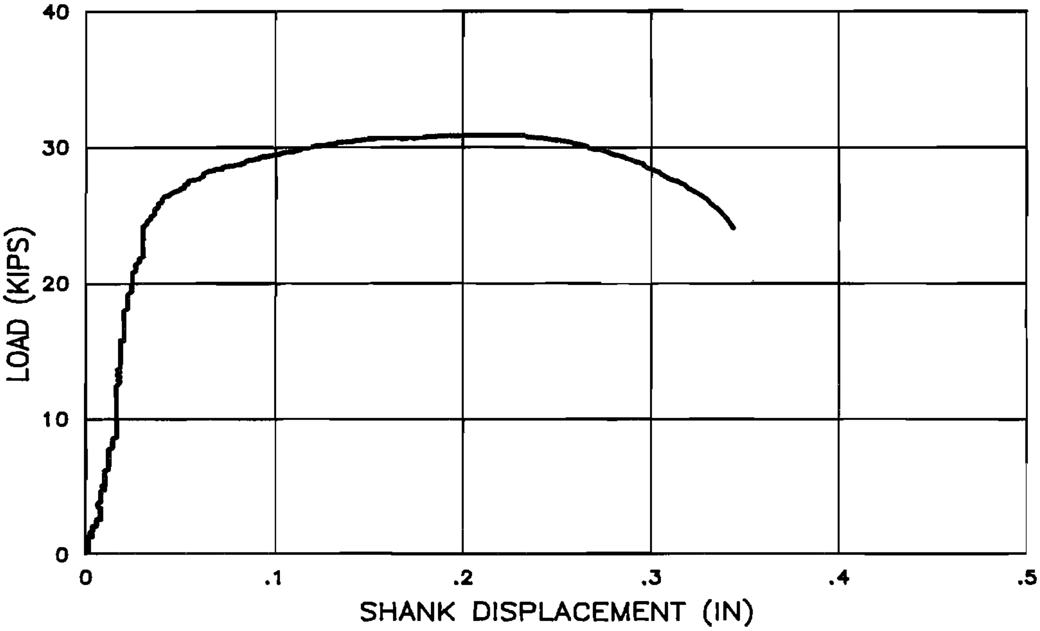
ACID RAIN WETTING AND DRYING



ECT B 4 d 6

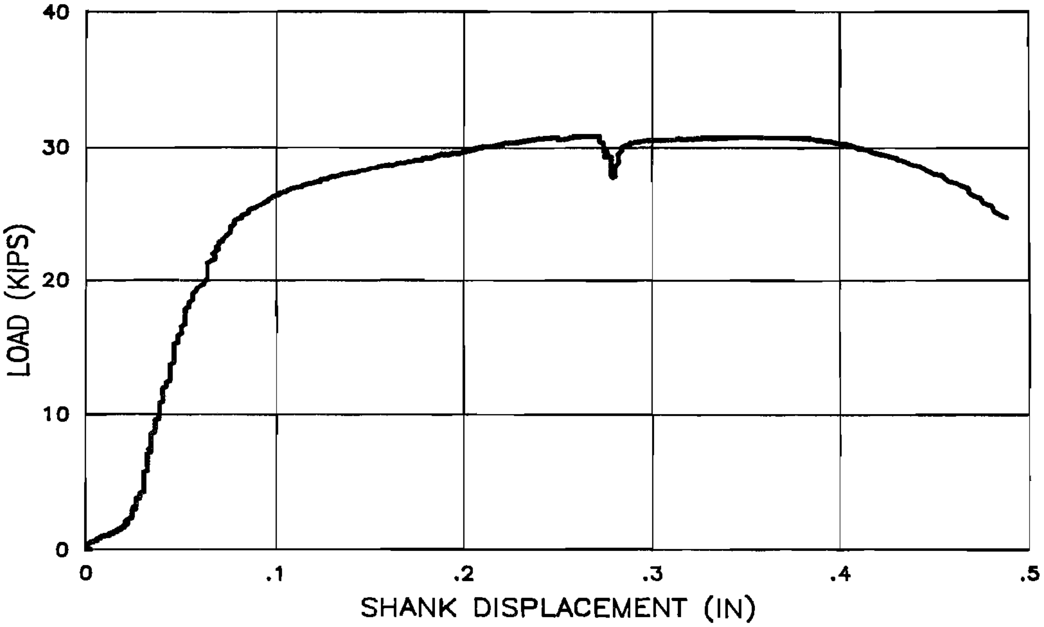
ACID RAIN WETTING AND DRYING





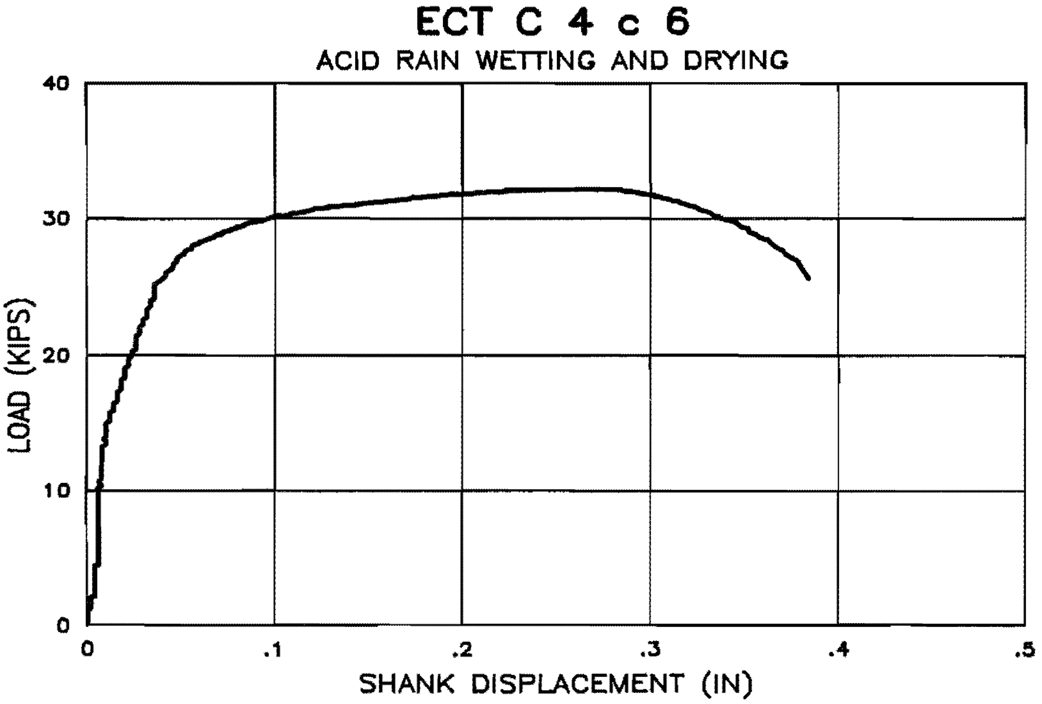
ECT C 4 a 6

ACID RAIN WETTING AND DRYING



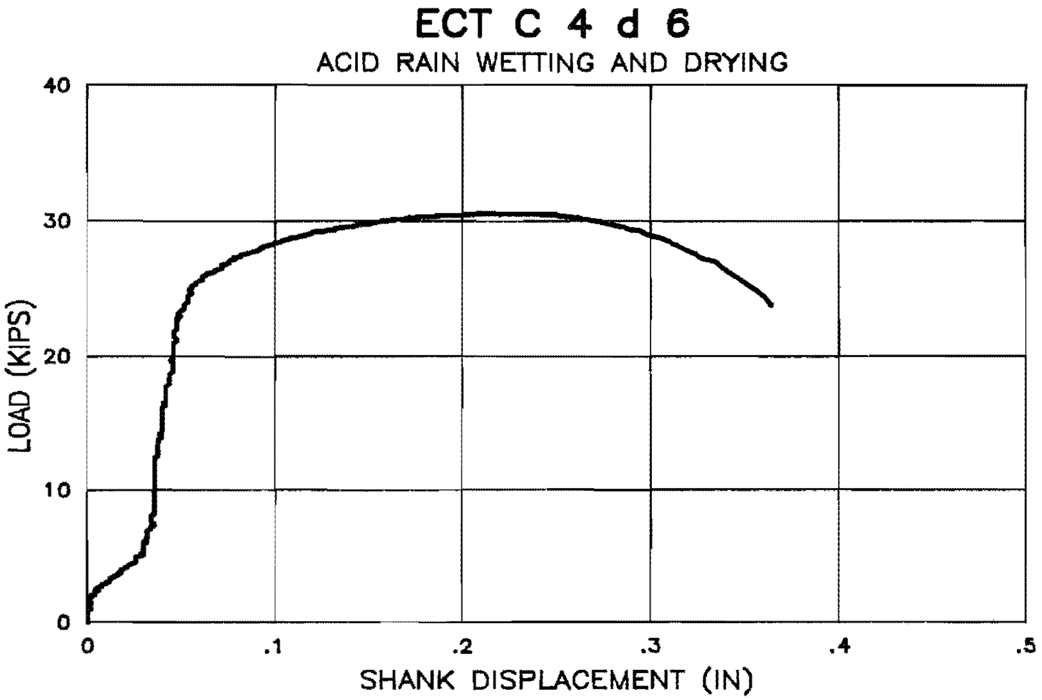
ECT C 4 b 6

ACID RAIN WETTING AND DRYING



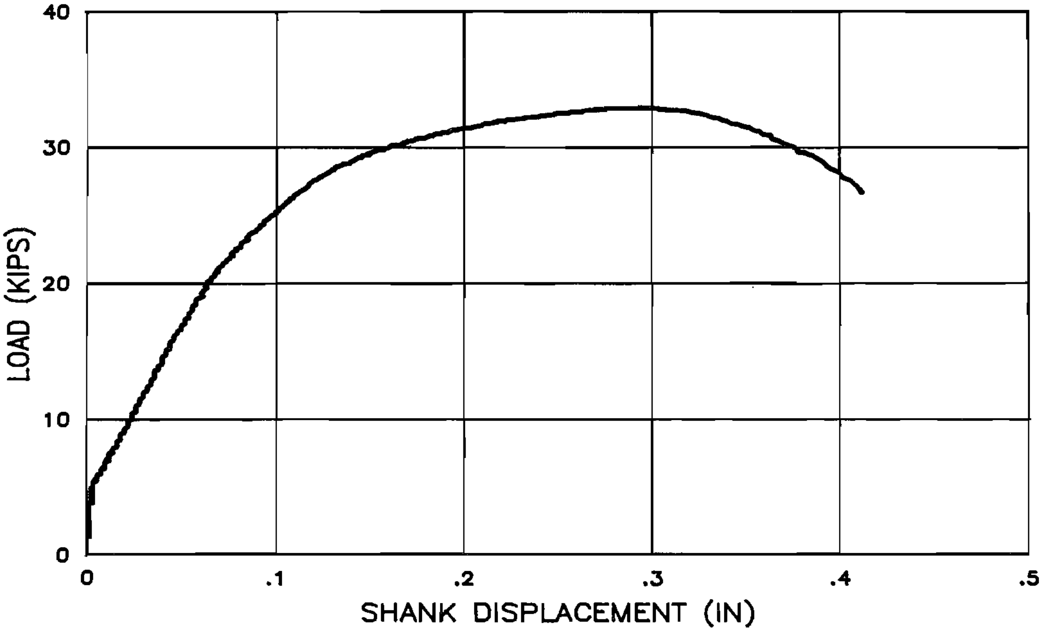
ECT C 4 c 6

ACID RAIN WETTING AND DRYING



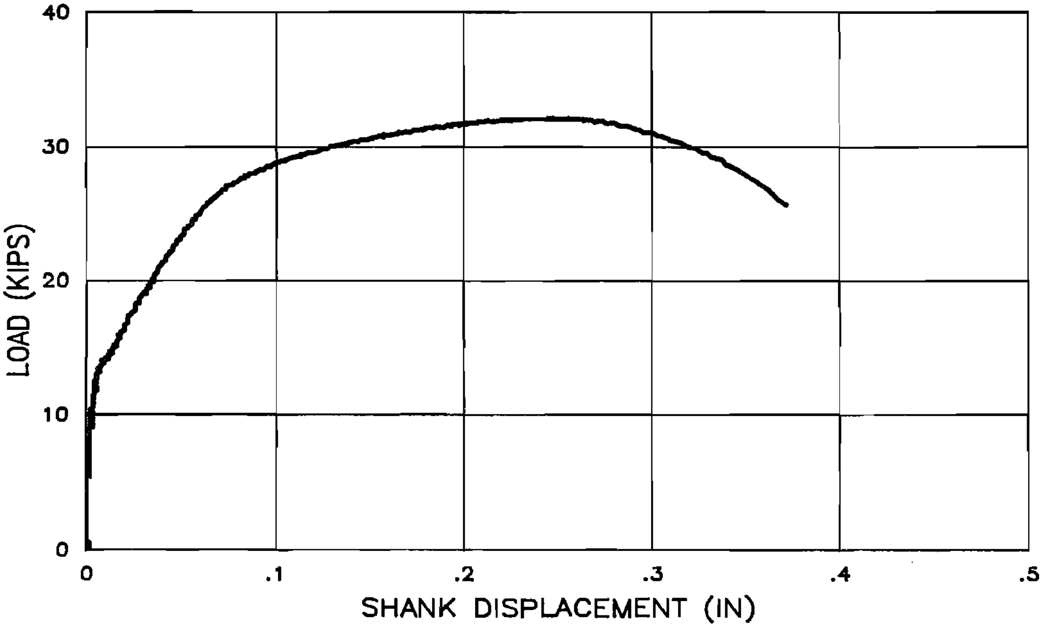
ECT C 4 d 6

ACID RAIN WETTING AND DRYING



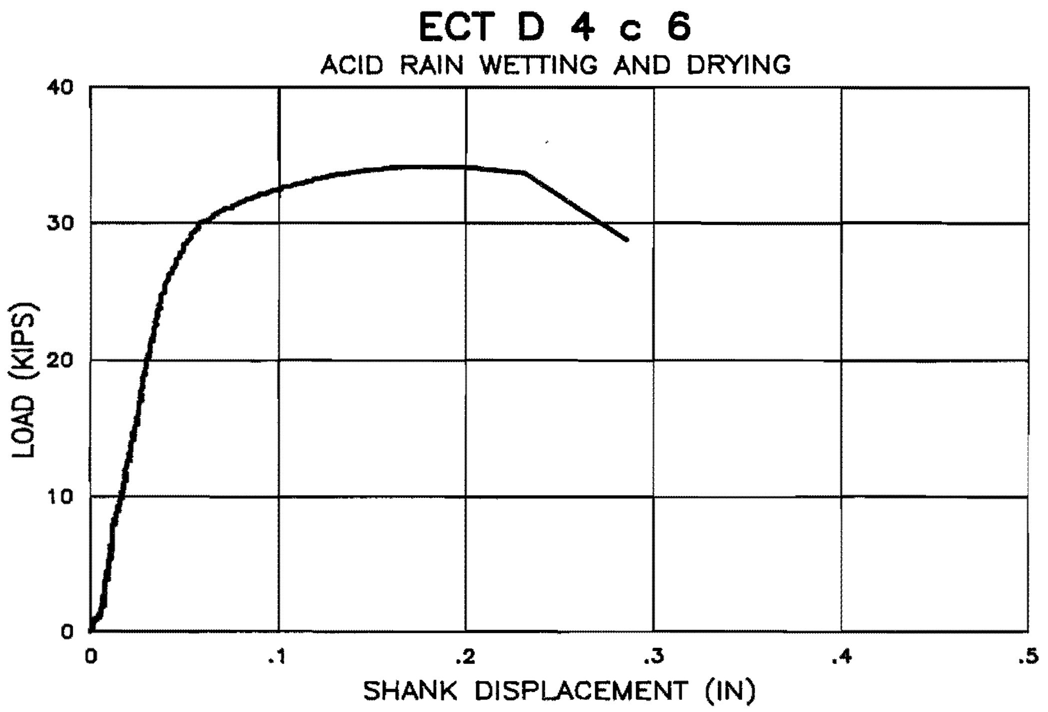
ECT D 4 a 6

ACID RAIN WETTING AND DRYING



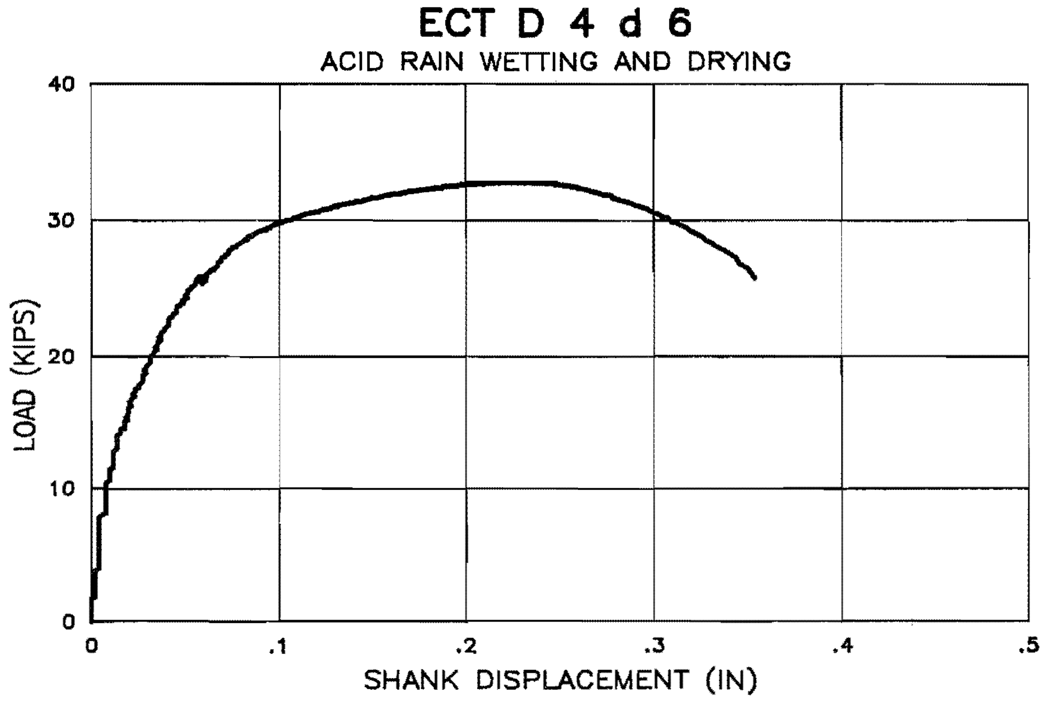
ECT D 4 b 6

ACID RAIN WETTING AND DRYING



ECT D 4 c 6

ACID RAIN WETTING AND DRYING

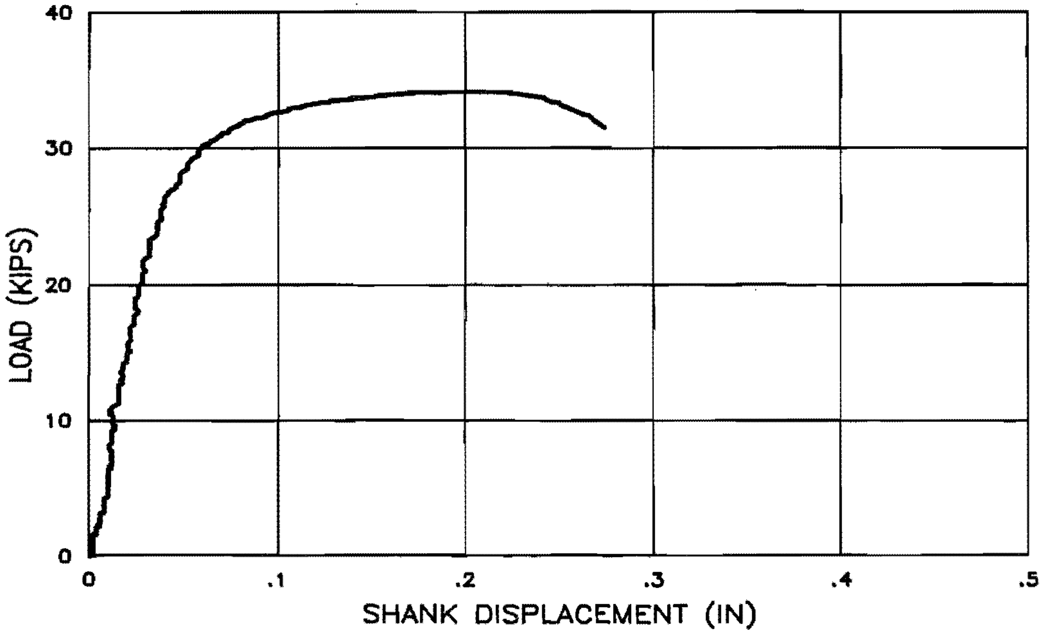


ECT D 4 d 6

ACID RAIN WETTING AND DRYING

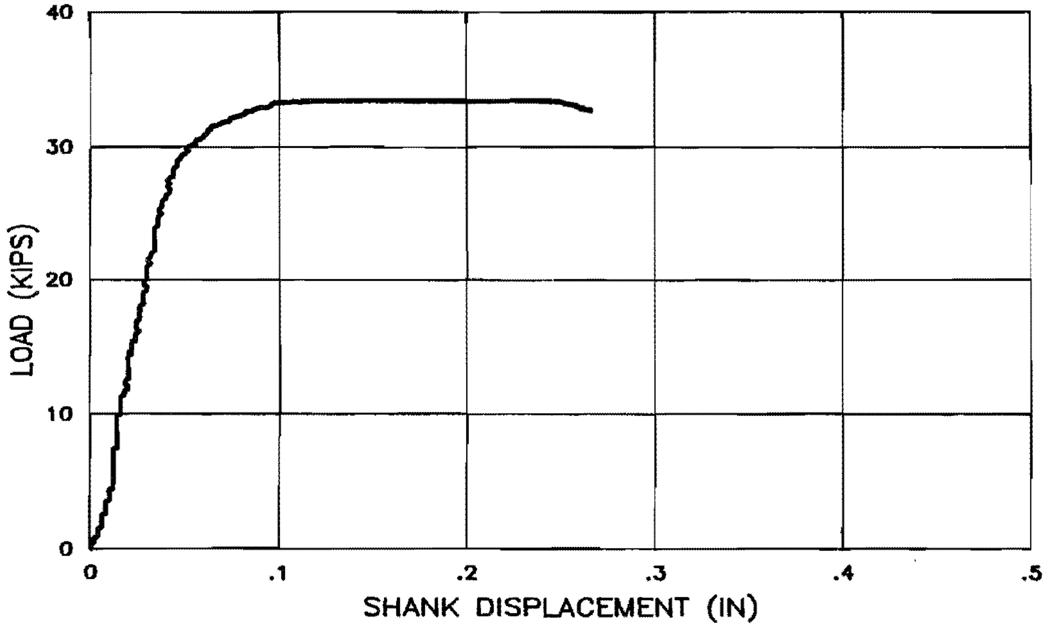
ECT E 4 a 6

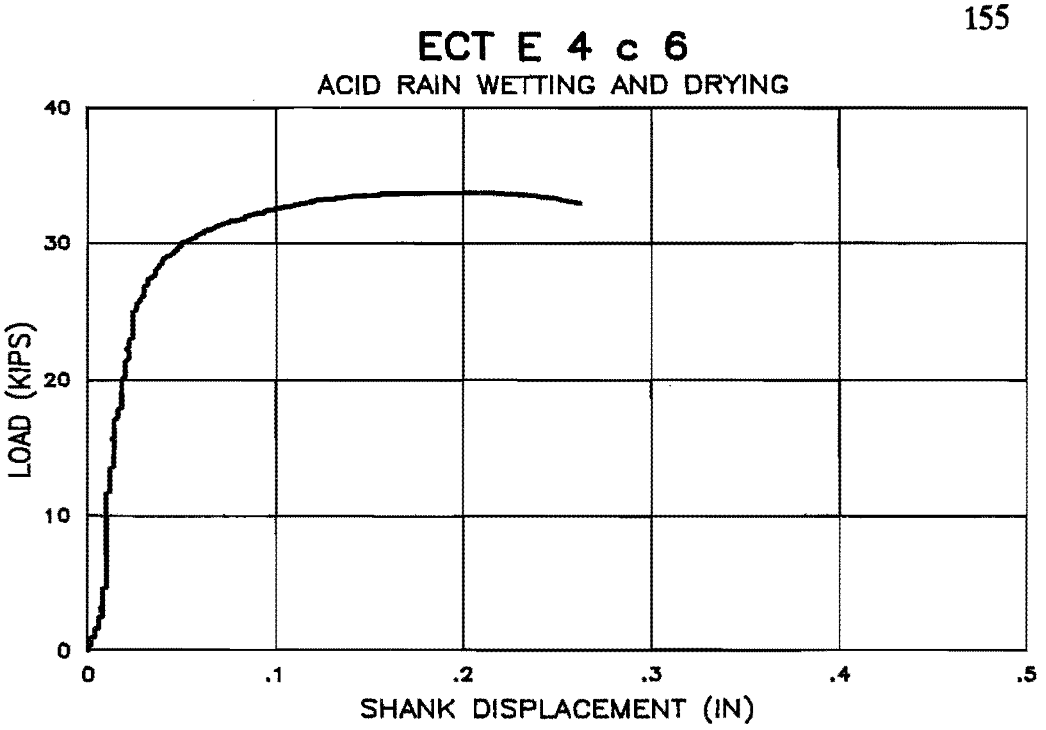
ACID RAIN WETTING AND DRYING

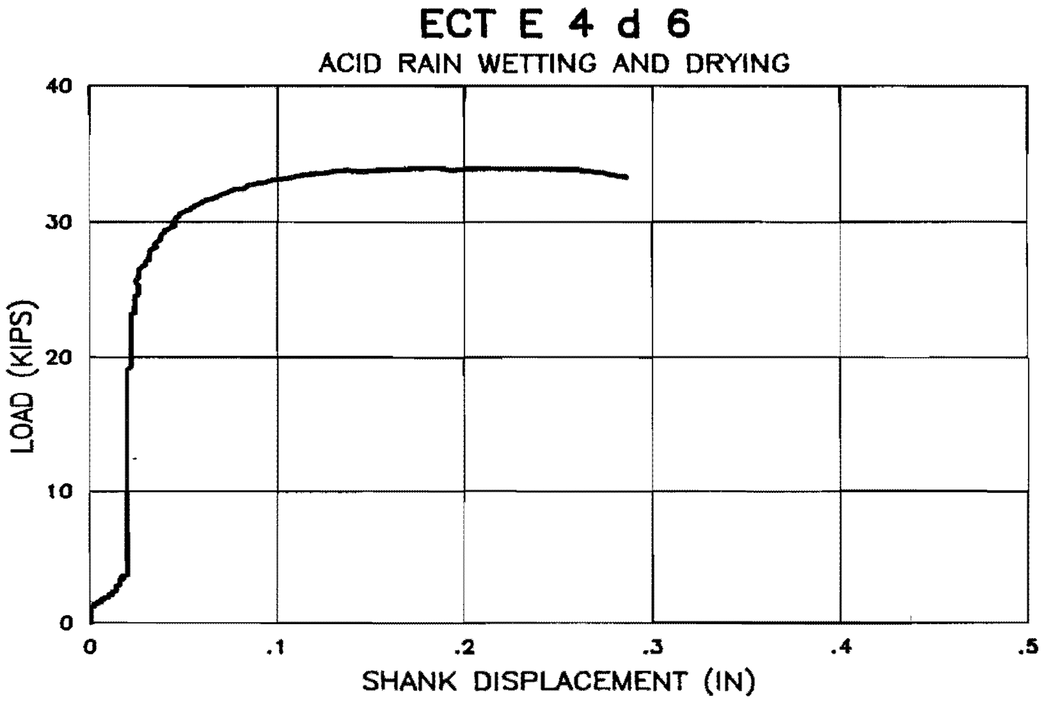


ECT E 4 b 6

ACID RAIN WETTING AND DRYING

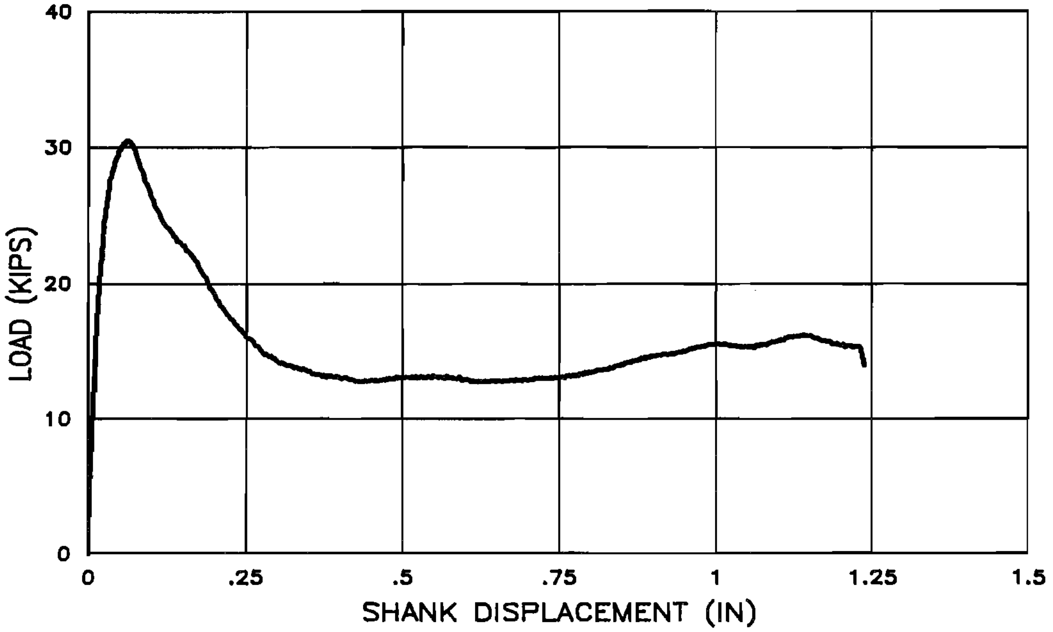



ECT E 4 c 6
ACID RAIN WETTING AND DRYING
LOAD (KIPS)
40
30
20
10
0
0
.1
.2
.3
.4
.5
SHANK DISPLACEMENT (IN)


ECT E 4 d 6
ACID RAIN WETTING AND DRYING
LOAD (KIPS)
40
30
20
10
0
0
.1
.2
.3
.4
.5
SHANK DISPLACEMENT (IN)

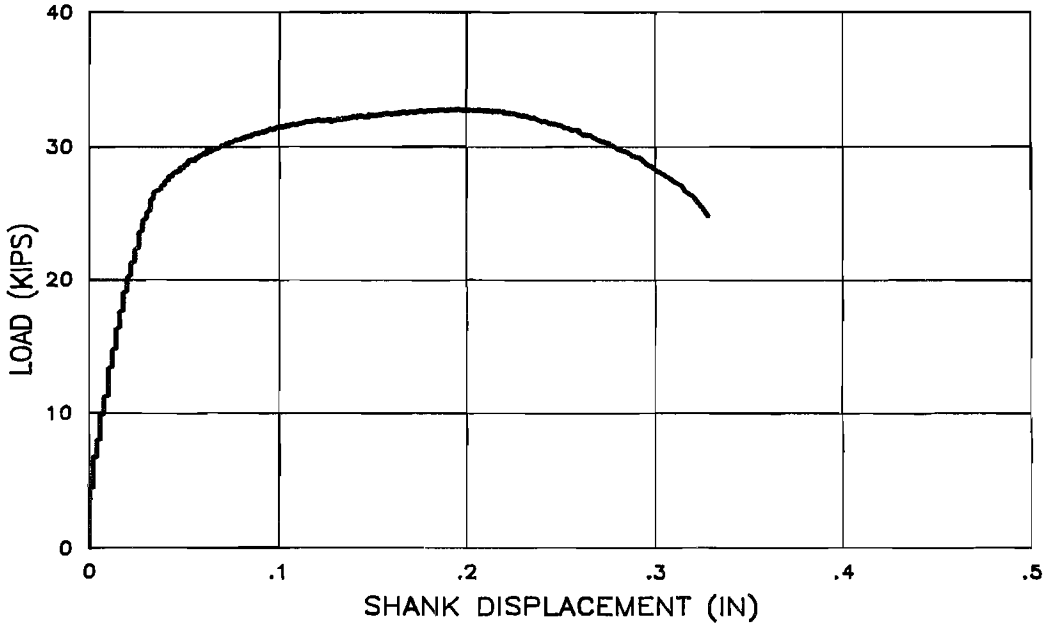
ECT F 4 a 6

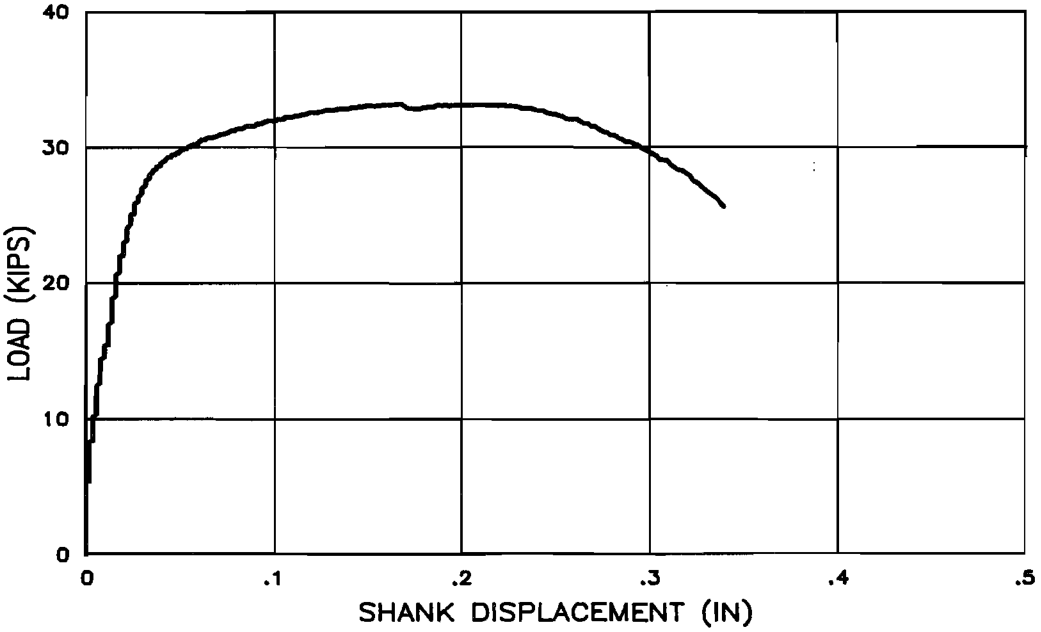
ACID RAIN WETTING AND DRYING



ECT F 4 b 6

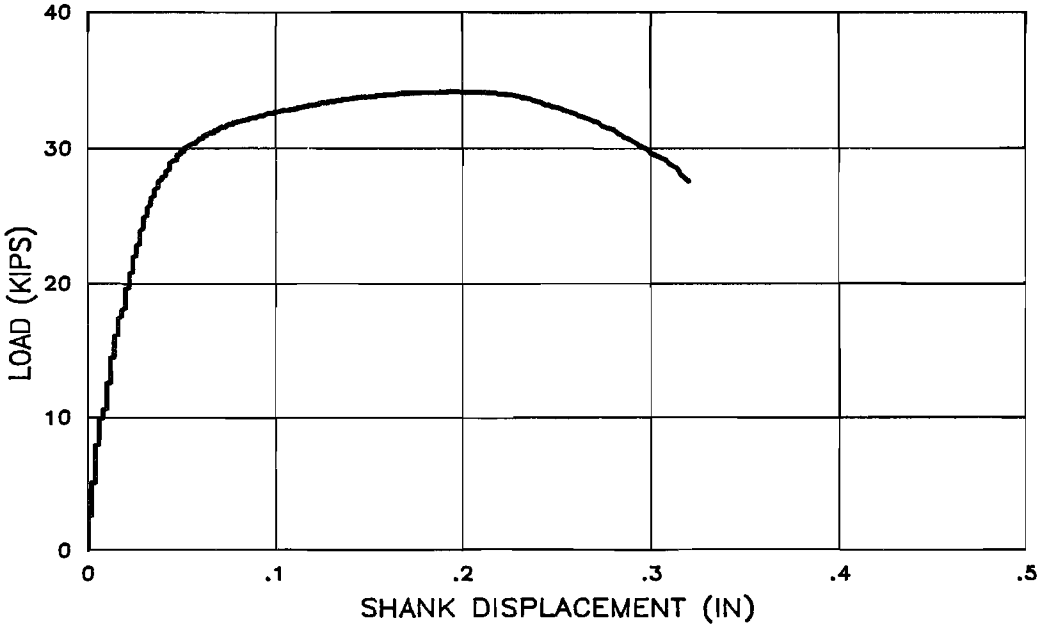
ACID RAIN WETTING AND DRYING





ECT F 4 c 6

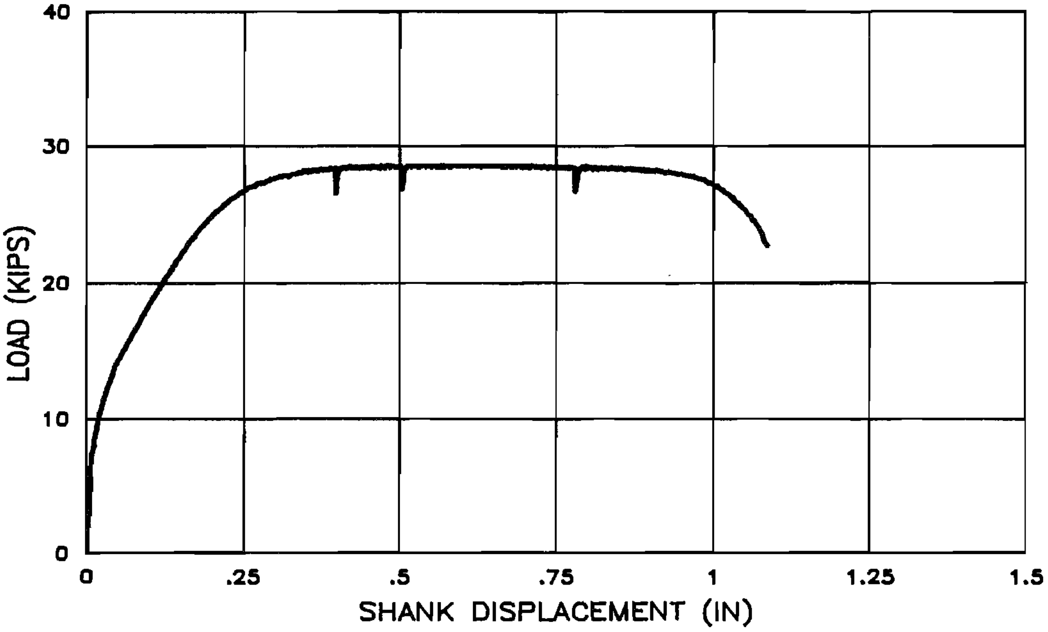
ACID RAIN WETTING AND DRYING



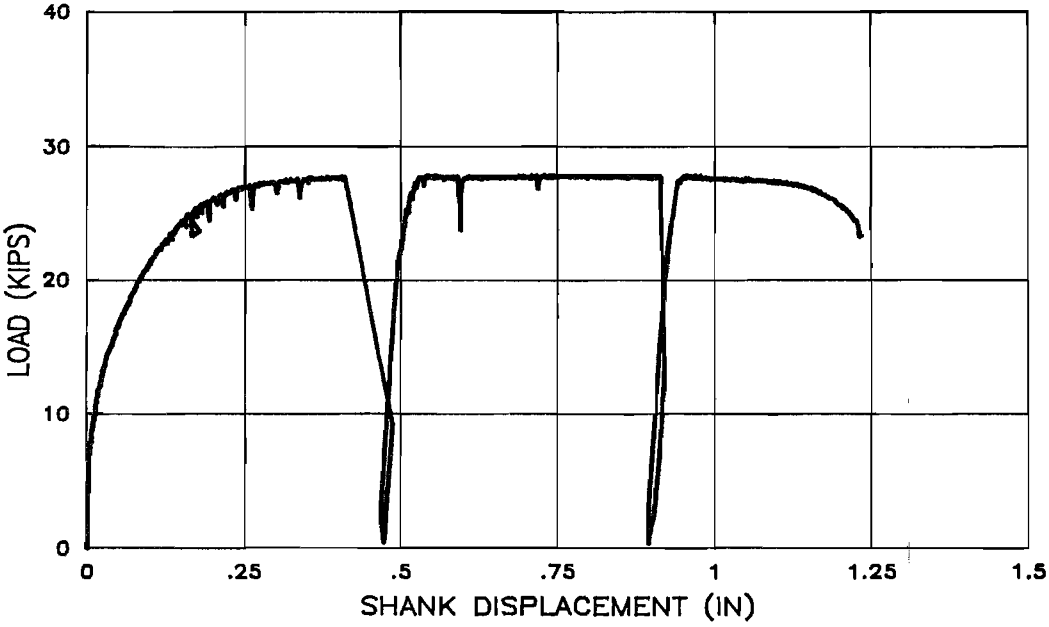
ECT F 4 d 6

ACID RAIN WETTING AND DRYING

ECT G 2 a 12
FREEZE–THAW

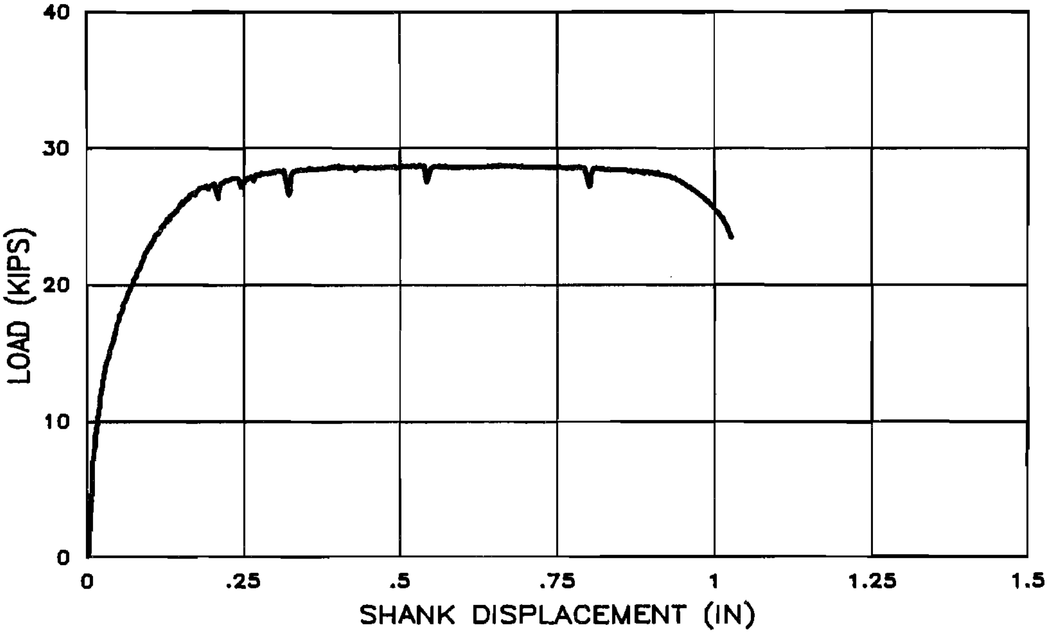


ECT G 2 b 12
FREEZE–THAW



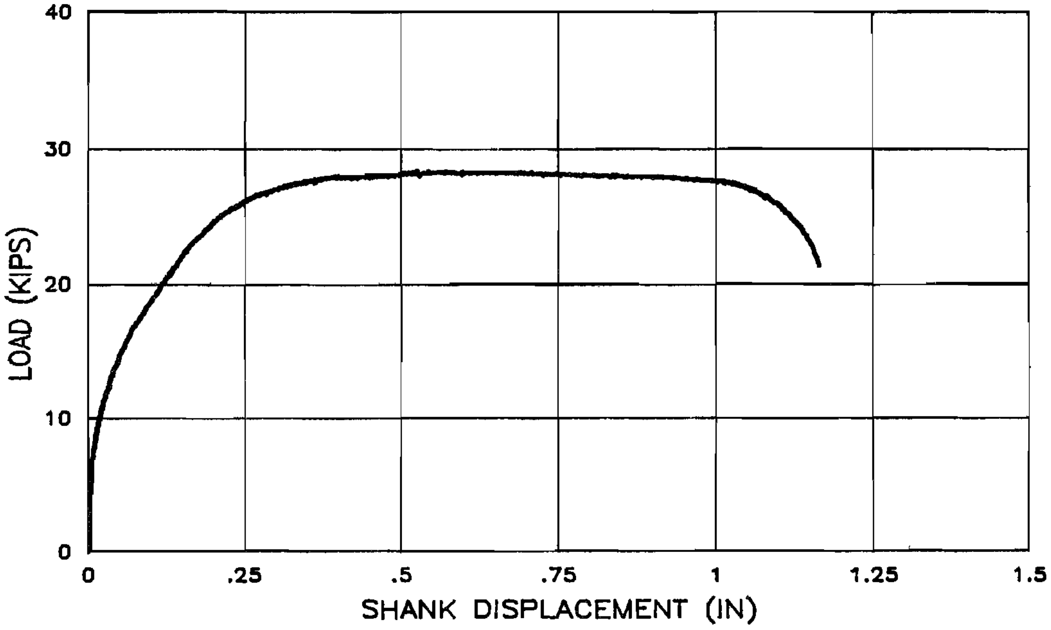
ECT G 2 c 12

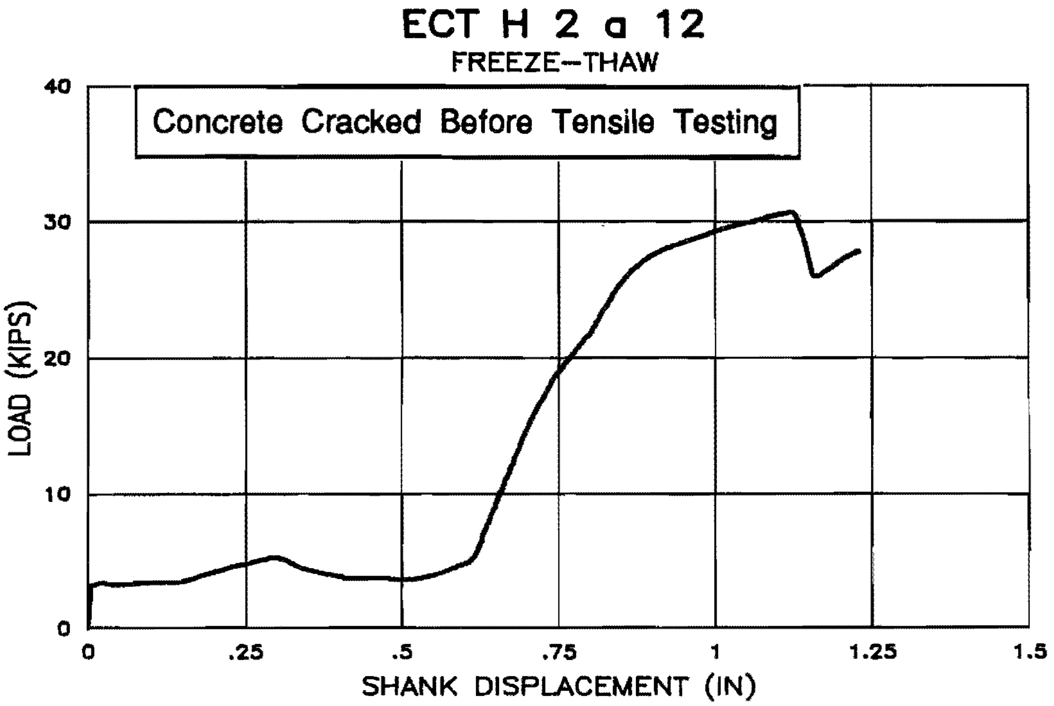
FREEZE—THAW

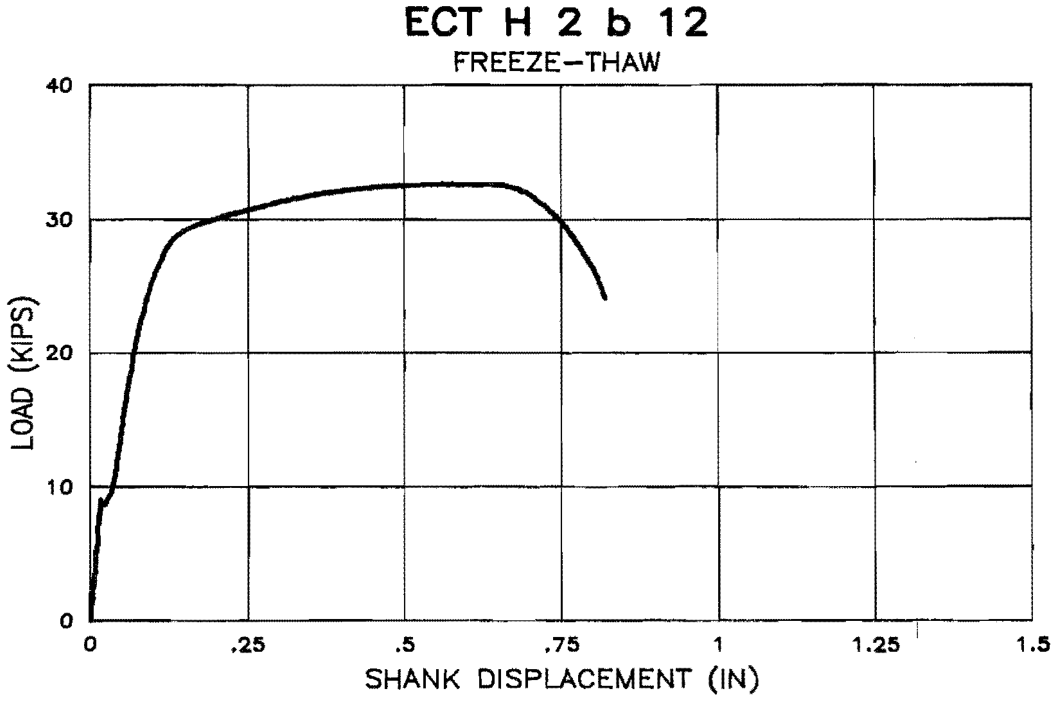


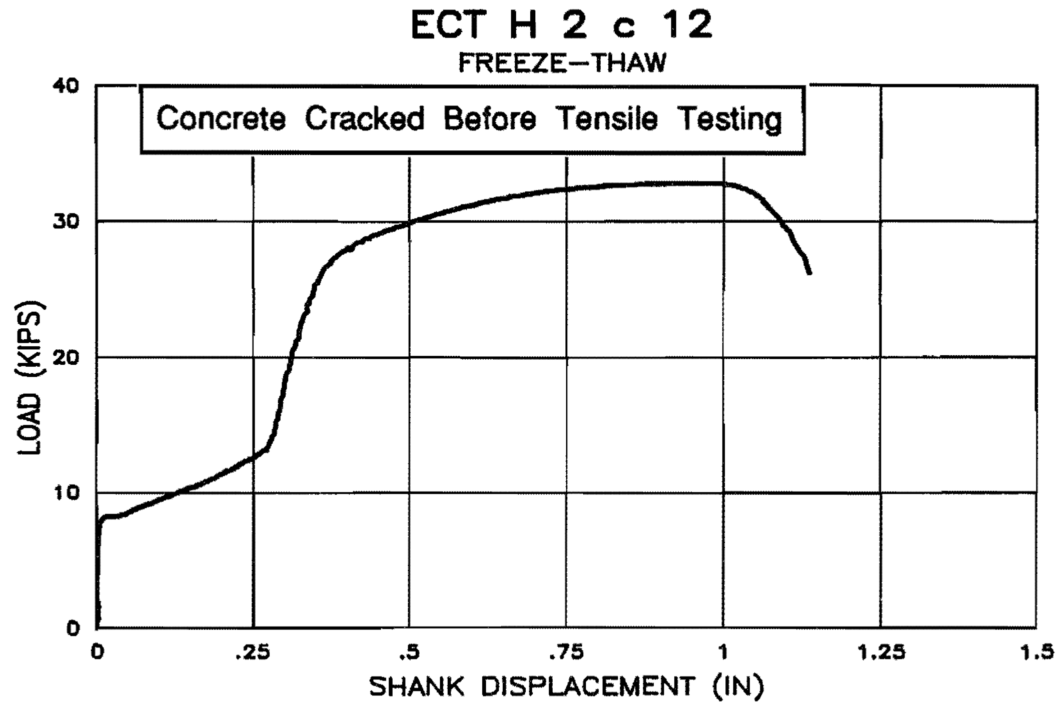
ECT G 2 d 12

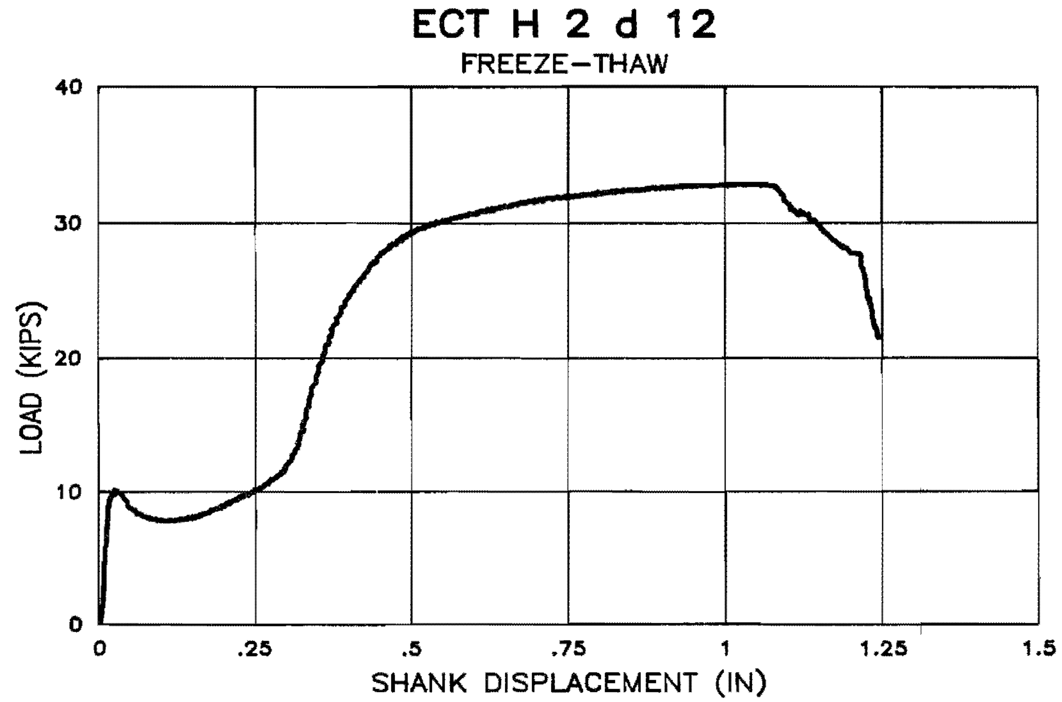
FREEZE—THAW

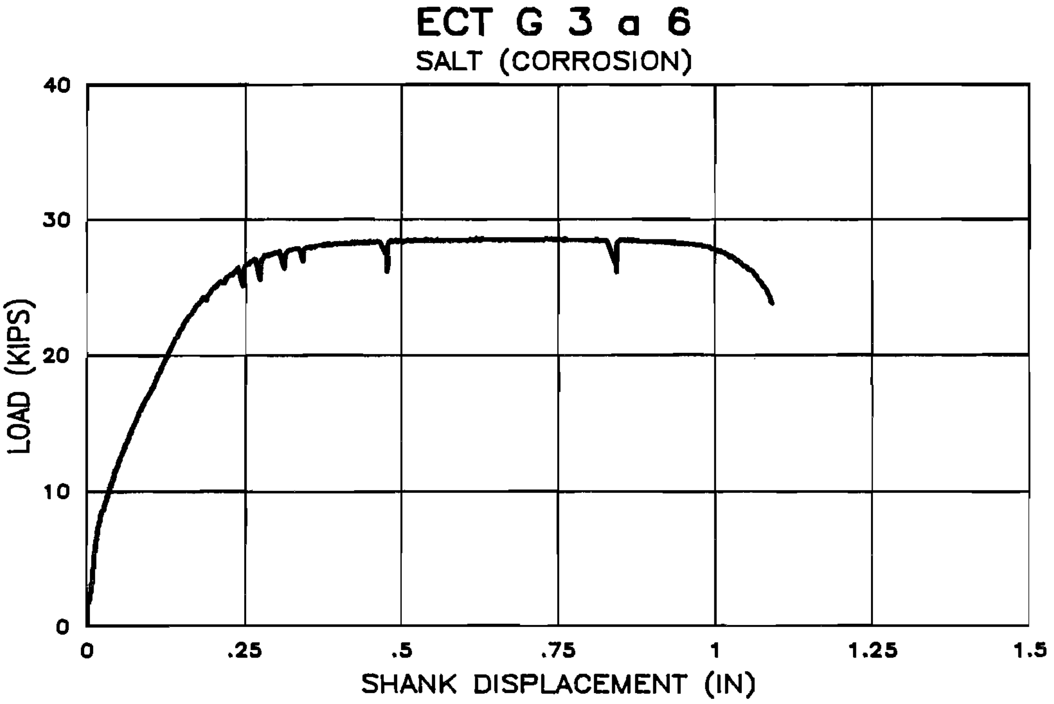



ECT H 2 a 12
FREEZE–THAW
Concrete Cracked Before Tensile Testing
LOAD (KIPS)
0
10
20
30
40
0
.25
.5
.75
1
1.25
1.5
SHANK DISPLACEMENT (IN)


ECT H 2 b 12
FREEZE–THAW
LOAD (KIPS)
0
10
20
30
40
0
.25
.5
.75
1
1.25
1.5
SHANK DISPLACEMENT (IN)

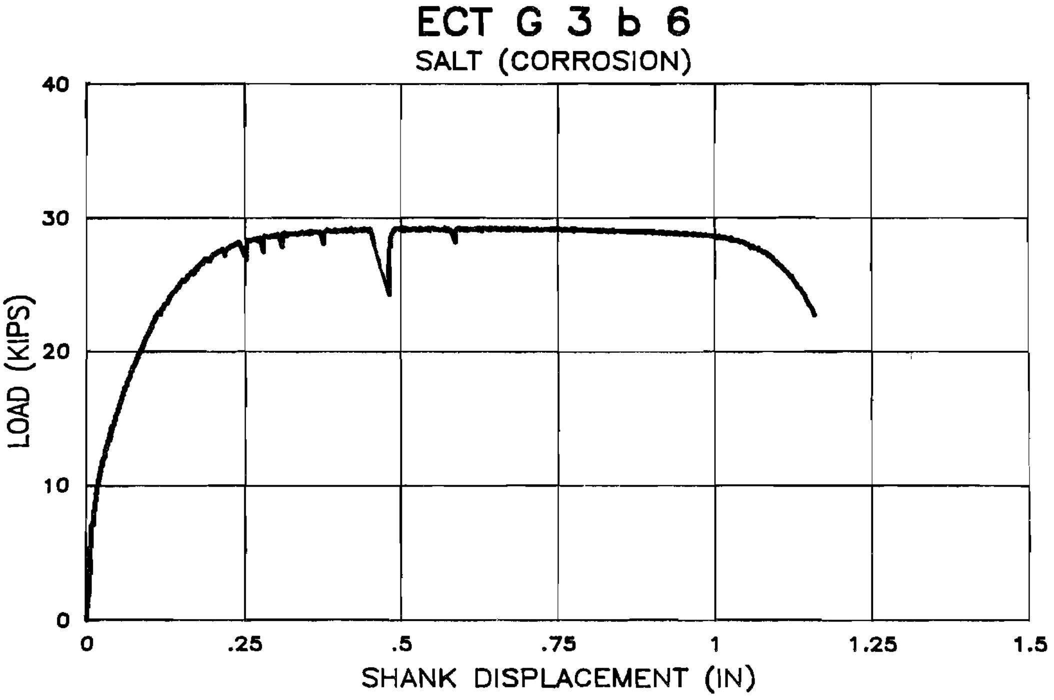

ECT H 2 c 12
FREEZE–THAW
Concrete Cracked Before Tensile Testing
LOAD (KIPS)
0
10
20
30
40
0
.25
.5
.75
1
1.25
1.5
SHANK DISPLACEMENT (IN)


ECT H 2 d 12
FREEZE–THAW
LOAD (KIPS)
0
10
20
30
40
0
.25
.5
.75
1
1.25
1.5
SHANK DISPLACEMENT (IN)



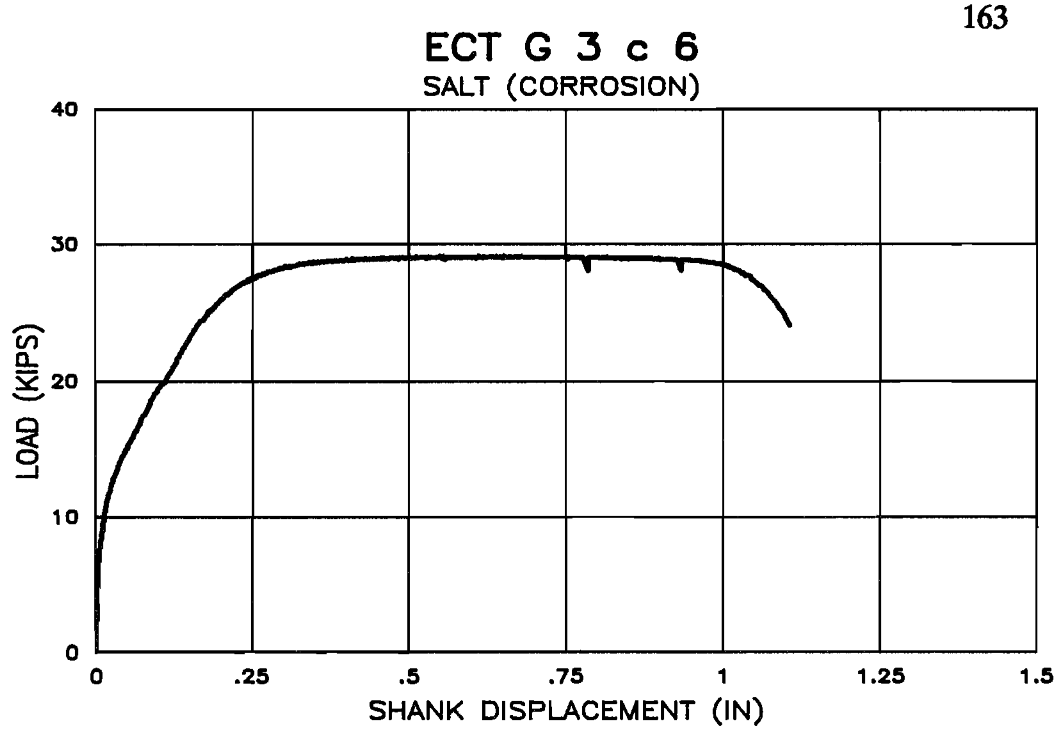
ECT G 3 a 6

SALT (CORROSION)

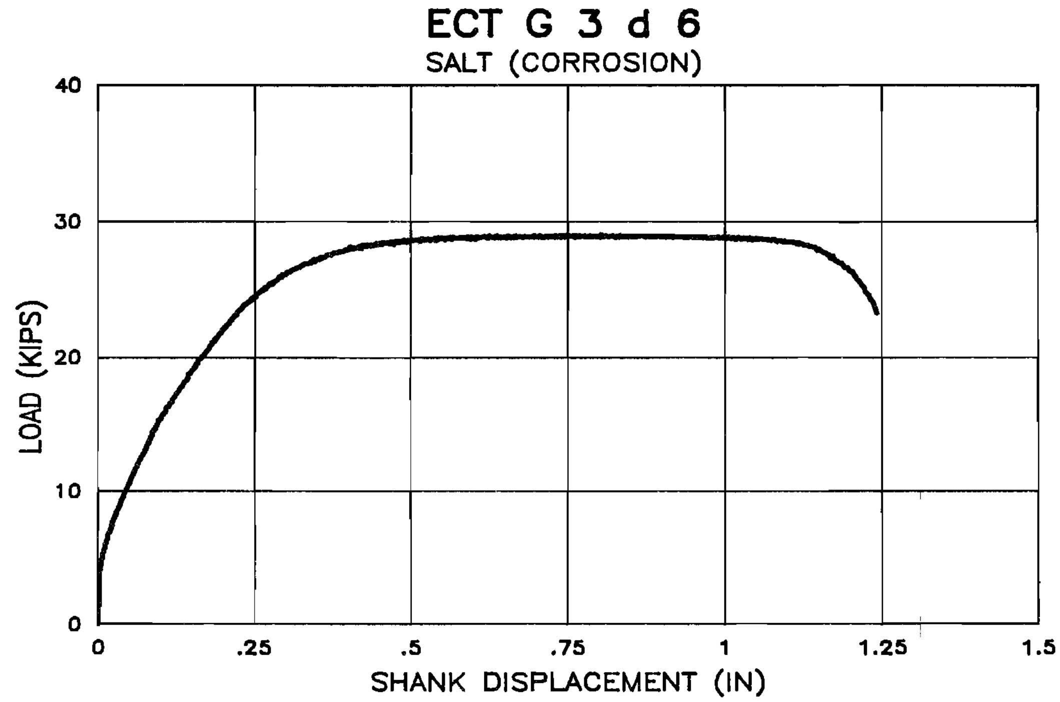


ECT G 3 b 6

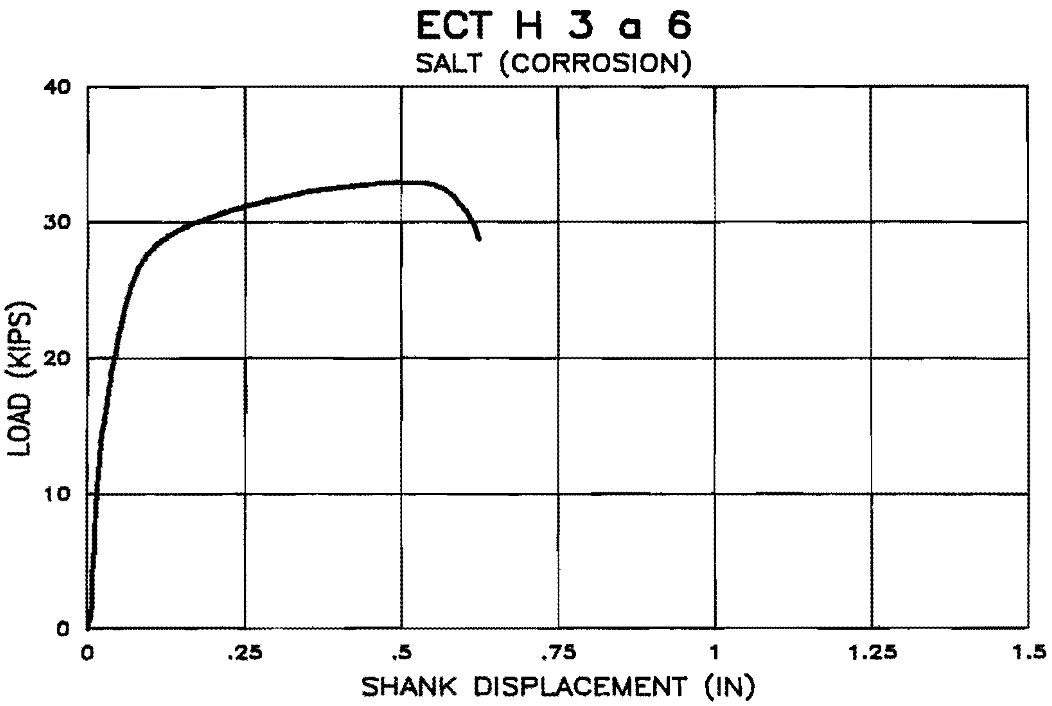
SALT (CORROSION)



ECT G 3 c 6
SALT (CORROSION)

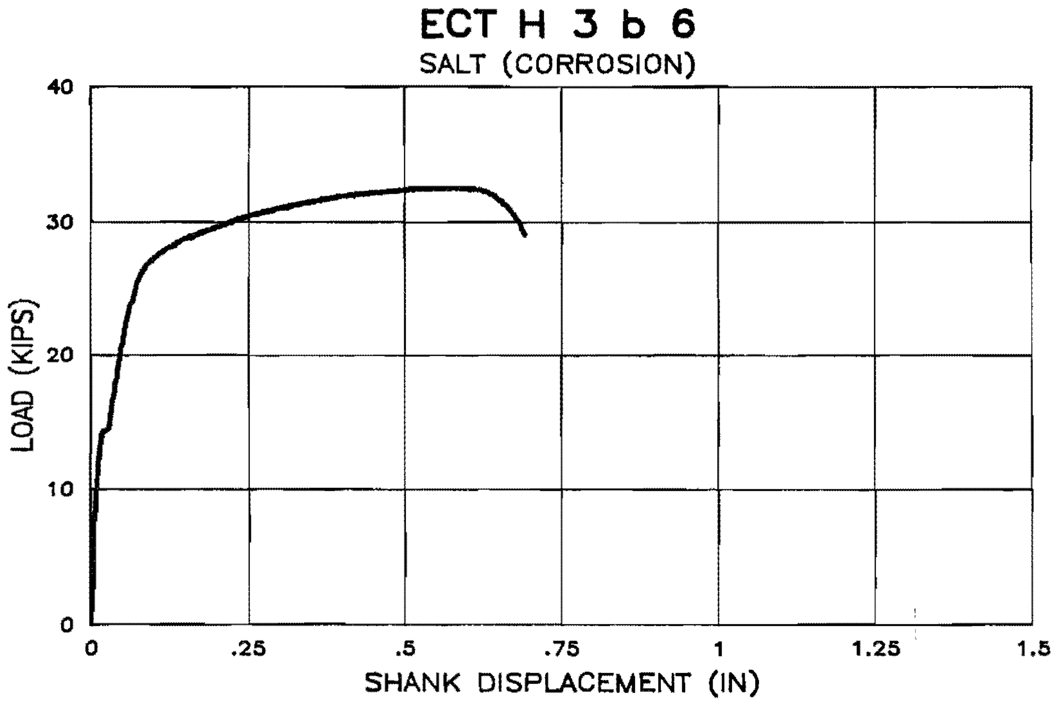


ECT G 3 d 6
SALT (CORROSION)



ECT H 3 a 6

SALT (CORROSION)

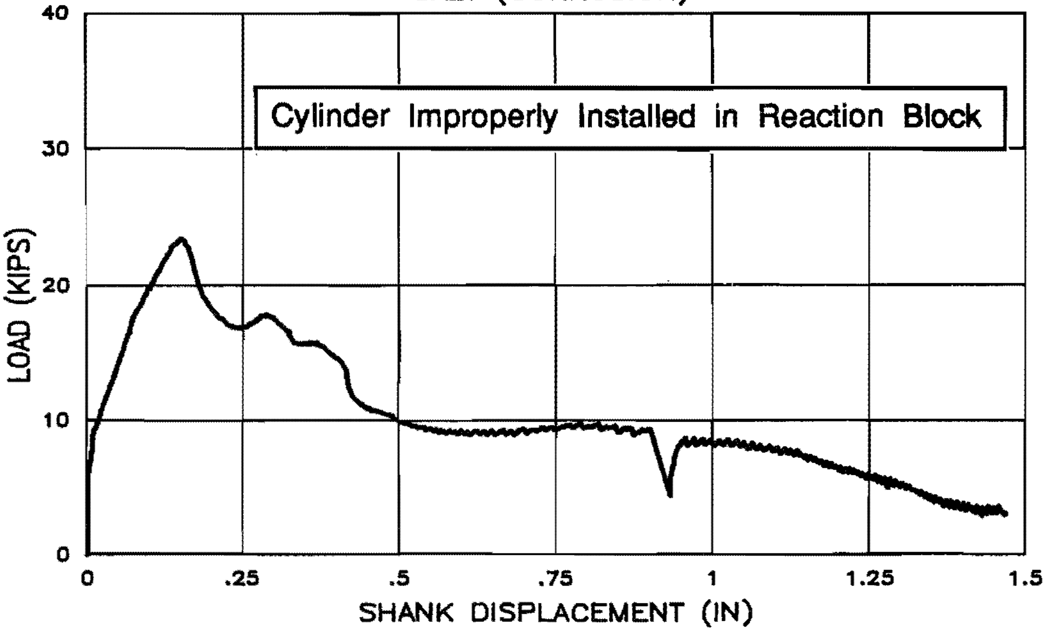


ECT H 3 b 6

SALT (CORROSION)

ECT H 3 c 6

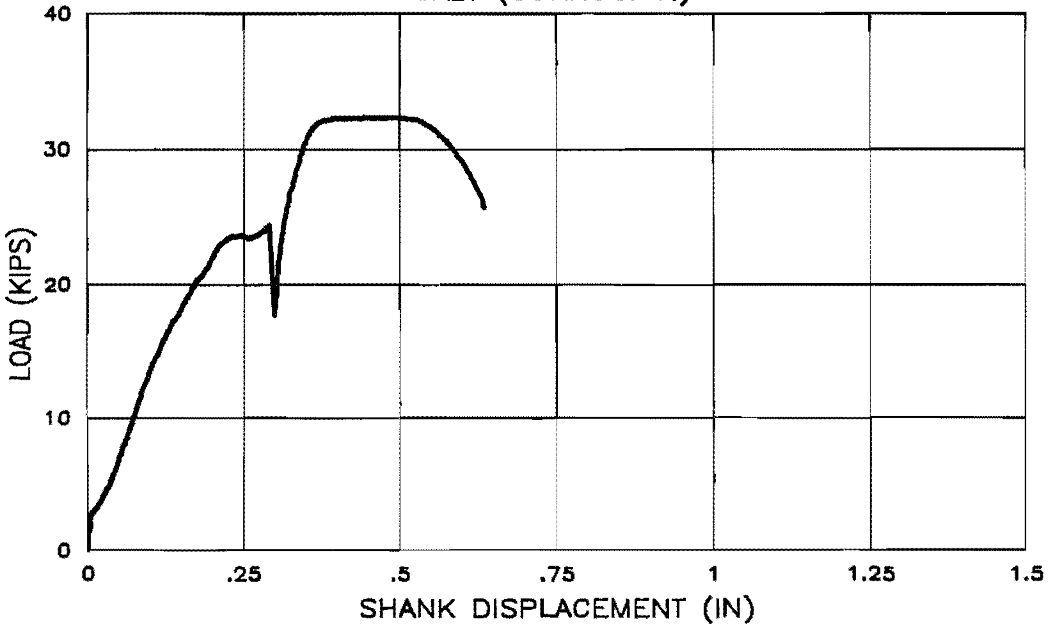
SALT (CORROSION)



Cylinder Improperly Installed in Reaction Block

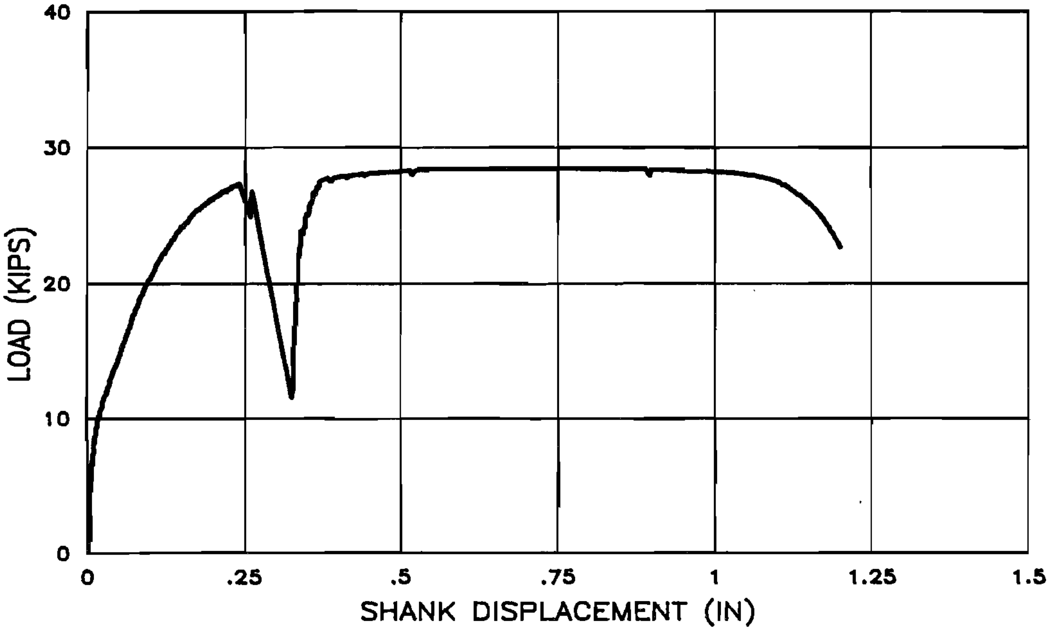
ECT H 3 d 6

SALT (CORROSION)



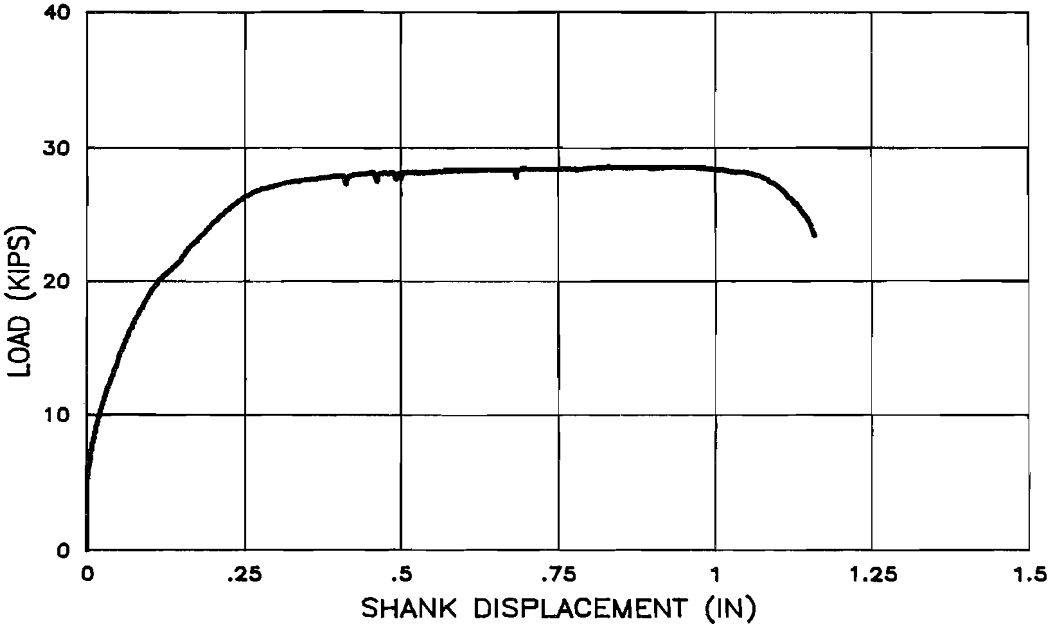
ECT G 4 a 6

ACID RAIN WETTING AND DRYING



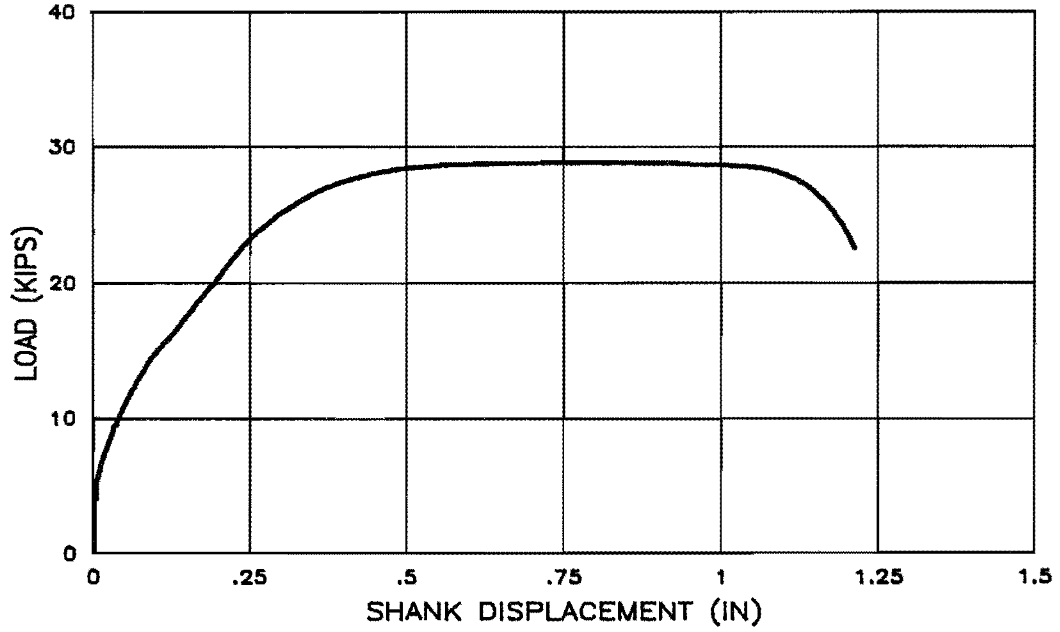
ECT G 4 b 6

ACID RAIN WETTING AND DRYING



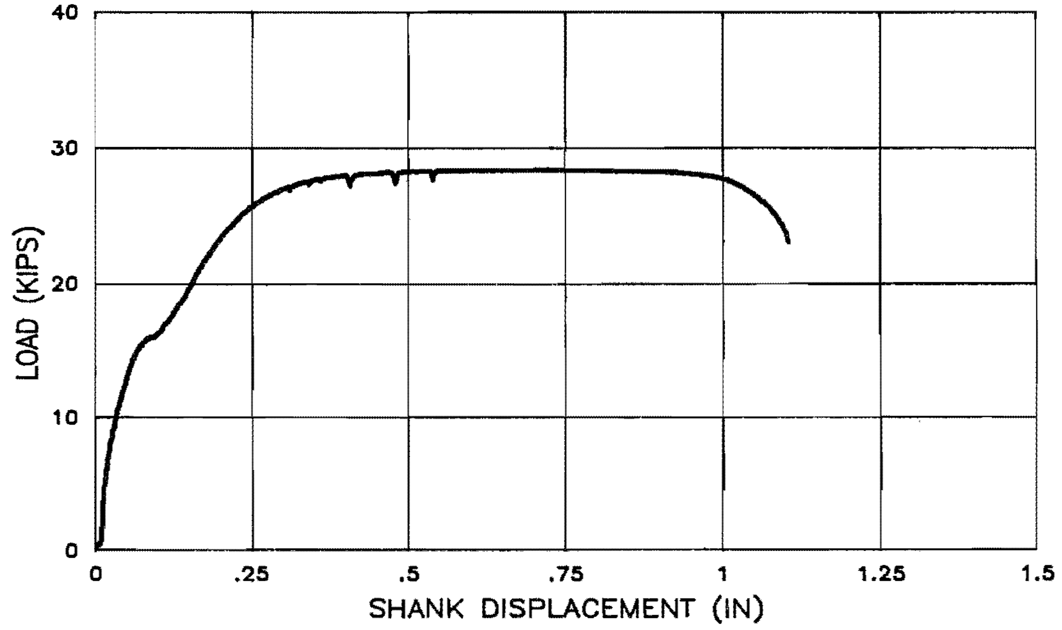
ECT G 4 c 6

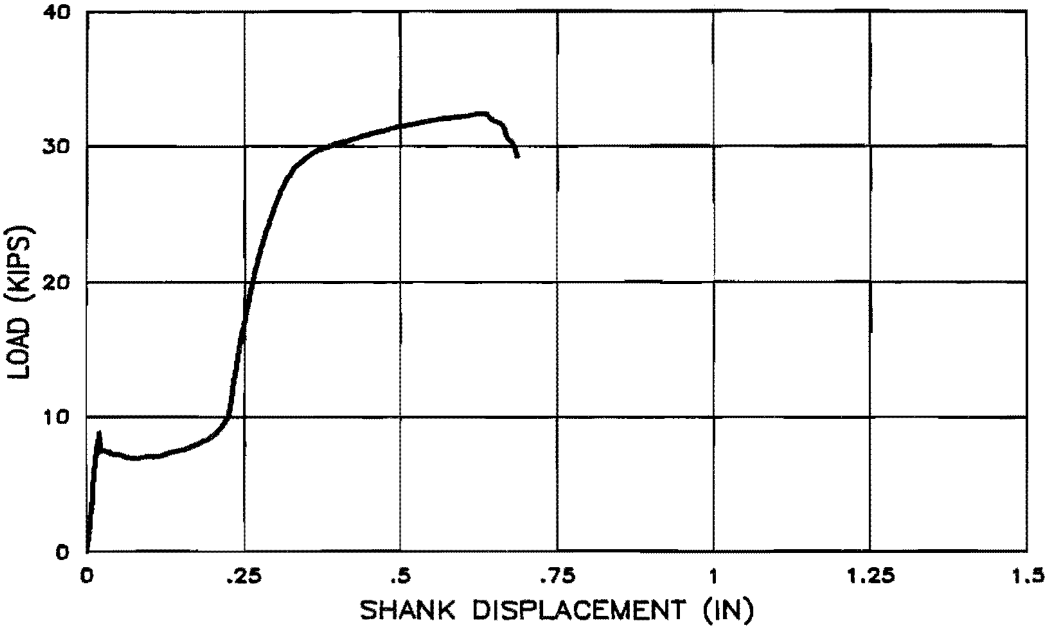
ACID RAIN WETTING AND DRYING



ECT G 4 d 6

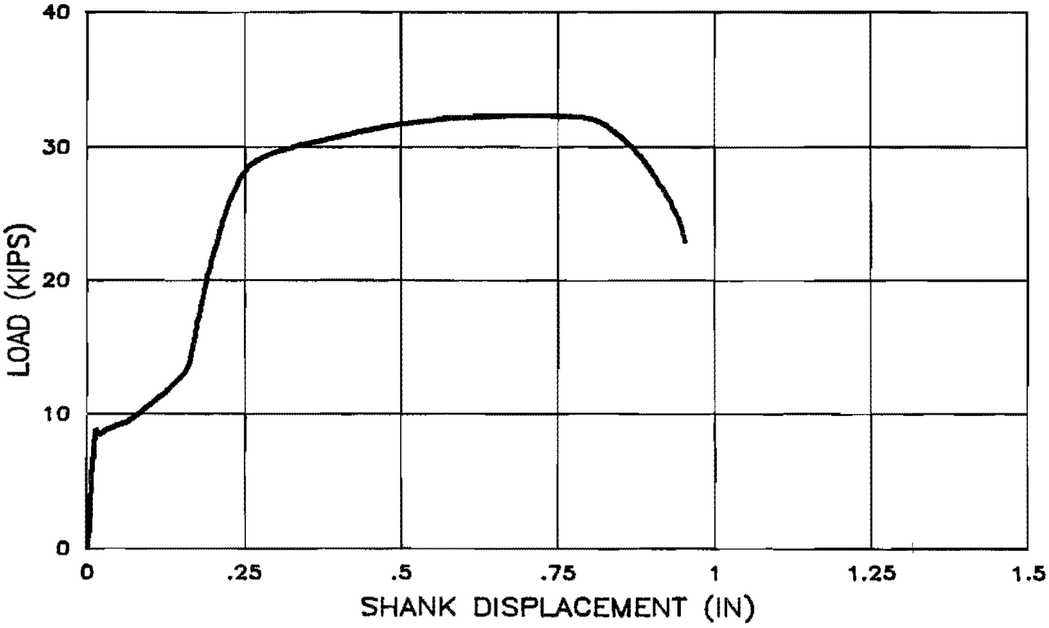
ACID RAIN WETTING AND DRYING





ECT H 4 a 6

ACID RAIN WETTING AND DRYING

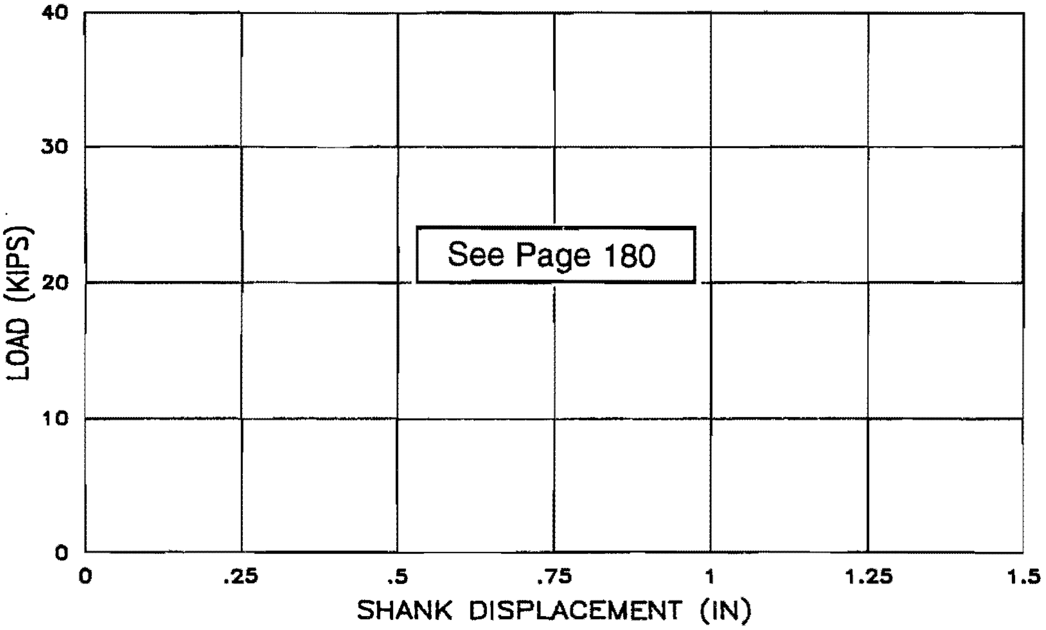


ECT H 4 b 6

ACID RAIN WETTING AND DRYING

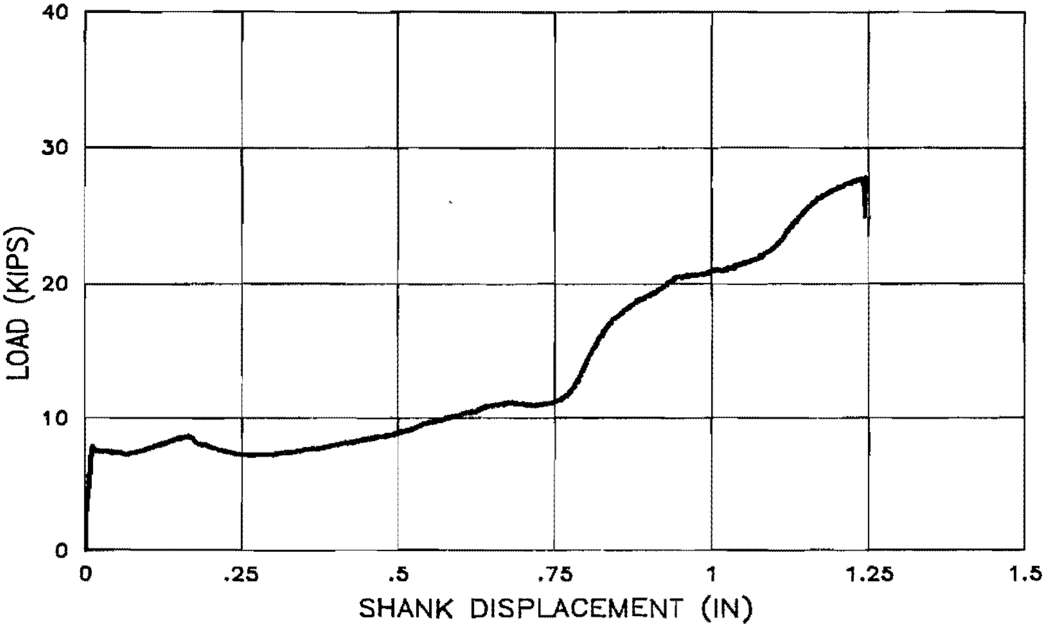
ECT H 4 c 6

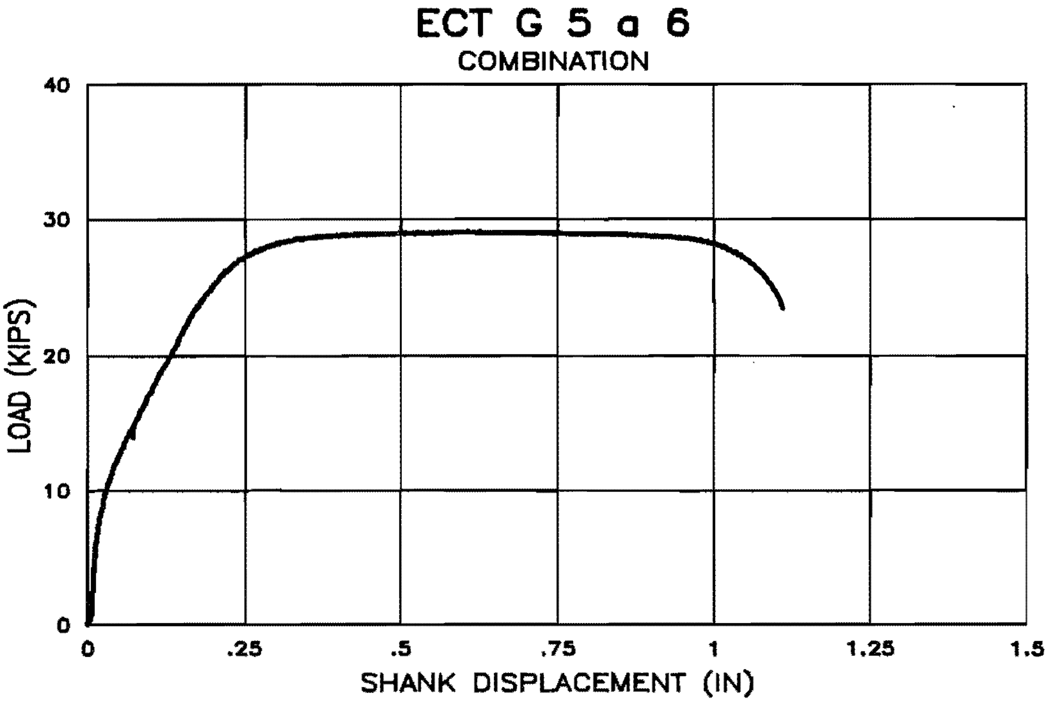
ACID RAIN WETTING AND DRYING

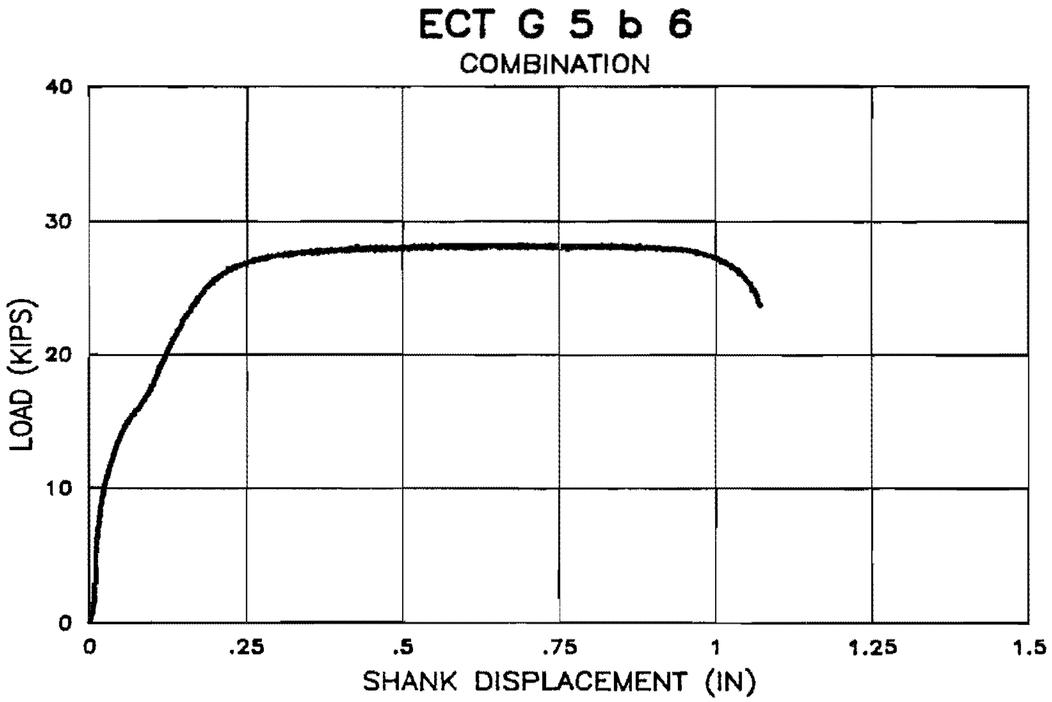


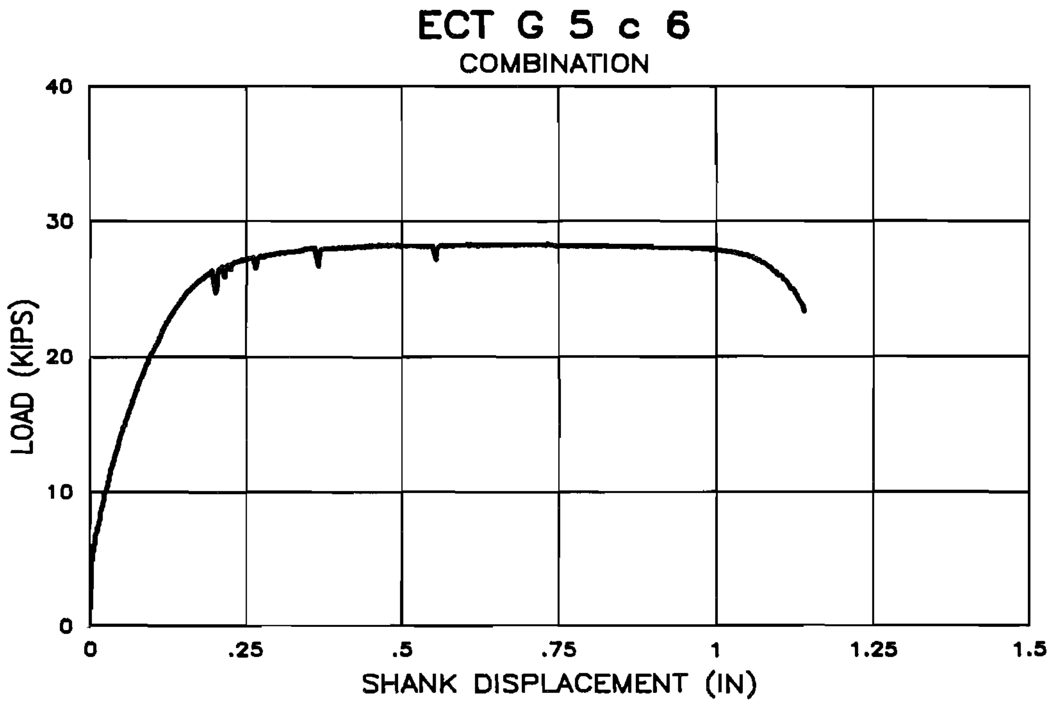
ECT H 4 d 6

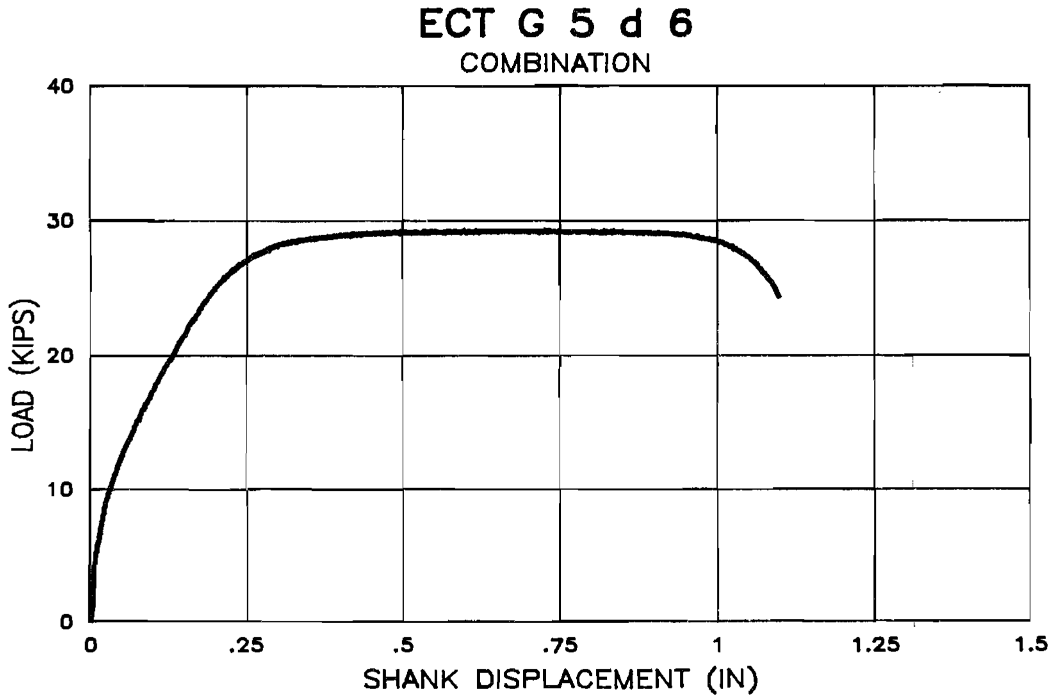
ACID RAIN WETTING AND DRYING



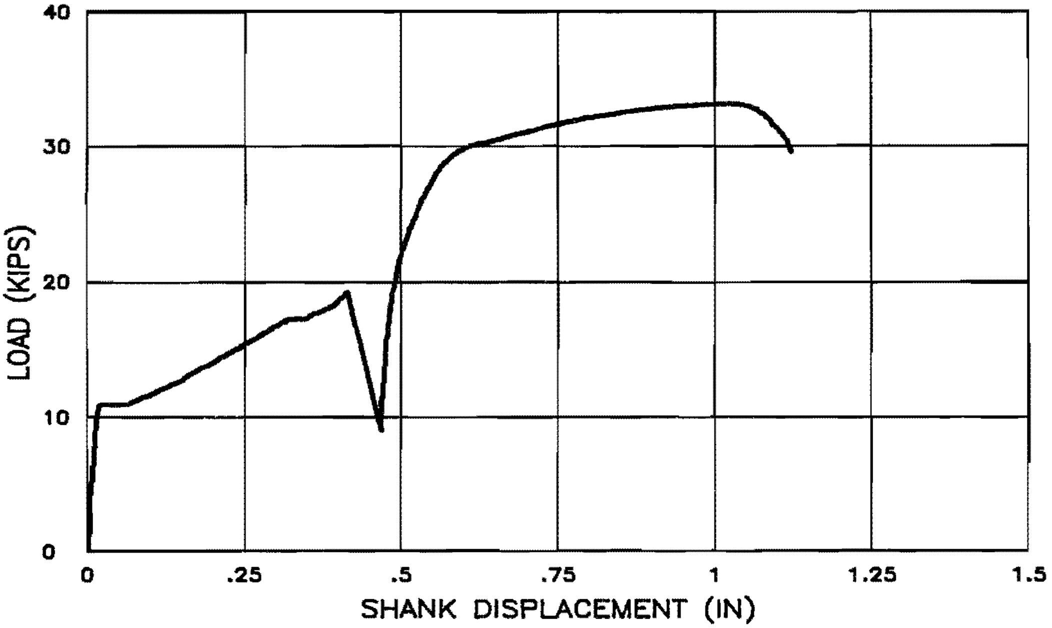

ECT G 5 a 6
COMBINATION
LOAD (KIPS)
0
10
20
30
40
SHANK DISPLACEMENT (IN)
0
.25
.5
.75
1
1.25
1.5


ECT G 5 b 6
COMBINATION
LOAD (KIPS)
0
10
20
30
40
SHANK DISPLACEMENT (IN)
0
.25
.5
.75
1
1.25
1.5

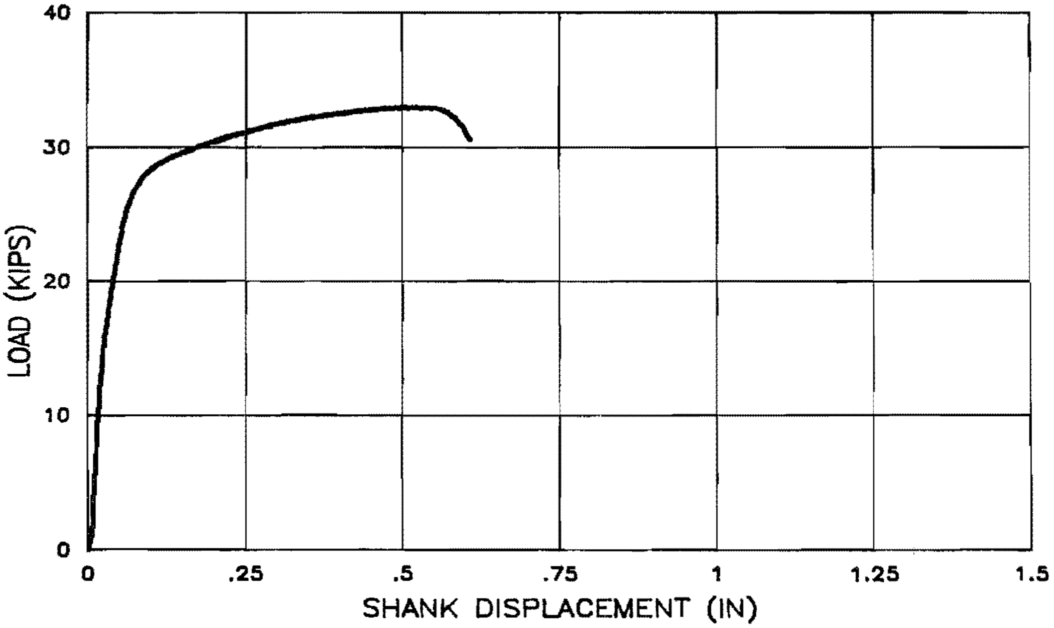

ECT G 5 c 6
COMBINATION
LOAD (KIPS)
40
30
20
10
0
0
.25
.5
.75
1
1.25
1.5
SHANK DISPLACEMENT (IN)

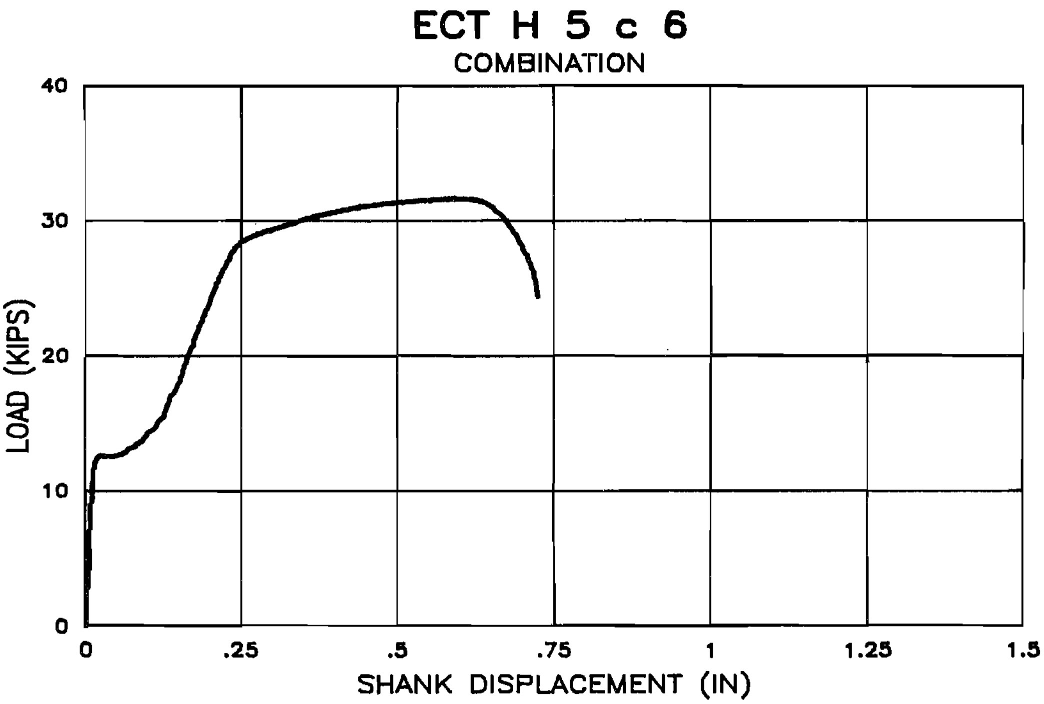

ECT G 5 d 6
COMBINATION
LOAD (KIPS)
40
30
20
10
0
0
.25
.5
.75
1
1.25
1.5
SHANK DISPLACEMENT (IN)

ECT H 5 a 6
COMBINATION

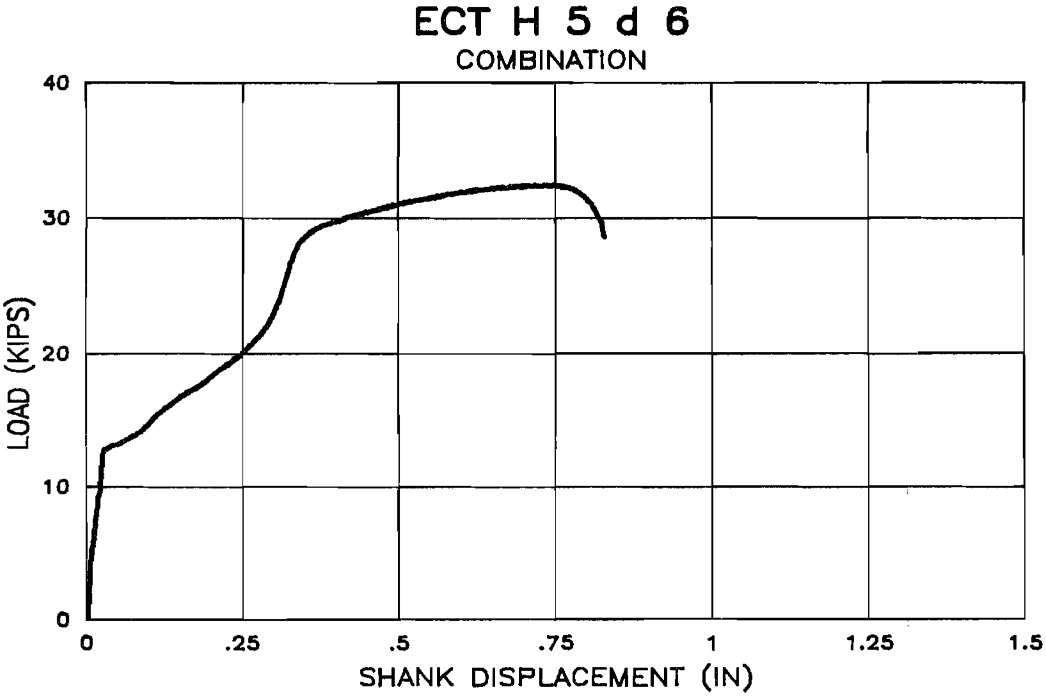


ECT H 5 b 6
COMBINATION

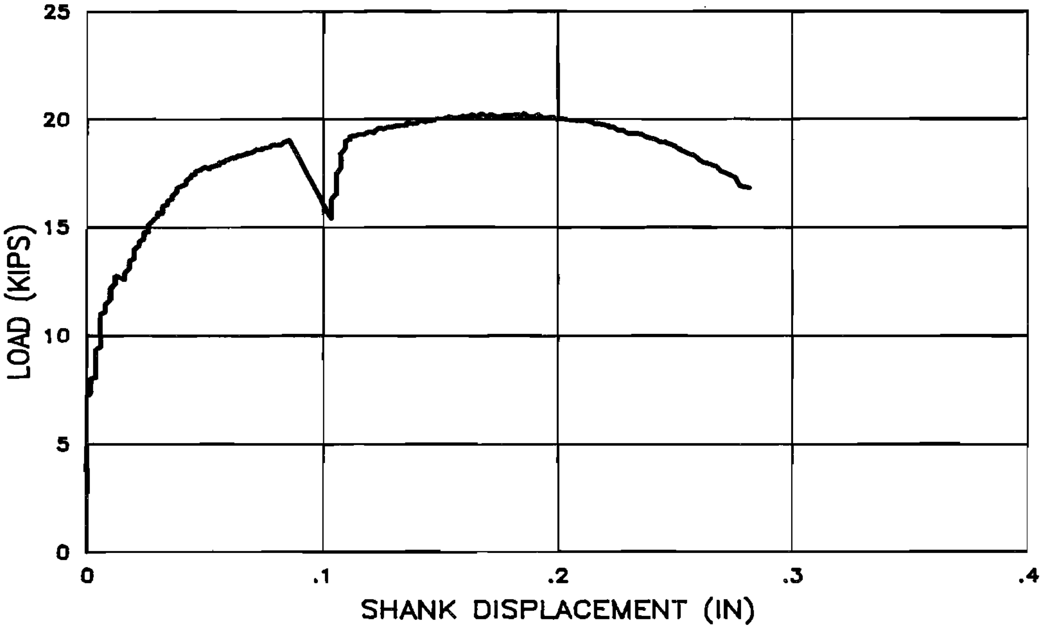




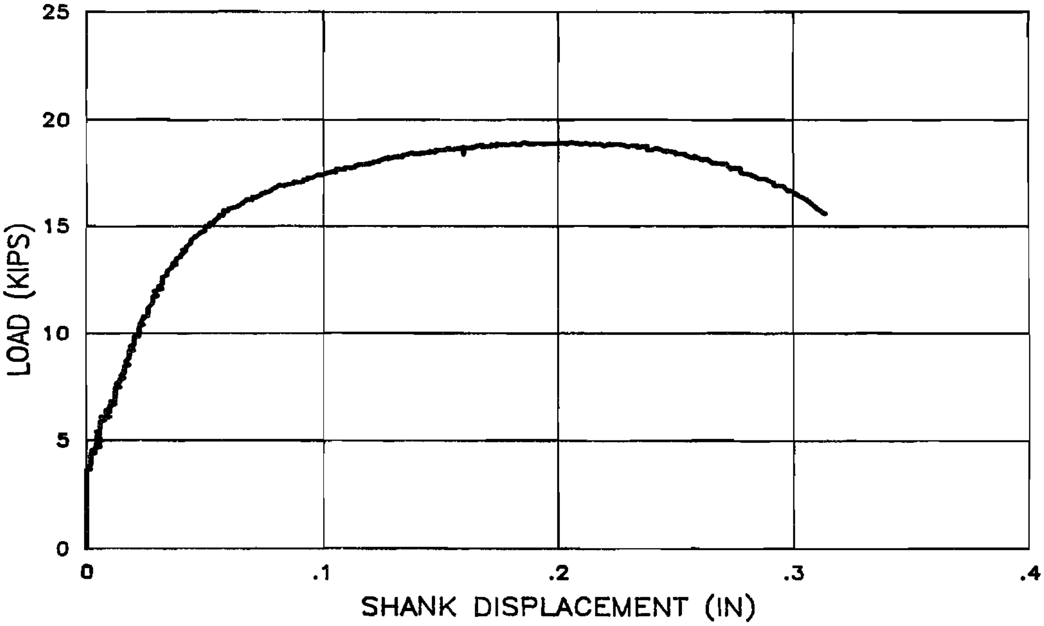
ECT H 5 c 6
COMBINATION



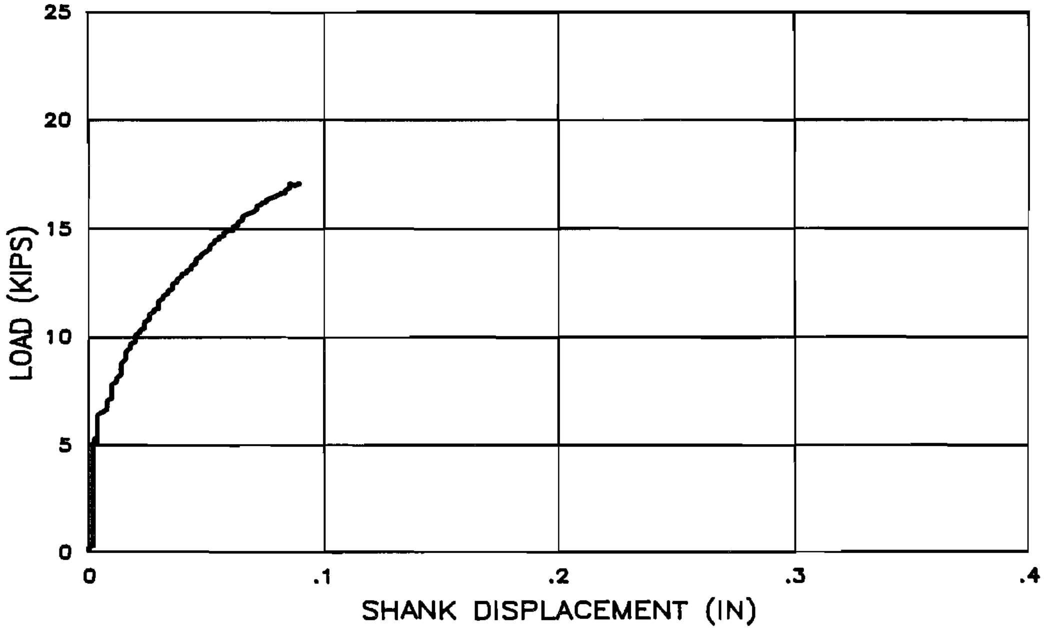
ECT H 5 d 6
COMBINATION

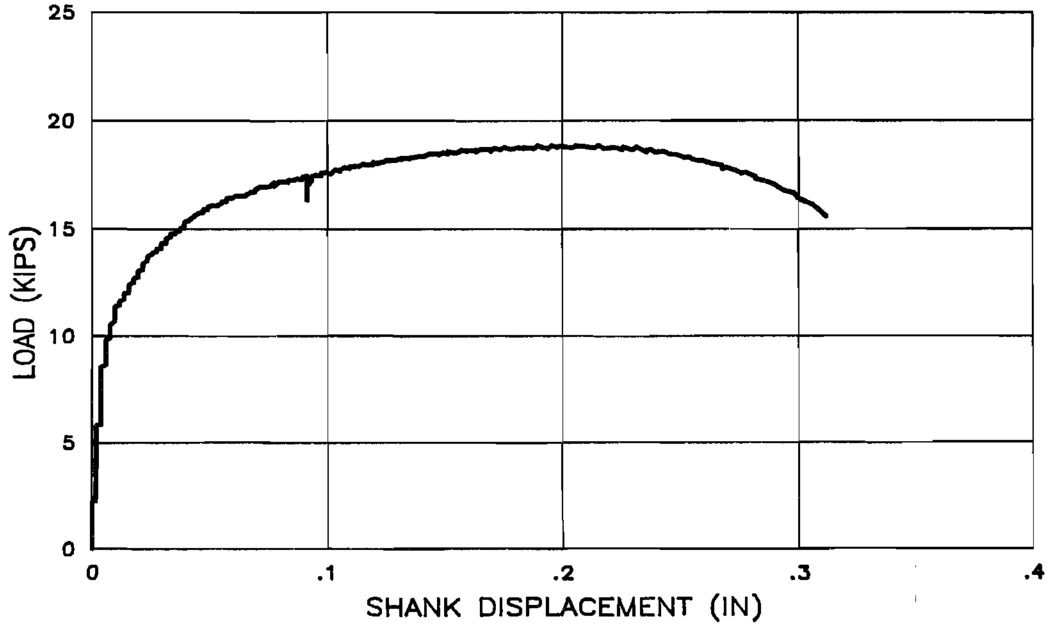


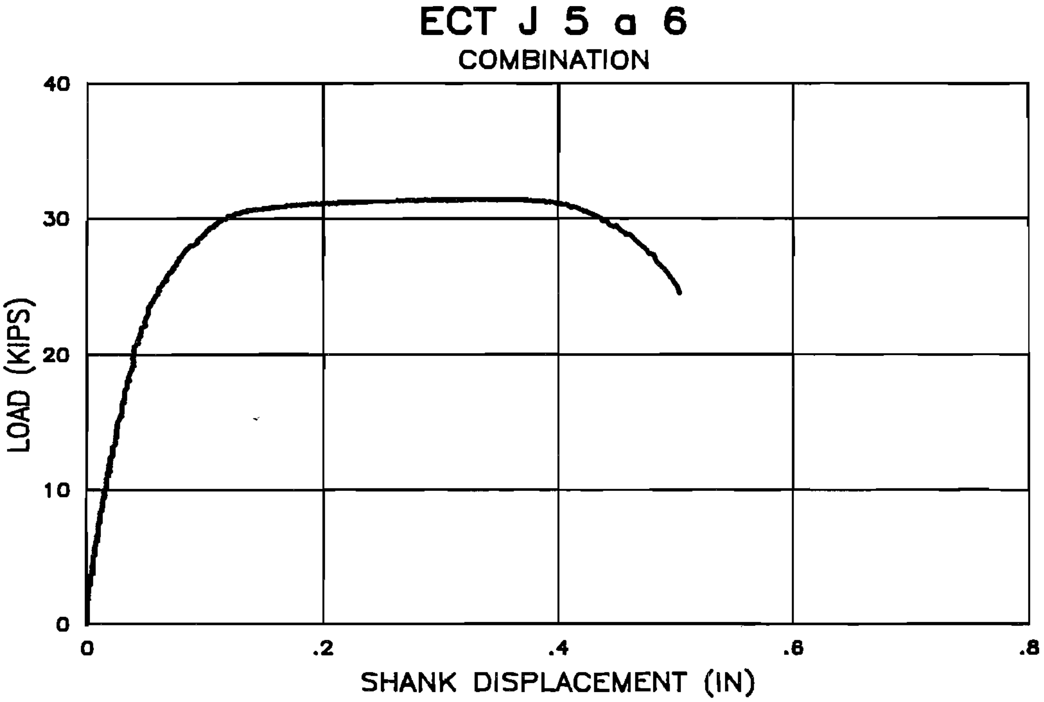
ECT I 5 a 6
COMBINATION

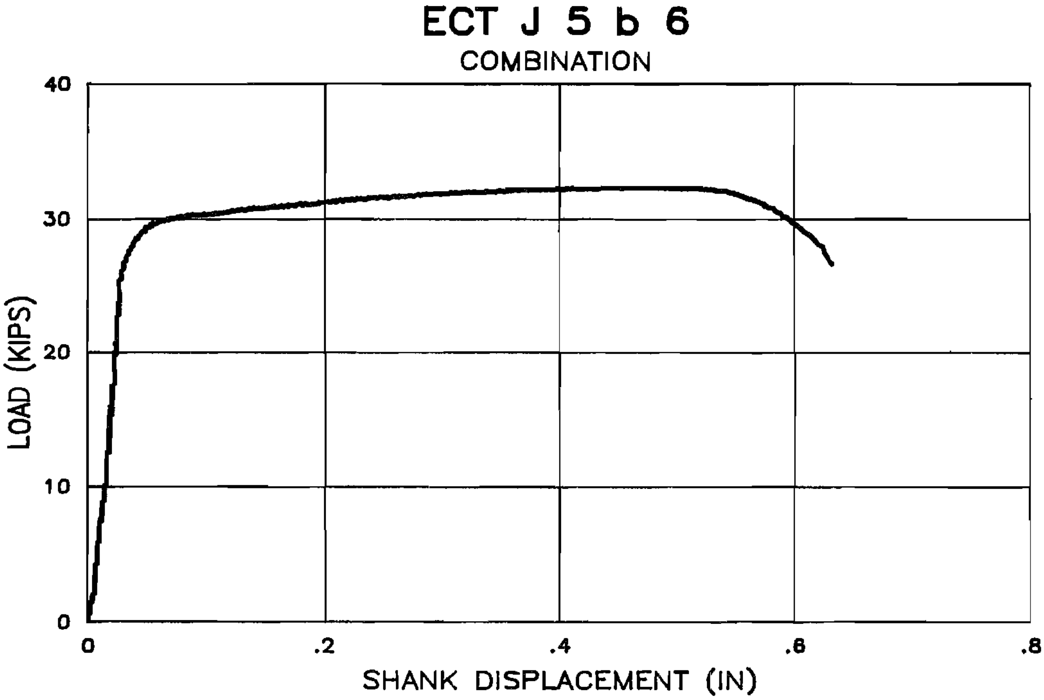


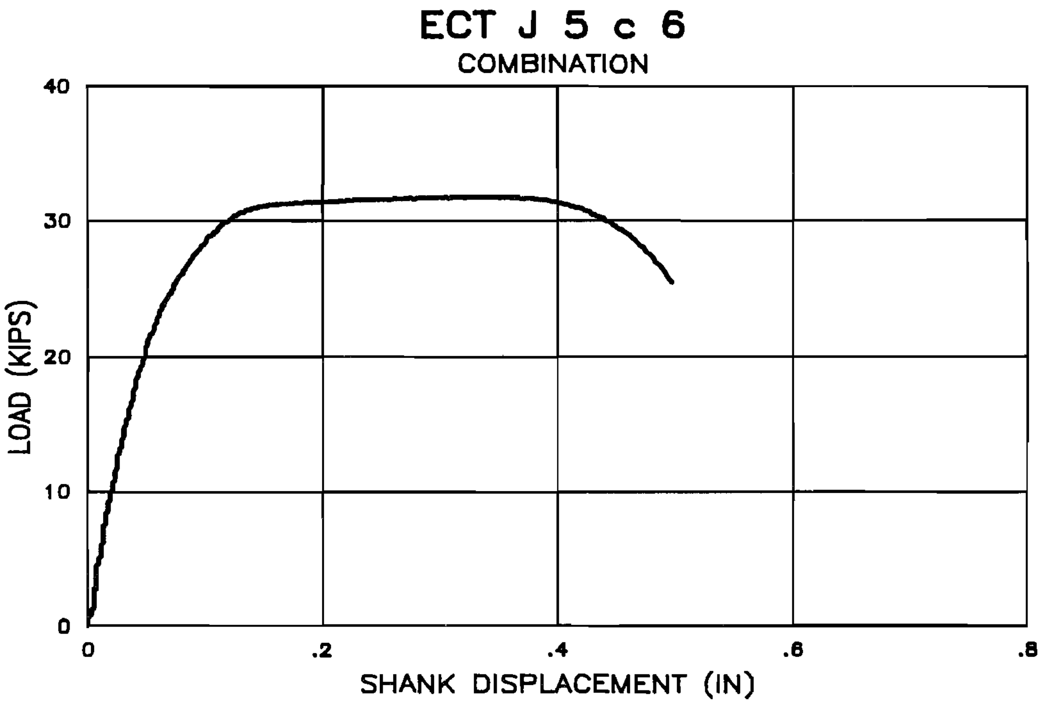
ECT I 5 b 6
COMBINATION

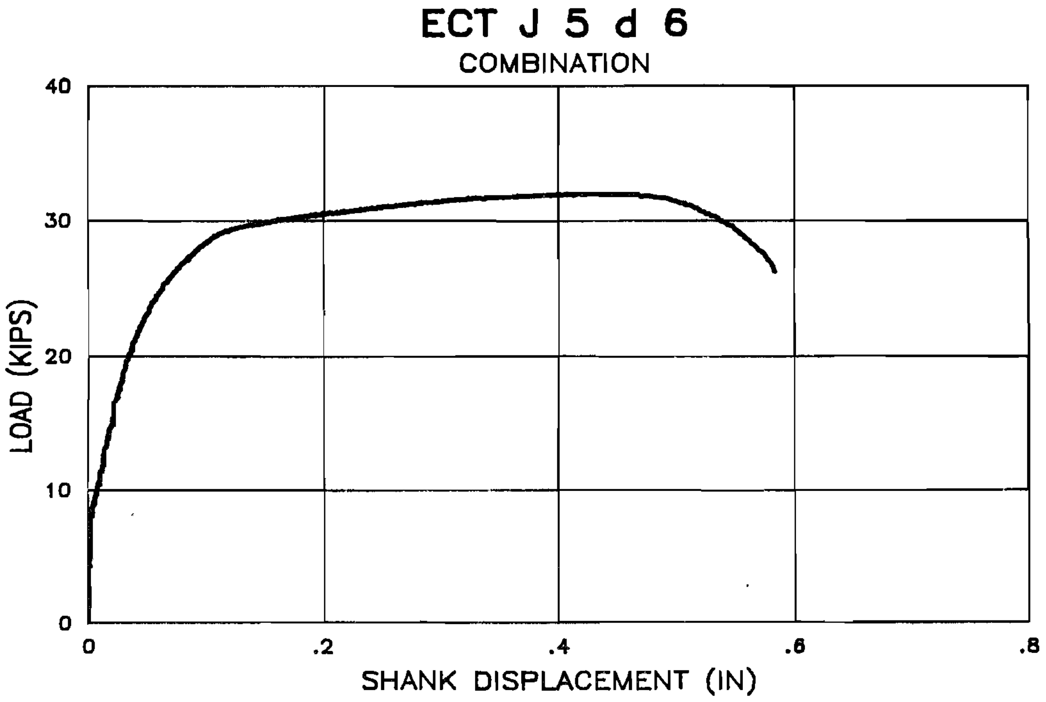

ECT I 5 c 6
COMBINATION

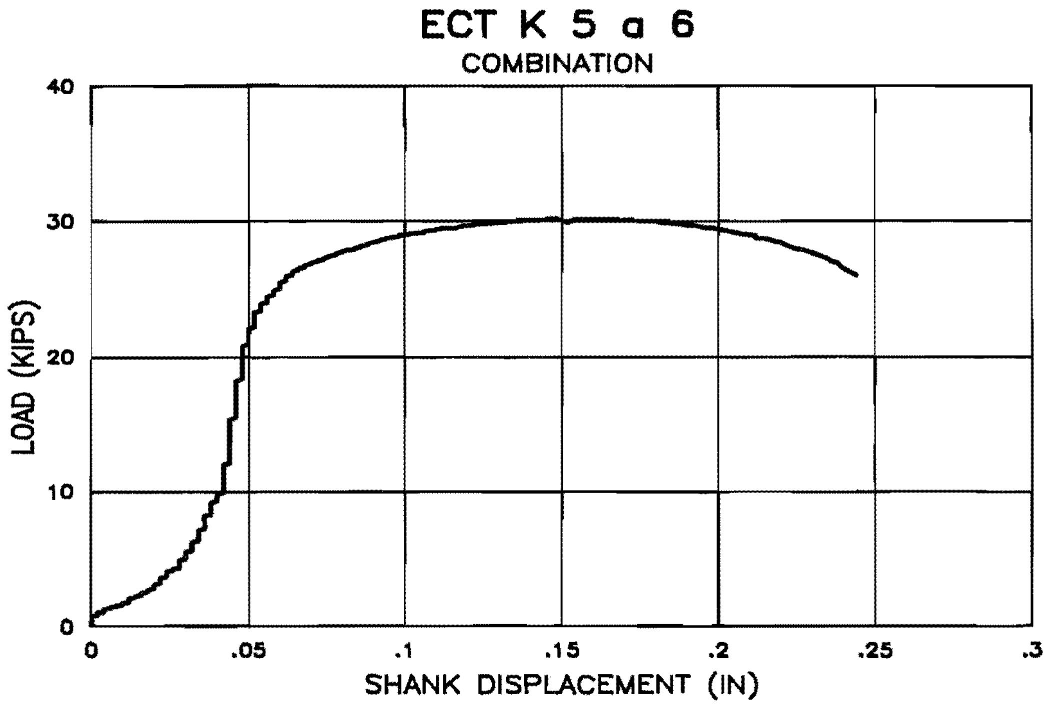

ECT I 5 d 6
COMBINATION

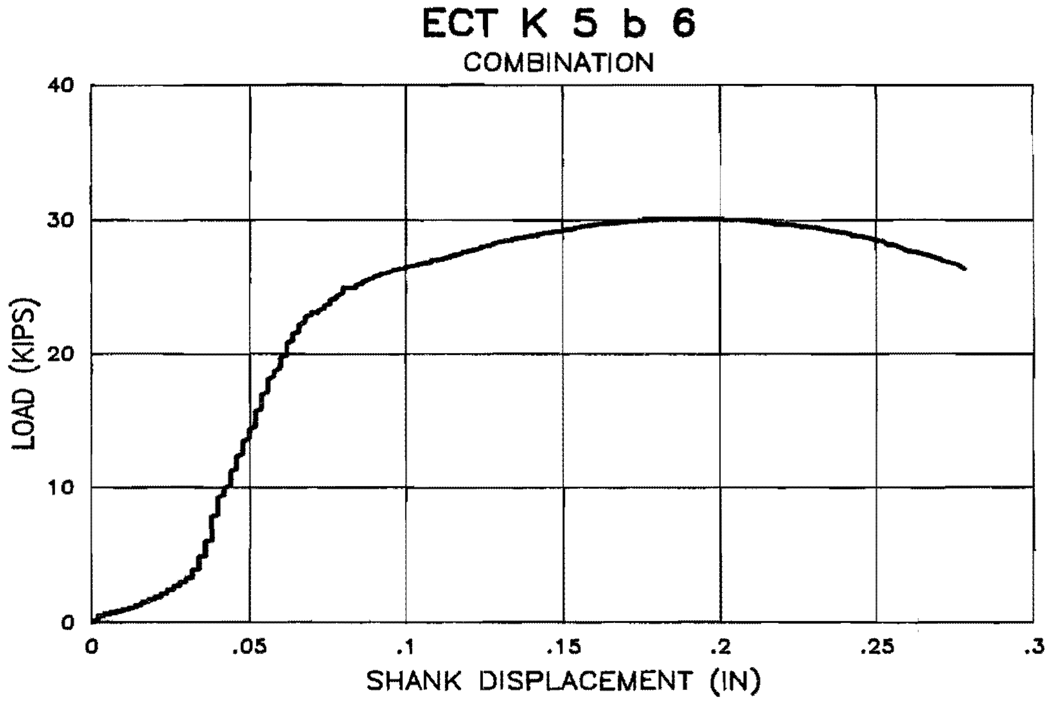

ECT J 5 a 6
COMBINATION
LOAD (KIPS)
40
30
20
10
0
0
.2
.4
.6
.8
SHANK DISPLACEMENT (IN)

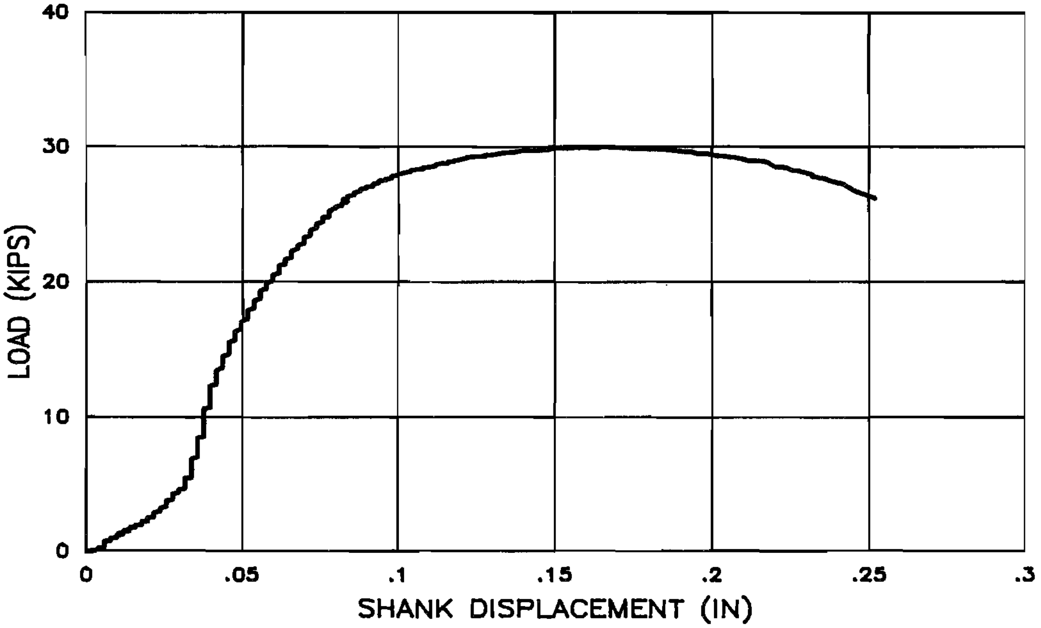

ECT J 5 b 6
COMBINATION
LOAD (KIPS)
40
30
20
10
0
0
.2
.4
.6
.8
SHANK DISPLACEMENT (IN)


ECT J 5 c 6
COMBINATION
LOAD (KIPS)
0
10
20
30
40
0
.2
.4
.6
.8
SHANK DISPLACEMENT (IN)

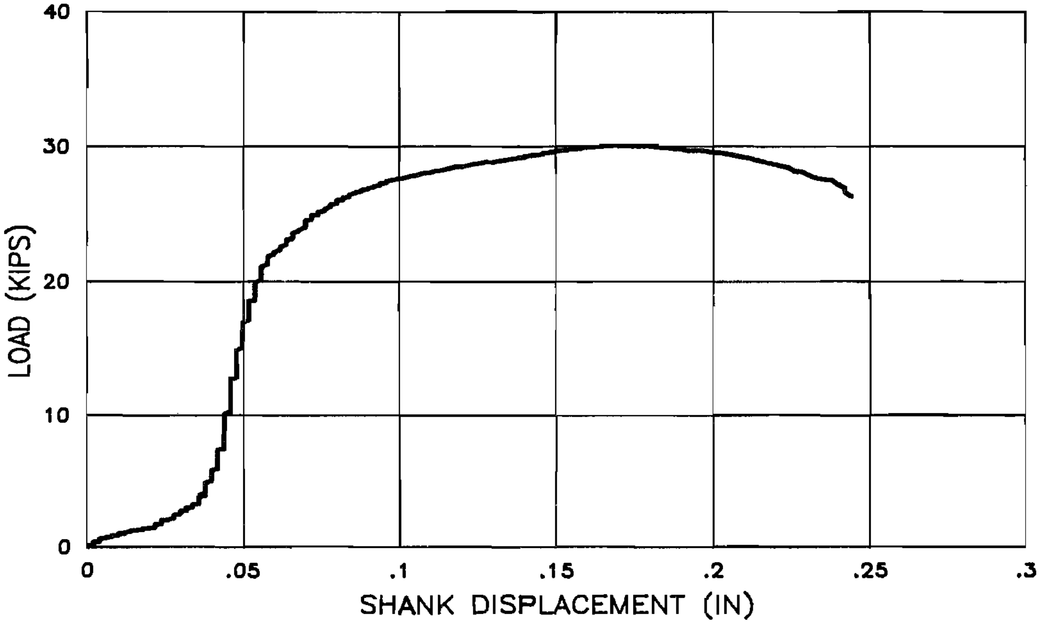

ECT J 5 d 6
COMBINATION
LOAD (KIPS)
0
10
20
30
40
0
.2
.4
.6
.8
SHANK DISPLACEMENT (IN)


ECT K 5 a 6
COMBINATION
LOAD (KIPS)
40
30
20
10
0
0
.05
.1
.15
.2
.25
.3
SHANK DISPLACEMENT (IN)


ECT K 5 b 6
COMBINATION
LOAD (KIPS)
40
30
20
10
0
0
.05
.1
.15
.2
.25
.3
SHANK DISPLACEMENT (IN)



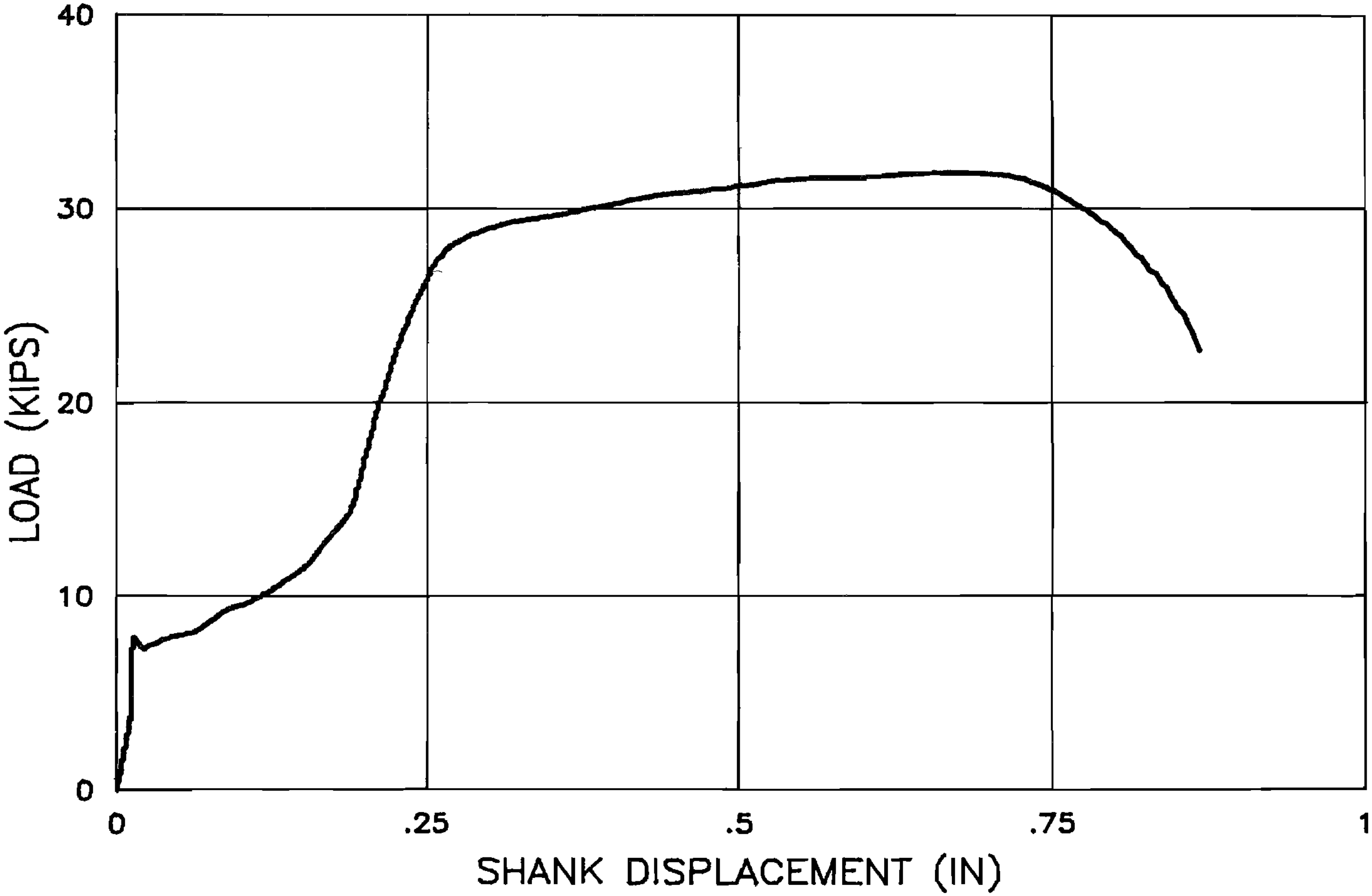
ECT K 5 c 6
COMBINATION

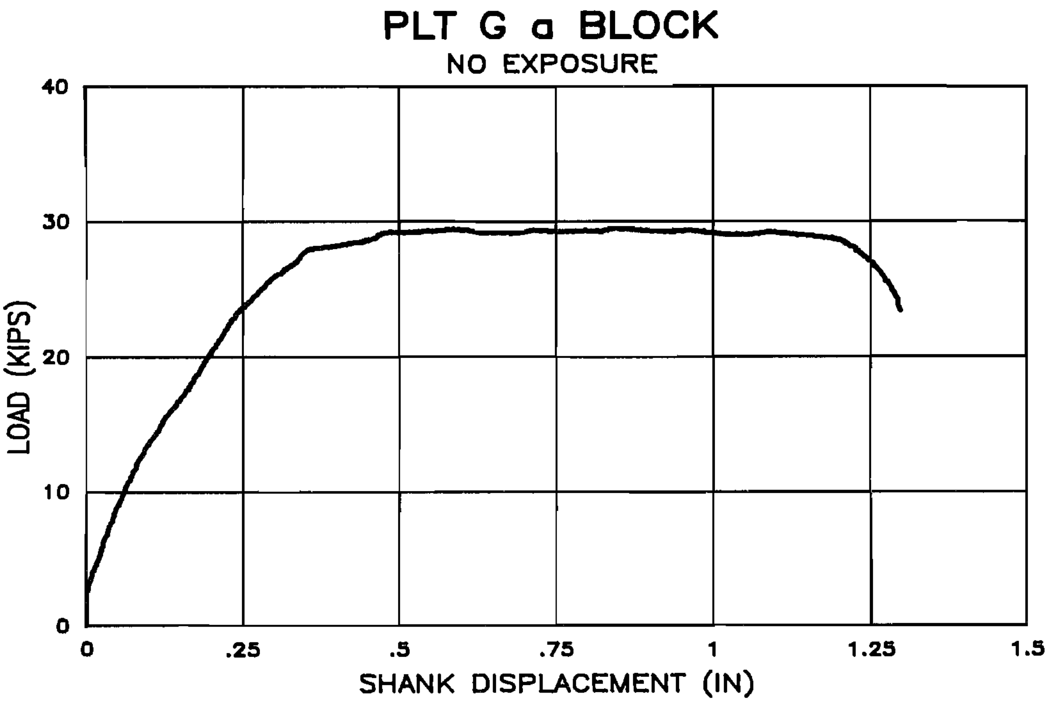


ECT K 5 d 6
COMBINATION

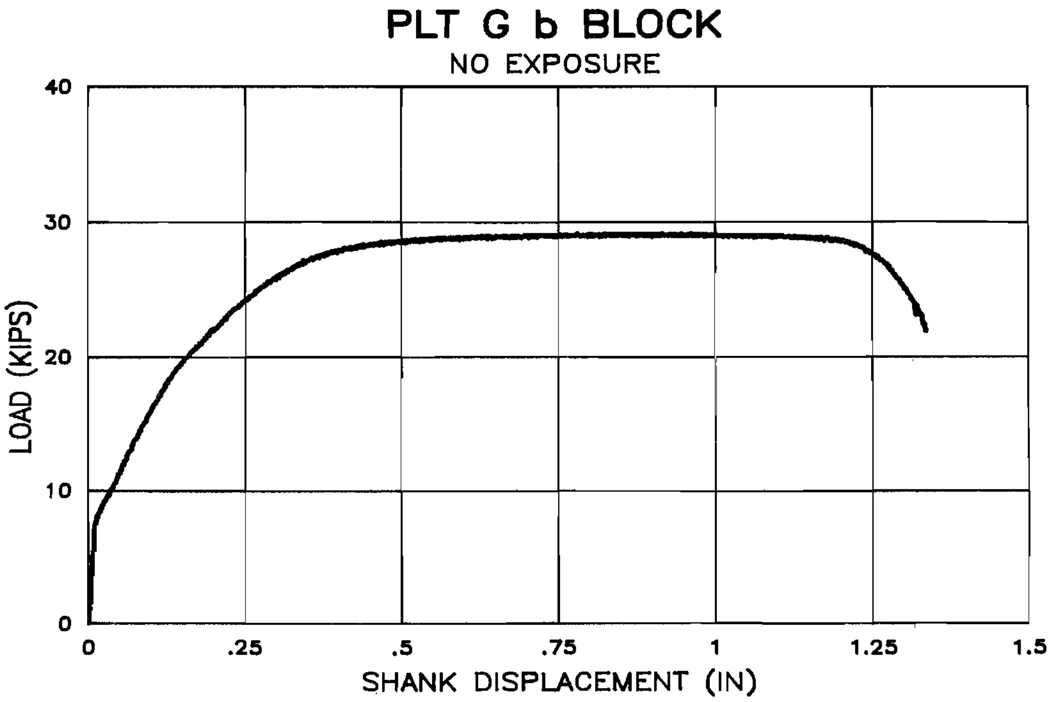
ECT H 4 c 6

ACID RAIN WETTING AND DRYING

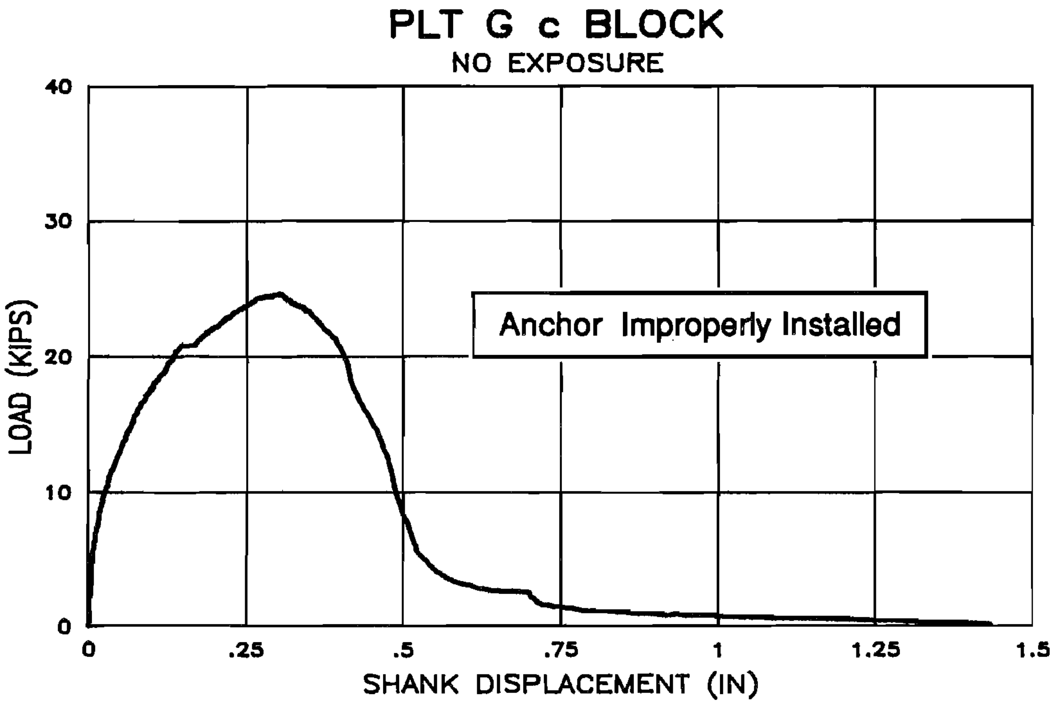


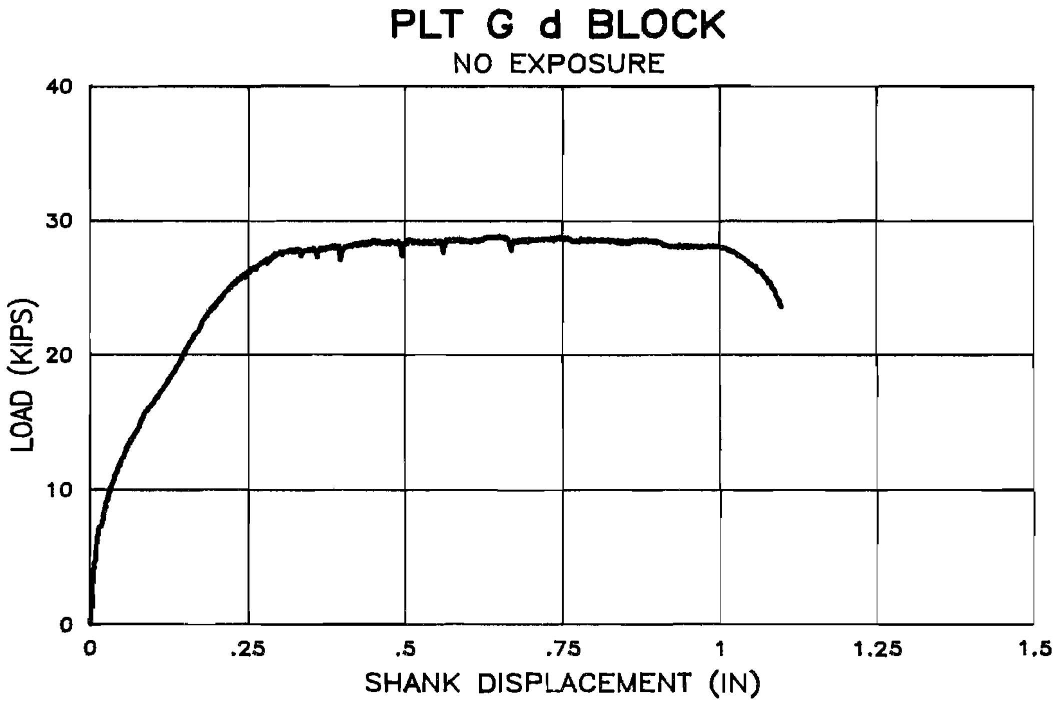


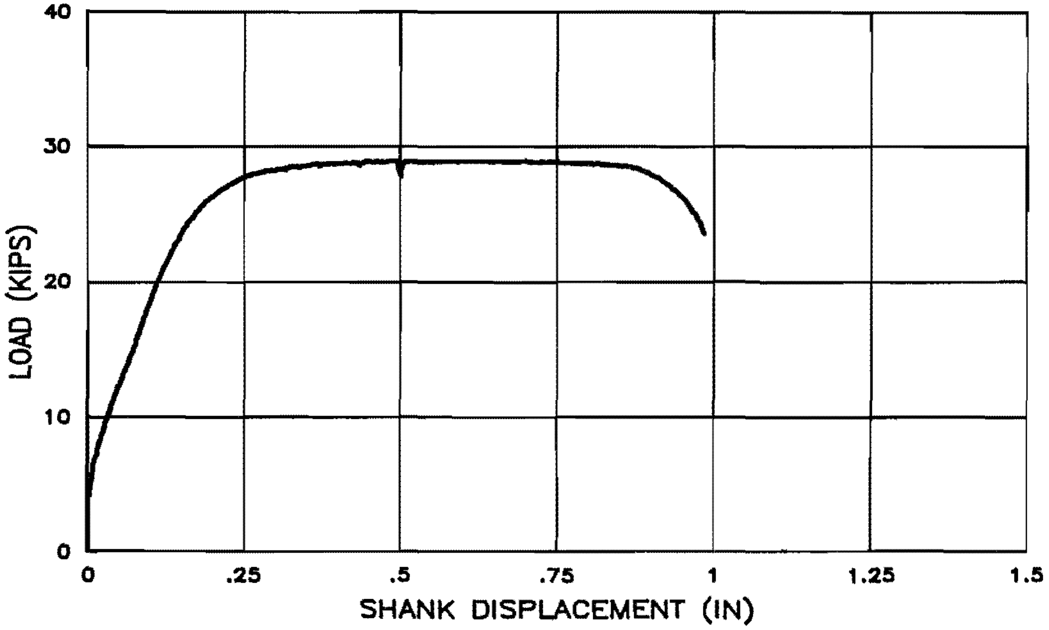
PLT G a BLOCK
NO EXPOSURE



PLT G b BLOCK
NO EXPOSURE

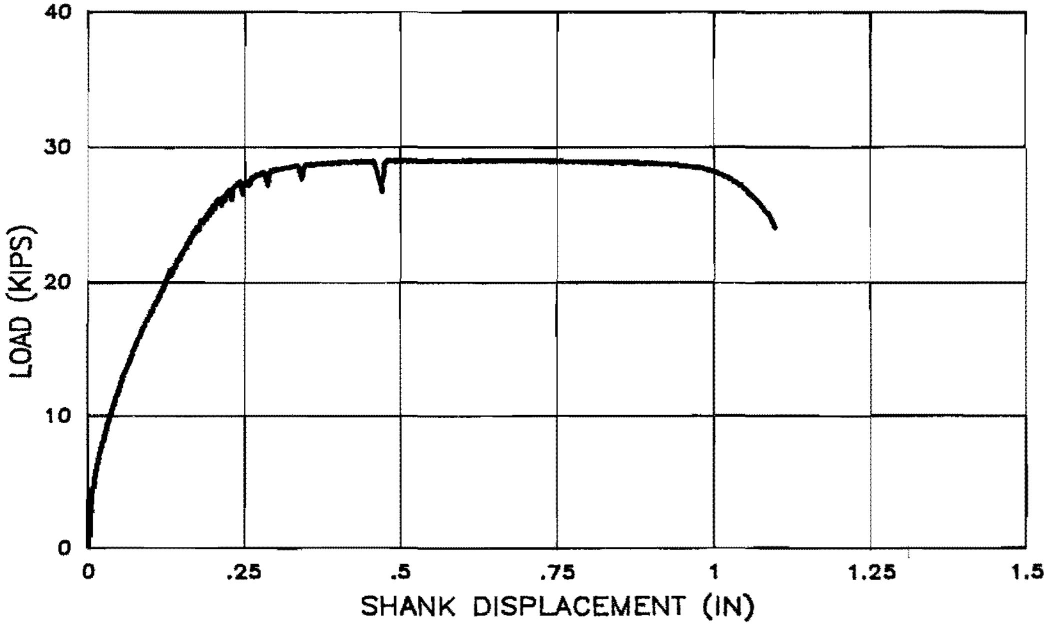

PLT G c BLOCK
NO EXPOSURE
Anchor Improperly Installed
LOAD (KIPS)
0
10
20
30
40
0
.25
.5
.75
1
1.25
1.5
SHANK DISPLACEMENT (IN)


PLT G d BLOCK
NO EXPOSURE
LOAD (KIPS)
0
10
20
30
40
0
.25
.5
.75
1
1.25
1.5
SHANK DISPLACEMENT (IN)



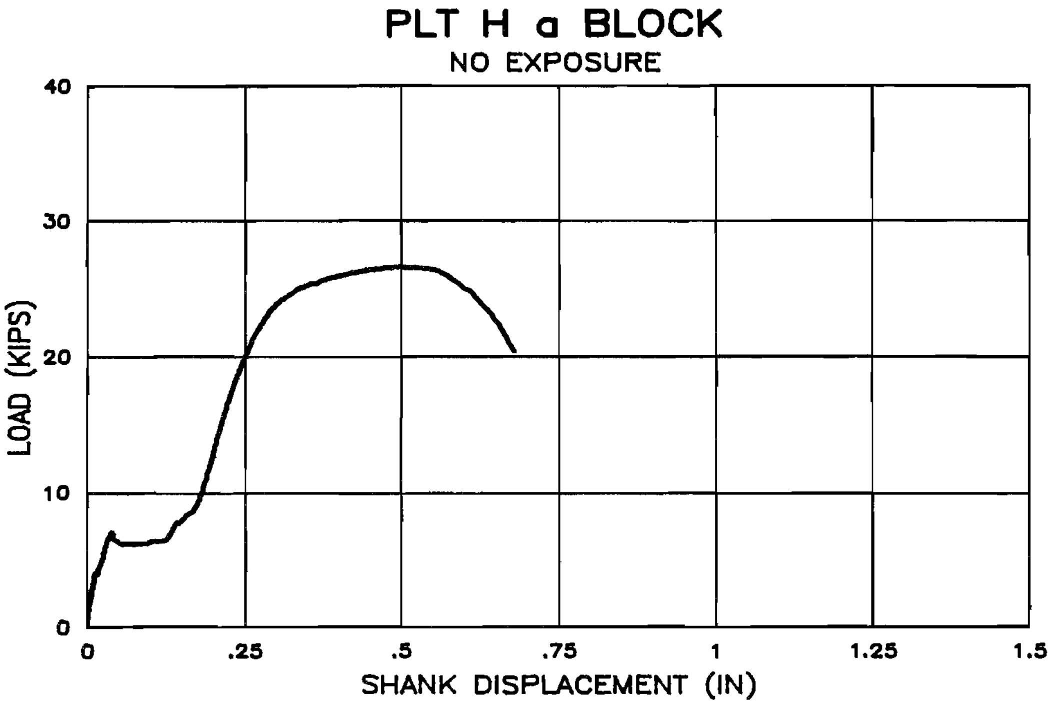
PLT G e 6

NO EXPOSURE



PLT G f 6

NO EXPOSURE


PLT H a BLOCK
NO EXPOSURE
LOAD (KIPS)
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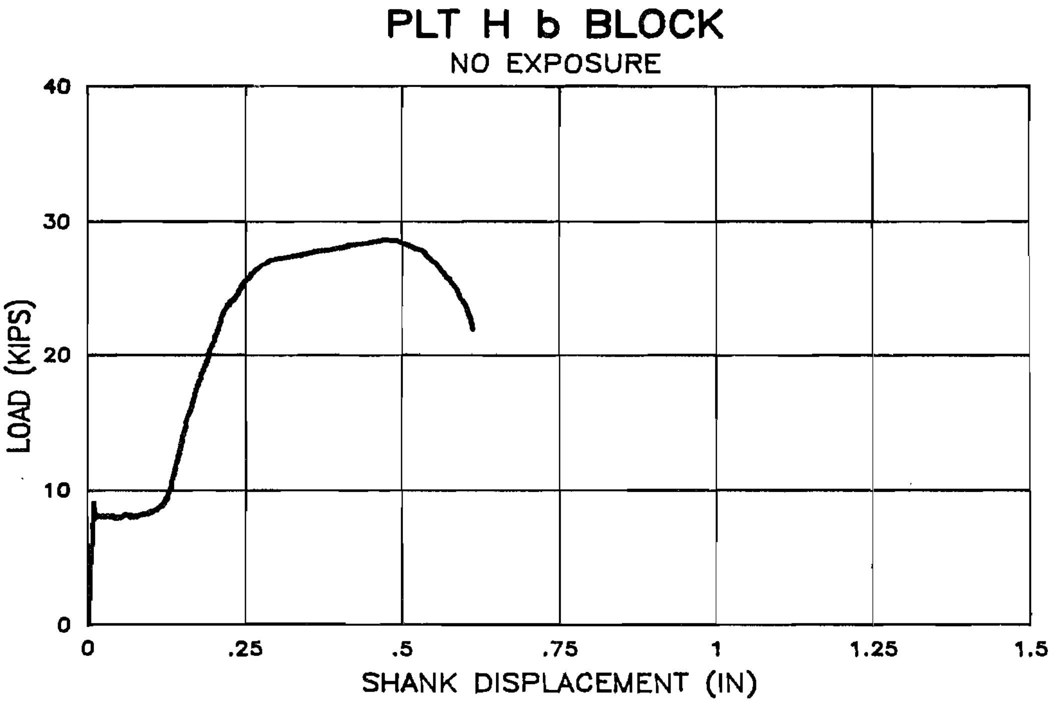
30
20
10
0
0
.25
.5
.75
1
1.25
1.5
SHANK DISPLACEMENT (IN)


PLT H b BLOCK
NO EXPOSURE
LOAD (KIPS)
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20
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0
0
.25
.5
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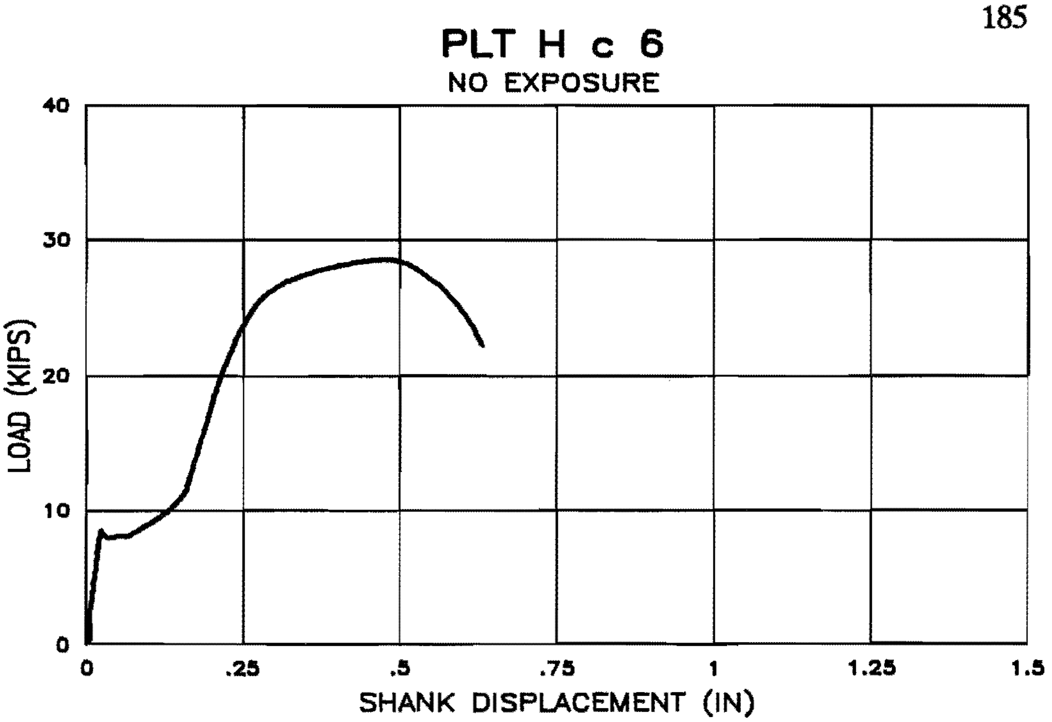
1
1.25
1.5
SHANK DISPLACEMENT (IN)


PLT H c 6
NO EXPOSURE
LOAD (KIPS)
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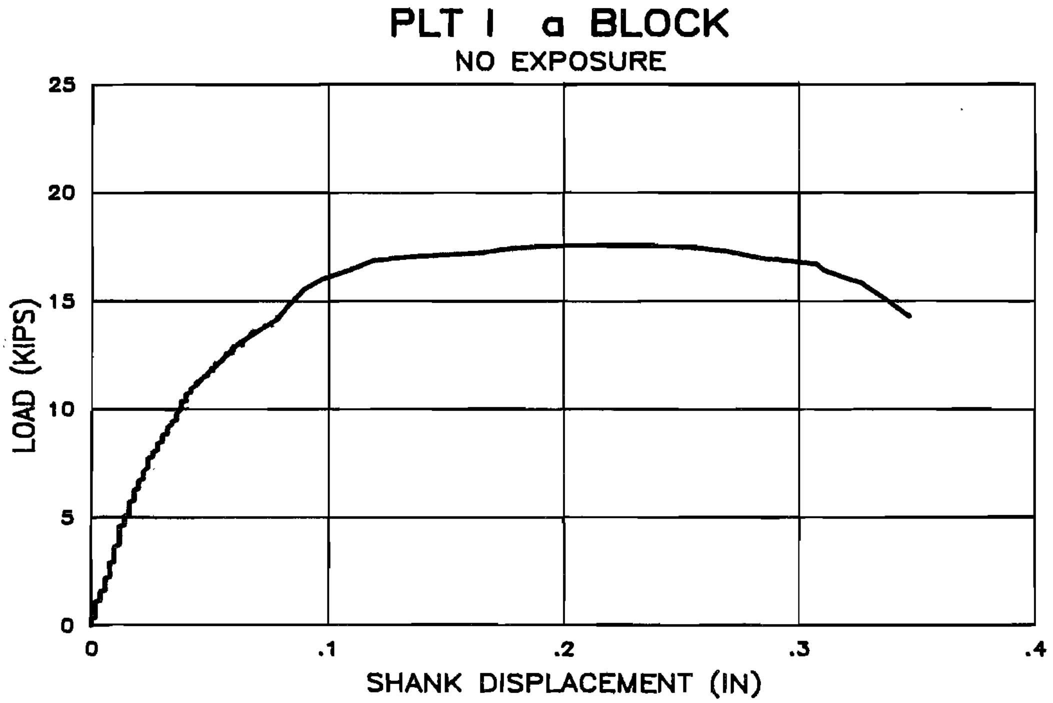
30
20
10
0
0
.25
.5
.75
1
1.25
1.5
SHANK DISPLACEMENT (IN)



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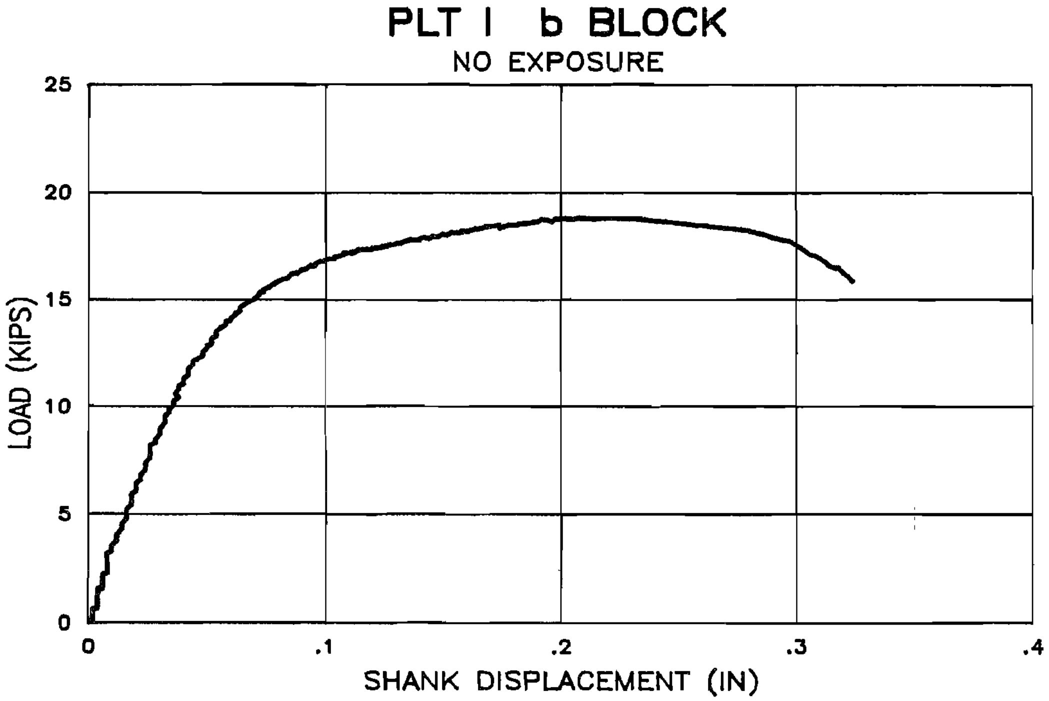

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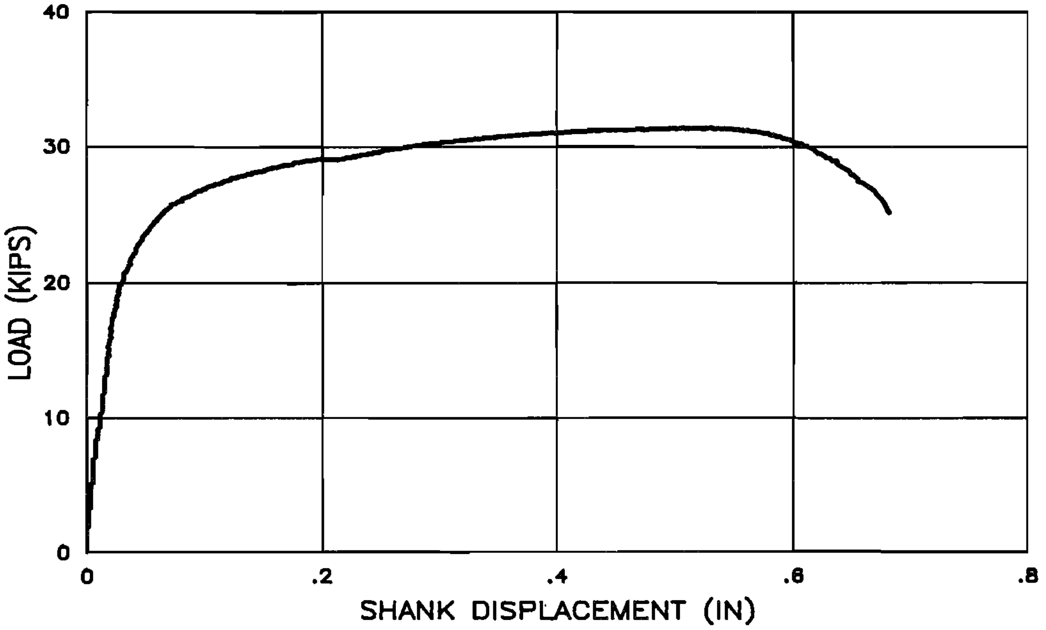

PLT J a BLOCK
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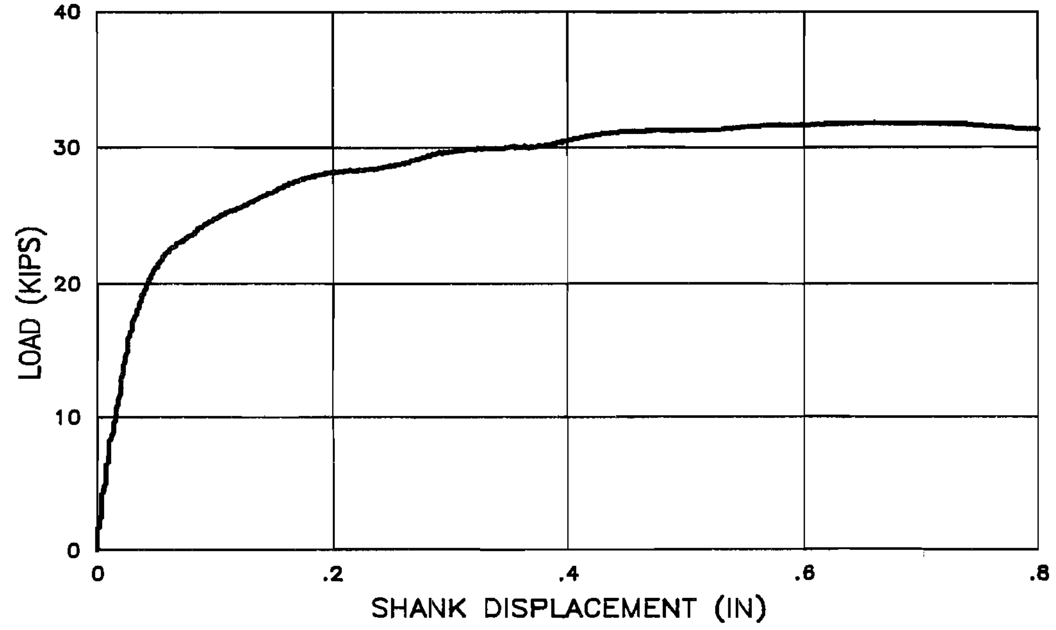

PLT J b BLOCK
NO EXPOSURE

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