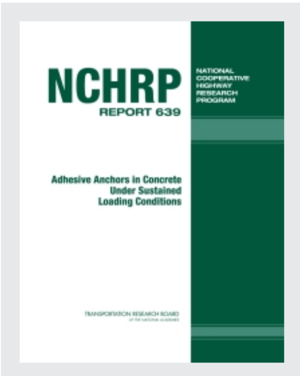

Adhesive Anchors in Concrete Under Sustained Loading Conditions

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 639

Adhesive Anchors in Concrete Under Sustained Loading Conditions

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Subject Areas
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TRANSPORTATION RESEARCH BOARD

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Dr. Ronald A. Cook, P.E., Professor of Civil Engineering at UF, was the Project Director and Principal Investigator. The other authors of this report were Dr. Elliot P. Douglas, Associate Professor of Materials Science and Engineering at UF, and Todd M. Davis, Research Assistant at UF. The work was done under the general supervision of Professors Cook and Douglas at UF.

FOREWORD

By Edward Harrigan
Staff Officer
Transportation Research Board

This report presents a test method recommended to determine an adhesive anchor's ability to resist sustained tensile loads. The report will be of immediate interest to public- and private-sector engineers with responsibility for the specification and use of adhesive anchor systems.

Adhesive anchor systems are commercial adhesives—often, but not exclusively, epoxy adhesives—used to anchor threaded metal rod and rebar into concrete. In many applications of these systems, the adhesive anchor is under a sustained tensile load, mandating the use of adhesives with strength and creep behavior appropriate to the load and expected service life, the anchor installation details, and the environmental conditions at the anchor.

The objective of this research was to develop a test method to determine the ability of adhesive anchors to resist sustained tensile load. This test method would build on current methods from AASHTO, ASTM, state departments of transportation, and other sources and would consider (1) the creep characteristics of the adhesive over the expected life of the structure, (2) site-specific ultimate strength requirements, and (3) the effects of temperature and moisture.

The research was performed by the University of Florida, Gainesville, Florida. The report fully documents a review and analysis of the highway engineering literature, agency specifications, and existing test methods applicable to the use of adhesive anchors under sustained tensile load and presents the results of a laboratory testing program to develop a recommended test method based on the stress versus time-to-failure approach. The recommended test method, which is presented in Appendix A in the form of a draft AASHTO standard, is under consideration for possible adoption by the AASHTO Highway Subcommittee on Materials.

CONTENTS

SUMMARY

Adhesive Anchors in Concrete Under Sustained Loading Conditions

The objective of this research was to develop a draft AASHTO standard test method to determine the ability of adhesive anchors to resist sustained tension load. The draft AASHTO test standard developed for this project is based on developing a stress versus time-to-failure interaction diagram for individual adhesive products. The interaction diagram (or simply a table) can be used to determine the percent of an adhesive's short-term design strength that is acceptable for use over the life of the structure. This research was divided into several phases: literature review, development of a testing procedure, demonstration and evaluation of the testing procedure, and conclusions and recommendations. The following is a summary of the report.

The current state of the art of adhesive anchors was investigated in the literature review. Extensive discussion was devoted to the behavior of adhesive anchors in concrete as well as the many factors that can affect their strength. Existing test methods for sustained load were investigated, and two approaches were identified to evaluate adhesive anchors: a pass/fail approach and a stress versus time-to-failure approach.

A review of the advantages and disadvantages of the two approaches led to the development of a draft test method for the evaluation of adhesive anchors in concrete under sustained loading conditions following the stress versus time-to-failure approach. This test method was evaluated by testing two adhesives. Static load tests were conducted to determine the mean static load and two sustained load (creep) test series were then conducted at reduced loads until failure.

A stress versus time-to-failure graph was created by plotting the data points, and a trendline was calculated from these points. The trendline relationship was used to generate a table of stress levels per adhesive for given structure lifetimes. This procedure generates a reduction factor due to sustained loads for a given structure lifetime.

Design procedures for adhesive anchors are not currently addressed in the AASHTO LRFD Design Specifications, but the reduction factor produced by this test method is consistent with an LRFD approach. The results of this study can be used in the development of comprehensive design criteria for adhesive anchors in AASHTO applications.

It was shown that the stress versus time-to-failure approach to evaluating adhesive anchors in concrete is a viable testing method. More research is necessary to validate this test method and to test for the other factors that may affect the long-term strength of adhesive anchors in concrete.

CHAPTER 1

Background

Introduction

The objective of this research was to develop a draft AASHTO standard test method to determine the ability of adhesive anchors to resist sustained tensile load. The research was divided into several phases: literature review, development of a testing procedure, demonstration and evaluation of the testing procedure, and conclusions and recommendations. The resulting draft AASHTO standard is presented in Appendix A.

This chapter summarizes the review of literature on adhesive anchors under sustained loads and presents possible test methods to assess the ability of adhesive anchors to resist sustained tensile loads under specific conditions of temperature and moisture. Information related to the following is provided:

- Behavior/design of anchors,
- Factors that influence the bond strength of adhesive anchors,
- Existing test standards for adhesive anchors under sustained loading conditions,
- Existing product evaluation standards for adhesive anchors under sustained loading conditions,
- Existing test standards for structural adhesives under sustained loading conditions,
- Other testing concepts related to sustained loads on adhesive anchors, and
- Proposed AASHTO test methods for evaluation of products for sustained loads.

Although information is provided on testing of the adhesive products alone, the majority of the information presented in this chapter relates to how to evaluate sustained load behavior of a particular adhesive product when installed in concrete. Although adhesive-only tests may be valuable in product development and perhaps in verification tests for products delivered to a job site, evaluation of products installed in concrete was considered to be of prime importance given the short-term scope of this project. If a sustained load evaluation procedure is implemented based on adhesive-only tests, then the question of what happens when the product is installed in concrete will not have been answered.

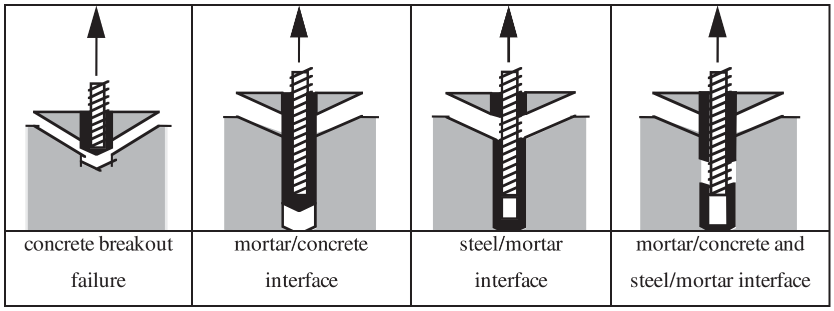
Behavior/Design of Anchors

A general review of the current behavior/design for anchoring to concrete is provided for background. Although the overall objective of this research was to provide an AASHTO standard for evaluation of adhesive anchor products for sustained loads, it was important to understand how the results of this evaluation could be applied in the design of adhesive anchors.

Current Standards for Anchoring to Concrete

Comprehensive design provisions for cast-in-place and post-installed mechanical anchors have been included in the American Concrete Institute's (ACI's) standards since the publication of ACI 318-02. Appendix D ("Anchoring to Concrete") of *ACI 318-05* (*1*) contains specific LRFD design criteria for connections designed using cast-in-place and post-installed mechanical anchors. Product approval for post-installed mechanical anchors is covered by the comprehensive product evaluation procedure in *ACI 355.Y: Qualification of Post-Installed Adhesive Anchors in Concrete* (Draft 5.0) (*2*). Although the design and product approval standards are not discussed here, it is important to note that these standards exist and could be incorporated into AASHTO standards in the future.

Design procedures for adhesive anchors are currently in the ACI 318 ballot process along with a comprehensive product evaluation standard addressing sustained loads that is in the ACI 355 ballot process. For adhesive anchors, the International Code Council Evaluation Service, Inc. (ICC-ES) *AC308* (*3*) is in place as an interim design/product approval standard and is intended to work with Appendix D of *ACI 318-05* (*1*) until the



Reprinted with permission from Cook et al. (*4*).

Figure 1. Potential embedment failure modes of bonded anchors.

ACI consensus review process is completed. These documents are discussed in this chapter. The definition of adhesive used in these adhesive anchor standards is the following:

> Any reactive adhesive comprised of chemical compounds (components) that react and cure when blended together. The adhesive compound may be formulated from organic polymer compounds, inorganic cementitious mortars, or a combination of organic and inorganic compounds. Organic adhesive materials include but are not limited to epoxies, polyurethanes, polyesters, methyl methacrylates, and vinyl esters. (*3*)

Behavior/Design of Adhesive Anchors

The behavioral model and resulting design procedures for adhesive anchors contained in *ICC-ES AC308* (*3*) and that are currently in the ACI ballot process have been under development for the past 15 years. Detailed information on single adhesive anchor behavior is presented in Cook et al. (*4*). Information on group and edge effects is presented in Eligehausen et al. (*5*). The following presents a general overview of the behavior/design model for single adhesive anchors.

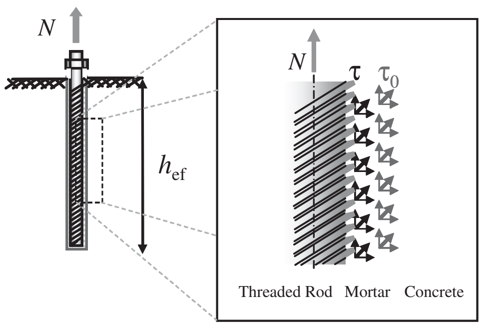
Figure 1 shows typical failure modes exhibited by bonded anchors. Figure 2 shows the mechanism for load transfer in bonded anchors (N = bond strength, τ = bond stress at the anchor, and τ_0 = bond stress at the edge of the hole). For adhesive bonded anchors with a hole diameter that does not exceed 1.5 times the anchor diameter and a ratio of embedment depth to anchor diameter not exceeding 20, the uniform bond stress model shown in Figure 3 and given by Equation 1 has been shown to be a valid behavioral model both experimentally and numerically. Equation 1 is the following:

$$\bar{N}_\tau = \bar{\tau}\pi d h_{ef} \quad (\text{lb or N}) \tag{1}$$

where

$\bar{N}_\tau$ = mean bond pullout strength in tension of a single anchor in uncracked concrete,
$\bar{\tau}$ = mean uniform bond strength at steel/mortar interface,
d = diameter of the anchor, and
h_{ef} = the effective embedment depth of anchor.

In Equation 1, the mean failure load is a function of the product's mean bond strength multiplied by the bond area calculated at the anchor diameter. As noted in Cook et al. (*4*), test samples in a worldwide database indicated that the hole size is less than 1.5 times the anchor diameter for adhesive anchor applications. For these typical adhesive anchor applications, it is not practical to establish two separate bond strengths, as shown in Figure 2. In fact, test data show that the uniform model works quite well when the bond stress is determined



Reprinted with permission from Eligehausen et al. (*5*).

Figure 2. Mechanism of load transfer of a bonded anchor.

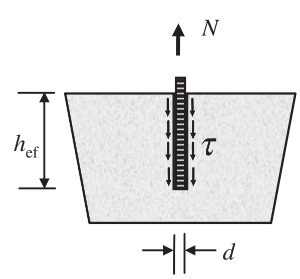


Figure 3. Uniform bond stress model for adhesive anchors.

from a series of product qualification tests by simply dividing the failure load by the bonded area calculated at the diameter of the anchor. Details of this use of the uniform model are provided in Cook et al. (*4*).

For design, the nominal bond strength of adhesive bonded anchors is dependent on the mean bond strength of anchors installed in accordance with manufacturer's guidelines, adjusted for scatter of the product's test results and for the product's sensitivity to installation and in-service conditions. As discussed in Cook and Konz (*6*), the bond strength of properly installed bonded anchor products varies considerably. Based on tests of 20 adhesive anchor products, Cook and Konz (*6*) found that the mean bond strength at the adhesive/anchor interface for individual products ranged from 330 psi to 2,830 psi.

Equation 2 provides the basic design relationship using LRFD design for a single adhesive anchor:

$$N_u \le \phi\left(\tau' \pi d h_{ef}\right) \quad (\text{lb or N}) \tag{2}$$

As shown by Equation 2, the factored tension load (N_u) would need to be less than the design strength determined as a capacity reduction factor (ϕ) multiplied by the nominal bond capacity. The nominal bond strength (τ') is the 5% lower fractile of mean bond strength adjusted for installation and in-service conditions.

The single anchor design model is provided for reference. Recommendations on how to incorporate the results of sustained-load tests on adhesive anchors into anchor design should be considered in developing the test standard. This incorporation could be as simple as including pass/fail criteria or it could result in the development of bond strength versus time-to-failure relationships.

Factors Influencing Bond Strength

While this research was focused on the ability of adhesive anchors to resist sustained tensile load at specified conditions of temperature and moisture, a general overview of many of the factors involved in adhesive anchor bond strength was beneficial to the development of the test standard (temperature and moisture effects will be addressed in more detail following this general discussion). As noted in several studies (*6, 7, 8*), there are many variables that affect the performance of adhesive anchors. Many of the common factors are listed below, grouped into four categories: in-service factors, factors related to the adhesive, installation factors, and factors related to the concrete. Each factor in the list is followed by a brief description; a more in-depth discussion of each factor follows the list. Most of the items in the list are incorporated into *ICC-ES AC308* (*3*), discussed later in this report.

In-service factors are the following:

- **Elevated temperature:** temperature when installed, temperature variations during the life of the structure, and effects of sustained elevated temperature.
- **Reduced temperature:** temperature when installed and brittleness associated with reduced temperature.
- **Moisture in service:** adhesive anchor subjected to dry, damp, or immersed conditions during the life of the anchor.
- **Freeze-thaw:** magnitude and frequency of freeze-thaw cycles.

Factors related to the adhesive are the following:

- **Type of adhesive:** e.g., epoxy-mercaptan, epoxy-amine, vinylester, polyester, or hybrid.
- **Mixing effort:** how well the constituent parts are mixed prior to installation.
- **Adhesive curing time when first loaded:** 24 hours, 7 days, 28 days, or longer.
- **Bond line thickness:** amount of space between the anchor and the sides of the hole.
- **Fiber content of adhesive:** type and proportion of fillers in the adhesive.
- **Chemical resistance:** alkalinity, sulfur, and other compounds.

Installation factors are the following:

- **Hole orientation:** downward, horizontal, and upward.
- **Hole drilling:** rotary hammer, core drill, or drilled in accordance with manufacturer's instructions.
- **Hole cleaning:** uncleaned, partially cleaned, or cleaned in accordance with the manufacturer's instructions.
- **Moisture in installation:** dry, damp, submerged, or installed in holes with moisture limitation conditions in accordance with manufacturer's instructions.
- **Depth of hole (embedment depth):** effects of the depth of the anchor on bond strength and type of failure.

Factors related to the concrete are the following:

- **Type of concrete:** Portland cement only or Portland cement with blast furnace slag, fly ash, or other additives.
- **Concrete strength:** low compressive strength and high compressive strength
- **Type of coarse aggregate:** mineralogy, absorptions, and hardness (affects hole roughness).
- **Cracked or uncracked concrete:** the effect of the presence of cracks on bond strength.

In-Service Factors

In-service factors that affect bond strength are described below.

Elevated Temperature. According to Messler (*9*), "the greatest shortcoming of many structural adhesives is their limited tolerance of elevated temperature." However, adhesives with an open-ring structure (polyimidazoles and substituted imidazoles) that closes under high temperatures become stronger. Messler further adds that it is important to measure an adhesive's resistance to creep under sustained loading conditions, especially if exposed to high temperature.

According to Adams and Wake (*10*), adhesive anchor systems with sustained loads at a temperature 18°F above the adhesive's heat deflection temperature will exhibit significant creep. Experimental tests in Dusel and Mir (*11*) confirm this; Dusel and Mir explain that the adhesive will "soften and become rubbery" above its glass transition temperature (comparable to heat deflection temperature), and its bond strength will decrease.

Reduced Temperature. While not as significant as elevated temperature, reduced in-service temperatures can make adhesives more brittle (*12*). Currently, *ICC-ES AC308* (*3*) has a reduced-temperature test only during installation. The commentary for *ACI 355.Y* (*2*) mentions that reduced temperature during installation increases viscosity and retards the cure time of adhesives.

Moisture in Service. While it has been widely known that the presence of moisture during the installation of the adhesive affects bond strength, a recent study conducted at the National Institute of Standards and Technology (NIST) indicates that the presence of moisture after curing can also affect the creep resistance of an anchor (*13*). The thermo-viscoelastic analysis on ambient cure epoxy adhesives used in construction conducted by Chin et al. (*13*) determined that the presence of absorbed moisture after curing can create the same creep-type behavior commonly seen in high temperature conditions.

Cognard (*12*) mentions that water can degrade adhesives in three ways: (1) penetrate into the adhesive and soften it, (2) penetrate between the adhesive and the substrate and thereby destroy the adhesion, and (3) penetrate into porous substrates causing swelling and detrimental movements. Cognard (*12*) also recommends that water resistance tests should be performed when the bonds will be subject to moisture during the life of the product.

Freeze-Thaw. It is well established that the expansion and contraction of materials due to temperature changes and the expansion of water when it freezes tend to disrupt the equilibrium/compatibility of structural systems. Adhesive anchor systems need to be tested for their susceptibility to freeze-thaw action.

Factors Related to the Adhesive

Factors related to the adhesive that affect bond strength are described below.

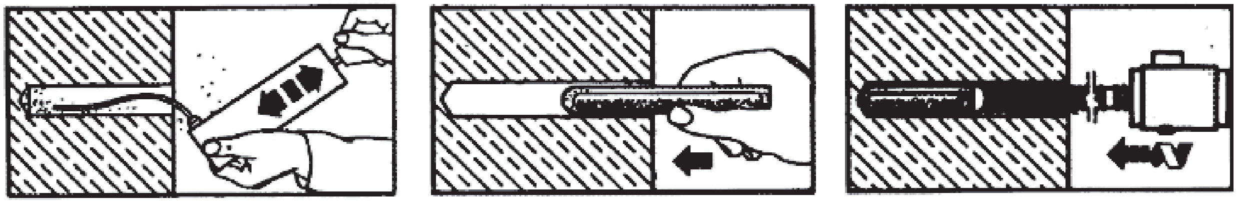
Type of Adhesive. According to Cook and Konz (*6*), adhesives can vary significantly among chemical groups and even within chemical groups. It was also noticed that on average epoxy-based adhesives had higher bond strengths than ester-based adhesives.

ASTM C881/C 881M-02 (*14*) classifies seven types of epoxy-resin bonding systems, specifying as Type IV those that are for use in load-bearing applications for bonding hardened concrete to other materials.

Fourier Transform Infrared Spectroscopy (FTIR) is one test method that can be used to chemically characterize an adhesive, as shown in the Massachusetts Institute of Technology (MIT) report to NTSB (*15*) on the adhesives from the Boston Tunnel collapse. The results of this type of test can be used to investigate correlations in the chemical make-up of an adhesive and its bond strength.

Mixing Effort. Bond strength is dependent on the proper composition of the adhesive. Adhesive systems come in components that need to be mixed thoroughly and in the proper proportions prior to installation. Some systems are designed to guarantee proper proportions and thorough mixing, and some are solely dependent on the installer. Common systems include the following:

- **Glass and foil capsule systems.** These systems contain specific amounts of polymer resin, accelerator, and a mineral aggregate. The capsules are placed in the hole, and the anchor (with a chiseled end) is set with a hammer drill that bores through the capsule and thereby mixes the adhesive. See Figure 4 for a typical capsule anchor system.
- **Injection systems.** These systems typically include plastic tubes of resin and hardener. The components are commonly mixed in a special nozzle as they are dispensed. The adhesive is injected into the hole, and the anchor is installed afterwards. The anchor is usually rotated slowly during installation to prevent the formation of air bubbles that result in voids in the adhesive. See Figure 5 for a typical injection anchor system.
- **Other systems.** These systems include pouches containing components that are mixed manually and then dispensed into the hole. It is also possible to purchase the components separately and mix them manually.



Reprinted with permission from Cook et al. (*4*).

Figure 4. Typical capsule anchor system.

Whatever system is used, it is important that the components are mixed thoroughly and in the proper proportions. Manufacturers typically recommend mixing until the mixture reaches a certain consistency and a consistent color. The adhesive must completely fill any voids between the anchor and the sides of the holes because the presence of any voids will reduce the effective area that resists the bond stress.

Adhesive Curing Time When First Loaded. According to Cook and Konz (*6*), the duration of adhesive curing affects bond strength. Adhesives were tested at 24 hours and 7 days of cure time. Most anchors showed a decrease in bond strength over a shorter adhesive cure time; the average bond strength for anchors with a 24-hour cure was 81% of the bond strength of anchors with a 7-day cure.

Bond Line Thickness. Current data on bond line thickness are not conclusive. According to Colak (*16*), the smaller the dimension between the anchor and the side of the hole, the lower the potential for creep. Similarly, Section 2.3.7 of *ACI 503.5R-92* (*17*) and another study by Colak (*18*) mention that creep resistance can be increased by decreasing the bond line thickness of the adhesive. Nonetheless, according to Krishnamurthy (*19*), the bond line thickness does not significantly affect the capacity of the anchor.

Fiber Content of Adhesive. Section 2.3.7 of *ACI 503.5R-92* (*17*) and Çolak (*18*) mention that creep resistance can be increased by increasing the fiber content of the adhesive.

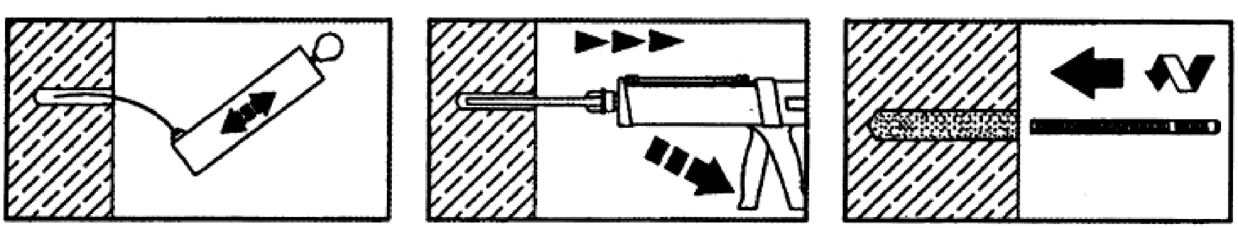
Chemical Resistance. Cognard (*12*) confirms that chemicals, oils, greases, and other compounds can penetrate the adhesive and degrade the adhesion with the anchor or the concrete thereby causing a bond failure. Adhesives should be tested for their sensitivity to various compounds.

Installation Factors

Factors related to installation that affect bond strength are described below.

Hole Orientation. The orientation of the hole can significantly affect the performance of adhesive anchors. Vertical or upwardly inclined holes prove difficult to fully fill with adhesive, as the adhesive will tend to run out of the hole. The subsequent voids reduce the bond area between the adhesive and the anchor and/or the concrete, and a smaller bond area will significantly reduce bond strength. The Florida Department of Transportation (FDOT), in Section 1.6 of its *Structures Design Guidelines* (*20*) and Section 937 of its *Standard Specifications for Road and Bridge Construction* (*21*), prohibits installation of adhesive anchors in overhead or upwardly inclined holes for the reason mentioned above.

Hole Drilling. The two common methods of hole drilling involve diamond-core drill bits, which produce a very smooth-sided hole, or carbide-tipped hammer drill bits, which produce a rough-sided hole. Since one of the ways the adhesive bonds with the concrete is by mechanical interlock, it has been thought that a rough-sided hole would provide a better bond. The results of a 2005 study in which tests were conducted on adhesive anchors in concrete with different coarse aggregate types confirmed that increased surface roughness did increase bond strength (*22*).



Reprinted with permission from Cook et al. (*4*).

Figure 5. Typical injection anchor system.

Hole Cleaning. According to Cook and Konz (*6*), the cleanliness of the hole has a significant impact on bond strength, as dust created during the drilling operation can interfere with the adhesive/concrete bond surface. Tests were performed in which some holes were cleaned with compressed air and a non-metallic brush. In holes that were not cleaned, the average bond stress was 71% of the bond stress of the cleaned holes (with a range of approximately 20% to 150%) and had an average coefficient of variation (COV) of 20%.

The type of brush used for cleaning is also significant. Section 416 of FDOT's *Standard Specifications for Road and Bridge Construction* (*21*) requires cleaning with a non-metallic brush because metallic brushes tend to polish the sides of the holes, thereby reducing the ability of the adhesive to create mechanical interlock with the sides of the hole.

Moisture in Installation. According to Cook and Konz (*6*), the dampness of the hole significantly affects bond strength in two ways. First, dampness in the hole can restrict the entrance of adhesive into the pores of the concrete and thereby reduce mechanical interlock. Second, moisture can interfere with the chemical reaction between the hardener and the resin.

It was demonstrated that anchors installed in damp holes (wet surface) produced an average of bond strengths for 20 products of 77% (with a range of approximately 20% to 150%) compared to a dry installation. Anchors installed in wet holes (standing water) produced an average bond strength of 43% (with a range of approximately 10% to 160%) compared to the dry installation (*6*).

Depth of Hole (Embedment Depth). Increasing the depth of the hole does have a slight impact on bond strength up to a point. According to Krishnamurthy (*19*), the load increases proportionally up to a limit of h_{ef}/d of 25, beyond which there is no significant increase.

Factors Related to the Concrete

Factors related to the concrete that affect bond strength are described below.

Type of Concrete. The concrete mix design can affect the bond strength of the adhesive anchor. This includes, but is not limited to, the type of cement, mix proportions, and the types of additives (air entrainment, plasticizers, fly ash, and blast furnace slag).

Concrete Strength. According to Cook and Konz (*6*), there was no correlation between bond strength and concrete strength among the adhesives tested. As concrete strength was increased, some adhesives showed an increase in bond strength, and others displayed a local maximum or minimum.

Type of Coarse Aggregate. Cook and Konz (*6*) determined through lab testing that the type of coarse aggregate plays a factor in bond strength. Additionally, tests conducted by Polymer Solutions Incorporated (*23*) show that the mineralogy of the aggregate also affects bond strength. Of all the samples tested, concretes that used calcium-rich aggregates such as limestone failed at the lowest anchor loads. Concretes that used aggregates with high silicon content failed at relatively higher loads, although the findings were not conclusive.

Cook and Jain *(22)* conducted tests on adhesive anchors in concrete with different coarse aggregate types. It was observed that adhesive anchors installed in concretes with harder coarse aggregates produced higher bond strengths. It was concluded that the harder aggregates created rougher surfaces when the holes were drilled or cored for the anchor. The rougher surface thereby increased bond strength.

Cracked or Uncracked Concrete. Research by Eligehausen and Balogh (*24*) shows that cracked concrete can have a significant impact on adhesive bond strength. The researchers point out that anchors in concrete, or the holes in the concrete created for adhesive anchors, will attract or even induce cracks at the anchor/hole location. Cracks in the concrete at an anchor will then tend to break down the bond between the concrete and the adhesive. The research findings of Fuchs et al. (*25*) and Eligehausen and Balogh show that bond strength in cracked concrete can vary from 33% to 70% of the bond strength in uncracked concrete. Similarly, Meszaros (*26*) estimates that bond strength in cracked concrete is approximately 50% of bond strength in uncracked concrete. See Figure 6 for an illustration of a crack in a typical adhesive anchor application.

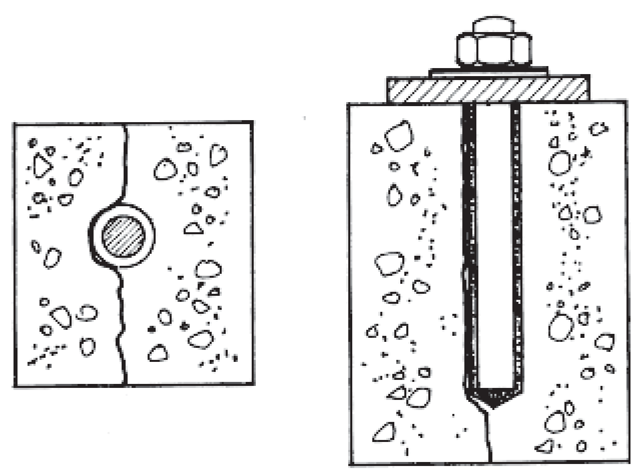


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Figure 6. Typical crack location of bonded anchor.

Synergistic Effects

The factors mentioned above are typically considered independently; however, a combination of factors can have amplified effects. According to Messler (*9*), the combination of several climatic factors can be particularly severe. Adhesive anchors historically have not been tested for moisture and temperature combinations. *ASTM D1151-00* (*27*) provides a standard for testing adhesives under different temperature and humidity exposures.

Provisions of Current Standards for Factors Influencing Bond Strength

The *ICC-ES AC308* (*3*) product evaluation provisions are currently being balloted by ACI Committee 355 for an ACI-approved consensus review standard. *ICC-ES AC308* provides a very comprehensive testing program to evaluate the performance of adhesive anchor products for all of the factors listed above that influence bond strength with the exception of in-service moisture conditions. Table 1 presents Table 4.2 of *ICC-ES AC308,* showing the types of tests required for product approval.

Figure 7 presents Equation 11-12 of *ICC-ES AC308* (*3*). In this equation, the characteristic bond strength (i.e., 5% fractile of baseline static load tests) is reduced by a series of factors to account for the factors influencing bond strength for use in design (i.e.,τ' in Equation 2 of this report). The objective of this research is to determine what additional reduction factor needs to be applied to account for long-term loads in AASHTO applications.

Test Standards Related to Sustained Loads on Adhesive Anchors

This section discusses two test standards related to sustained loads on adhesive anchors: *ASTM E488-96 Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements* (*28*) and *ASTM E1512-01 Standard Test Methods for Testing Bond Performance of Bonded Anchors* (*29*).

ASTM E488-96 Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements

Background

ASTM E488-96 (*28*) provides the fundamental test procedure for static tests on concrete anchors. The procedure serves as the basic building block and is either adopted in full or slightly modified by governing agencies. Figure 8 and Figure 9 show typical test setup apparatuses for a static test.

Test Procedure

ASTM E488-96 (*28*) covers various tests for concrete anchors, and Section 8 of the standard presents the procedure for the static test. This procedure tests five anchors per size and averages their results. The specimens are placed in holes drilled in concrete with a hole diameter no greater than 1.5 times the anchor diameter. The concrete is conditioned to 73°F and 50% relative humidity. The anchors are initially loaded to 5% of the estimated maximum capacity in order to set the anchor and the testing equipment.

The final load is applied until failure according to two loading rate options, continuous or incremental. The continuous load rate applies the load at a uniform rate of 25% to 100% of the mean anchor capacity per minute. The load must be applied within 1 to 3 min. The incremental load rate applies the load in steps not exceeding 15% of the maximum estimated test load, and each incremental load is held constant for 2 min.

ASTM E1512-01 Standard Test Methods for Testing Bond Performance of Bonded Anchors

Background

ASTM E1512-01 (*29*) provides the fundamental test procedure for many different tests on adhesive bonded anchors in concrete. As with *ASTM E488-96* (*28*), these test procedures serve as basic building blocks and are either adopted in full or slightly modified by governing agencies. The tests described below use test setup apparatuses similar to those shown in Figure 8 and Figure 9.

Test Procedure

ASTM E 1512-01 (*29*) covers many different tests for adhesive anchors, and Section 7.4.8 presents the creep test. The creep test includes three test series. A series has the following requirements:

- Either restrained (confined) or unrestrained (unconfined) test, but all test series shall be the same.
- Three 0.5-in. diameter rods embedded 4.5 in. in concrete.
- Concrete of the same mix design in all series with compressive strength between 2,500 psi and 3,500 psi at the time of the static load test and the start of the creep tests.
- Concrete cured for 28 days.
- Anchors installed at 75°F ±10°F.
- Anchors cured at 75°F ±10°F for 7 ±5 days before the beginning of the test.

Static Tension Test Series at 75°F ±10°F. This test series conducts a static load test in order to determine the mean static load used in later test series.

Table 1. Table 4.2 from ICC-ES AC308.

Table 4.2– Test program for evaluating adhesive anchor systems for use in cracked and uncracked concrete

Testing				Crack width Δw	Assessment				No. of tests
Test no.	Test ref.	Purpose	Test parameters	inches (mm)	α_{req}	Load & displ.	f_c	h_{ef} [d]	n_{min}
			Reference tests						
1a	§7.0	Reference tension in low-strength concrete	Tension, confined, single anchor away from edges	NA	NA	NA	low	min max	5 per batch
1b	§7.0	Reference tension in low-strength, cracked concrete	Tension, confined, single anchor away from edges	0.012 (0.3)	NA	NA	low	min	5 per batch
1c	§7.0	Reference tension in high-strength concrete	Tension, confined, single anchor away from edges	NA	NA	NA	high	min	5 per batch
1d	§7.0	Reference tension in high-strength, cracked concrete [j]	Tension, confined, single anchor away from edges	0.012 (0.3)	NA	NA	high	min	5 per batch
			Reliability tests						
2a	§8.5	Sensitivity to hole cleaning, dry substrate	Tension, confined, single anchor away from edges	NA	§11.3.6	§11.3.2 §11.3.4	low	max	5 [a]
2b	§8.6	Sensitivity to hole cleaning, installation in saturated concrete [h]	Tension, confined, single anchor away from edges	NA	§11.3.6	§11.3.2 §11.3.4	low	max	5 [a]
2c	§8.7	Sensitivity to hole cleaning, installation in a water-filled hole [h]	Tension, confined, single anchor away from edges	NA	§11.3.6	§11.3.2 §11.3.4	low	max	5 [a]
2d	§8.8	Sensitivity to hole cleaning, installation in submerged concrete [h]	Tension, confined, single anchor away from edges	NA	§11.3.6	§11.3.2 §11.3.4	low	max	5 [a]
2e	§8.9	Sensitivity to mixing effort	Tension, confined, single anchor away from edges	NA	§11.3.6	§11.3.2 §11.3.4	low	max	5 [b]
2f	§8.11	Sensitivity to installation in saturated concrete [h,k]	Tension, confined, single anchor away from edges	NA	§11.3.6	§11.3.2 §11.3.4	low	max	5 [a]
2g	§8.12	Sensitivity to installation in a water-filled hole [h]	Tension, confined, single anchor away from edges	NA	§11.3.6	§11.3.2 §11.3.4	low	max	5 [a]
2h	§8.13	Sensitivity to installation in submerged concrete [h]	Tension, confined, single anchor away from edges	NA	§11.3.6	§11.3.2 §11.3.4	low	max	5 [a]
3	§8.14	Sensitivity to crack width low-strength concrete	Tension, confined, single anchor away from edges	0.020 (0.5)	0.80	§11.3.2 §11.3.4	low	min	5 [a]
4	§8.15	Sensitivity to crack width high strength concrete [j]	Tension, confined, single anchor away from edges	0.020 (0.5)	0.80	§11.3.2 §11.3.4	high	min	5 [a]

(continued on next page)

Table 1. (Continued).

Table 4.2– Test program for evaluating adhesive anchor systems for use in cracked and uncracked concrete

Testing				Crack width Δw	Assessment				No. of tests
Test no.	Test ref.	Purpose	Test parameters	inches (mm)	α_{req}	Load & displ.	f_c	h_{ef} [d]	n_{min}
5	§8.16	Sensitivity to crack width cycling	Sustained tension, single anchor away from edges, residual capacity, confined test	0.004-0.012 (0.1-0.3)	0.90	§11.3.2 §11.3.4 §11.10	low	min	5 [e]
6	§8.17	Sensitivity to freeze/thaw conditions [h]	Sustained tension, residual capacity, confined test	NA	0.90	§11.3.2 §11.3.4 §11.11	high	min	5 [b]
7	§8.18	Sensitivity to sustained load	Sustained tension, residual capacity, confined test	NA	0.90	§11.3.2 §11.3.4 §11.12	low	min	5 [b]
8	§8.19	Sensitivity to installation direction [h]	Tension, confined, single anchor away from edges	NA	0.90	§11.3.2 §11.3.4 §11.13	low	max	5 [n]
9	§8.20	Torque test [f]	Application of torque, confined, single anchor away from edges	NA	NA	§11.9	high	min	5 [e]
Service-condition tests									
11a	§9.4	Tension in low-strength concrete	Tension, unconfined, single anchor away from edges [l]	NA	NA	§11.3.2 §11.3.4 §11.3.5	low	min max	5 [e]
11b	§9.4	Tension in high-strength concrete [j]	Tension, unconfined, single anchor away from edges [l]	NA	NA	§11.3.2 §11.3.4 §11.3.5	high	min	5 [e]
11c	§9.4	Tension in low-strength, cracked concrete	Tension, unconfined, single anchor away from edges [m]	0.012 (0.3)	NA	§11.3.2 §11.3.4 §11.3.5	low	min	5 [e]
11d	§9.4	Tension in high-strength, cracked concrete [j]	Tension, unconfined, single anchor away from edges [m]	0.012 (0.3)	NA	§11.3.2 §11.3.4 §11.3.5	high	min	5 [e]
12a	§9.5	Tension at elevated temperatures	Tension, confined single anchor away from edges	NA	NA	§11.3.2 §11.3.4 §11.14	low	min	5 [b]
12b	§9.6	Tension at decreased installation temperature [h]	Tension, confined single anchor away from edges	NA	NA	§11.3.2 §11.3.4 §11.15	low	min	5 [b]
12c	§9.7	Curing time at standard temperature	Tension, confined single anchor away from edges	NA	NA	§11.3.2 §11.3.4 §11.16	low	min	5 [b]

Table 1. (Continued).

Table 4.2– Test program for evaluating adhesive anchor systems for use in cracked and uncracked concrete

Testing				Crack width Δw	Assessment				No. of tests
Test no.	Test ref.	Purpose	Test parameters	inches (mm)	α_{req}	Load & displ.	f_c	h_{ef} [d]	n_{min}
13a	§9.8	Resistance to alkalinity	Slice tests	NA	NA	§11.17	low	NA	10 [b]
13b	§9.8	Resistance to sulfur [h]	Slice tests	NA	NA	§11.17	low	NA	10 [b]
14	§9.9	Edge distance in corner condition to develop full capacity	Tension, unconfined single anchor in corner with proximate edges [g]	NA	NA	§11.18	low	min max	4 [e]
15	§9.10	Minimum spacing and edge distance to preclude splitting	High installation tension (torque or unconfined tension) two anchors near an edge [g]	NA	NA	§11.19	low	min	5 [e]
16	§9.11	Shear capacity of anchor element having a non-uniform cross section [c]	Shear – single anchor away from edges	NA	NA	§11.20	low	min	5 [e]
17	§9.12	Seismic tension [h]	Pulsating tension, single anchor away from edges	0.020 (0.5)	NA	§11.3.2 §11.3.4 §11.21	low	min max	5 [e]
18	§9.13	Seismic shear [h]	Alternating shear, single anchor away from edges	0.020 (0.5)	NA	§11.22	low	min	5 [a]
Supplemental tests									
19	§10.1	Round-robin tests	Tension, confined and unconfined, single anchor away from edges	NA	NA	§11.3.1	low [i]	$7d$	5 [b]
20	§10.2	Minimum member thickness [h]	Installation tests [g]	NA	NA	§11.7	low	max	10 [e]

Notes for Table 4.2:

a. Test small, medium and large diameters.
b. Test the ½-in. (M12) diameter or the smallest nominal diameter if it is larger than 1/2 in. (M12).
c. Test is required only for anchors having a cross sectional area, within five anchor diameters of the shear failure plane, that is less than that of a threaded bolt having the same nominal diameter as the anchor.
d. Where the manufacturer's printed installation instructions specify multiple embedment depths for a single anchor diameter, test the anchor at the minimum or maximum embedment depth as noted, whereby $h_{ef,max}/h_{ef,min} \leq 5.0$. See also Section 5.7.2.
e. Test all diameters.
f. See also Section 4.5 for multiple anchor element types.
g. Minimum member thickness h_{min} shall be used for these tests.
h. Optional test.
i. Test in concrete having a measured strength of 3,000 psi ± 500 psi (20.7 MPa ± 3.3 MPa) at time of testing.
j. Tests are optional if test results of Test 1c can be shown to be statistically equivalent to or greater than the results of Test 1a. If any of Tests 1d, 4, 11b, and 11d are not performed, calculation of anchor tension resistance shall be limited to f'_c = 2,500 psi (17.2 MPa) regardless of the in-situ concrete strength.
k. Test 2f may be omitted if Test 2g is performed.
l. Alternatively, tests may be performed as confined tests.
m. These tests shall be permitted to be supplemented by confined tests.
n. For overhead and horizontal orientations, test the largest diameter for which recognition is sought.

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$$\tau_{k(cr,uncr)} = \tau_{k,nom(cr,uncr)} \cdot \beta \cdot \alpha_{lt} \cdot \alpha_{st} \cdot \alpha_{dur} \cdot \alpha_{\rho} \cdot \alpha_{conc} \cdot \alpha_{cov} \cdot \alpha_{cat\,3} \quad \text{psi (MPa)} \qquad \text{Eq. 11.12}$$

where:

β = $min\left[min\frac{\alpha}{\alpha_{req}}; min\,\alpha_{adh}\right]$ for the applicable reliability and service-condition tests listed in Table 11.2 and Table 11.3.

α = ratio of reliability test result to reference test result evaluated for all applicable reliability tests listed in Table 11.2, see Eq. 11.7.

α_{adh} = reduction factor for loss of adhesion as evaluated for all applicable reliability tests listed in Table 11.2 and for all service-condition tests listed in Table 11.3, see Section 11.3.4.2.

α_{req} = threshold value of α given in Table 4.1 or Table 4.2.

α_{lt} = reduction factor for maximum long-term temperature as applicable, see Eq. 11.31.

α_{st} = reduction factor for maximum short-term temperature as applicable, see Eq. 11.32.

α_{dur} = reduction factor for durability as applicable, see Eq. 11.34.

α_{ρ} = reduction factor for reduced sustained load in reliability tests as applicable, see Eq. 11.15.

α_{conc} = adjustment factor for regional concrete variation, see Section 11.3.1.

α_{cov} = reduction factor associated with the coefficient of variation of ultimate loads, see Eq. 11.6.

$\alpha_{cat\,3}$ = reduction factor for anchor category 3, see Eq. 11.14.

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Figure 7. Equation 11.12 from ICC-ES AC308.

Static Tension Test Series at Elevated Temperature. This test series conducts a static load test at a minimum concrete temperature of 110°F. The purpose of this test is to determine the average displacement at the mean static load.

Creep Test Series at Elevated Temperature. This test series requires the installation of thermocouples in the concrete to monitor the concrete temperature during the duration of the test. Upon completion of the adhesive curing period, the concrete temperature is raised to a minimum temperature of 110°F ±3°F and stabilized for at least 24 hours. Next, a preload of no more than 5% of the sustained creep load (40% of the mean static load determined from the static tension test series at 75°F) is applied to set the anchor and testing equipment before zeroing the test readings. Once the test equipment is zeroed, the remainder of the load is then applied. The initial elastic displacement is recorded within the first 3 min of the test, and subsequent displacement readings are taken every hour for the first 6 hours and then daily for the remainder of the test.

Concrete temperature readings are conducted during the test. If the concrete temperature falls below the minimum temperature for more than 24 hours, the test duration is extended to account for the total time below the minimum temperature. The test is continued for 42 days (1,000 hours).

A logarithmic trendline of the displacement versus time is projected out to 600 days using a least squares fit through the data points and using the general form of the equation $y = c \cdot \ln(x) + b$, where b and c are fitting coefficients. This trendline is constructed from not less than the last 20 days (minimum of 20 data points). See Figure 10 for a graphical presentation of this projection.

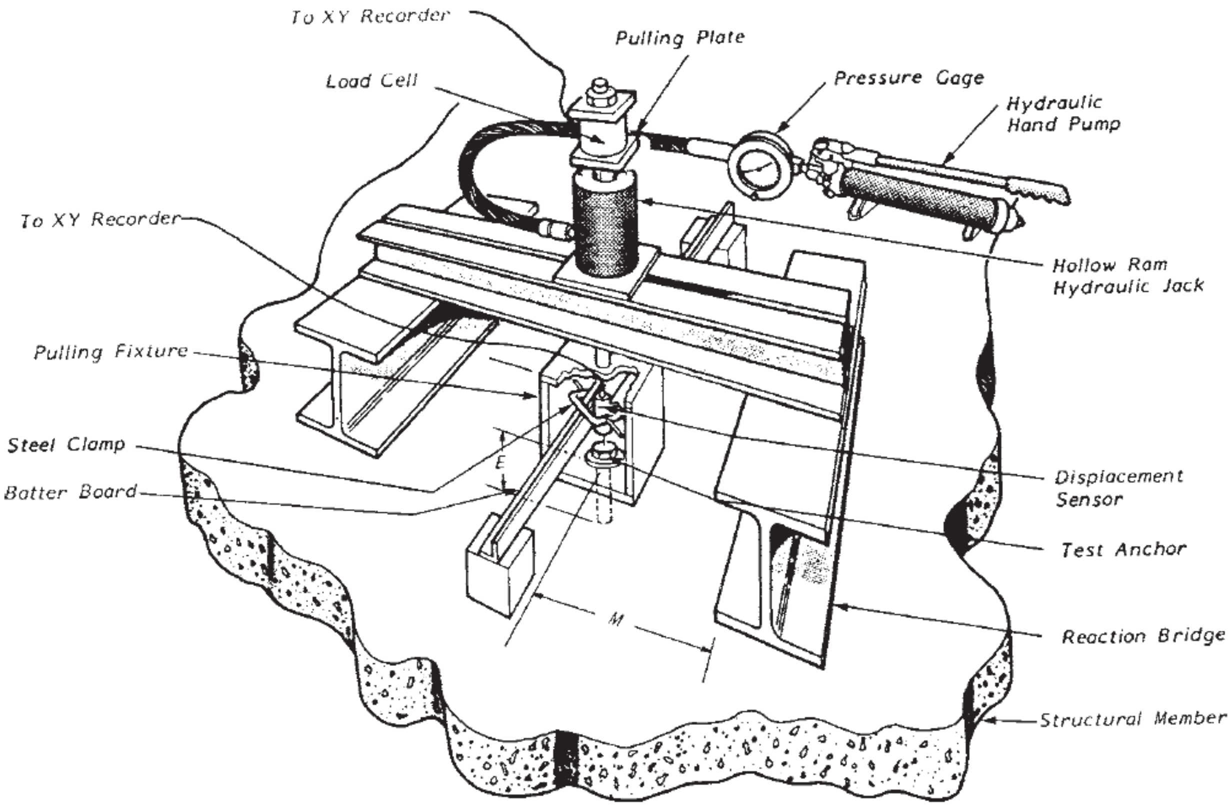

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Figure 8. Typical unconfined static tension test arrangement.

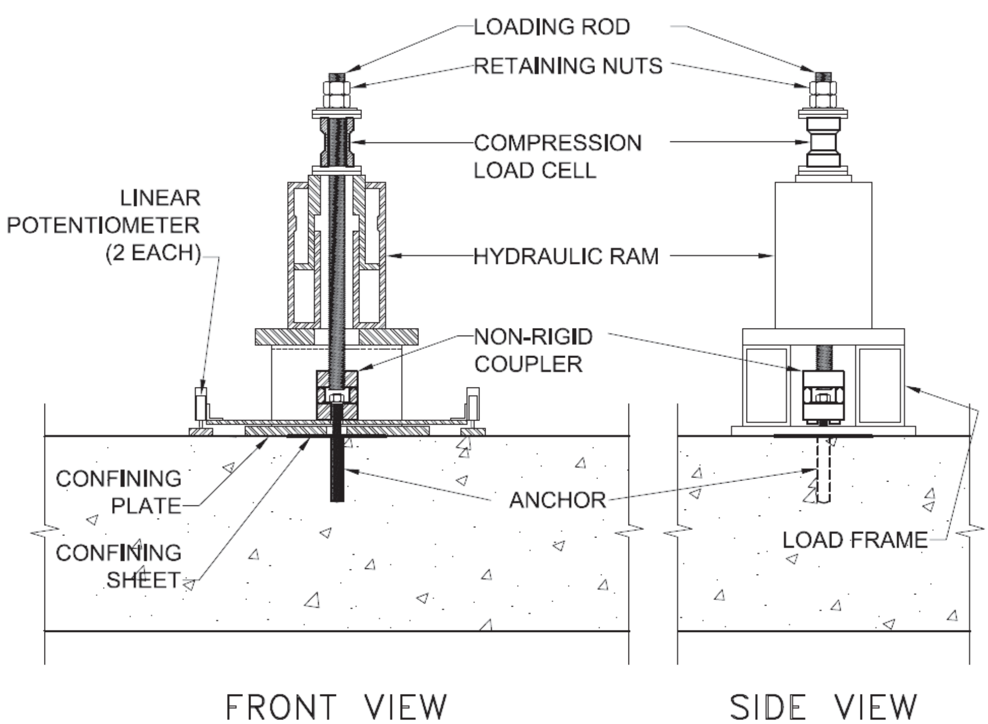

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Figure 9. Confined testing apparatus.

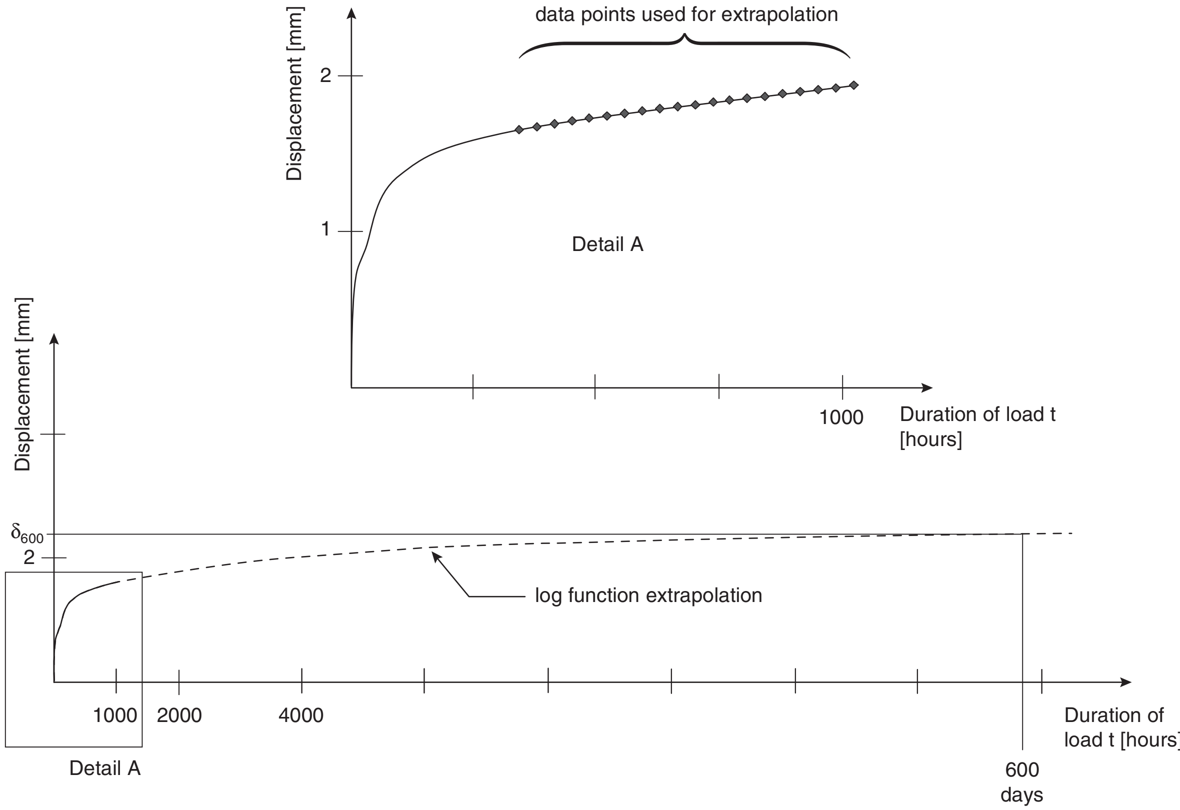

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Figure 10. Extrapolation of sustained load displacements per ASTM E1512-01.

Product Evaluation Standards Related to Sustained Loads on Adhesive Anchors

The following standards present a pass/fail approach to evaluating the ability of adhesive anchors to handle sustained loads. Several standards are presented, and the pass/fail criteria are discussed along with their limitations.

ICC-ES AC58 Acceptance Criteria for Adhesive Anchors in Concrete and Masonry Elements

Background

ICC-ES AC58 (*31*), developed by the International Code Council Evaluation Service, Inc. (ICC ES) and first approved in January 1995, is based on allowable stress design. The purpose of this acceptance criteria is to provide a standard method and report for manufacturers to qualify their adhesive anchor products. Since 2008, *ICC-ES AC58* has not been accepted by the International Building Code; *ICC-ES AC58* has been replaced by *ICC-ES AC308* (*3*), which is discussed later in this report.

Test Procedure

ICC-ES AC58 (*31*) covers many different tests for adhesive anchors, and Section 4.4.3 presents the optional creep test. If anchors are not tested for creep, they are prohibited from sustained loading applications. *ICC-ES AC58* refers to *ASTM E488-96* (*28*) and *ASTM E1512-01* (*29*) for the general test procedure, with *ICC-ES AC58* taking precedence in case of any differences. The differences in the creep test procedure in *ICC-ES AC58* and the ASTM standards are the following:

- Anchors for all test series are installed at 70°F ±5°F, and
- Anchors for all test series are cured at 70°F ±5°F for 7 ±5 days before beginning testing.

Static Tension Test Series at 70°F ±5°F. This test series is based on the static test procedure presented in *ASTM E1512-01*(*29*) but at a different temperature.

Static Tension Test Series at Elevated Temperature. *ICC-ES AC58* (*31*) follows the same procedure that is followed in *ASTM E1512-01*(*29*) but provides an allowable temperature tolerance of ±3°F. The average displacement at the mean static load must satisfy the displacement limitations presented in tables in *ICC-ES AC58*.

Creep Test Series at Elevated Temperature. Again, *ICC-ES AC58* (*31*) follows the same procedure that is followed in *ASTM E1512-01* (*29*), but provides an allowable temperature tolerance of ±3°F.

Acceptance Criteria

The anchor is accepted for creep if the average projected displacement at 600 days is less than (1) the average displacement at mean static load determined from static tension test series at elevated temperature (see Figure 11) and (2) 0.12 in.

Rationale of Test Procedure

The basis for the creep test procedure for adhesive anchors used to develop *ICC-ES AC58* (*31*) is used in many other test procedures, and it is therefore important to understand the rationale behind the chosen parameters.

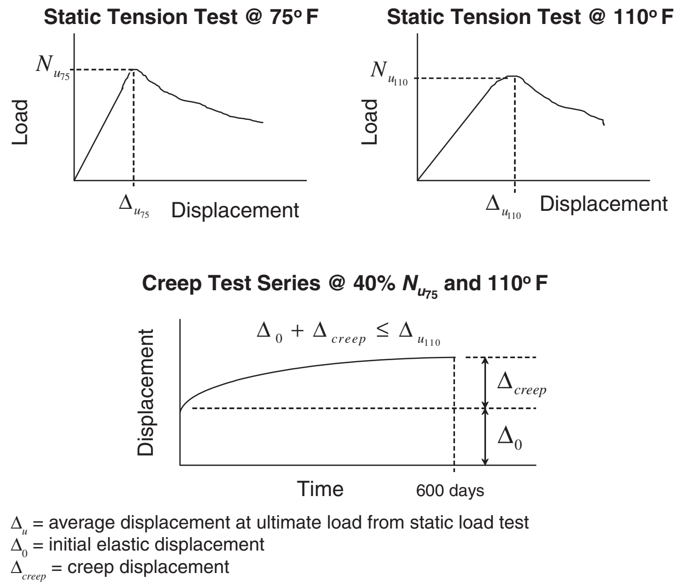
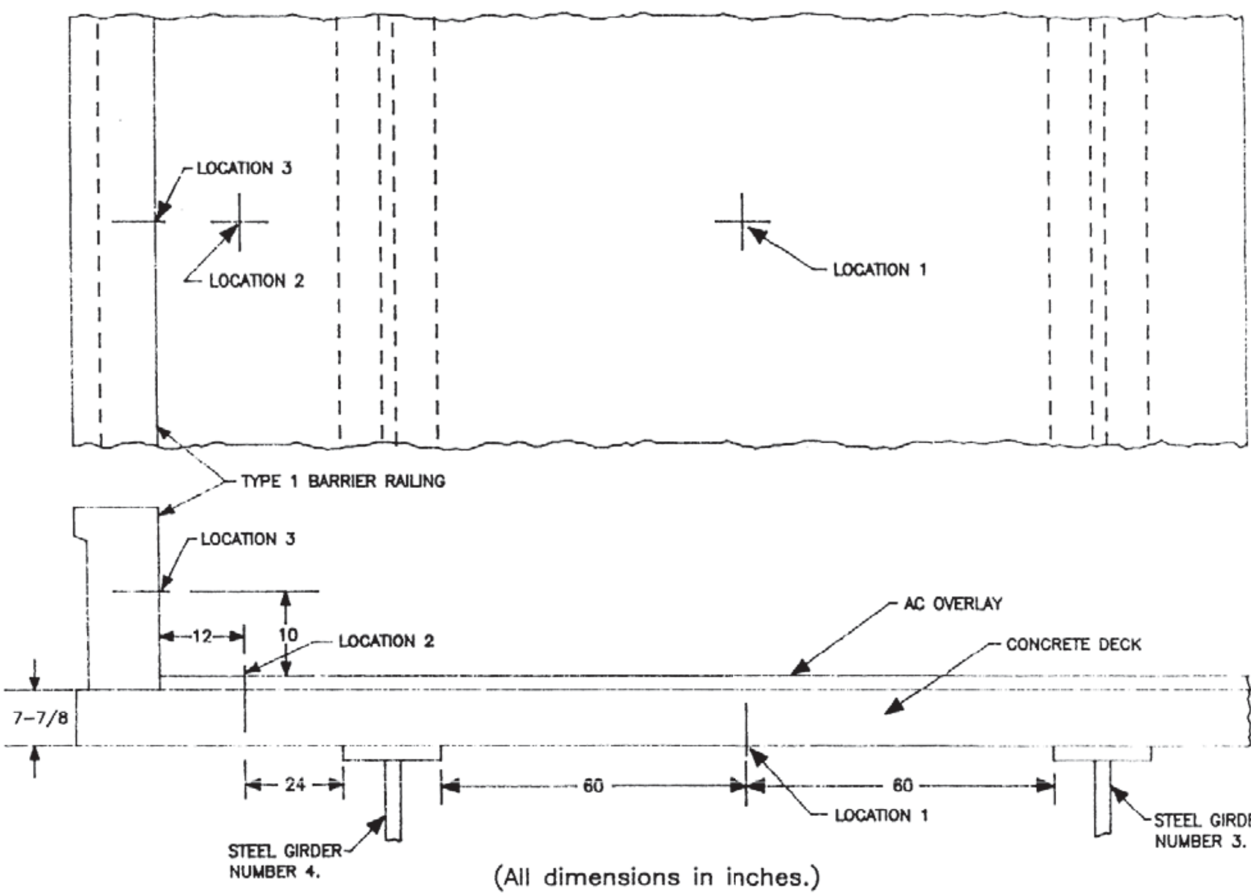


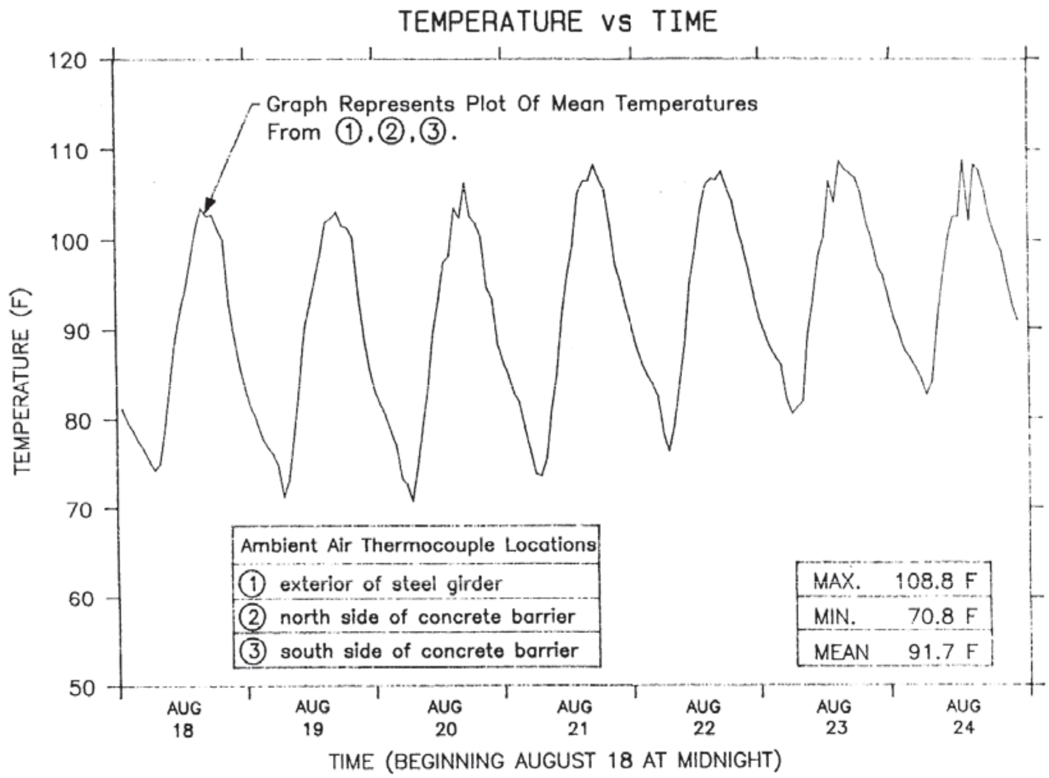
Figure 11. Basic pass/fail criteria per ICC-ES AC58.

Test Temperature. According to a 1991 Caltrans bridge study in Barstow, California (*11*), the maximum temperature experienced at a particular location (Location 1 in Figure 12) in the bridge was 115°F, and an average of the peaks was approximately 110°F. Furthermore, the internal temperature of the bridge was, on average, 10°F to 15°F above the ambient air temperature (see Figures 12 through 14). A study of bridges in the San Antonio, Texas, area (*32*) confirmed that



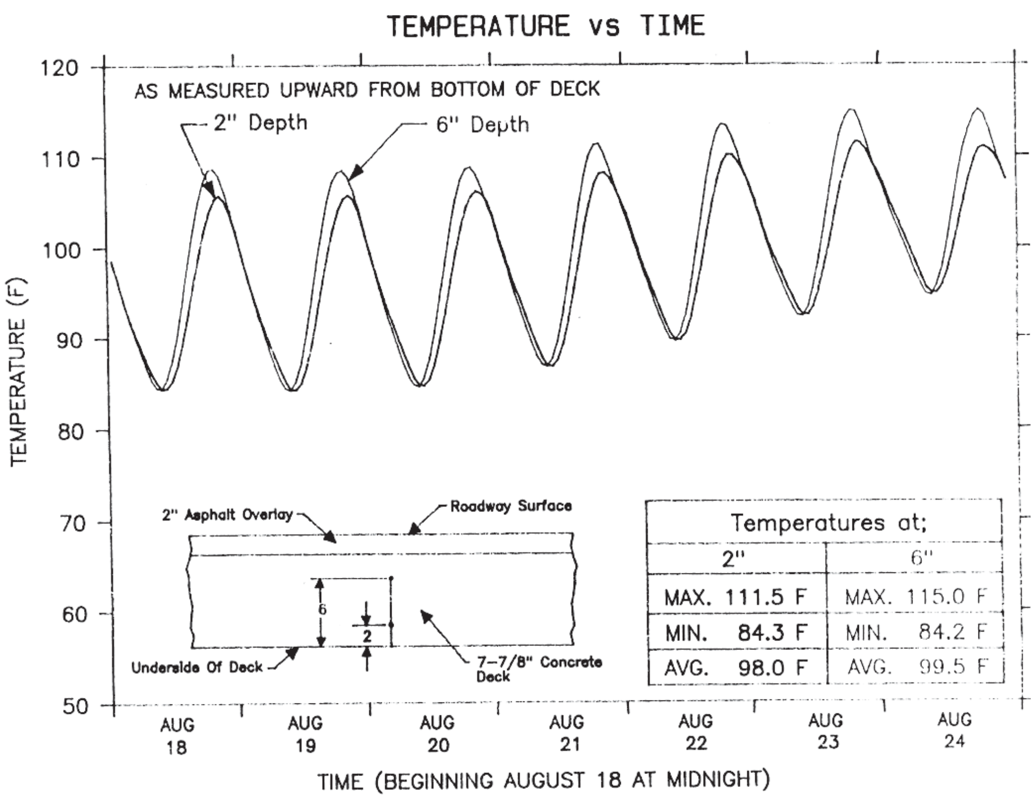
Source: Dusel and Mir (*11*).

Figure 12. Internal temperature sensor locations in Caltrans Barstow Bridge Study.



Source: Dusel and Mir (*11*).

Figure 13. Average ambient air temperature in Caltrans Barstow Bridge Study.



Source: Dusel and Mir (*11*).

Figure 14. Internal temperatures of concrete deck at Location 1 in Caltrans Barstow Bridge Study.

the internal temperature of bridges can be higher than the ambient air temperature. Therefore, the test temperature was set at 110°F.

Sustained Load. The determination of the sustained load was based on an allowable stress design (ASD) approach. For ASD and using a factor of safety (FS) of 4, the maximum sustained load is the mean strength divided by the FS, or maximum sustained load equal to 25% of the mean strength.

For inclusion in *ICC-ES AC58* (*31*), the sustained load was proposed as 40% of the mean strength (1.6 times the maximum anticipated sustained load). During the development of *ICC-ES AC308* (*3*) discussed below, the sustained load was increased to 55% of the mean strength due to consideration of Load and Resistance Factor Design (LRFD). This increase was based on ~1.4 times the maximum anticipated sustained load.

Test Duration. The test duration was based on a summary of 69 adhesive anchor tests in which only 29 failed by obvious pull-out failure, and 21 of the 29 failed in less than 1 day. The last to fail was between 14 and 21 days; there were no pullout failures after 21 days, with tests continued to 120 days. It was concluded that if an anchor did not fail during a time period that was twice the duration of the time period in which the last pull-out failure occurred (42 days), it could be assumed to never result in a pull-out failure. The test duration was therefore set at 42 days.

Acceptance Time Period. Based on the Caltrans bridge study (*11*), it was assumed that the temperature in a bridge will be higher than 110°F for 10% of a typical summer day. Assuming 4 months of summer weather and a 50-year design life for a typical structure (assumed in most building codes), it is estimated that there will be 600 days that the temperature of the anchor will be above the test temperature over its life span (600 days = 0.10 × 30 days/month × 4 months/year × 50 years). The acceptance time period was therefore set at 600 days.

Acceptance Criteria. An anchor would be accepted if the total projected displacement calculated at 600 days under the 110°F temperature sustained loading test was less than the maximum displacement from a static tension test at 110°F.

In summary, the basis for *ICC-ES AC58* (*31*) is a 42-day sustained load test, at 110°F, with a sustained load of 40% of the mean static strength. The data should be projected to 600 days, and the displacement at 600 days should be less than the maximum displacement of the anchor in a static tension test at 110°F.

ICC-ES AC308 Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements

Background

ICC-ES AC308 (*3*) is an acceptance criteria based on ultimate strength (LRFD) design that was developed by ICC-ES and approved in February 2007. The purpose of these acceptance criteria is to provide a standard method and report for manufacturers to qualify their post-installed adhesive anchor products. Beginning in 2008, *ICC-ES AC308* replaced the previous acceptance criteria, *ICC-ES AC58* (*31*). Creep testing under *ICC-ES AC308* is mandatory whereas under *ICC-ES AC58* it was optional. *ICC-ES AC308* covers many different tests for post-installed adhesive anchors. Section 8.18 of *ICC-ES AC308* presents the test procedure for sensitivity to sustained loading at standard and maximum long-term temperature. Section 9.5 presents the procedure for tension tests at elevated temperature.

Test Procedure for Sensitivity to Sustained Loading at Standard and Maximum Long-Term Temperature

These tests are conducted on uncracked concrete. Thermocouples are installed in the concrete to monitor the temperature, or the chamber temperature is monitored if a correlation can be proven between the chamber temperature and the concrete temperature. Both tests are run for 42 days. A confined tension test to failure is conducted on the anchor following each sustained loading test, and the anchor must have at least 90% of its tension capacity.

Standard Temperature Sustained Loading Test. After curing and stabilization of the temperature, a preload of 5% of the sustained load is applied to the anchor to set the anchor and the equipment before zeroing the equipment. The sustained load is 55% of the mean tension capacity multiplied by a multiplication factor based on the concrete strength. The test load is increased to the sustained load and maintained. Displacement readings are taken on the following suggested schedule:

- Every 10 min for the first hour,
- Every hour for the next 6 hours,
- Every day for the next 10 days, and
- Every 5 to 10 days following.

The concrete temperature is allowed to vary by ±11°F, but if the temperature falls below this tolerance for more than 24 hours, the test duration is extended to account for the time below the target temperature.

Maximum Long-Term Temperature Sustained Loading Test. This test is conducted in a concrete member from the same batch of concrete as the previous test. After curing, the temperature is raised to the maximum long-term temperature by a rate of 35°F per hour. The long-term temperature ranges for two categories are set forth in Table 9.1 of *ICC-ES AC308* (*3*). For temperature category "A," the long-term test temperature is 110°F. A preload of 5% of the sustained load is applied in order to set the anchor before zeroing the equipment. The load is then raised to the sustained long-term temperature load, which is the previously calculated sustained load multiplied by a long-term temperature multiplier. The load is maintained, and displacement readings are taken according to the schedule listed earlier.

Test Procedure for Tension Test at Elevated Temperature

This test conducts static tension tests in uncracked concrete at the long-term and short-term concrete temperatures. Table 9.1 of *ICC-ES AC308* (*3*) presents two temperature categories. These two categories are summarized in Table 2. Anchors tested for Temperature Category A are tested at the long-term and the short-term temperatures. Anchors tested for Temperature Category B are tested at the standard temperature, the long-term temperature, the short-term temperature, and two temperatures in between, with a maximum increment of 35°F.

The anchors are installed and cured at the standard temperature and then raised to the testing temperature and maintained for 24 hours prior to testing. A static tension test is conducted on the anchor with continuous load and displacement measurement.

Acceptance Criteria

The displacement versus time is projected over the service life using a least squares fit through the data points using the Findley Power Law equation:

$$\Delta_{(t)} = \Delta_{(t=0)} + a \cdot t^b$$

where
t = time,
a = mathematical constant from regression analysis, and
b = mathematical constant from regression analysis.

The estimated displacement is calculated at 50 years for the standard temperature test and 10 years for the elevated temperature test. The average estimated displacement values must be less than the limiting displacement value calculated in Section 11.3.4 of *ICC-ES AC308* (*3*), and no single value can be more than 120% of the limiting displacement value. See Table 3 for a comparison of the two ICC-ES acceptance criteria tests.

ACI 355.Y Draft Criteria for Adhesive Anchors—Draft 5.0

ACI 355.Y Qualification of Post-Installed Adhesive Anchors in Concrete (*2*) is currently in the balloting process, with the expectation that it will be included in the 2011 code and, once approved, will replace *ICC-ES AC308* (*3*).

Test Procedure for Sensitivity to Sustained Loading at Standard and Maximum Long-Term Temperature

Section 7.17 of Draft 5.0 of *ACI 335.Y* (*2*) presents the test procedure for sensitivity to sustained loading at standard and maximum long-term temperatures. The procedure is essentially the same as the procedure presented in Section 8.18 of *ICC-ES AC308* (*3*), with a few minor modifications. In Draft 5.0 of *ACI 355.Y,* the testing temperatures have been slightly modified for both categories (see Table 4), and there is no long-term temperature multiplier in the calculation for sustained load at long-term temperature ($N_{sus,lt}$).

Test Procedure for Tension Test at Elevated Temperature

Section 8.5 of Draft 5.0 of *ACI 355.Y* (*2*) presents the test for tension at elevated temperature. The procedure is similar to that presented in Section 9.5 in *ICC-ES AC308* (*3*) with a few minor modifications. As mentioned above, the minimum test temperatures have been modified for both categories, and *ACI 355.Y* specifies five test specimens for testing at temperature category B, as opposed to three specimens in *ICC-ES AC308.*

FM 5-568 Anchor System Tests for Adhesive-Bonded Anchors and Dowels

Background

FM 5-568 (*33*) is FDOT's test method for anchor systems with adhesive-bonded anchors and dowels. Its purpose is to determine the bond strength and performance characteristics of adhesive-bonded anchors in uncracked concrete.

Table 2. ICC-ES AC308 Table 9.1 minimum test temperatures.

Temperature Category	Long-term Test Temperature ˚F	Long-term Test Temperature ˚C	Short-term Test Temperature ˚F	Short-term Test Temperature ˚C
A	110	50	180	80
B	≥ 0.60 x (short-term test temp)	≥ 0.60 x (short-term test temp)	≥ 110	≥ 50

Table 3. Summary comparison of creep test parameters in ICC-ES AC58 and ICC-ES AC308.

Test Condition	ICC-ES AC58	ICC-ES AC308
Static tension load	$0.40 \cdot \bar{N}_{u,std\ temp}$ *	$0.55 \cdot \bar{N}_{u,std\ temp}$
Temperature(s) during test	110°F	Standard (room) temp. Max. short-term elevated temp.
Duration of test	Min. 42 days	Min. 42 days
Extrapolation period	600 days (elevated temp.)	50 years (room temp.) 10 years (elevated temp.)
Extrapolation method	Logarithmic $\Delta(t) = \Delta_0 + a \cdot ln(t) + b$	Findley Power Law $\Delta_{(t)} = \Delta_{(t=0)} + a \cdot t^b$
Residual capacity	No test required	Test anchors in tension to failure following application of sustained load
Acceptance criteria	$\bar{\Delta}(600\ days) \le min \begin{vmatrix} \bar{\Delta}_{u,elevated\ temp} \\ 3\ mm \end{vmatrix}$	$\bar{\Delta}(50\ yrs) \le \bar{\Delta}_{lim,room\ temp}$ $\bar{\Delta}(10\ yrs) \le \bar{\Delta}_{lim,elevated\ temp}$ ** Residual load: $\alpha_{req} = 0.90$

* The mean ultimate loads ($\bar{N}_u$) associated with standard temperature and elevated temperature conditions are used for the sustained-load tests at room temperature and elevated temperature, respectively.

**The calculated estimated displacement Δservice (extrapolated estimate of the total displacement over the anchor intended service life) for any one test may not exceed 1.2Δlim.

Source: Eligehausen and Silva (*30*)

Test Procedure

FM 5-568 (*33*) references *ASTM E488-96* (*28*) and *ASTM E1512-01* (*29*) for the test procedures. Section 8.1.6 presents the long-term load (creep) test procedures. These consist of a static tension test on single anchors with a few modifications from the referenced ASTM standards as follows:

- Three separate test series of different anchor diameters and embedment depths:
  - Diameter of 16 mm (⅝ in.) and an embedment depth of 102 mm (4 in.)
  - Diameter of 16 mm (⅝ in.) and an embedment depth of 152 mm (6 in.)
  - Diameter of 19 mm (¾ in.) and an embedment depth of 152 mm (6 in.).
- Minimum temperature is 110°F.
- The long-term test load in the creep test is set at 40% of the average tension failure load.
- After the standard 42-day test, the concrete temperature is reduced to 70°F ±5°F and an unconfined tension test is conducted.

Acceptance Criteria

Section 937 of FDOT's *Standard Specifications for Road and Bridge Construction* (*21*) specifies the minimum per-

Table 4. Minimum test temperatures from Table 8.1 of Draft 5.0 of ACI 355.Y.[1]

Temperature Category	Long-term Test Temperature (T_{lt})		Short-term Test Temperature (T_{st})	
	°F	°C	°F	°C
A	110	43	176	80
B[2]	$1.0T_{st} \ge T_{lt} \ge 0.63T_{st}$	$1.0T_{st} \ge T_{lt} \ge 0.54T_{st}$	≥ 110	≥ 43

[1] All test temperatures have a minimum tolerance of 0°F.
[2] Short-term temperature, T_{st}, shall be ≥ 110°F.

formance requirements for adhesive anchors under the creep test of *FM 5-568* (*33*). The three performance requirements are the following:

- The displacement rate shall decrease during the 42-day test period.
- The total displacement at 42 days (with load still applied) shall be less than 0.03 in., and the total displacement due to creep during the last 14 days must be less than 0.003 in.
- After the 42-day test, the uniform bond stress from the confined tension test shall not be less than 1,800 psi.

ETAG 001 Guideline for European Technical Approval of Metal Anchors for Use in Concrete

Background

The European Organisation for Technical Approvals' (EOTA's) *ETAG 001* (*34*) presents many tests on metal anchors in concrete. Part 5 of the document is for bonded anchors. Suitability Test 6 is for anchors functioning under sustained loads and is presented in Section 5.1.2.5. The tests are conducted in uncracked concrete at a normal and a maximum temperature. Following both tests, the anchor is unloaded and then a confined tension test is conducted.

Section 5.1.3.1 of *ETAG 001* presents three test temperature ranges. Range (a) has a maximum long-term temperature of 75°F and a maximum short-term temperature of 104°F. Range (b) has a maximum long-term temperature of 122°F and a maximum short-term temperature of 176°F. Range (c) is reserved for the manufacturer's request.

Test Procedure at Normal Ambient Temperature

The applied load is calculated from Equation 5.6a of *ETAG 001.* The load is applied to the anchor, and displacements are measured until they have stabilized. The test must be run for at least 3 months (Section 5.7 of Annex A mentions that the test will generally last 6 months). Displacements should be recorded so as to reflect the behavior of the anchor and the adhesive. The following suggested schedule is presented by EOTA:

- Every 10 min for the first hour,
- Every hour for the next 6 hours,
- Every day for the next 10 days, and
- Every 5 to10 days following.

Test Procedure at Maximum Temperature

The applied load is calculated from Equation 5.6b of *ETAG 001,* which is similar to the load applied in the ambient temperature test except that it does not include a multiplication factor, α_2 that deals with the ratio of the maximum long-term temperature to the standard temperature. The anchor is installed and the load applied at ambient temperature. The temperature is then raised to the maximum temperature at a rate of 36°F per hour. Displacements are recorded at the same frequency as before.

Data Projection Techniques

Both *ICC-ES AC58* (*31*) and *ICC-ES AC308* (*3*) project creep displacement data and compare the estimated creep displacement at a particular point in time (600 days, 10 years, and 50 years) to a maximum limit. This projection introduces two points of possible uncertainty: (1) the uncertainty of the mathematical model of the data projection method and (2) the uncertainty of the maximum limit on creep displacement at some point in time.

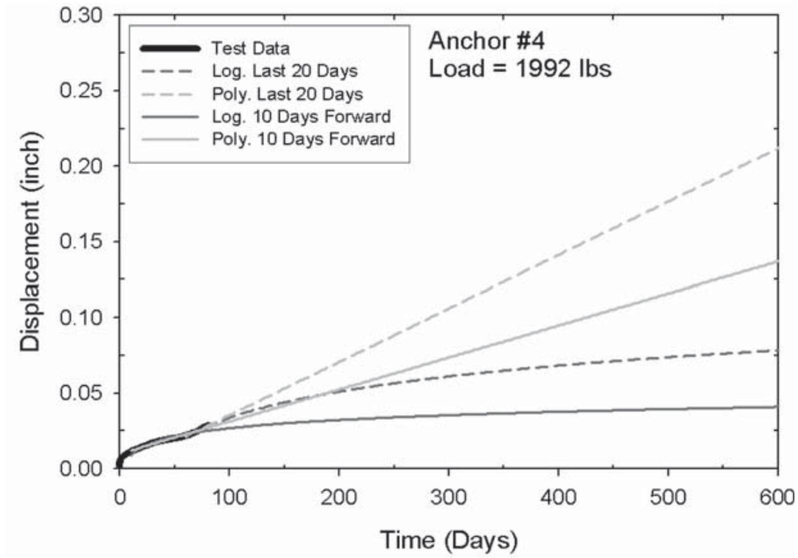
Several mathematical models have been proposed. The first model is the logarithmic model, discussed earlier in this chapter in the section on *ASTM E1512-01* (*29*), and has the form $\Delta = A \cdot \ln(t) + B$, where A = a mathematical constant from regression analysis, t = time, and B = a mathematical constant from regression analysis. The second is the Findley Power Law discussed earlier in this chapter in the section on *ICC-ES AC308* (*3*) and has the form: $\Delta_{(t)} = \Delta_{(t=0)} + a \cdot t^b$. A third model is what has been called the polynomial model—a three-parameter polynomial of the form: $\Delta = A \cdot (t^B) + C \cdot (t)$, where C = a mathematical constant from regression analysis.

The polynomial model was presented in a study on the adhesive used with the anchor bolts from the I-90 Seaport Portal Tunnel in Boston, Massachusetts (*35*). The creep data were extrapolated to 600 days and 7 years by the logarithmic model and the polynomial model. One disadvantage of the logarithmic model compared with the polynomial model is that the logarithmic model assumes that the displacements level off at a maximum value (creep rate approaches zero) whereas the displacements calculated in the polynomial model continue to increase, which is probably a better approximation.

In the case of the research by Ocel et al. (*35*), the displacements predicted from the polynomial model were on average three times the displacements predicted from the logarithmic model. The polynomial model predicted failure in less than 7 years whereas the logarithmic model predicted a life of over 100 years. The adhesive anchors being tested actually failed at around 7 years. Figure 15 shows the comparison of the logarithmic model and the polynomial model on an anchor. This particular anchor was chosen by the researchers because it best represented the condition of the anchors that failed in the Boston Tunnel.

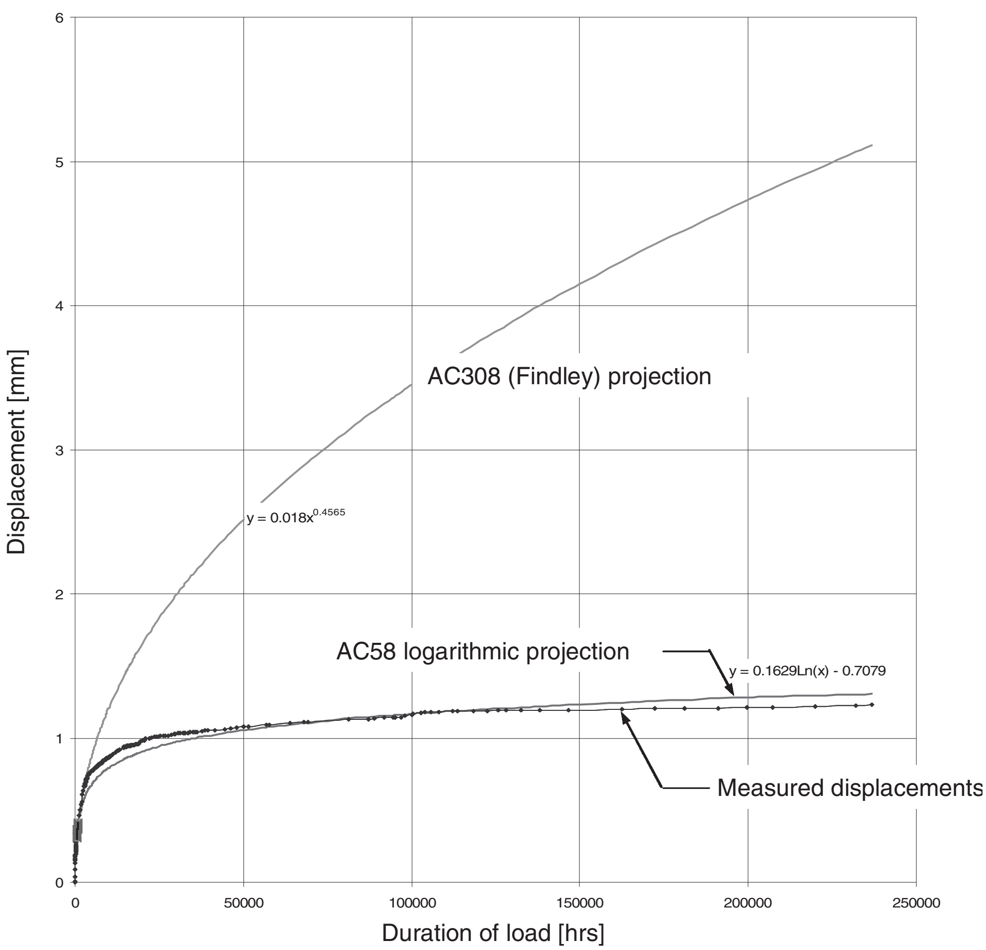
Looking at other research, however, suggests that the mathematical model depends on the data. In a 27-year creep study by Eligehausen and Silva (*30*), the actual creep displacement data were compared to both a logarithmic projection and a Findley projection. It can be seen in Figure 16 that the logarithmic projection more closely resembles the actual data.

In addition to the uncertainty about the mathematical projection used to estimate creep displacement at some time in the future, it can also be concluded from Figure 15 and



Reprinted with permission from Ocel et al. (*35*).

Figure 15. Creep displacement projections to 600 days for Anchor 4.



Reprinted with permission from Eligehausen and Silva (*30*).

Figure 16. Data projection comparison in a 27-year creep test.

Figure 16 that some uncertainty exists as to the maximum limit to place on the creep displacement in the pass/fail evaluation of an adhesive anchor.

Other Structural Adhesive Standards Related to Sustained Loads

Due to the uncertainty involved with the pass/fail criteria in the standards mentioned earlier, alternatives to product evaluation were also investigated. Methods for testing the performance of adhesives with other structural materials were reviewed to explore possible alternatives to the standard test procedures mentioned above. One promising alternative was the stress versus time-to-failure method.

ASTM D4680-98 Standard Test Method for Creep and Time to Failure of Adhesives in Static Shear by Compression Loading (Wood-to-Wood)

Background

ASTM D4680-98 (*36*) presents test methods for creep of wood joints bonded with adhesives. The standard states that creep data obtained through this test method over short time periods can be used to indicate an adhesive's ability to withstand load over longer time periods. It further states that time-to-failure data from a relatively short time frame can be extrapolated (with caution) to determine the adhesive's life at a particular stress level. It is recommended that at least 10 specimens be tested for every test condition (stress, temperature, etc.).

Creep Test

This test uniformly applies the load to the specimen within 1 min and takes displacement readings at times that will plot relatively equally spaced intervals on a logarithmic scale (i.e., 1, 2, 5, 10, 20, 50, 100 . . .). A total test time of about 7 days is suggested. This standard recommends three stress levels for each temperature for adhesives that display small stress dependency and five stress levels for those adhesives highly affected by stress.

Time-to-Failure Test

This test first determines mean strength by applying a load to the specimen to produce failure within 1 min. Subsequent tests are conducted at lower stress levels until failure. The standard recommends at least four equally spaced stress levels and suggests 90%, 80%, 70%, and 60% of the mean strength determined at the beginning of the test. It recommends that the lowest stress level produce failure at about 3,000 hours (~4 months).

The data are used to calculate a linear regression equation of the stress over log of time to failure (or a linear regression of log of stress over log of time to failure). An equation is calculated for each temperature and plotted on a stress (or log stress) versus log time-to-failure graph. This type of curve can provide engineers with a safe envelope in which to design given the lifetime of their system. Specifically, for adhesive anchors it will provide the designer with a safe stress level to use if the lifecycle of the anchor is known. The curves can be extrapolated to obtain the time to failure for lower stress levels; the extrapolation should be limited to one log cycle. Figure 17 is a stress versus log of time-to-failure graph.

ASTM D2990-01 Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics

Background

ASTM D2990-01 (*37*) presents the test procedures for creep and creep-rupture of plastics under specified conditions. The tests are conducted on samples at various temperatures that span the anchor's useful temperature range. During both tests, deflection is measured at 1, 6, 12, and 30 min; 1, 2, 5, 20, 50, 100, 200, 500, 700, and 1,000 hours; and then on a monthly basis. As mentioned before, these times are chosen so as to produce relatively equally spaced points on a log scale graph. Logarithmic scales are usually used in presenting creep data because the curves plot essentially as straight lines due to the long time frames encountered in creep testing.

Creep-Rupture Test

This test procedure is presented in Section 10.2 of *ASTM D2990-01* (37) and measures the time to failure of a specimen under a constant stress. Samples are tested at each temperature level and at seven stress levels. The stress levels are chosen to coincide with an estimated time of failure at approximately 1, 10, 30, 100, 300, 1,000, and 3,000 hours. Rupture is defined as failure for materials that fail catastrophically. The onset of tertiary creep (yielding, flowing, or drawing) is defined as failure for materials that do not fail catastrophically. See Figure 18 for a sample creep curve for hypothetical data that shows the levels of creep and the location of tertiary creep.

The data are used to create stress-at-failure versus time-to-failure curves at each temperature using a statistical least squares regression equation. Figure 17 is a stress versus time-to-failure graph. A creep-rupture envelope can also be created that plots strain versus time for many stress levels. The rupture points are connected for each stress level curve producing a creep-rupture envelope curve on the strain versus time graph. Figure 19 presents a creep-rupture envelope.

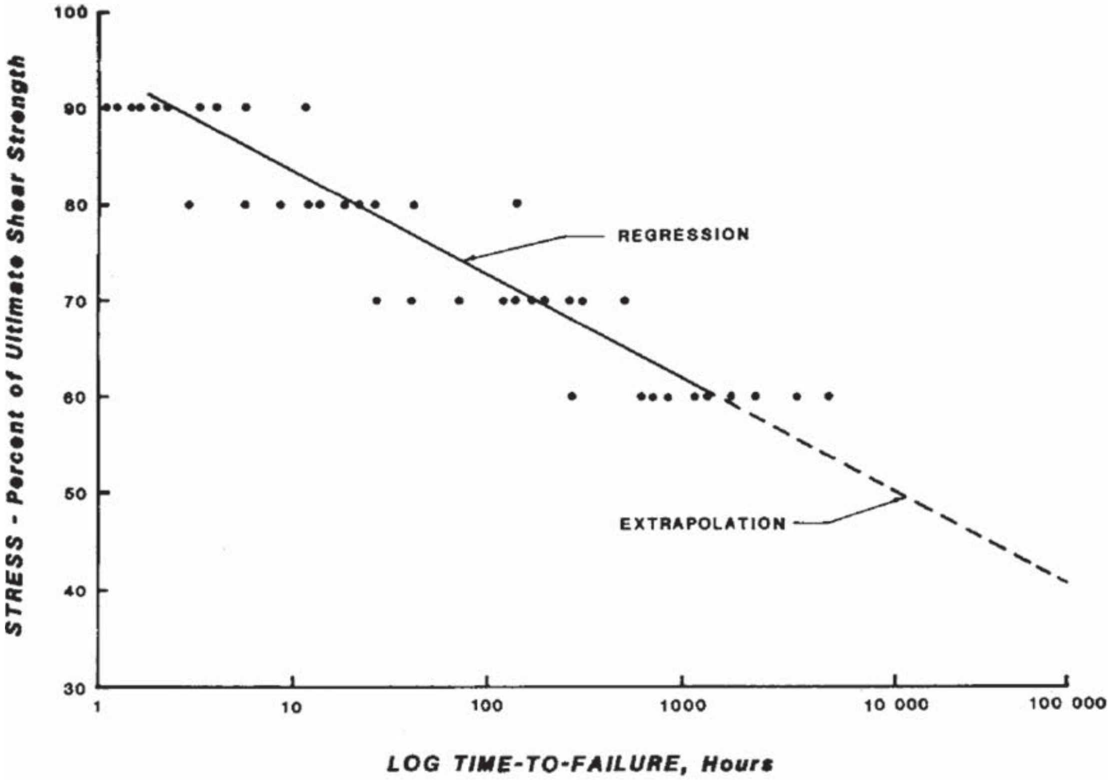


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Figure 17. Stress versus log of time to failure.

Creep Test

This procedure is presented in Section 10.3 of *ASTM D2990-01* (37) and measures the dimensional changes to a specimen over time under a constant stress. Samples are tested at three to five stress levels for each temperature. The goal is to obtain the stress level that produces 1% strain at 1,000 hours. This is accomplished by choosing stresses above and below the stress level required to produce the 1% strain, plotting the data on an isochronous stress-strain curve (at 1,000 hours), and interpolating. The 1%-strain condition was proposed by ASTM, but it can be modified for adhesive anchors and an isochronous stress-strain curve can be created for an adhesive anchor.

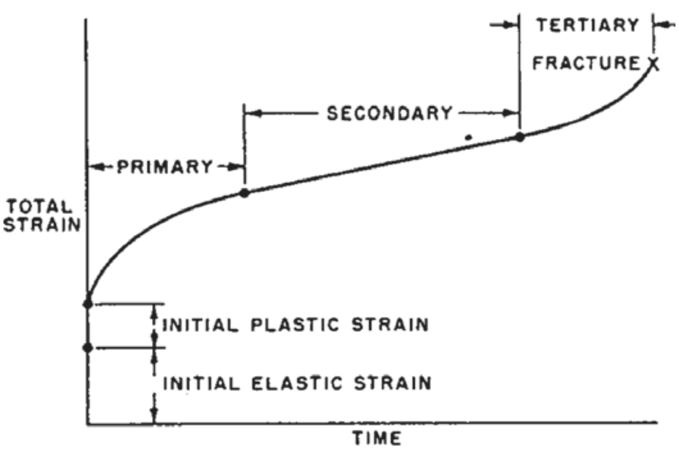

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Figure 18. Sample creep curve for hypothetical data.

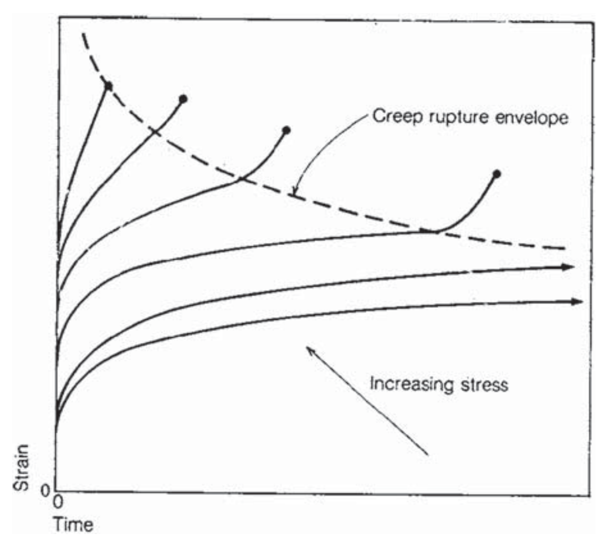

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Figure 19. Creep-rupture envelope.

ASTM D1780-05 Standard Practice for Conducting Creep Tests of Metal-to-Metal Adhesives

ASTM D1780-05 (*38*) subjects metal specimens lap-joined with adhesive to a constant stress and measures displacement over time in order to measure the creep properties of an adhesive under certain conditions. The standard indicates that "creep is a very sensitive index of strength, and usually does not vary as a linear function of stress. (It depends on the material, stress, temperature, and time.)" The standard further indicates that temperature is the most important variable in creep tests because small differences in temperature can cause large differences in creep rate.

The standard recommends that the results of deformation versus time be plotted on log-log charts, which create relatively straight lines and thereby make interpolation and extrapolation easier.

ASTM D2294-96 Standard Test Method for Creep Properties of Adhesives in Shear by Tension Loading (Metal-to-Metal)

ASTM D2294-96 (*39*) loads metal specimens similar to those used in *ASTM D1780-05* (*38*) in tension and measures deflection over time. *ASTM D2294-96* recommends using the following time intervals: 1, 3, 5, 10, 30, 50, 100, 300, 500, 1,000, etc., as they produce relatively equally spaced intervals on a log scale.

ASTM D2919-01 Standard Test Method for Determining Durability of Adhesive Joints Stressed in Shear by Tension Loading

ASTM D2919-01 (*40*) is similar to *ASTM D1780-05* (*38*) and *ASTM D2294-96* (*39*) and points out that "the time to failure for a given adhesive joint generally decreases with increasing stress, temperature, and relative humidity."

ISO 15109 Adhesives—Determination of the Time to Rupture of Bonded Joints Under Static Load

The International Organization for Standardization's *ISO 15109* (*41*) is for the determination of the time to failure of an adhesive bonded joint. The procedure is very general with no specific information on time-to-failure graphs.

Testing Adhesive Alone

Another possible testing alternative is to test an adhesive alone, without the concrete and anchor. This approach could be simpler, cheaper, and quicker than alternatives that involve the entire adhesive anchor system. However, testing adhesive alone to evaluate its performance in concrete would not be acceptable because the interaction of the adhesive with the concrete is an important variable to creep resistance and is essential to the test. Nonetheless, an adhesive-only test could possibly serve as the following:

- A qualifying or prescreening test before further, more expensive/timely testing;
- A fingerprint test to confirm the identity of an adhesive on site; or
- A comparison test between adhesives.

Time-Temperature Superposition and Master Curves

Time-temperature superposition is the idea that a change in temperature produces the same effect as a change in measurement time for a viscoelastic material. This proposal allows the investigator to conduct tests on a sample over a range of temperatures and shift the results on a graph until they superimpose, creating what is called a master curve, and thereby providing predictions of the material's behavior over a broader range of time.

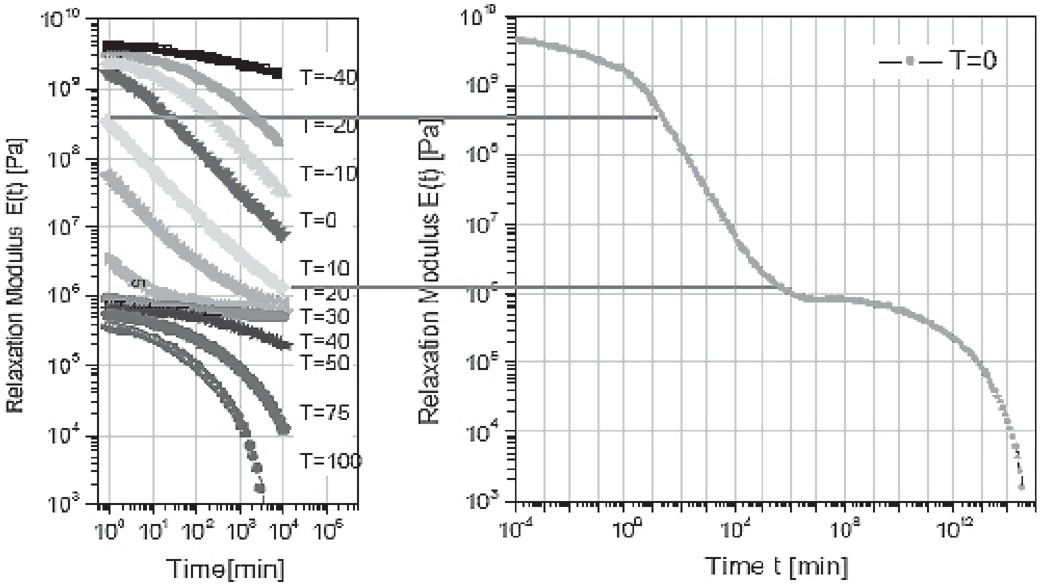
Crawford (*42*) explains that the glass transition temperature (T_g) is usually taken as the reference temperature. If the properties of an adhesive are known at T_g, then the properties at any temperature can be determined. Per Hunston et al. (*43*), this relationship is valid for materials with more simple chemistries, but may not be valid for more complex materials.

Master curves are a common method of simplifying and presenting data dealing with time-temperature equivalence and can be used to extend the data beyond the testing range. Vuoristo and Kuokkala (*44*) conducted creep tests at different temperatures and used master curves to predict the behavior of an epoxy used on rolls in the paper-making industry by expanding the data by two orders of magnitude. Master curves are also used in *ASTM D2990-01* (*37*) as an accepted method for predicting the long-term properties of plastics.

Figure 20 is a sample of a master curve created from stress relaxation data illustrating the procedure of creating a master curve. The left side of the figure shows the stress relaxation data for various temperatures. These curves were then shifted until they lined up and formed the master curve as shown on the right side of the figure.

Dynamic Mechanical Thermal Analysis Tests

Chin et al. (*13*) conducted Dynamic Mechanical Thermal Analysis (DMTA) tests on two adhesives. DMTA tests take thin samples of the adhesive and subject them to many cycles of a tensile load. In the Chin et al. DMTA tests, tensile strain sweeps were conducted at different temperatures, and the test



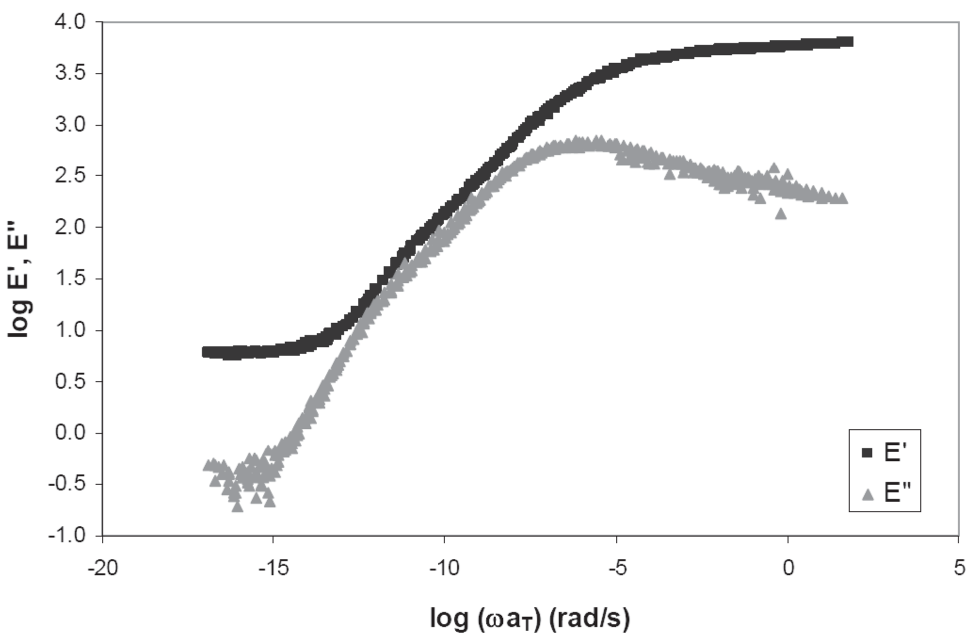
Source: Hunston and Chin (*45*).

Figure 20. Sample master curve.

data were used to perform a time-temperature superposition. The storage modulus (E'), loss modulus (E''), and tan delta (E''/E') were calculated, and master curves were generated for both adhesives. Figures 21 and 22 present the E', E'', and tan delta curves (respectively) generated by the researchers.

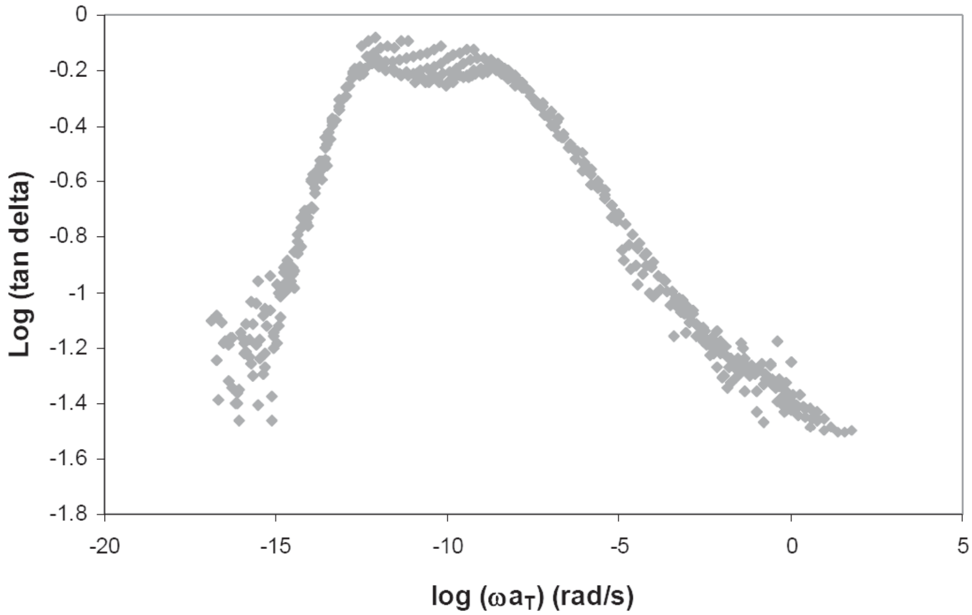
Creep Compliance Curves

Creep compliance is defined as the strain due to creep divided by stress. Creep compliance curves are plotted versus time. Since the strain is normalized by stress, these curves provide an indication of displacement versus time and can be used to show a material's creep deformation properties over time. In the National Institute of Standards and Technology (NIST) study (*13*), creep compliance curves were generated that displayed the predicted creep behavior of two adhesives over time. The graph, shown as Figure 23, clearly illustrates that the two adhesives tested are predicted to have different creep properties. The NIST study (*13*) warns that these estimated creep compliance curves are "not a substitute



Reprinted from Chin et al. (*13*).

Figure 21. E′ and E″ master curves for an epoxy.



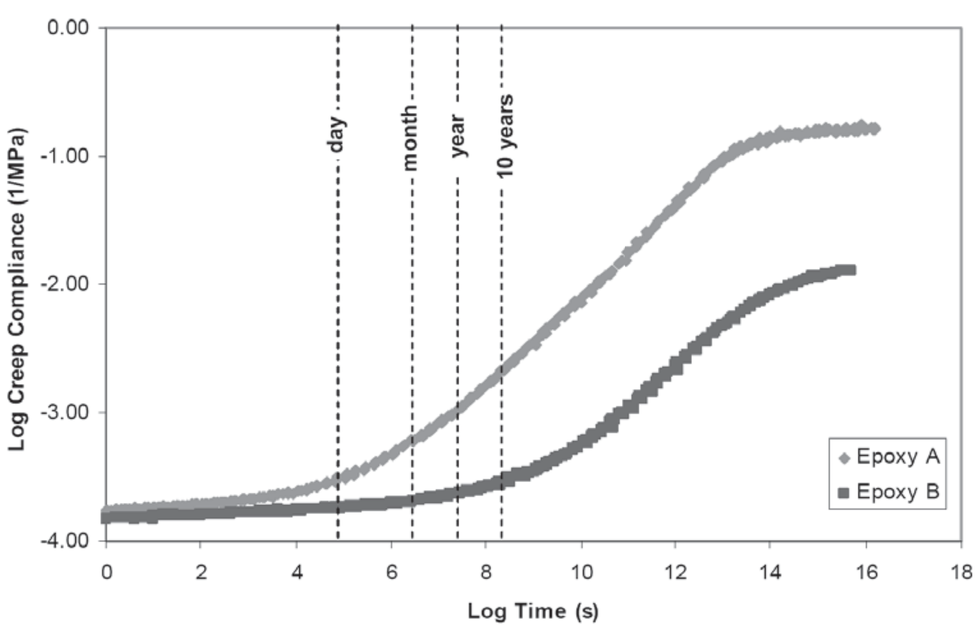
Reprinted from Chin et al. (*13*).

Figure 22. Tan delta master curve for an epoxy.

for the direct measurement of creep behavior" because they are limited to the linear viscoelastic region, and adhesive anchors under sustained load may function in the non-linear region, especially as failure is approached. However, creep compliance curves can be valuable as prescreening tools to indicate which adhesives warrant further/more exact testing.

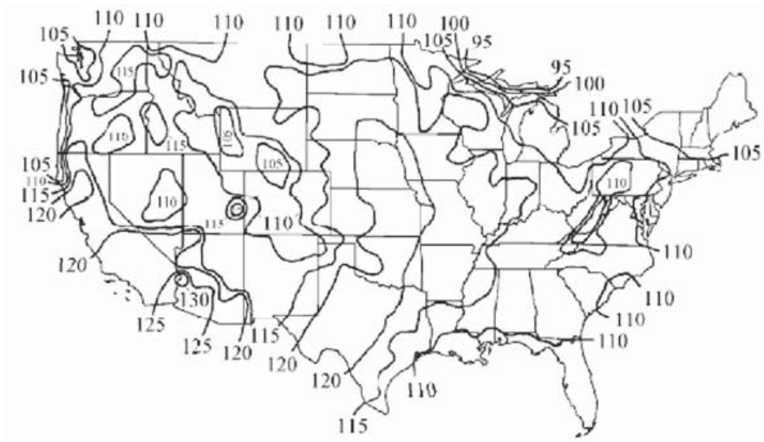
California Department of Transportation (Caltrans) Test Method 438

Caltrans Test Method 438 (*46*) determines rheological properties of adhesives using a dynamic shear rheometer. This test method, also confined to the linear viscoelastic range as discussed above, cannot be used as a direct measurement



Reprinted from Chin et al. (*13*).

Figure 23. Creep compliance curve for two epoxies.



From *AASHTO LRFD Bridge Design Specifications*, 2004 (*47*), by the American Association of State Highway and Transportation Officials, Washington, D.C. Used by permission.

Figure 24. $T_{MaxDesign}$ for concrete deck with steel structure.

of creep performance, but might be able to be used as a prescreening test.

Factors Related to AASHTO Applications

The following discussion presents factors specific to AASHTO applications related to test conditions for adhesive anchors.

Elevated Temperature

As discussed above, the elevated testing temperature for *ICC-ES AC58* (*31*) (precursor to *ICC-ES AC308* [*3*]) at 110°F was established from experiments by Dusel and Mir (*11*) in Barstow, California.

Figure 24 and Figure 25 are the AASHTO *LRFD Bridge Design Specifications* (*47*) contour maps for $T_{MaxDesign}$, which is the maximum design temperature for determination of movements of bridges and expansion joints. These contour maps were developed in an NCHRP research project conducted by Roeder (*48*) using meteorological data from over 1,150 locations in the United States with a minimum history of 60 years. Table 5 shows a summary of the *approximate* percentage of locations in the United States that have a maximum temperature above the specified temperature contour for the two types of bridges.

Figure 25 shows that for concrete girder bridges with concrete decks about a third of the United States has a maximum design temperature above 110°F; Figure 24 shows that for steel girder bridges with concrete decks about two-thirds of the United States has a maximum design temperature above

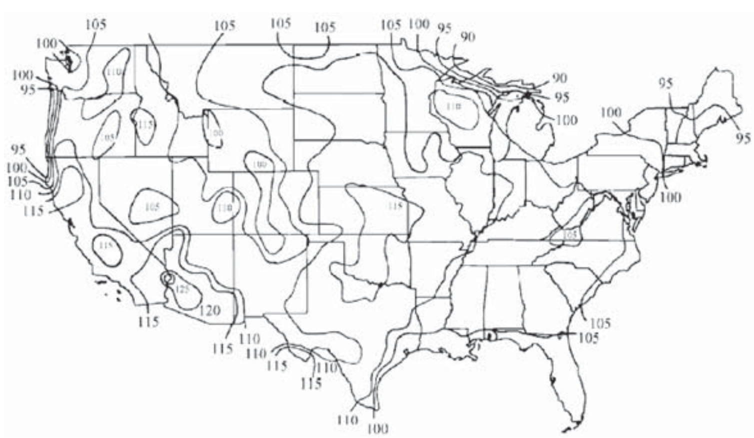


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Figure 25. $T_{MaxDesign}$ for concrete deck with concrete structure.

Table 5. Approximate percentage of U.S. locations above specified temperature contour for given bridge structure type.

Temperature Contour (°F)	Steel Structure with Concrete Deck (%)	Concrete Structure with Concrete Deck (%)
120	15	2
115	40	10
110	67	33

110°F. While these percentages might seem high, and it might seem that a higher temperature could be chosen, 110°F is recommended for two reasons: (1) it is still a reasonable extreme temperature for adhesive anchor testing; and (2) it has been the industry standard for elevated temperature testing of adhesive anchors, and much experimental and product acceptance data exist at that temperature that can be useful for future testing.

Sustained Load

As discussed earlier, the basis for *ICC-ES AC308* (*3*) is a 42-day, sustained load test at 110°F, with a sustained load of 55% of the mean static load. The data are projected to 10 years, and the displacement at 10 years should be less than the maximum displacement of the anchor in a static tension test at 110°F. In keeping with this approach, the following equation presents the rationale of the sustained load calculations for AASHTO applications. The basic premise of LRFD is that the loads must not exceed the resistance:

$$N_{FL} \le N_{res}$$

Where

N_{FL} = load resulting from the factored load combinations,
N_{res} = resistance or capacity of anchor = $\phi \cdot N_{nom}$,
ϕ = capacity reduction factor,
N_{nom} = nominal tensile strength (5% fractile) = $\alpha_{5\%} \cdot N_{mean}$,
$\alpha_{5\%}$ = statistical adjustment factor to obtain the 5% fractile from N_{mean}, and
N_{mean} = average tensile strength.

Therefore the governing equation becomes the following:

$$N_{FL} \le \phi \cdot \alpha_{5\%} \cdot N_{mean}$$

If both sides of the equation are multiplied by the ratio of the sustained load (N_{sust}) to factored load (N_{sust}/N_{FL}):

$$N_{FL} \cdot \left[\frac{N_{sust}}{N_{FL}}\right] \le \left[\frac{N_{sust}}{N_{FL}}\right] \cdot \phi \cdot \alpha_{5\%} \cdot N_{mean}$$

Which then reduces to Equation 3:

$$N_{sust} \le \left[\frac{N_{sust}}{N_{FL}}\right] \cdot \phi \cdot \alpha_{5\%} \cdot N_{mean} \qquad (3)$$

In determining the value of the N_{sust}/N_{FL} ratio for AASHTO applications, the AASHTO load combinations were analyzed. The AASHTO load combinations can be found in section 3.4.1 of the *LRFD Bridge Design Specifications* (*47*). STRENGTH I and STRENGTH IV were the only load combinations considered due to the transient or temporary nature of the other load combinations.

The STRENGTH I load combination includes the effects of the following loads (*47*):

- Dead load of structural components and nonstructural attachments (DC);
- Downdrag (DD);
- Dead load of wearing surfaces and utilities (DW);
- Horizontal earth pressure load (EH);
- Vertical pressure from dead load of earth fill (EV);
- Earth surcharge load (ES);
- Accumulated locked-in force effects resulting from the construction process, including the secondary forces from post-tensioning (EL);
- Vehicular live load (LL);
- Vehicular dynamic load allowance (IM);
- Vehicular centrifugal force (CE);
- Vehicular braking force (BR);
- Pedestrian live load (PL);
- Live surcharge load (LS);
- Water load and steam pressure (WA);
- Friction (FR);
- Uniform temperature (TU);
- Creep (CR);
- Shrinkage (SH);
- Temperature gradient (TG); and
- Settlement (SE).

The following earth-related loads—DD, EH, EV, ES, and EL—were not considered because it was determined that they would not typically be involved in an adhesive anchor application. The following transient loads—IM, CE, BR, PL, LS, WA, FR, TU, CR, SH, TG, and SE—were not considered to be long-term loads. The permanent loads DC and DW and the transient load LL were the only loads considered for the STRENGTH I load combination.

The STRENGTH IV load combination includes the effects of the following loads: DC, DD, DW, EH, EV, ES, EL, WA, FR, TU, CR, and SH. As for the STRENGTH I load combination, the following earth-related loads—DD, EH, EV, ES, and EL—and transient loads—WA, FR, TU, CR, and SH—were not considered. The STRENGTH IV load combination will only consider the permanent loads DC and DW. The load combinations used are defined in Section 3.3.2 of the *LRFD Bridge Design Specifications* (*47*).

In Tables 3.4.1-1 and 3.4.1-2 of the *LRFD Bridge Design Specifications* (*47*), the load factors for the load combinations are the following:

$$N_{\text{STRENGTH I}} = 1.25\ \text{DC} + 1.50\ \text{DW} + 1.75\ \text{LL}$$

$$N_{\text{STRENGTH IV}} = 1.50\ \text{DC} + 1.50\ \text{DW}$$

If it is assumed that DC is 95% of the total dead load (defined herein as D) and that DW is 5% of the total dead load, then the above equations for the STRENGTH I load combination reduce to

$$N_{\text{STRENGTH I}} = 1.25\ (0.95\ \text{D}) + 1.50\ (0.05\ \text{D}) + 1.75\ \text{LL or}$$

$$N_{\text{STRENGTH I}} = 1.26\ \text{D} + 1.75\ \text{LL}$$

Recognizing that a lower load factor will yield a higher sustained load testing value when the resistance side of the equation is divided by the load factor, it was decided to choose a 1.25 multiplier for D. Additionally, this multiplier removes any doubt as to the percentage estimate of the total dead load for DC and DW. Therefore, the STRENGTH I load combination reduces to

$$N_{\text{STRENGTH I}} = 1.25\ \text{D} + 1.75\ \text{LL}$$

Similarly, the STRENGTH IV load combination reduces to

$$N_{\text{STRENGTH IV}} = 1.50\ \text{D}$$

Ratio of Sustained Load to Factored Load

The ratio (N_{sust}/N_{FL}) will be maximized when N_{FL} is minimized. Table 6 provides the ratio (N_{sust}/N_{FL}) if the full live load is assumed to be a sustained load, and Table 7 provides the ratio (N_{sust}/N_{FL}) if only 60% of the live load is assumed to be sustained. According to Table 6, for a small live load, the controlling ratio of the sustained load to the factored load is 0.76 for a full sustained live load. However, it is more likely that the entire live load will not always be present; therefore the ratio is probably closer to the controlling value of 0.72 in Table 7.

Table 6. Controlling ratio for N_{sust}/N_{FL} assuming a full sustained live load.

Ratio of live load to dead load (LL/D)	(D + LL) / (1.25D + 1.75LL)	D / 1.50D	Controlling N_{sust}/N_{FL} ratio
0.143	0.76	0.67	0.76
0.15	0.76	0.67	0.76
0.20	0.75	0.67	0.75
0.50	0.71	0.67	0.71
1.00	0.67	0.67	0.67
1.50	0.65	0.67	0.67
2.00	0.63	0.67	0.67

Table 7. Controlling ratio for N_{sust}/N_{FL} assuming a 60% sustained live load.

Ratio of live load to dead load (LL/D)	(D + 0.60LL) / (1.25D + 1.75LL)	D / 1.50D	Controlling N_{sust}/N_{FL} ratio
0.143	0.72	0.67	0.72
0.15	0.72	0.67	0.72
0.20	0.70	0.67	0.70
0.50	0.61	0.67	0.67
1.00	0.53	0.67	0.67
1.50	0.49	0.67	0.67
2.00	0.46	0.67	0.67

Capacity Reduction (Resistance) Factor

Appendix D of *ACI 318-05*(*1*) was consulted for a capacity reduction or resistance factor because Section 5.5.4 of the *LRFD Bridge Design Specifications* (*47*) does not have a capacity reduction dealing with adhesive anchors. Appendix D of *ACI 318-05* specifies a resistance factor of $\phi = 0.65$.

5% Fractile Statistical Adjustment Factor

The mean strength is converted to the nominal strength based on the 5% fractile ($\alpha_{5\%}$) which is defined as

$$\alpha_{5\%} = (1 - K \cdot \text{COV})$$

Where

K is obtained from standard statistical charts based on the number of tests and assuming a 90% confidence level. Since the highest value of $\alpha_{5\%}$ will control, this means that the lowest value of K will control. The lowest value of K is 1.65 for an infinite number of tests.

COV is assumed to be 0.10, which is conservative, based on tests by Cook and Konz (*6*).

Therefore

$$\alpha_{5\%} = (1 - (1.65) \cdot (0.10))$$

$$\alpha_{5\%} = 0.84$$

Sustained Load

Substituting the values obtained above into Equation 3 yields

$$N_{sust} \le (0.72) \cdot (0.65) \cdot (0.84) \cdot N_{mean}$$

$$N_{sust} \le 0.39 \cdot N_{mean}$$

Finally, applying a 1.5 multiplication factor (in *ICC-ES AC58* [*31*] this factor was 1.6 and in *ICC-ES AC308* [*3*] this factor was ~1.4), the sustained load should be 60% of the mean load for AASHTO applications.

Possible AASHTO Test Methods for Evaluation of Sustained Tension Loads on Adhesive Anchors

As a result of the literature review, two possible sustained load methods were identified: the pass/fail test method and the stress versus time-to-failure test method. A discussion of each of these methods is presented below. Advantages (pros) and disadvantages (cons) for each test method are summarized at the end of this section.

ICC-ES AC308 (or ACI 355.Y) with Modifications for Pass/Fail Sustained Load Test

Overview and Modification

One option would be to incorporate *ICC-ES AC308* (*3*) or *ACI 355.Y* (*2*), pending its approval, and make slight modifications pertinent to AASHTO for a pass/fail sustained load test. A recommended modification to *ICC-ES AC308* would be to change the applied sustained load to $0.60 \cdot N_{mean}$.

Advantages and Disadvantages

ICC-ES AC308 (*3*) would be a good option because it is an accepted standard with years of testing to demonstrate its reliability as a test procedure. It is widely used in the industry, and many adhesives have been tested under this standard, facilitating the comparison between new and existing anchors. One disadvantage is that pass/fail criteria do not demonstrate relative performance among products and do not allow for a high-quality product to stand out. Additionally, because the curve created is based on projected displacement over time as opposed to rupture points, the selection of the mathematical projection method over long time periods as well as the displacement limit at the projected time lead to uncertainty.

Stress versus Time-to-Failure Test

Overview

Another potential test method would be to create a time-to-failure chart or a table of values of failure load at specified lifetimes. This method would consist of a series of tests at varying stress levels recording the time to failure. In this case, failure would be defined as the initiation of tertiary creep.

The method would begin by placing five specimens under confined static tests to determine the mean static load. Subsequent sustained load test series would be conducted on three specimens at lower stress levels at an elevated temperature of 110°F. Future tests could be conducted at standard room temperature if it were deemed appropriate. It is recommended that these lower stress levels be at 85% and 75% of the mean static load. Ideally, the stress levels chosen would create data points in separate log cycles. Care would have to be taken not to choose too low a stress level, since the lower the stress level the longer the time to failure. The data would be plotted on a stress versus time-to-failure graph.

A least squares trendline would then be drawn through the mean time to failure at each stress level and extended linearly (on the log scale) to the x-axis. This trendline would be conservative since it is understood that the stress versus time-to-failure graph will tend to develop a shallower slope at the high-lifetimes/low-stress levels. While a linear projection would be conservative and most likely sufficient, a manufacturer would have the option of performing longer term tests at lower stress levels in order to better define the graph. See Figure 26 for a sample stress versus time-to-failure graph.

If the anchor does not fail within 3,000 hours (~4 months) at the 75% stress level, the manufacturer would have the option of stopping the test and using the (75%, 3,000-hour) data point and creating the stress versus time-to-failure graph. This curve will be conservative as opposed to the curve that would have been created if the experiment had continued to failure of the anchor.

A sample table of common structure lifetimes (e.g., 50, 100, and 200 years) and respective stress levels at failure (percent design strength) can be developed if it has been decided that it is better not to include a graph in a manufacturer's literature. See Table 8 for a sample table.

Incorporation of Previous Test Data

If existing data for an adhesive are available from *ICC-ES AC308* (*3*) tests, a stress versus time-to-failure graph can be created without further testing. If the product passed *ICC-ES AC308* and did not pull out at 55% mean static load at 42 days (1,000 hours), the point (55%, 1,000 hours) can be plotted on the stress versus time-to-failure graph, and a curve plotted linearly on the log graph would be very conservative. The trendline of this curve would pass through ~25% mean static load at 50 years and ~18% for 200 years. The manufacturer would have the option to (and would most likely choose to) run additional tests at stress levels above 55% (neglecting the data at 55%), with the hope of obtaining a more realistic curve for the adhesive, thereby qualifying for a higher percent static load at a given life-

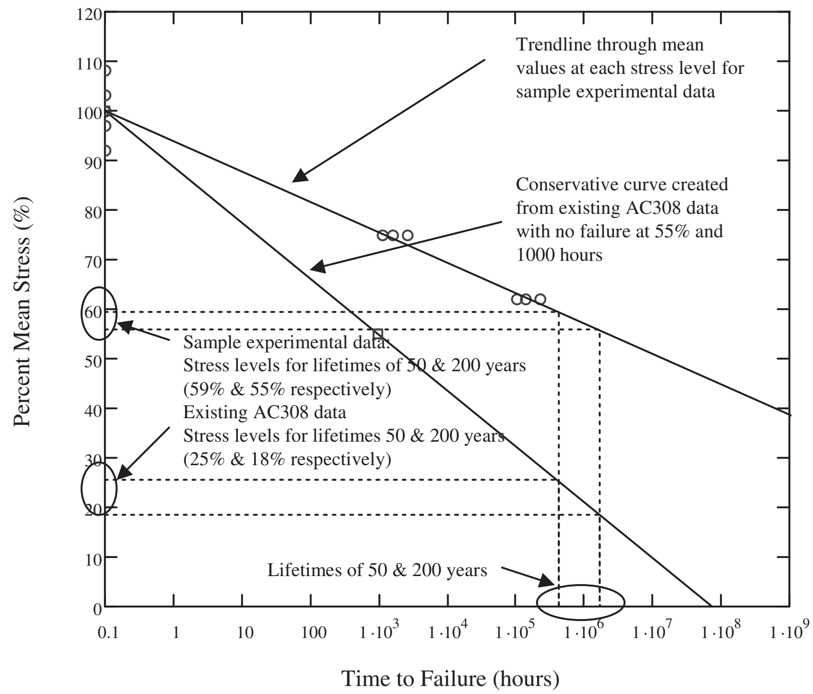


Figure 26. Sample stress versus time-to-failure graph.

time. Figure 26 displays how the existing *ICC-ES AC308* data can be plotted and used on a stress versus time-to-failure graph. Table 8 lists the lower bound values at 50 and 200 years.

If product-specific data are not available, the results from an *ICC-ES AC308* (*3*) test can serve as the lower bound for design. If long-term test data can be generated, a more accurate curve at longer times to failure can improve this conservative lower-bound value. A lower-bound value is important for the practicing engineer during preliminary design when product-specific design values are not known.

Incorporation of Other Temperatures

ASTM D4680-98 (*36*) points out that stress versus time-to-failure curves at different temperatures for adhesives that are minimally affected by temperature will be nearly parallel. If temperature has a significant effect, these curves will have different slopes at higher temperatures, and it can be expected that the slopes will differ at lower temperatures where the curves are extrapolated to long time periods. If there is no change in slope in the curves, then the extrapolation at lower temperatures can be made with more confidence.

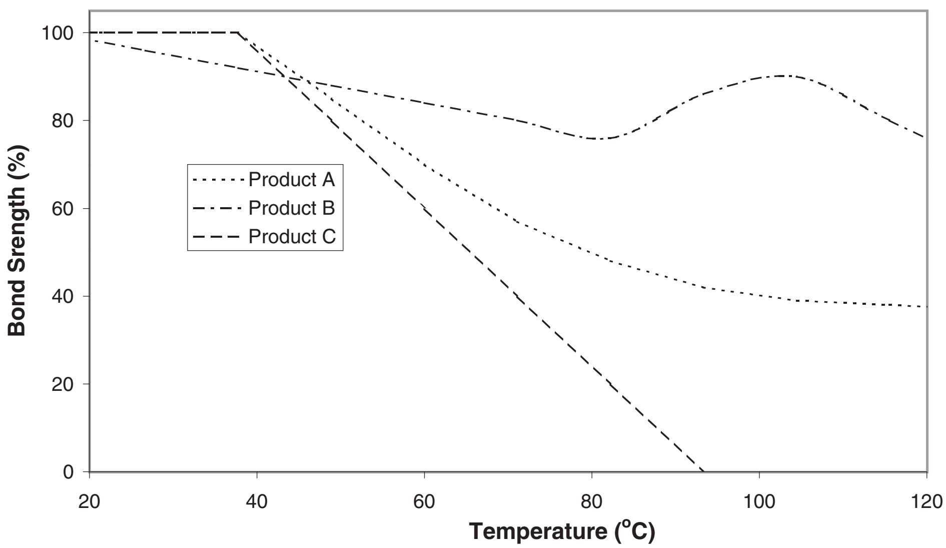
Trendlines at different temperatures can be plotted on the stress versus time-to-failure graph from tests conducted at various temperatures. While the trendlines require confirmation, in the absence of test data at other temperatures, it is possible to plot these trendlines using a ratio calculated from a bond strength versus temperature curve (shown in Figure 27), which is common for adhesive anchor systems. Using this curve, one can calculate the ratio of bond strength between any given temperature and 110°F. This ratio can be used to set the offset of the stress versus time-to-failure trendline from the 110°F curve at the 100% stress level on the stress versus time-to-failure graph (see Figure 28). While temperature differences might induce different curvatures, parallel lines at temperatures lower than the standard elevated temperature of 110°F should be conservative because lines at lower temperatures will have shallower slopes.

Table 8. Sample table of design stress levels at selected lifetimes.

Lifetime (years)	Percent Design Strength Stress Level at Failure (%)	ICC-ES AC308 Lower Bound Value (%)
50	59	25
200	55	18

Advantages and Disadvantages

The main advantage to the stress versus time-to-failure test is that the curves generated from the test will be very useful to the practicing engineer. Knowing the lifetime expected for an anchor, the engineer can consult the graph (or table) for the percent design strength for the anchor. The value from the graph (or table) will be used as a resistance multiplier, herein referred to as α_{sl}.



Reprinted with permission from Cook et al. (*4*).

Figure 27. Sample bond strength versus temperature curves for three hypothetical adhesives.

Referring back to Equation 2, the sustained load percent design strength multiplier (α_{sl}) would be applied to the resistance side of the equation, resulting in Equation 4:

$$N_u \le \phi \cdot \alpha_{s1} \cdot \left(\tau' \cdot \pi \cdot d \cdot h_{ef}\right) \quad \text{(lb or N)} \tag{4}$$

Another advantage is that stress versus time-to-failure graphs can be easily generated by using existing *ICC-ES AC308* (*3*) data, with no requirement to conduct additional tests. The curves obtained would be very conservative, but the manufacturer would have the option to run additional tests in order to obtain curves with higher resistance factors. This method also provides an opportunity for manufacturers to qualify their product under different stress levels, thereby allowing a higher quality product to stand out among its competitors.

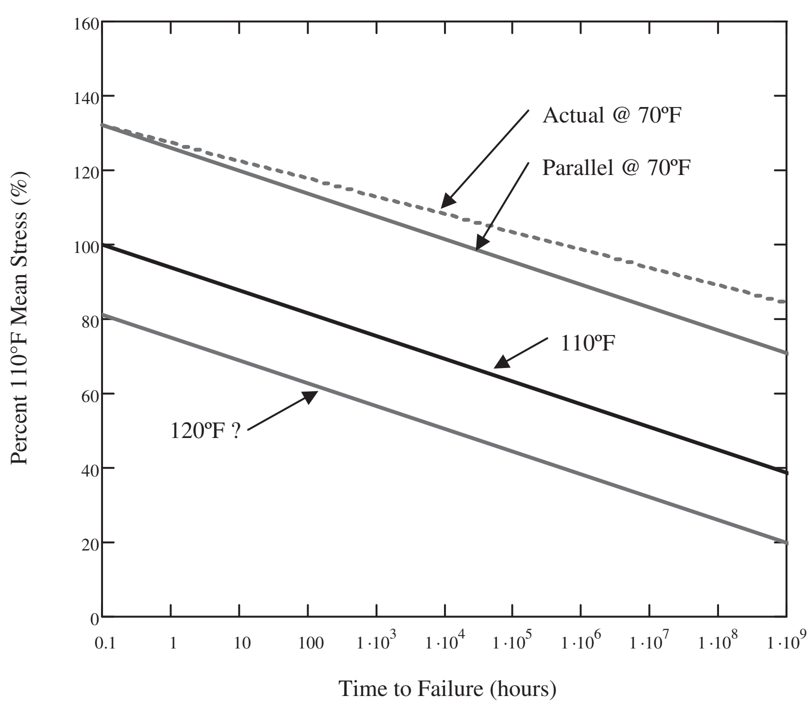


Figure 28. Stress versus time-to-failure graph incorporating other temperatures.

Additionally, since the data points are based on rupture, it is unnecessary to develop methods for projecting displacement versus time data to a certain time and then determining limits on the projected displacement, as is done in *ICC-ES AC308* (*3*). If the anchors do not fail, the projection is conservative. Finally, test results at other temperatures can easily be incorporated on the stress versus time-to-failure graph. If test data are not available, a rational method exists for creating conservative curves for temperatures lower than the test temperature of 110°F.

A possible disadvantage to the stress versus time-to-failure test is that it could extend over a long period of time. Nonetheless, 3,000 hours (~4 months) does not seem too long for product approval. Once the minimum testing requirement is completed, the manufacturer could choose to run the additional tests at lower stress levels to obtain more exact numbers at longer lifetimes. However, the manufacturer would have the option of placing the product on the market with the information from the minimum tests during the continued (voluntary) tests and updating the product information later.

The advantages (pros) and disadvantages (cons) to the possible AASHTO test methods for sustained load are summarized in Table 9.

Proposed AASHTO Test Method for Sensitivity of Adhesive Anchors to In-Service Moisture

As mentioned earlier, the research conducted by Chin et al. (*13*) of NIST determined that the presence of absorbed moisture after curing can create the same creep-type behavior commonly seen in high-temperature conditions. It was additionally noted that the "moisture effects were observed to be not fully reversible upon drying."

ICC-ES AC308 (*3*) has a sensitivity test only for moisture during installation. Currently there is no test for in-service moisture. Due to doubts as to whether in-service moisture significantly affects adhesive anchors, it would be beneficial to investigate this issue by means of a series of tests. It is proposed to conduct two series of tests as described below.

Test Series 1: Wet versus Dry. In this test series, five specimens are maintained dry at 110°F for 1 month while five other specimens are maintained wet at 110°F for 1 month. Static load tests are conducted on the specimens at the end of the month and their mean values are calculated to determine the bond stress ratio of wet specimens to dry specimens.

Table 9. Pros and cons of possible AASHTO test methods for sustained load.

Test Method	Advantages (Pros)	Disadvantages (Cons)
Modified ICC-ES AC308	• Accepted industry standard not requiring much development of test protocol and procedure	• Pass/fail results do not reward a high-quality product • Uncertainty of the mathematical projection method of displacement • Uncertainty of the displacement limit at projected time
Stress versus Time-to-Failure	• Test results provide useful design data for the practicing engineer • Existing data from ICC-ES AC308 can easily be incorporated into stress versus time-to-failure graphs • Allows a method for manufacturers to qualify a product above a minimum standard in order to distinguish their product amongst competitors • Removes uncertainty associated with the mathematical projection of displacement • Removes uncertainty associated with establishing limit on projected displacement • Rational method of incorporating test results from other temperatures	• Test duration is possibly three times as long as ICC-ES AC308 test duration

Test Series 2: Wet and Dried versus Dry. In this test series, five specimens are maintained dry at 110°F for 2 months while five other specimens are maintained wet at 110°F for 1 month and then allowed to dry at 110°F for 1 month. Static load tests are conducted on the specimens at the end of the second month and their mean values are calculated to determine the bond stress ratio of wet specimens to wet-and-then-dried specimens.

Ideally, all the specimens for all of the test series are cast at the same time, subjected to elevated temperature at the same time, removed to standard temperature at the same time, and static-load tested at the same time in order to remove the effect of concrete strength. Following the series of tests, it can be determined whether in-service moisture significantly affects bond stress. If a significant effect is present, the ratio of wet specimens to dry specimens can be used by a designer as a resistance multiplier for the effect of in-service moisture, herein referred to as α_m.

Referring back to Equation 2, the in-service moisture multiplier (α_m) would be applied to the resistance side of the equation resulting in Equation 5:

$$N_u \leq \phi \cdot \alpha_m \cdot (\tau' \cdot \pi \cdot d \cdot h_{ef}) \quad (\text{lb or N}) \qquad (5)$$

Test Series 2 is conducted to determine whether the losses found in the wet versus dry series (assuming there are losses) are recoverable/reversible by comparing the two ratios computed.

Recommendations Resulting from the NCHRP Panel Review

Based on the pros and cons presented in Table 9 and as a result of the NCHRP project panel meeting, the stress versus time-to-failure test method performed at elevated temperature was selected for trial testing to determine whether it is a viable method for evaluating adhesive anchor products used in AASHTO applications. The following test specifics were agreed upon in the NCHRP project review panel meeting:

- Two Adhesives would be tested.
  - They would be different adhesive types.
  - They would be adhesives that have passed *ICC-ES AC308* (*3*).
- Static load tests would be performed to determine the 100% stress level.
  - There would be five samples per adhesive for the static load tests.
- Sustained load tests would be performed at the 85% and 75% stress levels.
  - There would be three samples per adhesive per stress level.
- The test would be performed at 110°F.

Additionally, if the project budget and schedule allow, it was suggested that a test series on sensitivity to in-service moisture be conducted to investigate the significance of in-service moisture.

Summary and Conclusion

This chapter has provided a summary of the literature on adhesive anchors in concrete focusing on the influence of sustained loads and the effects of elevated temperature and in-service moisture. Standards, tests methods, and design procedures for adhesive anchors in concrete and for other structural applications/systems have been summarized as well. In addition, recommendations on test methods to evaluate adhesive anchor performance under sustained load with elevated temperature and to evaluate the effects of in-service moisture have been presented for suggested trial testing and potential incorporation into AASHTO standards.

The majority of the content of this chapter was presented as an interim report to the NCHRP project panel at a meeting in Gainesville, Florida, on May 29, 2008. The NCHRP project panel decided to proceed with a stress versus time-to-failure approach on two adhesives as recommended by the researchers. It was also decided that the recommended test method for sensitivity to in-service moisture would be conducted only if the project budget and timeline allowed.

CHAPTER 2

Research Approach

This chapter presents the test program conducted at the University of Florida in the summer and fall of 2008 to validate the draft AASHTO test method. The draft AASHTO "Standard Method of Test for Evaluation of Adhesive Anchors in Concrete Under Sustained Loading Conditions" is presented in Appendix A of this report. The project timeline and budget did not allow for testing the effects of in-service moisture. It is expected that this effect will be studied under NCHRP Project 04-37, "Long-Term Performance of Epoxy Adhesive Anchor Systems."

Overview of Test Procedure

Based on the recommendations in Chapter 1, the stress versus time-to-failure sustained load test program was developed with the intent to follow *ASTM E488-96* (*28*), *ASTM E1512-01* (*29*), and *ICC-ES AC308* (*3*) as much as possible. The test method is briefly described below. Changes to the recommendations in Chapter 1 are briefly explained below:

- Concrete
  - As recommended in *ICC-ES AC308* (*3*), the concrete mix should be plain concrete without any admixtures.
  - Per *ICC-ES AC308,* the concrete mix should have a compressive strength between 2,500 and 4,000 psi at the time of testing.
- Adhesive
  - As discussed in Chapter 1, adhesives were chosen that had passed *ICC-ES AC308.*
  - Adhesives of different chemistries were chosen to investigate sensitivities to the test method.
- Anchor
  - Due to the bond strengths of the adhesives, a ⅝-in. diameter bar was used instead of the ½-in. diameter recommended by *ASTM E1512-01* (*29*) to avoid a steel failure mode.
  - To further reduce the possibility of steel failure, *ASTM A193* (*49*) Grade B7 steel was chosen because of its high strength and wide availability to U.S. laboratories. Other steels were investigated, but none were found that met the requirements of strength and availability prior to the test. After completion of the tests, an ASTM A540Grade B23 threaded rod with a 150 ksi yield strength and a 165 ksi ultimate strength was identified that could be used in future tests.
  - An embedment depth of 3⅛ in. was chosen to ensure adhesive failure, based on minimum recommendations from Table 1.2 in *ICC-ES AC308* (shown below as Table 10).
- Test Procedure
  - As noted in Chapter 1, it was recommended to test five specimens per adhesive in the static load test. Six specimens were installed, and it was later decided to test four specimens under the continuous load rate and two under the incremental load rate in order to investigate the possibility of the incremental load rate as an indicator to sensitivity to sustained load.
  - The elevated temperature was chosen as 110°F based on *ICC-ES AC308.*
  - The load rate in the static load test was chosen to produce failure at 2 min ±1 min in accordance with *ASTM E488-96* (*28*).
  - Data in the static load tests were sampled at 1-s intervals in accordance with *ASTM E488-96.*
  - The stress levels set for the sustained load (creep) test were changed from the recommended levels of 85% and 75% in Chapter 1.
  - For the sustained load (creep) test, the upper percent load level was set at 75% of mean static load. This value was chosen to avoid a short failure time. Also, 75% was assumed to be safely below any possible statistically low value for the mean static load.

Table 10. Minimum embedment depth.

d (in)	$h_{ef,min}$ (in)
1/2	2 3/4
5/8	3 1/8
3/4	3 1/2
≥ 1	4d

– The lower percent load series was set at 62% of mean static load. This was chosen to be sufficiently below 75% and yet not low enough to cause a very long test duration. Since the adhesives tested had passed *ICC-ES AC308,* it was known that percent load levels of 55% and below would cause failure beyond 1,000 hours (6 weeks).
– The confining sheet thickness specified in *ICC-ES AC308* was determined to be too thin and was increased.

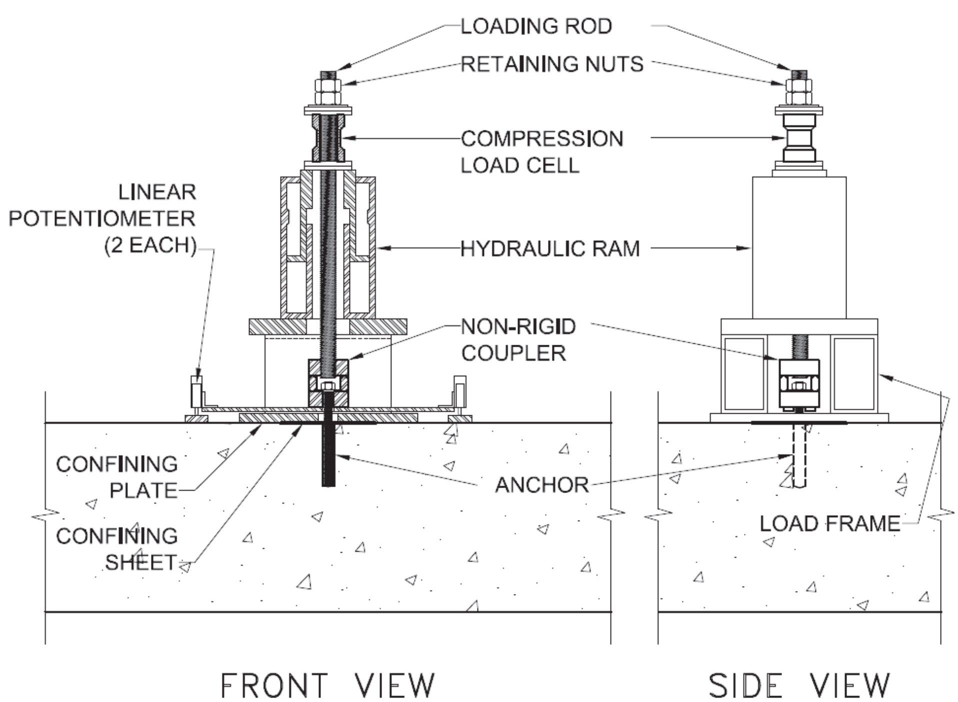
Test Apparatus

Static Load Test

The testing apparatus for the static load test (see Figure 29) used a 6- × 6- × 0.03-in. thick Teflon PTFE (Polytetrafluoroethylene) confining sheet placed under an 8- × 8- × ⅝-in. thick steel confining plate. The confining sheet was used to correct for any surface irregularities in the concrete. A 1¼-in. hole was drilled though the center of the confining sheet and confining plate to fit around the anchor. Two 3- × 5- × ¼-in. rectangular steel tubes 8-in. long were placed parallel to each other on either side of the anchor. A 10- × 10- × 1-in. thick steel plate with a 2¾-in. diameter hole in the center was placed on the rectangular steel tubes to support an Enerpac Model RCH-603 Holl-O-Cylinder (60-ton) hydraulic ram. A Houston Scientific Model 3500 100-kip load cell was placed on top of the ram, sandwiched between four 3- × 3- × ¼-in. square plates (two above and two below) with a 1⅛-in. diameter hole in the center.

The ⅝-in. diameter anchor was fed through an 11⁄16-in. diameter hole in a non-rigid coupler and secured with a nut. The oversized hole in the coupler prevented bending forces from being transferred from the coupling rod to the anchor. A 1-in. diameter loading rod was threaded into a hole in the top of the coupler, passed through the ram and load cell, and secured at the top with a washer and two nuts.

A 2- × 16- × ¼-in. steel flat bar was welded to the bottom of the coupler and BEI Duncan Electronics Model 9610 linear motion position sensors (linear potentiometers) were secured to each end of the flat bar equidistant from the center line of the anchor. The linear potentiometers were oriented downward and measured displacement between the flat bar and the surface of the concrete. The linear potentiometers were oriented in this manner so that as the flat bar raised, the plunger extended, ensuring that the linear potentiometer was not damaged if the anchor failed drastically. Small metal pieces were placed on top of the concrete surface to raise the initial bearing point of the linear potentiometer plunger and to provide a smooth measuring surface.



Source: Modified from Cook et al. (*7*).

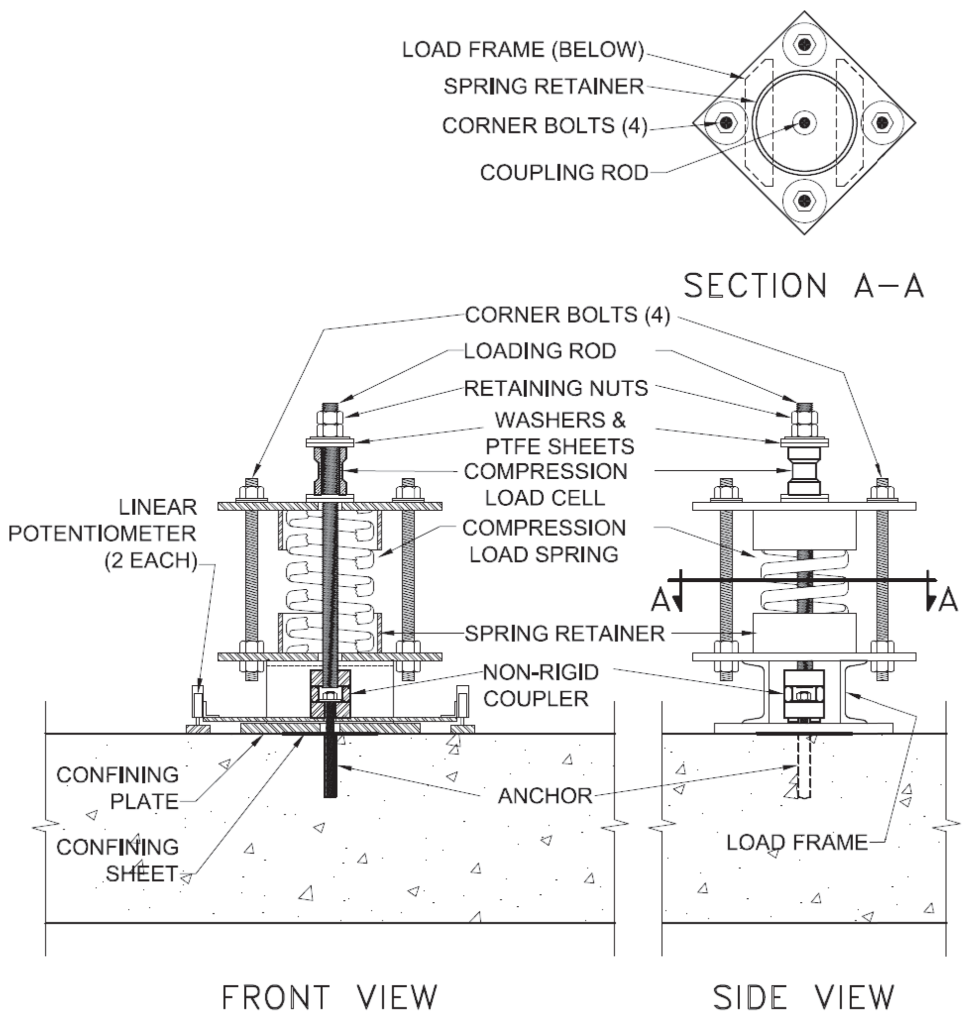
Figure 29. Static load test apparatus.

Sustained Load (Creep) Test

The testing apparatus for the sustained load (creep) test (see Figure 30) used the same Teflon PTFE (Polytetrafluoroethylene) confining sheet and steel confining plate used in the static load test apparatus. Existing steel frames from previous sustained load (creep) tests conducted at the University of Florida (*7*) were used to contain compression springs to apply the sustained load. Springs were chosen instead of a hydraulic ram for these long-term tests in order to reduce the chance of loss of load caused by a hydraulic leak. The springs used were provided by the FDOT State Materials Office in Gainesville, Florida. The steel wire springs were approximately 5.5 in. in diameter and 8 in. in uncompressed height. The springs had an average approximate spring stiffness of 10.8 kips/in. and a working load range up to 16 kips.

The load frames, shown in Figure 30, straddled the anchor on top of two 1¾- × 4- × ¼-in. steel channels. A University of Florida fabricated aluminum load cell was placed on top of the load frame sandwiched between four 3- × 3- × ¼-in. square plates (two above and two below) with a 1⅛-in. diameter hole in the center. Above the square plates, a washer was placed, as well as two 0.03-in. thick PTFE sheets and another washer welded to a nut. The two PTFE sheets were placed between the washers to provide for a low-friction surface to facilitate the tightening of the nut during initial loading and later re-tightening of the spring. The nut was welded to the washer to ensure that the friction surface would be between the washers and not between the washer and the nut.

The ⅝-in. diameter anchor was connected to the 1-in. diameter loading rod by means of the same non-rigid coupler as in the static load test apparatus. Linear potentiometers were used to measure displacement in the same configuration as in the static load test apparatus. To prevent the test apparatus from falling over due to the dynamic load on the frame caused by an anchor pullout, the test frames were tied down with rebar wire to eye hooks set in the concrete.



Source: Modified from Cook et al. (*7*).

Figure 30. Sustained load (creep) test apparatus.

Specimen Preparation

The test specimen consisted of three parts: the concrete test member, the adhesive, and the anchor rod.

Concrete Test Member

The concrete test members were poured in six 48- × 46½- × 12-in. forms. In order to accommodate handling, minimal reinforcement (a single mat of six #4 60-ksi steel reinforcing bars each way) was placed 3 in. from the bottom of the slab.

The concrete was batched, mixed, and delivered by a local concrete batch plant, and all slabs were poured from the same batch. Concrete was poured directly from the truck into the forms and vibrated with an electric vibrator. Concrete with granite aggregate without any admixtures was specified with a mean compressive strength of 3,000 psi at 28 days; this was not the specified compressive strength (f'_c). The top surface was finished with standard finishing tools, and the bottom and four sides had a form finish. Temperature, slump, and percent air were measured, and their values are presented in Table 11. The 4- × 8-in. cylinder and the 6- × 12-in. cylinder were made for concrete strength testing. A temperature sensor was placed 2.5-in. deep in the center of the top of each slab during pouring.

The concrete slabs and cylinders were covered with tarps and plastic and maintained wet for 7 days. After 7 days, the side forms were removed and the cylinders de-molded. The slabs and cylinders were maintained in the laboratory thereafter. Concrete compressive strength was determined by testing the cylinders in general accordance with *ASTM C39* (*50*). A concrete strength-age relationship was determined by testing the 4- × 8-in. cylinders and 6- × 12-in. cylinders each week for the first 5 weeks and, thereafter, testing only the 4- × 8-in. cylinders at a reduced frequency. The 6- × 12-in. cylinders were not tested beyond 5 weeks because it was noted that there was an agreement between the strengths calculated from the 4- × 8-in. and the 6- × 12-in. cylinder tests. Table 12 presents the concrete strength and age data.

Table 11. Concrete properties.

Property	Value
Temperature	88°F
Slump	3.5 in
Percent Air	2.0%

Adhesive

Three adhesives, which will be identified as Adhesives A, B, and C, were used in this project. These adhesives had the following chemistries:

- Adhesive A was a hybrid with methacrylate hardener and quartz filler with cementitious material,
- Adhesive B was an amine epoxy with quartz filler, and
- Adhesive C was a mercaptan/amine blend epoxy with talc filler.

The three adhesive products were stored in an environmentally controlled room that was maintained within the temperature and humidity range specified by the manufacturer.

Static load tests were conducted on all three adhesives. Upon completion of the static load tests, due to the project budget and timeline, it was decided to conduct sustained load (creep) tests on only two adhesives—Adhesives A and B. This decision, as well as the choice of the two adhesives, was approved by the NCHRP project panel prior to commencing the sustained load (creep) tests.

Anchor Rods

ASTM A193 (*49*) Grade B7 ⅝-in. diameter steel threaded rod was used to fabricate the anchor rods. This grade of steel has a specified yield strength of 105 ksi and a specified tensile strength of 125 ksi. The anchor rods were cut to length from

Table 12. Concrete strength and age data.

Date	Age (days)	4- x 8-in Cylinder Average (psi)	6- x 12-in Cylinder Average (psi)	Average (psi)
06/12/2008	7	1,766	1,266	1,566
06/19/2008	14	2,815	2,884	2,305
06/26/2008	21	2,189	2,439	2,859
07/03/2008	28	3,431	3,090	3,112
07/10/2008	35	3,643	3,202	3,472
07/24/2008	49	3,833	NA	3,833
08/14/2008	70	3,944	NA	3,944
09/18/2008	105	3,492	NA	3,492
10/16/2008	133	3,164	NA	3,164
12/04/2008	182	3,135	NA	3,135
02/26/2009	265	3,614	NA	3,614

6-ft stock, and their ends ground and chamfered with a bench grinder and steel brush to remove burrs and to clean up the threads in order to install the nuts. Prior to installation, the rods were cleaned with acetone, allowed to air dry, and protected with paper until installed.

Instrumentation

This section discusses the instrumentation used to make data measurements and the calibration of the instrumentation.

Measurement

Displacement. Direct measurement of the anchor displacement was not possible due to the location of the test apparatus; therefore, a 16- × 2- × ¼-in. *ASTM A36* (*51*) steel flat bar was attached to the bottom of the non-rigid coupler that connected the anchor to the 1-in. diameter coupling rod. Two BEI Duncan Electronics Model 9610 linear motion position sensors (linear potentiometers) were affixed to this flat bar, one on each end, equidistant from the centerline of the anchor. The displacement was calculated as the average of the two linear potentiometer measurements.

Load. The tension in the anchor was measured indirectly as a compressive reaction of either the hydraulic ram or the compression spring in the test apparatus. For the static load tests, the load was measured by a Houston Scientific Model 3500 100-kip load cell. For the twelve sustained load (creep) tests, the loads were measured by twelve 30-kip aluminum load cells fabricated and calibrated at the University of Florida Structural Laboratory.

Temperature. Temperature in each concrete test slab was measured with National Semiconductor LM35 Precision Centigrade Temperature Sensors located 2.5 in. deep in the top center of the concrete surface (sensors were placed during the concrete pour). Ambient air temperature in the test chamber was measured with another National Semiconductor LM35 Precision Centigrade Temperature Sensor placed at the same elevation as the top of the test slabs and, additionally, at 5-min intervals, with a La Crosse Model WS-8610U Wireless Data Logging Weather Station placed 5.5 ft high on the back wall of the test chamber.

Humidity. Relative humidity in the test chamber was recorded at 5-min intervals with the La Crosse Model WS-8610U Wireless Data Logging Weather Station placed 5.5 ft high on the back wall of the test chamber.

Time. Time was measured using the computer's internal clock.

Instrument Calibration

Displacement. The linear potentiometers were calibrated against a Fowler digital caliper over their full range of 1 in. at ¼-in. increments. The measurements were adjusted for variations in power supply voltage and normalized to a 10-volt power supply.

Load. The load cells were calibrated in September 2008 at the University of Florida on a Tinius-Olsen universal testing machine calibrated by Tinius-Olsen on November 8, 2007. The Houston Scientific Model 3500 100-kip load cell used in the static load tests was calibrated over a range of 0 to 39 kips with about 300 data points. The 12 University of Florida fabricated 30-kip aluminum load cells used in the sustained load (creep) tests were calibrated over a range of 5 to 20 kips with about 130 data points.

The 30-kip aluminum load cells fabricated at the University of Florida and used in the sustained load (creep) tests were recalibrated at elevated temperature following the conclusion of the tests. This calibration was conducted at 110°F, and the load cells were calibrated against the Houston Scientific Model 3500 100-kip load cell used in the static load tests. This recalibration resulted in calibration equations with different slopes (stiffness) than the calibration equations derived from the calibration tests performed at room temperature. The data were modified to account for the new calibration equations.

Temperature. The National Semiconductor LM35 Precision Centigrade Temperature Sensors were calibrated against a 32°F ice bath and a 212°F boiling bath. The temperature sensor in the Wireless Data-Logging Weather Station was calibrated in a certified environmental chamber at the FDOT State Materials Office in Gainesville, Florida.

Humidity. The humidity sensor in the Wireless Data Logging Weather Station was calibrated in a certified environmental chamber at the FDOT State Materials Office in Gainesville, Florida.

Environmental Control

Standard Temperature

An air-conditioned space was used to store the adhesive and to condition the slabs to the required condition for installation and static load testing of 75°F ±10°F and 50% ±10% relative humidity. Temperature was controlled by a Frigidaire Model FAA07457A electronically controlled air conditioner.

Elevated Temperature

A 7.5- × 12- × 8-ft insulated environmental chamber was used to condition and test at the elevated testing temperature of 110°F +10°F/–0°F and below 40% relative humidity for the sustained load (creep) test. The temperature was maintained by a Modine electric-coil convection heater controlled by a Honeywell pneumatic thermostat. Temperature sensors placed in the room at the elevation of the test slabs and in each of the concrete test slabs were used to record the temperature at varying intervals during conditioning and testing. Additionally, a wireless data logging weather station was used to monitor the temperature and humidity of the chamber at 5-min intervals during conditioning and testing. The concrete slabs were raised off the ground by 25 in. to promote better air flow and a uniform temperature within the concrete.

Two test slabs were placed in the test chamber before the installation of the anchors to determine how much time to allocate for the conditioning of the slabs during the test procedure. The test slabs were initially at 84°F, which was the temperature of the laboratory and within the installation temperature tolerance of 75°F ±10°F. It took 1½ days to raise the temperature from 84°F to 110°F. It was determined that the temperature would be raised from 75°F over 2 days and that stabilization would take an additional day, thereby making a total of 3 days for conditioning.

The slabs were then removed from the chamber, and their temperature was monitored to see how fast they cooled. It would be useful to know the rate of cooling when the slabs were removed from the chamber to pull the anchors during the static load test at elevated temperature. It would also be useful to have this information when the anchors were initially loaded and then tightened (if necessary) on the test apparatus during the sustained load (creep test). Please refer to Table 13 for the cooling times.

It was determined that if the test slabs were conditioned to 112°F prior to the static load test and bolt loading and tightening phases during the sustained load (creep) test, which is within the temperature tolerance of 110°F +10°F/–0°F, then there would be about 1.5 hours to conduct tests before the test slab temperature fell below 110°F. It was decided that 1.5 hours would be enough time to conduct the static load tests and to tighten the sustained load (creep) test apparatus.

During the actual static load test, the heater remained on during the entirety of the test. The heater, however, was turned off during the loading phase of the sustained load (creep) tests. In all tests, the slabs were kept inside the environmental chamber.

Table 13. Test slab cooling times.

Temperature Range	Time Elapsed
112°F – 110°F	1.5 hours
110°F – 105°F	4.5 hours
105°F – 100°F	6.5 hours

Data Management and Acquisition

During the tests and conditioning of the test slabs to the elevated temperature, a Microsoft-compatible computer ran several LabVIEW 8.0 software programs developed to collect, record, and display the data. Measured values included load, displacement, temperature, and time. Data acquisition was performed with a National Instruments NI cDAQ-9172 chassis with several National Instruments modules to interface with the instrumentation. A National Instruments NI-9205 module was used to collect power supply voltage, position, and temperature readings. Three National Instruments NI-9219 modules were used to excite the load cells and collect their subsequent data readings.

Due to minor fluctuations in the 10-volt power supply, the LabVIEW programs recorded the power supply voltage with each data reading, and the position readings were appropriately adjusted to a normalized 10-volt power supply. Humidity was not recorded with the LabVIEW programs, but was monitored with the wireless data logging weather station.

Static Load Program

A LabVIEW 8.0 program was developed for the static load test. Load and position readings were taken at 1-s intervals, and a load versus displacement curve was displayed on the screen for real-time feedback. Load rate control was monitored by plotting the actual load rate from the hydraulic hand pump against an ideal load rate to cause bond failure of the estimated load in 120 s for the continuous load rate tests. This real-time plot was used to assist the pump operator in applying as constant a load rate as possible. The latest data readings were displayed on the screen, and all data readings were automatically recorded in a Microsoft Excel spreadsheet.

Sustained Load (Creep) Program

A LabVIEW 8.0 program developed for this project was used for the sustained load (creep) test. Load, displacement, and temperature readings were taken at progressively longer intervals over the course of the test. The intervals were the following:

- Every 3 s during the loading process (the interval was initially 20 s for the first series of sustained load (creep) tests, but was changed to 3 s before starting the second series).

- Every minute for the first hour following the loading process.
- Every 10 min for 9 hours.
- Every hour thereafter.

If it becomes necessary to apply additional load to the anchor during the test, the program enters a tightening phase in which it records data at 3-s intervals. Once tightening is completed, the program returns to its former cycle.

Displacement versus time curves for each anchor and a temperature versus time curve of the chamber and the concrete test slabs were displayed on the screen for real-time feedback. The latest data readings were displayed on the screen, and all data readings were automatically recorded in a Microsoft Excel spreadsheet.

Temperature Conditioning Program

Another LabVIEW 8.0 program developed for this project was used during conditioning of the test slabs to the elevated testing temperature. Temperature readings were taken of the ambient air temperature in the room and the internal concrete temperature in each test slab at 1-min intervals. A temperature versus time graph was displayed on the screen for real-time feedback. Data were also downloaded from the wireless data logging weather station and plotted with the data obtained from the LabVIEW program to check for correlation. The latest data readings were displayed on the screen, and all data readings were automatically recorded in a Microsoft Excel spreadsheet.

Installation Procedure

All anchors were installed according to the manufacturer's specifications. The holes were created with a ¾-in. Hilti carbide-tipped concrete bit and a Hilti Model TE52 hammer drill, as specified by the manufacturer. A small wooden frame was used as a drilling guide in order to ensure that the holes were drilled perpendicular to the surface of the concrete. Observers were also used to ensure that the drilling was perpendicular.

The holes were cleaned according to the manufacturer's specifications, which included blowing with oil-free compressed air, brushing with a steel brush provided (and specified) by the manufacturer, and then blowing again with compressed air until no dust was discharged from the hole. Durations and numbers of brushing/blowing cycles varied by manufacturer, but for each case the holes were cleaned according to the manufacturer's specifications.

The adhesive products were dispensed with a manufacturer-supplied cartridge gun. According to the manufacturer's specifications, several squeezes of adhesive were discharged and disposed of before dispensing into the holes to ensure that the adhesive was of uniform color and consistency, indicating that it was properly/thoroughly mixed.

A washer and nut were placed on the anchor and set at the appropriate embedment depth of 3⅛ in., and the nuts were taped with duct tape to prevent them from turning. During installation in the hole, the anchor rod was rotated counterclockwise and jiggled until the washer came to bear on the concrete. Excess adhesive was carefully wiped away from around the anchor. The anchors were left undisturbed, and the adhesive was allowed to cure for a minimum of 48 hours prior to conditioning.

Eighteen anchors were installed per adhesive product:

- Six for an elevated temperature 110°F static load test,
- Six for a reference 75°F static load test,
- Three for a 75% sustained load (creep) test, and
- Three for a 62% sustained load (creep) test.

All anchors were installed on August 19, 2008.

Specimen Conditioning

Static Load Tests

Upon completion of the adhesive curing time, the slabs for the static load test began conditioning. For a baseline comparison, one slab was tested at 75°F ±10°F and 50% ±10% relative humidity. The slab for the reference 75°F test did not need conditioning since it was tested under environmental conditions that were the same as the installation conditions. In an attempt to test the anchors in the reference 75°F test as close to the time of the testing of the anchors at the 110°F elevated temperature, testing did not begin on all anchors until the slab in the elevated temperature test reached its final temperature. The reference 75°F static load test slab was tested on August 26, 2008.

The slab for the elevated temperature test was conditioned at 110°F +10°F/–0°F and below 40% relative humidity in the environmental test chamber until the slab reached its final condition and stabilized for 24 hours. The elevated temperature static load test slab began conditioning on August 21, 2008, and after 5 days (on August 26, 2008) it reached 110°F. The slab was then allowed to stabilize for 48 hours, with the 110°F temperature static load test performed on August 28, 2008.

Sustained Load (Creep) Tests

Due to space limitations in the environmental chamber, the slabs for the sustained load (creep) tests could not begin conditioning until the slab for the static load test was removed

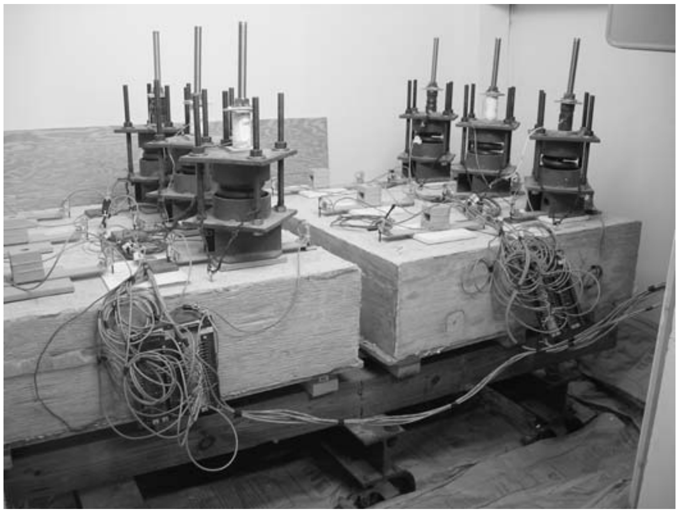


Figure 31. 75% sustained load (creep) test.

from the chamber. It was decided to test the first series of sustained load (creep) tests independently of the second series in order to use information gained from the test of the first series to help determine an appropriate percentage of mean static load for the second test series.

The slabs for the 75% sustained load (creep) tests began conditioning on October 2, 2008, and after 2 days (on October 4, 2008) they reached their final condition of 110°F. The slabs were then allowed to stabilize for 3 days, with testing beginning on October 7, 2008. The photo presented in Figure 31 was taken at the beginning of the 75% sustained load (creep) tests.

The slabs for the 62% sustained load (creep) tests began conditioning on October 17, 2008. Due to a tripped circuit breaker on the heater over the weekend, the heater had to be reset on October 20, 2008. After 2 days (on October 22, 2008), the slabs reached 110°F. The slabs were then allowed to stabilize for 24 hours. Testing for the 62% sustained load (creep) tests began on October 23, 2008.

Testing Procedure

Static Load Test

The following procedure was followed for the baseline 75°F test and the 110°F elevated temperature static load tests. The tests began with removing the nuts and washers from the anchors and scraping the excess adhesive off of the concrete surface to create a flat contact surface for the confining sheet and confining plate. One or two 0.03-in. thick PTFE confining sheet(s) (depending on the roughness of the concrete surface) and a confining plate were placed over the anchor, and the non-rigid coupler was attached to the anchor. A $\frac{1}{16}$-in. to $\frac{1}{8}$-in. gap was left between the confining plate and the coupler to allow for rotation of the coupler in order to prevent bending forces from being transferred between the anchor and the loading rod. The static load test apparatus was placed over the anchor, as previously discussed. Steel spacers were placed under the linear potentiometers so that the initial position reading was in the 0.300-in. to 0.500-in. range (this was done because the position readings at the far extremes of the instrument are less accurate).

The Enerpac Model RCH-603 Holl-O-Cylinder (60-ton) hydraulic ram was placed on the frame and connected to the Enerpac Model P802 (10,000 psi) hydraulic hand pump. The loading rod was connected to the coupler. The Houston Scientific Model 3500 100-kip load cell was placed on top of the hydraulic ram sandwiched between four $\frac{1}{4}$-in. plates (two above and two below). The loading rod nut was hand tightened to remove slack in the system.

The LabVIEW 8.0 program was started to confirm that the program was functioning correctly and that the linear potentiometer values were within acceptable ranges. The program was then reset, and the test was started. Pumping started after a few seconds elapsed in order to determine the initial load reading and to allow the program to zero out the initial position reading in order to calculate displacement. Pumping then began, according to one of two pumping rates (the constant load rate or the incremental load rate).

Four of each set of six anchors were loaded at a constant load rate. The operator adjusted the pump rate to conform to an ideal pump rate—one that would cause failure at the expected load within 120 s—by following the ideal load rate curve on the load versus time plot on the screen.

Two of each set of six anchors were loaded at an incremental load rate. The load was applied in steps and held constant for 2 min. Based on the four previous constant load rate anchor tests, an average ultimate load was calculated. The load was applied in increments (steps) of roughly 50%, 60%, 75%, and 85% of the ultimate load and then loaded until failure. Since the load was applied by a ram and hand pump using displacement control, the operator had to monitor the load and gradually pump in order to maintain a constant load. The load steps were maintained constant to an accuracy of ±2% of the desired load.

In order to avoid the possibility of the slab temperature falling below 110°F, it was decided to allow the heater to continue heating during the anchor pullout tests. The operator was in the environmental chamber only to disconnect and connect the testing apparatus to the anchors. The pumping and test observation were conducted outside the chamber, with the doors closed. For safety reasons, the door was always left open when the operator was inside the chamber.

The LabVIEW 8.0 program automatically recorded the test data in a Microsoft Excel spreadsheet, and the on-screen plots were saved to a file as well. Photos were taken of the failed anchors and are presented in Appendix C.

Sustained Load (Creep) Test

The tests began with scraping of the concrete and locating the confining sheet(s), confining plate, coupler and linear potentiometers as described in the static load test. The compression springs were compressed in an INSTRON System 3384 150KN universal loading machine, and the load was monitored with its respective University of Florida fabricated aluminum load cell, the Houston Scientific Model 3500 100-kip load cell used in the static load tests, and the on-screen display from the INSTRON System 3384 150KN universal testing machine. A 5% overload was applied to the compression spring above the desired load to allow for the loss in the load due to initial set and primary displacement of the anchor (80% mean static load was applied for the 75% tests and 67% mean static load was applied for the 62% tests). Once the desired load was obtained, the four corner bolts on the test frame were hand tightened to maintain the load. Both samples were tested at 75% and 62% of their mean static load as calculated in the static load test.

The compression spring frame was placed over the anchor, and the loading rod was connected to the coupler. The same University of Florida fabricated aluminum load cell used in monitoring the load applied to the spring was placed on top of the frame with two ¼-in. plates on top of it and two ¼-in. plates underneath it (so the load cell was sandwiched between the plates). The LabVIEW 8.0 program was started to confirm that the program was functioning correctly and that the linear-pot values were within acceptable ranges. The program was then reset, and the test was started. The data acquisition system initially entered a loading cycle and collected data every 3 s (20 s for the 75% series) while the loads from the springs were transferred to their respective anchors. The loading rod nut was hand tightened to remove slack in the system. The load was applied by tightening the loading rod nut. After the load from each spring was transferred to its anchor, the time was recorded for future data analysis. When all anchors were loaded, the loading cycle was terminated and the program began taking data readings according to the progressively increasing schedule previously discussed.

The LabVIEW 8.0 program automatically recorded the test data in a Microsoft Excel spreadsheet. Photos were taken of the failed anchors and are presented in Appendix C.

Post-Test Procedure

Following the completion of each test, photos (presented in Appendix C) were taken of each anchor. Additionally, a small hammer was used to check for cracked concrete around each anchor because cracked concrete would indicate a possible shallow concrete failure with bond failure. A few of the anchors were cored to a depth of 7 in. with a 4-in. diameter concrete cylinder core bit using a Hilti DD-160E core drill. The resulting concrete core provided a more detailed investigation of the failure mode and is discussed in Chapter 3. Photos were taken of the cores and are presented in Appendix C.

Recommendations

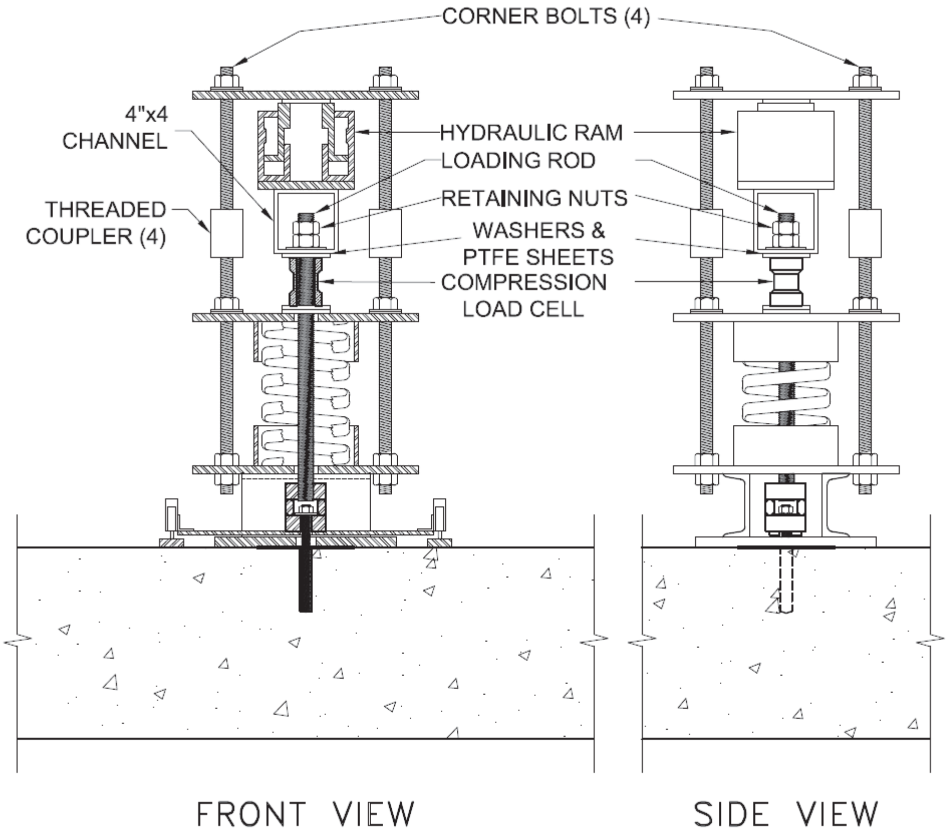
The initial testing yielded a few recommendations for improving the test procedure. These recommendations addressed three areas: materials, static load tests, and sustained load (creep) tests.

Materials. After testing, it was discovered that a higher strength threaded rod is available in the United States. Using an ASTM A540 Grade B23 threaded rod that has a 150-ksi yield strength and a 165-ksi ultimate strength could allow for smaller diameter rods and/or deeper embedment depths to be tested.

Static Load Tests. The data were sampled at 1-s intervals as suggested by *ASTM E488-96* (*28*). However, during the data analysis it was determined that a faster data collection would provide smoother graphs. A faster sampling rate would be especially helpful in the incremental load tests in analyzing the deflection and load steps.

Sustained Load (Creep) Tests. A faster data collection rate could also be more beneficial in the sustained load (creep) test, specifically in the loading phase. The data were initially sampled at 20-s intervals during the loading phase of the 75% sustained load (creep) test. This was later adjusted to 3-s intervals for the 62% sustained load (creep) test. An even faster sampling rate might be beneficial, but could make the data file large. The current schedule of increasing sampling intervals beyond the loading phase should remain unchanged.

Another recommendation for the sustained load (creep) test is that the method of loading should be as smooth as possible. In the initial testing, the pre-compressed spring load was transferred from the four corner bolts to the center loading rod by using a wrench to tighten the nut on the center loading rod. This was very difficult, even with a pipe placed over the wrench to provide more leverage. This also created a very jerky load rate. It is recommended that a rig be fabricated



Source: Modified from Cook et al. (7).

Figure 32. Possible solution for a smoother load transfer for sustained load (creep) tests.

to enable the hydraulic ram to apply the pre-compressed spring load to the anchor. It would be critical that the ram apply the load through the load cell. Using the ram would produce a smoother, more even load rate and provide more control to the operator. Figure 32 shows a possible solution in which a ram can be used to transfer the pre-compressed spring load, and, once the four corner bolts are loose, the loading rod nut can be tightened by hand and the ram released.

Finally, in the sustained load (creep) test, it is very important that the surface of the concrete around the anchors be as smooth as possible. Any surface irregularities will prevent full bearing of the confining plate and increase the possibility of concrete spalling due to lack of confinement. In the initial testing, the PTFE sheets were able to amend slight irregularities, but concrete spalling did occur in a few of the anchors. A smoother surface finish could have reduced this chance of concrete spalling in these instances.

CHAPTER 3

Findings and Applications

The purpose of this chapter is to describe the procedures used to reduce the experimental data into usable results. This included determining the mean static load from the 110°F static load test and the time to failure from two series of 110°F sustained load (creep) tests at reduced loads in order to create a stress versus time-to-failure graph for each adhesive. As mentioned in Chapter 2, static load tests were conducted on all three adhesives. Following the static load tests, sustained load (creep) tests were conducted on Adhesives A and B only. For all of the tests, the anchors were labeled with a letter and a number. The letter referred to the adhesive (A, B, or C), as described in Chapter 2. The numbers corresponded to the types of tests, which are listed in Table 14.

Static Load Test

The static load tests were conducted as described in Chapter 2. The following discussion provides information related to data reduction and the results of the static load tests.

Data Reduction

Displacement Adjustments

As the anchors were initially loaded, the system took up slack, producing large initial displacement readings. Instead of adjusting the displacement readings for the initial slack in the system during testing, all data were recorded, and adjustments were made after testing. The data acquisition system did, however, zero out the first position reading from the linear potentiometers, and all displacement readings were calculated from that initial position reading.

The initial displacement readings were later adjusted to account for the slack in the system by extending the slope of the portion of the load deflection curve not affected by the slack back to the x-axis to determine the x-intercept. The lower (slack) section of the load-displacement curve was then adjusted to this slope, and the entire curve was essentially shifted to a new origin at the x-intercept. This procedure is illustrated in Figure 33.

Definition of Terms

The following terms are similar in name and will be used extensively in this chapter. They are briefly described here, but more detailed explanations are provided later in the chapter:

- **Maximum static load** is the maximum value experienced by an anchor during a static load test.
- **Peak static load** is similar to the maximum static load, but the peak static load is specific to a strength-controlled failure in which there is a sharp rise in strength to a peak value and a sudden loss in strength beyond this point.
- **Static load strength** is the strength of an adhesive determined from the static load test. Due to various possible failure modes, this might not be the maximum static load or the peak static load.

Determining Static Load Strength

There are several methods available to analyze the load-displacement behavior of a static load test in determining the static load strength, which is referred to as N_{adh}. Section 11.3.4 of *ICC-ES AC308* (*3*) presents the following procedure:

- Determine a tangent stiffness at 30% of the factored tension load (N_u), which is typically approximated as the secant stiffness from the origin to the point on the load-displacement curve at $0.30N_u$.
- If the displacement at $0.30N_u$ is less than 0.002 in., the origin is shifted to the point on the load-displacement curve at $0.30N_u$.
- Multiply the tangent stiffness by ⅔ and project this line until it intersects with the load-displacement curve.

Table 14. Anchor numbering.

Anchor Number Range	Type of Test	Test Description
1 – 6	Static Load Test	110°F reference test
7 – 9	Sustained Load Test	75% peak load at 110°F
10 – 12	Sustained Load Test	62% peak load at 110°F
13 – 18	Static Load Test	75°F reference test

- N_{adh} is taken as the intersection if $N_{adh} < N_u$.
- N_{adh} is taken as N_u if $N_{adh} > N_u$.

This method was analyzed and was not recommended, as it tended to drastically underestimate the static load strength in a few cases, as can be seen in Figure 37.

Another procedure was presented by Cook and Konz (6), who classified three types of load-displacement response (strength-controlled, stiffness-controlled, and displacement-controlled) and described methods to determine the static load strength for each type of situation. The responses and methods of analysis are summarized below:

- **Strength-controlled.** This failure mode is defined by a very sharp peak in the load-displacement curve with a drastic reduction in the stiffness of the adhesive anchor beyond the peak. The static load strength is determined to be at the peak on the load-displacement graph. Figure 34 shows a typical curve of a strength-controlled failure.
- **Stiffness-controlled.** This failure mode is defined by a large initial stiffness and a drastic change in stiffness, which does not decrease but rather continues to increase at a lower slope. Due to the absence of a "peak" in the curve, the static load strength is determined by finding the point at a tangent stiffness of 30 kips/in. The tangent stiffness (slope) at a given data point can be approximated by calculating the slope between a point five data points after and five data points before the given point. Figure 35 shows a typical curve of a stiffness-controlled failure.
- **Displacement-controlled.** This failure mode has a load-displacement curve with a relatively constant stiffness above the stiffness-controlled threshold of 30 kips/in. The maximum static load occurs at very high and impractical displacements. In this case, the static load strength is set at

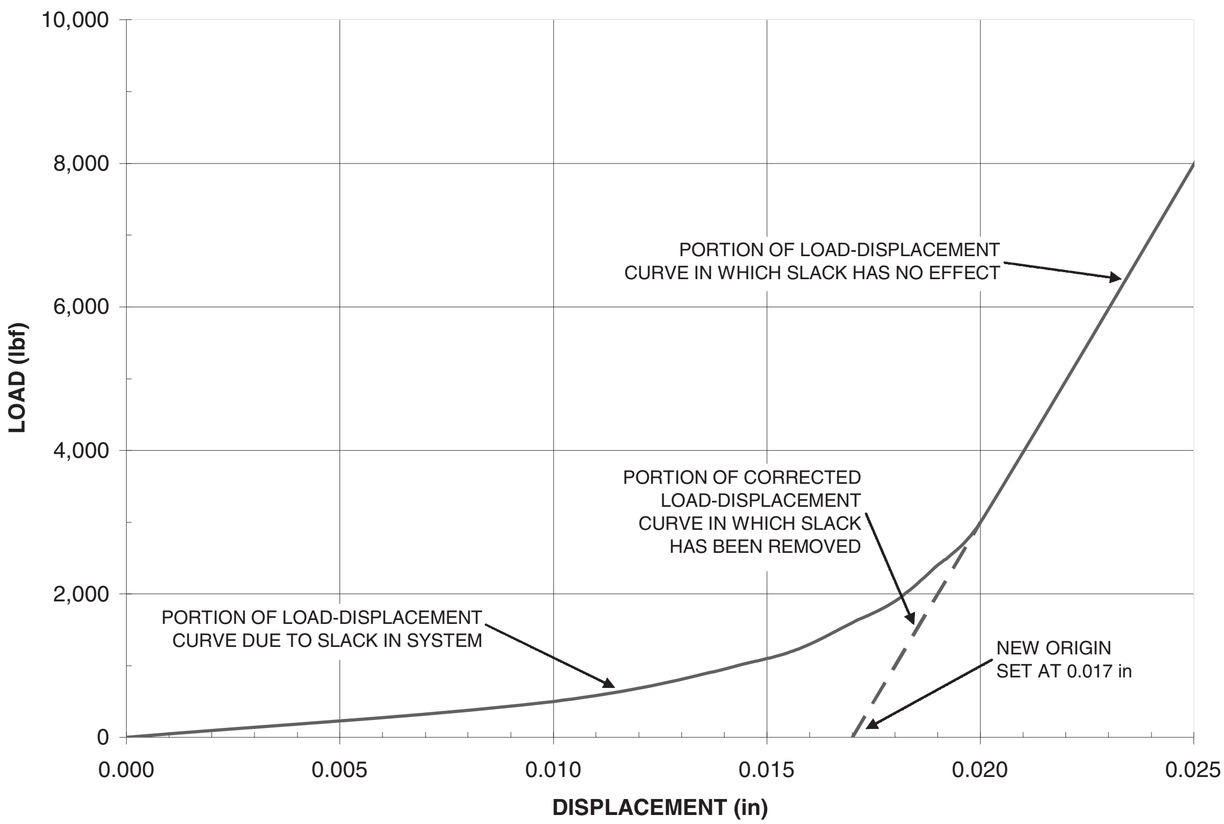
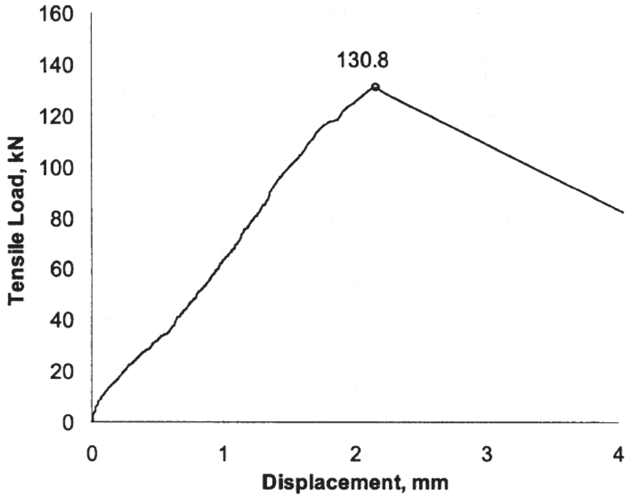
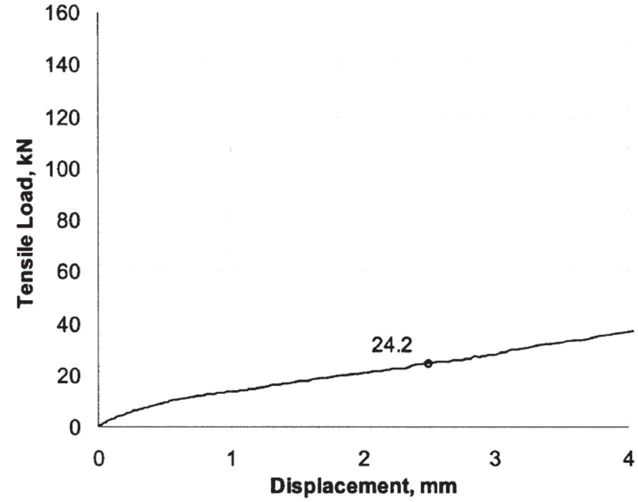


Figure 33. Removing the effect of slack in the load-displacement graph.



Reprinted with permission from Cook and Konz (*6*).

Figure 34. Typical strength-controlled failure.

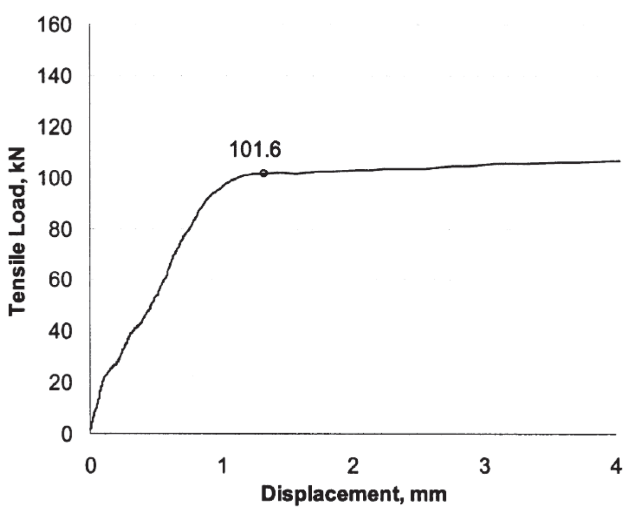


Reprinted with permission from Cook and Konz (*6*).

Figure 36. Typical displacement-controlled failure.

a point with a displacement of 0.1 in. While the 0.1-in. displacement seems arbitrary, this failure mode usually occurs only in inferior products. Since this research was limited to products that had passed *ICC-ES AC308* (*3*), this failure mode was not expected and was not observed. Figure 36 shows a typical curve of a displacement-controlled failure.

The method presented by Cook and Konz (*6*) exhibited better results than the *ICC-ES AC308* (*3*) approach and was the approach chosen for the project and draft AASHTO test procedure. Figure 37 is a load-displacement graph for the 110°F static load test conducted on Anchor B-01 and shows the static load strength calculated by three different methods: The *ICC-ED AC308* (*3*) procedure, the strength-controlled method, and the stiffness-controlled method. The *ICC-ES AC308* procedure estimated N_{adh} as 11,100 lbf. The strength-controlled method estimated N_{adh} as 19,905 lbf. The stiffness-controlled method (not required) estimated N_{adh} as 19,751 lbf.



Reprinted with permission from Cook and Konz (*6*).

Figure 35. Typical stiffness-controlled failure.

For each test, the static load strength was recorded, and the mean static load for each adhesive was determined from the average of the tests.

Static Bond Stress

The static bond stress (τ_{adh}) was calculated as the static load strength (N_{adh}) divided by the adhesive area at the interface with the anchor, A_{adh}, or

$$\tau_{adh} = N_{adh} / A_{adh}$$

where

$A_{adh} = \pi\, d\, h_{ef}$,

d = diameter of anchor (0.625 in.), and

h_{ef} = embedment depth of hole (3.125 in.).

Discussion of Load Rate

Six anchors were installed per adhesive per static load test series (110°F and 75°F). During the testing, it was decided to test four anchors per series with the continuous load rate and two anchors with the incremental load rate in order to evaluate the incremental load rate test procedure as a possible option for determining an anchor's creep sensitivity. Due to the differences in the static load strength results from the two types of loading rates, it was decided to use only the four continuous load rate results in determining the mean static load.

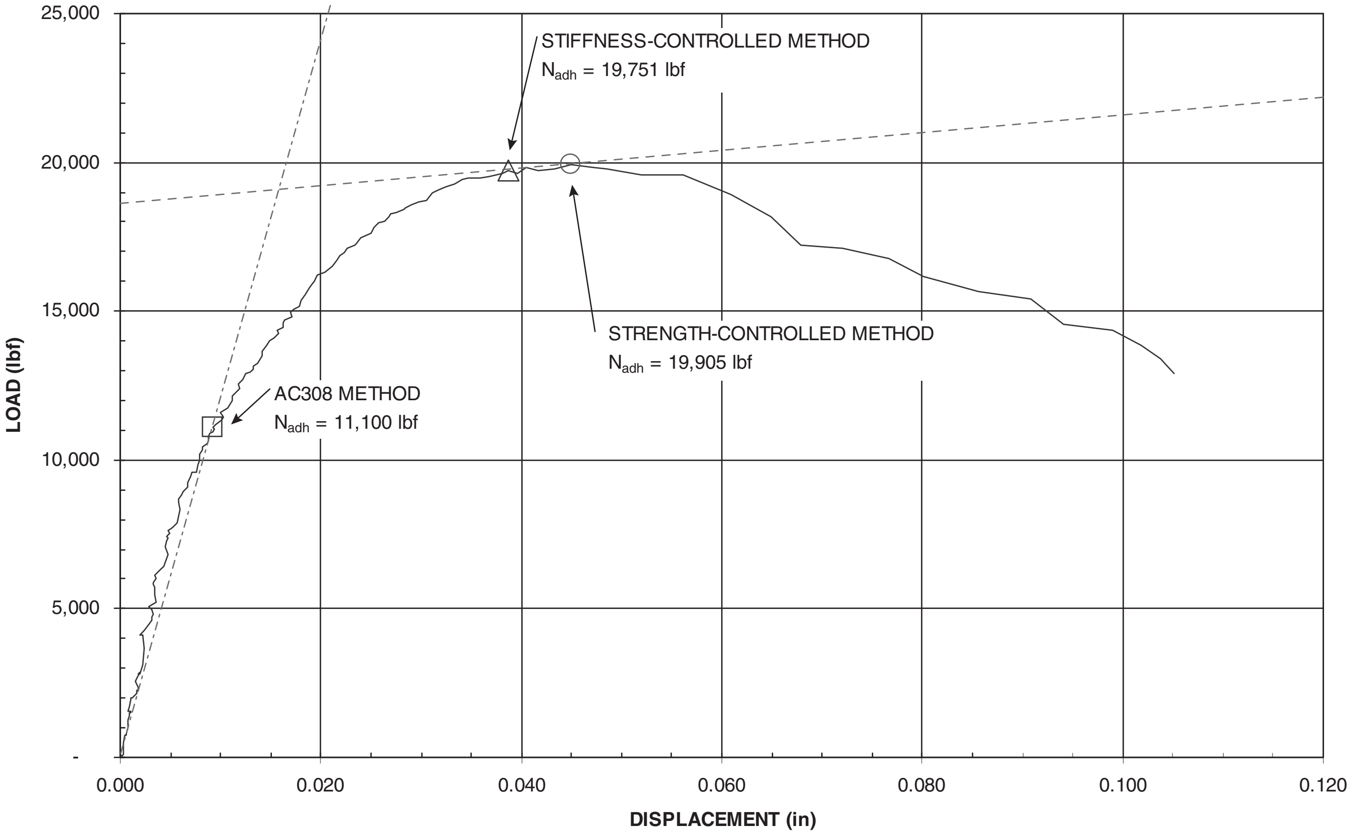


Figure 37. Example of calculating static load strength from various methods on Anchor B-01.

For the 110°F static load tests, Adhesives B and C exhibited lower maximum static loads under the incremental load rate than they exhibited under the continuous load rate. This trend was not observed in the 75°F static load tests to any great extent statistically. The difference in maximum static load values between the anchors tested under different load rates at 110°F might be due to the total duration of the loading. The continuous load rate loaded the specimen over about 2 min while the incremental load rate loaded the specimen over about 10 min.

The fact that the specimens did not reflect a statistical difference in maximum static loads between the anchors under different load rates at 75°F while they did at 110°F, might be attributed to the adhesive's composition. Some adhesives may be more susceptible to load rate at higher temperatures. It should be specified in the test method that the sustained load (creep) test specimens should be initially loaded under the same load rate used for the static load tests.

110°F Static Load Tests

This section presents the results from the 110°F static load tests for Adhesives A, B, and C. Individual and combined load-displacement graphs for each adhesive can be found in Appendix B. Combined load-displacement graphs are also included as Figure 38, Figure 39, and Figure 40.

Slab Conditioning

The test slab for the 110°F static load test was conditioned as discussed in Chapter 2. Charts of the temperature and humidity readings during the conditioning phase are presented in Appendix B.

Adhesive A

Table 15 presents the results from the four continuous load rate tests for Adhesive A. Table 16 presents the results from the two incremental load rate tests for Adhesive A. The mean static load calculated from the four continuous load tests for Adhesive A was 14,413 lbf with a COV of 12%. Individual and combined load-displacement graphs (see Figure 38) for the six 110°F static load tests for Adhesive A can be found in Appendix B.

Adhesive B

Table 17 presents the results from the four continuous load rate tests for Adhesive B. Table 18 presents the results from the two incremental load rate tests for Adhesive B. The mean static load calculated from the four continuous load tests for Adhesive B was 20,123 lbf with a COV of 3%. Individual and

Table 15. 110°F static load test results for Adhesive A (continuous load rate).

Anchor	Static Load Strength (lbf)	Static Bond Stress (psi)	Percent of Mean (%)	Failure Mode	Type of Failure
A-01	15,248	2,485	106%	Strength-controlled	Adhesive
A-02	15,962	2,601	111%	Strength-controlled	Adhesive
A-03	14,527	2,368	101%	Strength-controlled	Adhesive
A-04	11,915	1,942	83%	Strength-controlled	Partial Concrete
Mean	14,413	2,349			

Table 16. 110°F static load test results for Adhesive A (incremental load rate).

Anchor	Static Load Strength (lbf)	Static Bond Stress (psi)	Percent of Average of 4 (%)	Failure Mode	Type of Failure
A-05	16,359	2,666	114%	Strength-controlled	Adhesive
A-06	16,249	2,648	113%	Strength-controlled	Adhesive

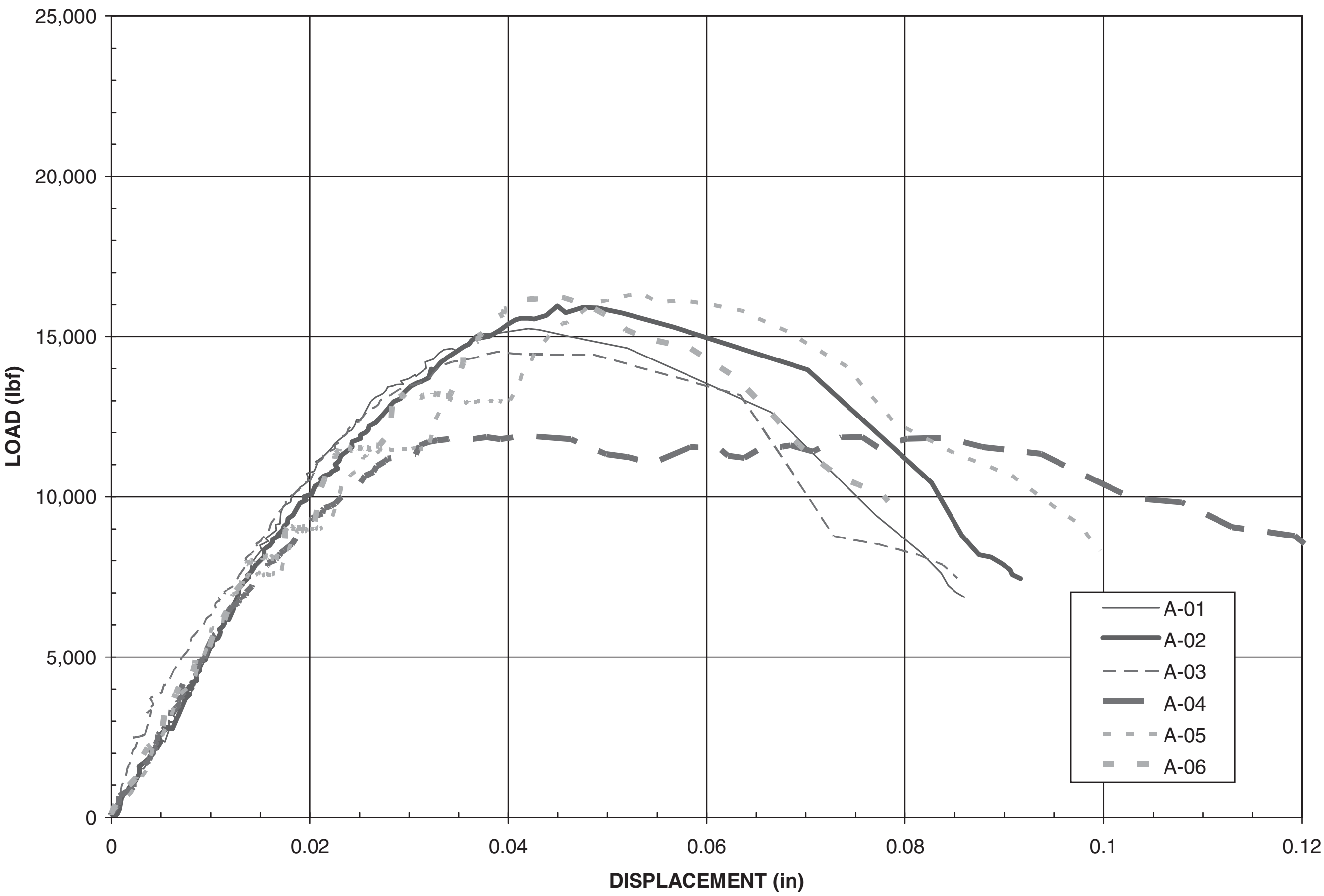


Figure 38. Combined load-displacement graphs for Anchors A-01 to A-06.

Table 17. 110°F static load test results for Adhesive B (continuous load rate).

Anchor	Static Load Strength (lbf)	Static Bond Stress (psi)	Percent of Mean (%)	Failure Mode	Type of Failure
B-01	19,905	3,244	99%	Strength-controlled	Adhesive
B-02	20,817	3,393	103%	Strength-controlled	Adhesive
B-03	20,137	3,282	100%	Strength-controlled	Adhesive
B-04	19,632	3,199	98%	Strength-controlled	Adhesive
Mean	20,123	3,279			

combined load-displacement graphs (see Figure 39) for the six 110°F static load tests for Adhesive B can be found in Appendix B.

Adhesive C

Table 19 presents the results from the four continuous load rate tests for Adhesive C. Table 20 presents the results from the two incremental load rate tests for Adhesive C. The mean static load calculated from the four continuous load tests for Adhesive C was 18,067 lbf with a COV of 9%. Individual and combined load-displacement graphs (see Figure 40) for the six 110°F static load tests for Adhesive C can be found in Appendix B.

Failure Type

As discussed in Chapter 2, following the anchor test, the surface of the specimens was sounded with a hammer to check for concrete spalling. A hollow sound indicated possible shallow concrete failure with bond failure. Several anchors were identified as having possible shallow concrete failures and were cored with a core drill for further investigation. Anchors A-03, A-04, B-04, and C-05 were identified as having possible concrete failures and selected for investigation. Anchor A-02 was cored as a control since it was assumed that it had an adhesive failure.

Upon investigation, it was noticed that the core for Anchor A-04 had cracks encircling the core about ¾ in. below the top surface. The core for Anchor C-05 had cracks encircling about two-thirds of the core perimeter at a depth of about ¾ in. below the top surface. The cores for Anchors A-03 and B-04 had small cracks (~ one-fourth of the core perimeter) at a depth of about ½ in. below the top surface on the side of the core facing Anchor A-04. It was concluded that Anchors A-04 and C-05 did indeed have a shallow concrete failure with bond failure. It was concluded that Anchors A-03 and B-04 did not have a shallow concrete failure; however, it was also concluded that the hollow sound on Anchors A-03 and B-04 was due to the spreading of cracks caused by the shallow concrete failure of Anchor A-04, which was located next to these two anchors. The core for the control anchor, Anchor A-02, did not have any cracks around its perimeter.

75°F Reference Static Load Tests

It was decided to run a series of static load reference tests at 75°F in order to have a record of the static load values of the adhesives as a reference point in case it was needed during this research project. The following section presents the results from the 75°F static load tests for Adhesives A, B, and C. Individual and combined load-displacement graphs for each adhesive can be found in Appendix B. Combined load-displacement graphs are also included as Figure 41, Figure 42, and Figure 43.

Adhesive A

Table 21 presents the results from the four continuous load rate tests for Adhesive A. Table 22 presents the results from the

Table 18. 110°F static load test results for Adhesive B (incremental load rate).

Anchor	Static Load Strength (lbf)	Static Bond Stress (psi)	Percent of Average of 4 (%)	Failure Mode	Type of Failure
B-05	16,283	2,654	81%	Strength-controlled	Adhesive
B-06	16,663	2,716	83%	Strength-controlled	Adhesive

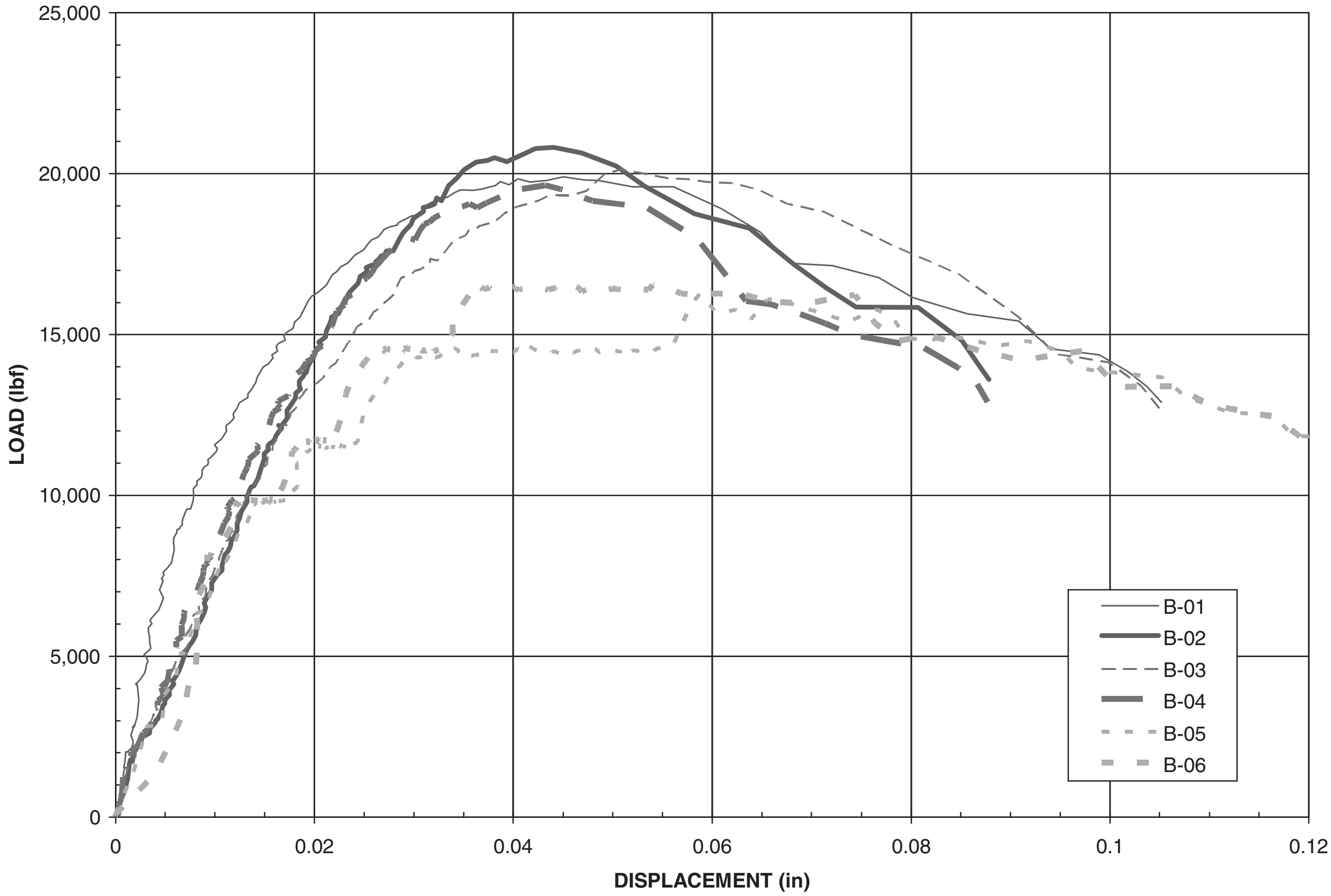


Figure 39. Combined load-displacement graphs for Anchors B-01 to B-06.

Table 19. 110°F static load test results for Adhesive C (continuous load rate).

Anchor	Static Load Strength (lbf)	Static Bond Stress (psi)	Percent of Mean (%)	Failure Mode	Type of Failure
C-01	18,596	3,031	102%	Strength-controlled	Adhesive
C-02	18,695	3,047	103%	Stiffness-controlled	Adhesive
C-03	19,350	3,153	107%	Stiffness-controlled	Adhesive
C-04	15,627	2,547	86%	Strength-controlled	Adhesive
Mean	18,067	2,944			

Table 20. 110°F static load test results for Adhesive C (incremental load rate).

Anchor	Static Load Strength (lbf)	Static Bond Stress (psi)	Percent of Average of 4 (%)	Failure Mode	Type of Failure
C-05	15,686	2,556	87%	Strength-controlled	Partial Concrete
C-06	13,855	2,258	77%	Strength-controlled	Adhesive

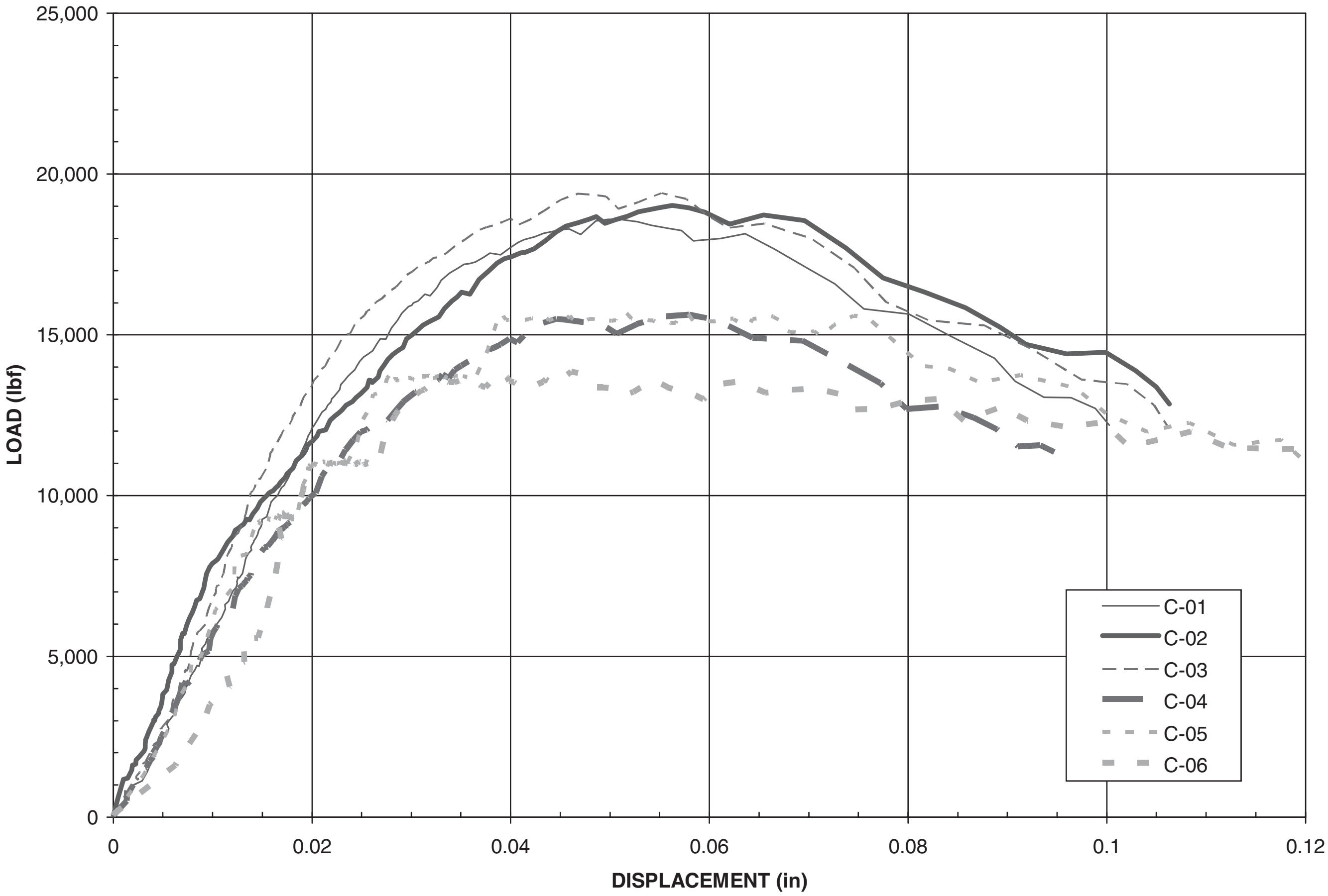


Figure 40. Combined load-displacement graphs for Anchors C-01 to C-06.

Table 21. 75°F static load test results for Adhesive A (continuous load rate).

Anchor	Static Load Strength (lbf)	Static Bond Stress (psi)	Percent of Mean (%)	Failure Mode	Type of Failure
A-13	18,533	3,020	111%	Strength-controlled	Adhesive
A-14	15,011	2,446	90%	Strength-controlled	Partial Concrete
A-15	17,692	2,883	106%	Strength-controlled	Adhesive
A-16	15,292	2,492	92%	Strength-controlled	Partial Concrete
Mean	16,632	2,711			

Table 22. 75°F static load test results for Adhesive A (incremental load rate).

Anchor	Static Load Strength (lbf)	Static Bond Stress (psi)	Percent of Average of 4 (%)	Failure Mode	Type of Failure
A-17	19,104	3,113	115%	Strength-controlled	Adhesive
A-18	15,903	2,592	96%	Strength-controlled	Adhesive

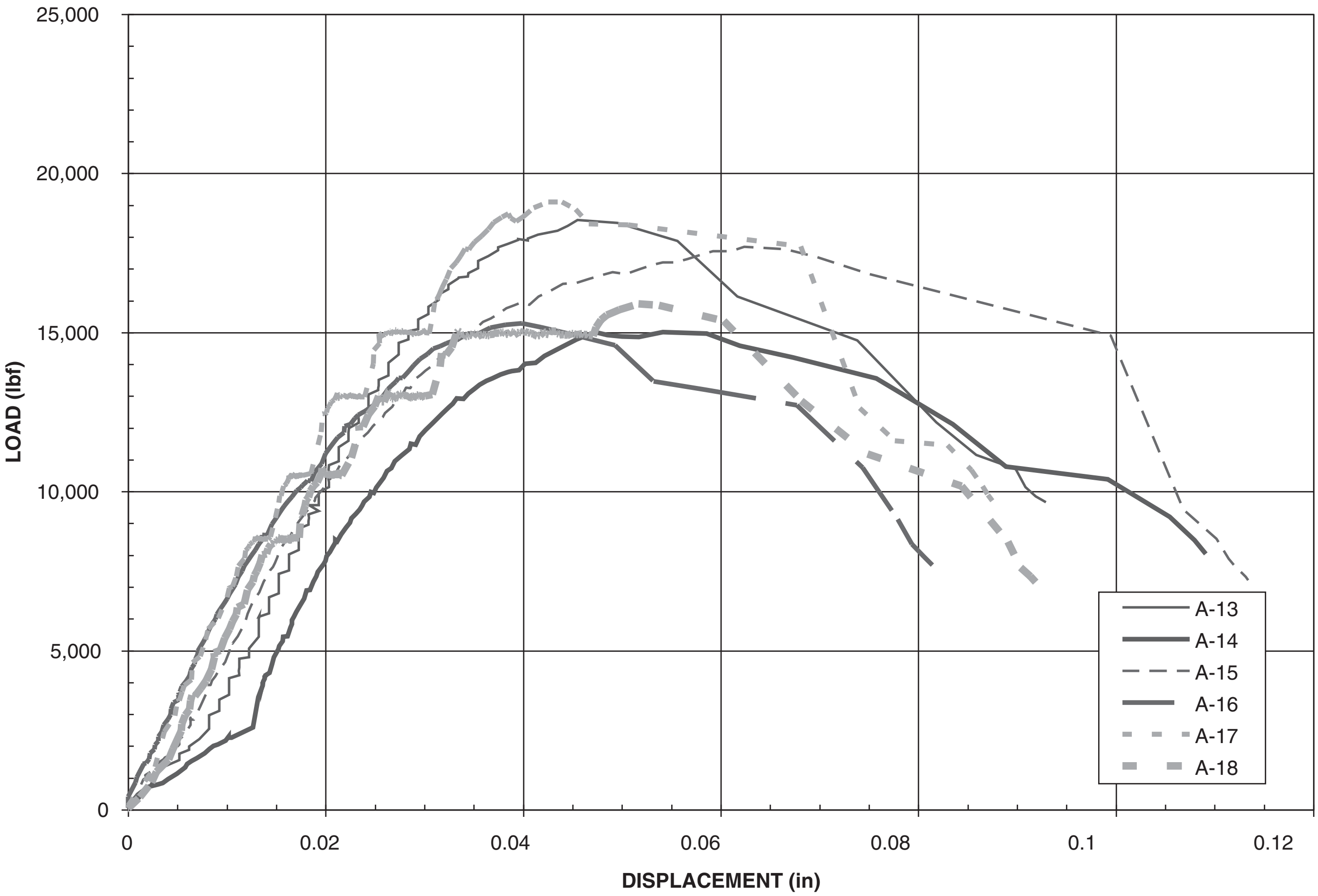


Figure 41. Combined load-displacement graphs for Anchors A-13 to A-18.

two incremental load rate tests for Adhesive A. The COV for the four continuous load tests was 11%. Individual and combined load-displacement graphs (see Figure 41) for the six 75°F static load tests for Adhesive A can be found in Appendix B.

Adhesive B

Table 23 presents the results from the four continuous load rate tests for Adhesive B. Table 24 presents the results from the two incremental load rate tests for Adhesive B. The COV for the four continuous load tests was 3%. Individual and combined load-displacement graphs (see Figure 42) for the six 75°F static load tests for Adhesive B can be found in Appendix B.

Adhesive C

Table 25 presents the results from the four continuous load rate tests for Adhesive C. Table 26 presents the results from

Table 23. 75°F static load test results for Adhesive B (continuous load rate).

Anchor	Static Load Strength (lbf)	Static Bond Stress (psi)	Percent of Mean (%)	Failure Mode	Type of Failure
B-13	19,707	3,212	96%	Strength-controlled	Adhesive
B-14	21,188	3,453	104%	Strength-controlled	Adhesive
B-15	20,533	3,346	101%	Strength-controlled	Adhesive
B-16	20,282	3,305	99%	Strength-controlled	Adhesive
Mean	20,427	3,329			

Table 24. 75°F static load test results for Adhesive B (incremental load rate).

Anchor	Static Load Strength (lbf)	Static Bond Stress (psi)	Percent of Average of 4 (%)	Failure Mode	Type of Failure
B-17	21,516	3,507	105%	Strength-controlled	Partial Concrete
B-18 *	21,975	3,581	108%	Strength-controlled	Partial Concrete

* Power outage at 17-kips, lost monitor display until breaker reset

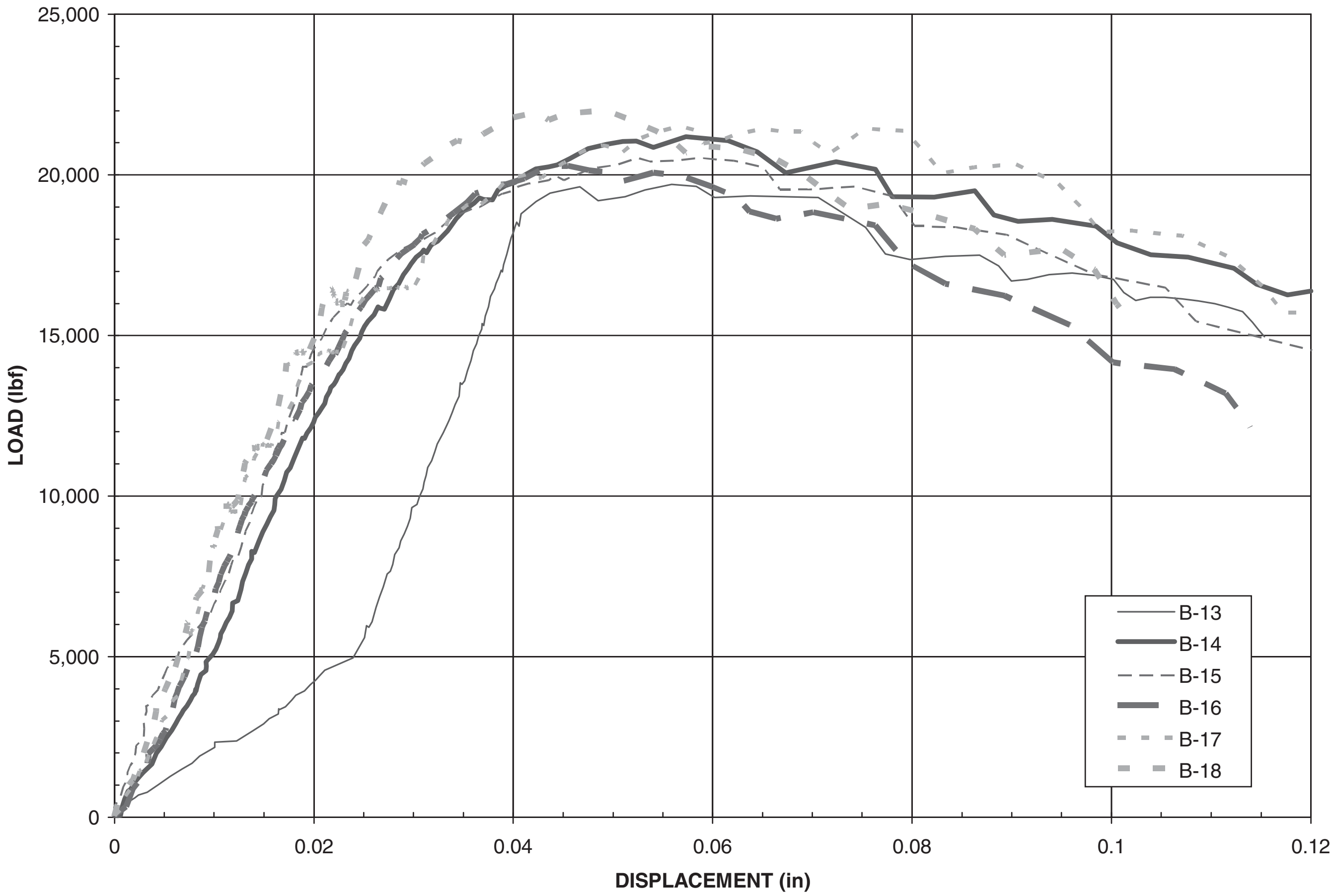


Figure 42. Combined load-displacement graphs for Anchors B-13 to B-18.

Table 25. 75°F static load test results for Adhesive C (continuous load rate).

Anchor	Static Load Strength (lbf)	Static Bond Stress (psi)	Percent of Mean (%)	Failure Mode	Type of Failure
C-13 *	16,802	2,738	87%	Strength-controlled	Adhesive
C-14	20,467	3,336	106%	Strength-controlled	Adhesive
C-15	19,440	3,168	101%	Strength-controlled	Adhesive
C-16	20,456	3,334	106%	Strength-controlled	Adhesive
Mean	19,291	3,144			

* Bolt not completely threaded and threads yielded.

Table 26. 75°F static load test results for Adhesive C (incremental load rate).

Anchor	Static Load Strength (lbf)	Static Bond Stress (psi)	Percent of Average of 4 (%)	Failure Mode	Type of Failure
C-17 *	18,554	3,024	96%	Strength-controlled	Adhesive
C-18 *	16,318	2,659	85%	Strength-controlled	Adhesive

* No Teflon sheet due to short bolt, threads yielded.

the two incremental load rate tests for Adhesive C. The COV for the four continuous load tests was 9%. Individual and combined load-displacement graphs (see Figure 43) for the six 75°F static load tests for Adhesive C can be found in Appendix B.

Sustained Load (Creep) Test

The sustained load (creep) tests were conducted as described in Chapter 2. The following provides information related to data reduction and results of the sustained load (creep) tests.

Data Reduction

Due to project budget and timeline, sustained load (creep) tests were conducted on only Adhesives A and B. Three anchors were installed per adhesive (A and B) per percent peak-load series (75% and 62%). These percentages were determined from the mean static load that was determined from the four continuous load rate results in the 110°F static load test.

Displacement Adjustments

During the loading phase of the test, the data acquisition system recorded load and position readings at about every

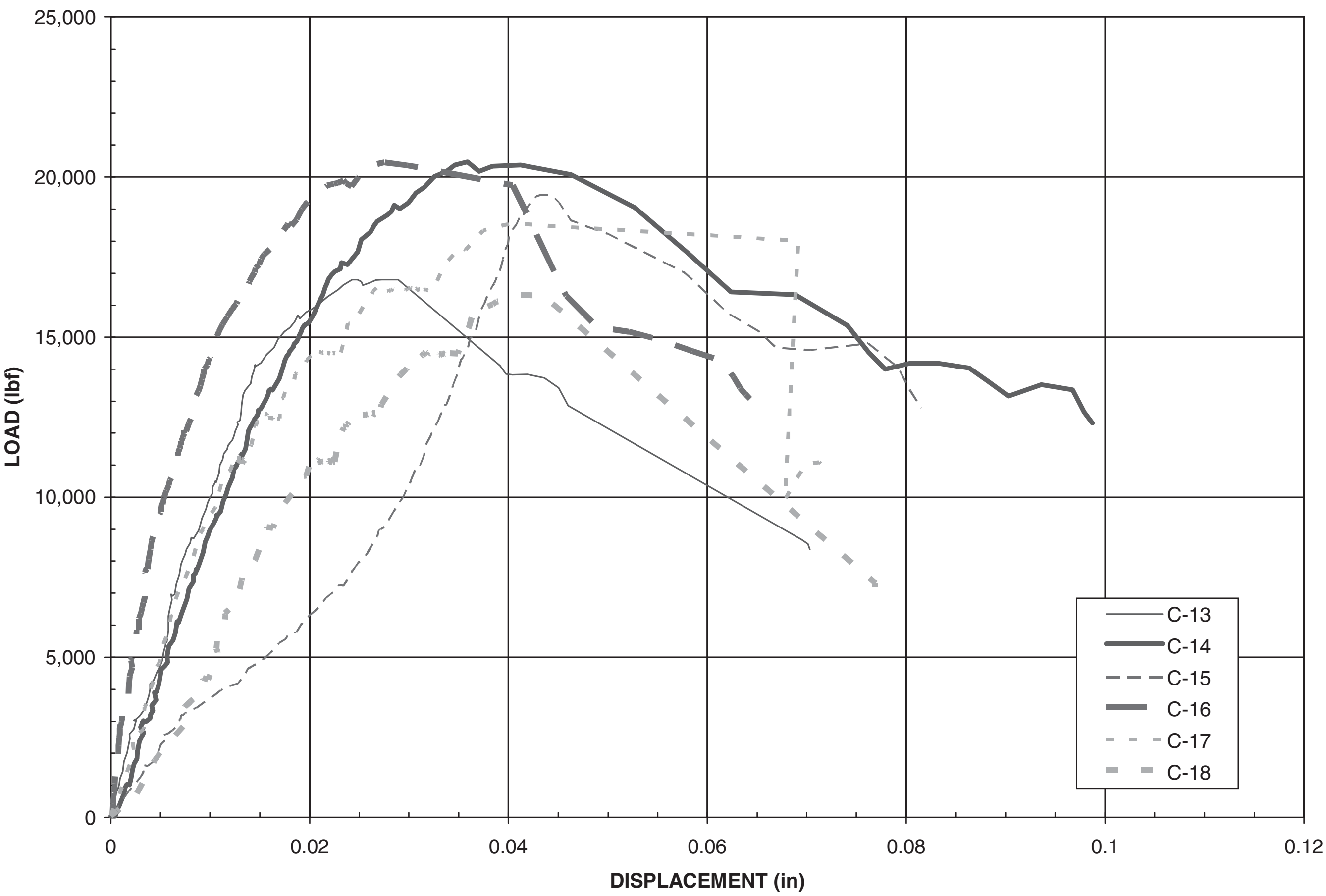


Figure 43. Combined load-displacement graphs for Anchors C-13 to C-18.

20 s for the 75% tests. This schedule of recording was increased to about every 3 s for the 62% test. Once started, the data acquisition system took readings for each anchor whether it was loaded or not. Because it took several minutes to load each anchor, all anchors were not loaded at the initiation of the data recording. Therefore, the start time for each anchor was determined later, from the data, and the actual start and failure times were adjusted accordingly in the data analysis. Displacement was determined by subtracting the initial position reading from the linear potentiometers. Since actual displacement values were not important to this test, but rather the initiation of tertiary creep, displacement adjustments were not made to account for slack in the system.

During the loading phase, a few couplers rotated, causing the plunger of the linear potentiometer to slip off its bearing surface on top of the concrete. The coupler was returned to its initial position, and the linear potentiometer plunger was repositioned on its bearing surface. This caused a few erroneous displacement readings, which were corrected in the data analysis by extending a linear line between the data reading before and the data reading after the period during which the linear potentiometer was disturbed. It is important to note that this happened during the loading phase (in the primary creep portion of the creep curve), and the adjustments did not affect the data analysis for the time to tertiary creep failure.

Determination of Tertiary Creep

Per *ASTM D2990-01* (*37*) and discussed earlier, time to failure was determined as the onset of tertiary creep. Several methods of determining the onset of tertiary creep were investigated. The following methods were investigated:

- **Secondary creep curve offset.** This method calculates a linear trendline of the secondary creep curve. The standard deviation is determined for the differences between the actual data points and the estimated values from the trendline. A parallel line is then offset three standard deviations from the trendline in order to lie outside any statistical variation of the data points. The onset of tertiary creep is defined as the point where this offset line intersects the tertiary creep curve. This method is illustrated in Figure 44. In this investigation, for some of the curves, the separations among the portions on the creep curve were not easily distinguished. This made choosing a range of data to generate the trendline unclear and arbitrary. This

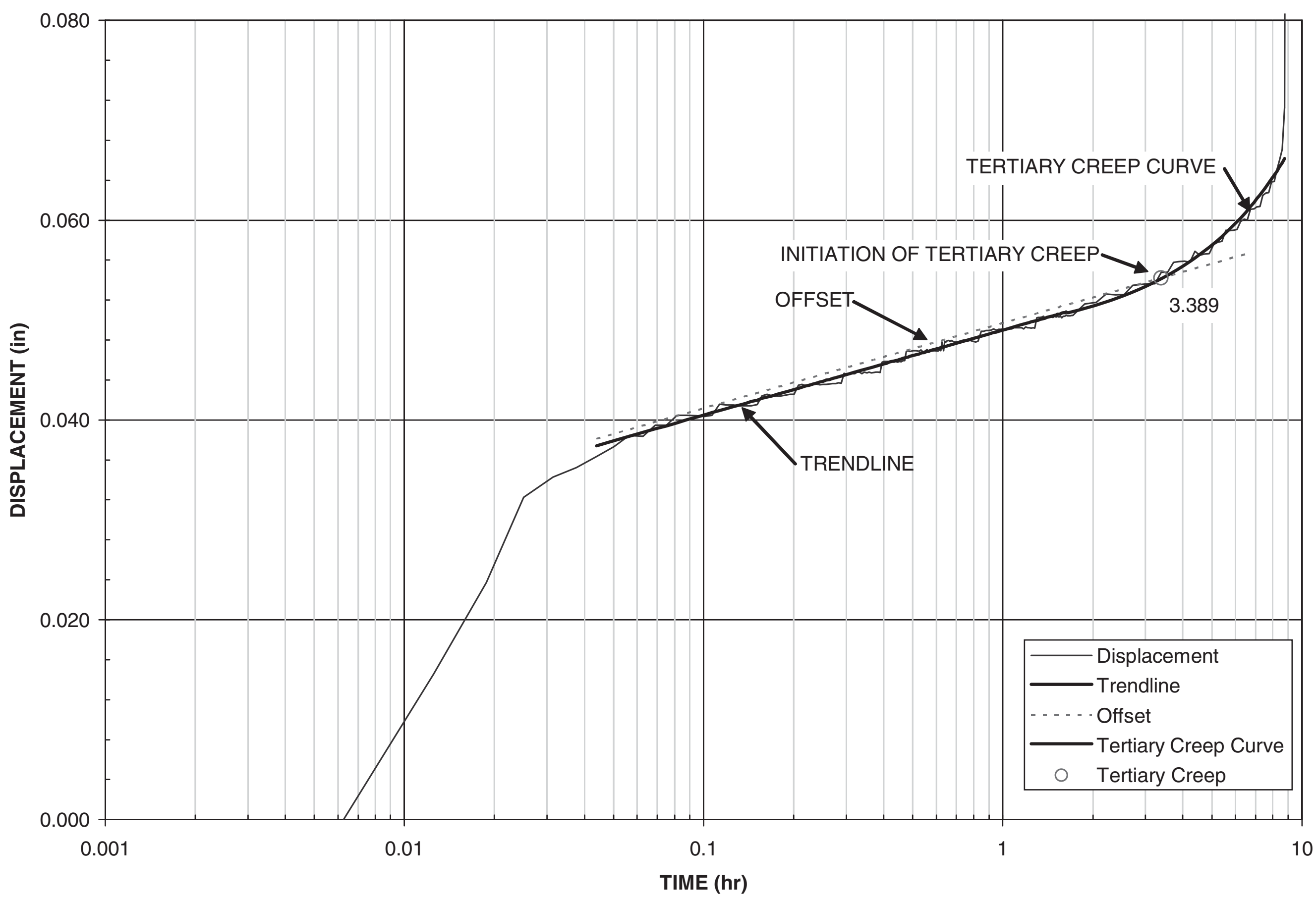


Figure 44. Secondary creep curve offset method.

method was rejected due to the inherent difficulty of reproducing it among laboratories.

- **High-order polynomial regression analysis.** This method calculates a high-order polynomial of the secondary and tertiary portions of the creep curve. The onset of tertiary creep is defined as the point where the change in the slope (second derivative of the polynomial function) is zero. This point depends highly on the order of the polynomial, and, in this investigation, increasing the order did not increase the accuracy of the point. This method was determined to be unreliable because a high-order polynomial was not a good model for the creep equation.
- **Change in slope method.** This method calculates the slope at a given point as the slope between the given point and the prior data point. The change in slope between the given point and the following data point is plotted and examined over the region just prior to rupture. It is suggested that this examination be conducted on a normal graph (not log time). The rupture point is easily identified on the displacement versus time graph by its near vertical slope. A suggested range for examining the change in slope is from 80% to 100% of time to rupture. Due to minor fluctuations in the displacement readings, the slope might change from positive to negative several times over this range. Tertiary creep is defined as the last time the change in slope becomes positive prior to rupture. In this investigation, this method produced favorable results. A sample graph is shown in Figure 45.

The change in average slope method for determining the onset of tertiary creep was chosen due to its simplicity and reproducibility.

Stress versus Time to Failure

Each sustained load (creep) test data point was plotted on the stress versus time-to-failure graph. The four individual data points from the 110°F static load test were plotted on the stress versus time-to-failure graph as well. It was determined that the static load test results could be plotted on the stress versus time-to-failure graph along with the sustained load (creep) test results under the following conditions:

- The initial load in the sustained load (creep) test was applied in the same manner as the initial load was applied in the static load tests.

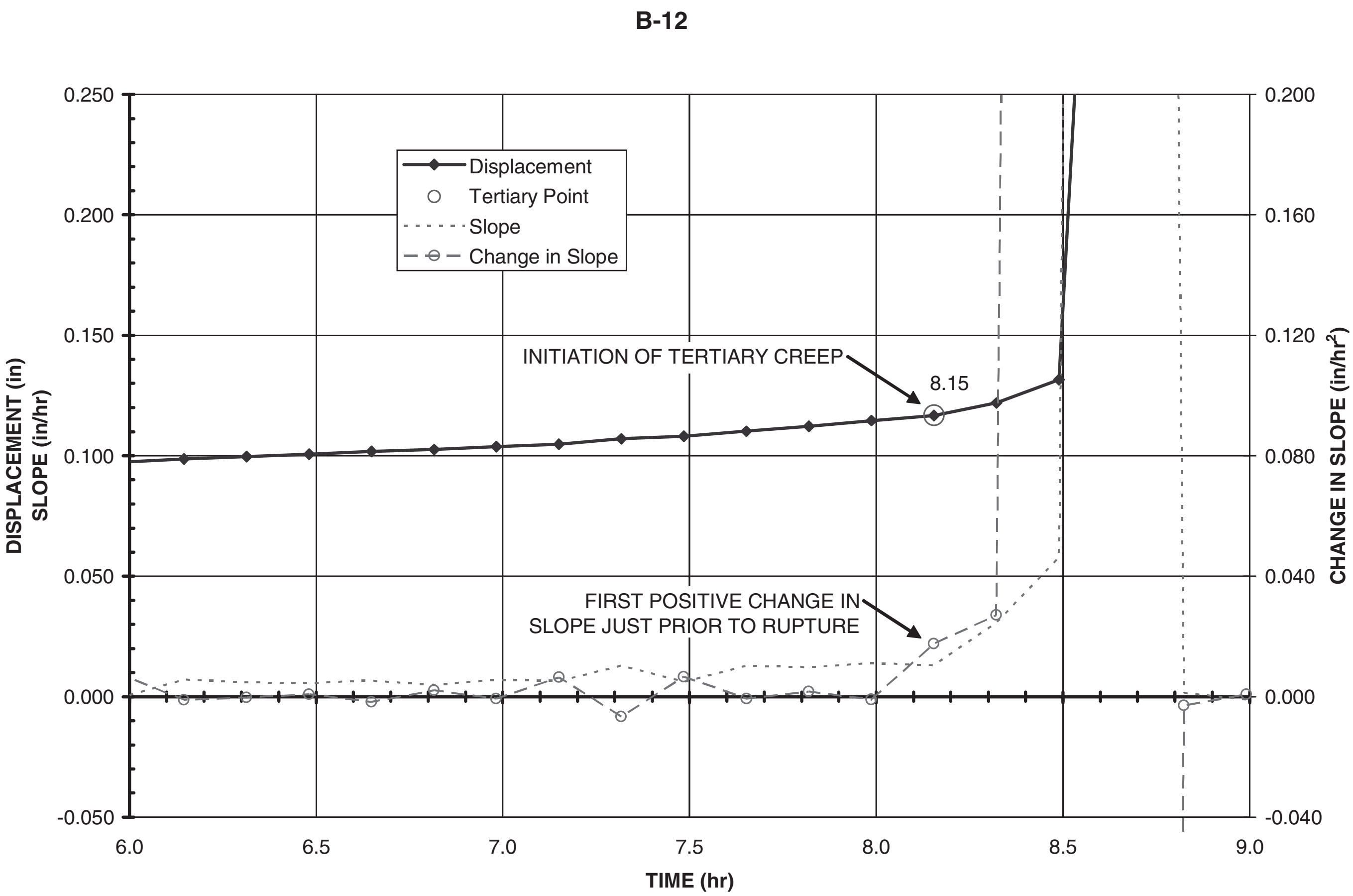


Figure 45. Example of change in slope method for Anchor B-12.

Table 27. Sustained load (creep) test initial loading durations.

Anchor	Loading Time (min)	Anchor	Loading Time (min)
A-07	12.6	B-07	7.8
A-08	1.8	B-08	13.8
A-09	3	B-09	7.8
A-10	2.4	B-10	4.2
A-11	7.8	B-11	3
A-12	15.6	B-12	3
Mean	7.2	Mean	6.6

- The load was applied to anchors in the static load test, and the initial load was applied to the anchors in the sustained load (creep) test within 2 min ±1 min
- The time to failure for all tests included the loading time.
- The time to failure for the static load tests was approximately 2 min (0.03 hours).

Due to difficulties in the loading procedure of the sustained load (creep) tests, the anchors were loaded over durations longer than the duration used in the static load tests. This issue and the methods used to analyze the test results are discussed later. The initial loading durations for each of the sustained load (creep) tests are presented in Table 27.

Determination of Load

During the sustained load (creep) tests, the load on each anchor was recorded with a load cell. The load cells were calibrated prior to the tests at room temperature, and the calibration was verified at the elevated testing temperature of 110°F following the tests. Differences were noticed between the two calibrations. Discussions with other laboratories that regularly conduct sustained load (creep) tests on adhesive anchors indicate that variability in load cell calibration is common. In fact, some laboratories have abandoned the use of load cells and determine loads on the basis of spring stiffness and displacement calculations.

The draft AASHTO test method specifies that the load be recorded with a load cell, but it includes a provision to determine the load based on spring stiffness and displacement calculations. For the sustained load (creep) tests, to calculate the load from the spring, the initial load on the spring was recorded as the pre-compression load placed on the spring by the INSTRON test machine. The springs were previously calibrated in the INSTRON test machine to determine their stiffness. The spring displacement was determined by using the displacement readings from the anchors. During the loading process, the nut on the loading rod was tightened in order to transfer the pre-compression load from the four corner bolts in the test apparatus to the center loading rod. During this process, the anchor displaced, but the spring did not. Therefore, the initial spring displacement reading was determined as the anchor displacement reading at the end of initial loading. The load on the anchor was then determined to be the initial pre-compression load minus the displacement beyond the end of initial loading multiplied by the spring stiffness.

The test results from the two sustained load (creep) test series for Adhesives A and B are presented below. The test results are presented from the load cell readings (using the calibration at 110°F) and from calculations based on spring stiffness and displacement. Due to the variability in the load cell readings, the results from the spring calculations were determined to be a better representation of the actual values and were used for further analysis in this research.

75% Sustained Load Test

The following sections present the results from the 75% sustained load (creep) test series. Stress versus time-to-failure graphs for each adhesive are included later in this chapter, and the actual time-displacement test graphs can be found in Appendix B.

Slab Conditioning

The test slabs for the 75% sustained load (creep) tests were conditioned as discussed in Chapter 2. A chart of the temperature and humidity readings during the conditioning phase is presented in Appendix B.

Adhesive A

Table 28 presents the loads calculated from the spring stiffness and displacement for the 75% sustained load (creep) test for Adhesive A. Table 29 presents the load cell results, and Table 30 presents the spring stiffness results for Adhesive A.

Table 28. Loads calculated from the spring stiffness and displacement for the 75% sustained load test (Adhesive A).

Anchor	Initial Load (lbf)	Spring Stiffness (lbf/in)	Position: End of Initial Loading (in)	Position: Initiation of Tertiary Creep (in)	Displacement (in)	Loss in Load (lbf)	Failure Load (lbf)
A-07	11,500	10,488	0.055	0.015	0.040	420	11,080
A-08	11,461	11,284	0.044	0.014	0.030	339	11,122
A-09	11,481	10,682	0.067	0.038	0.029	310	11,171

Table 29. 75% sustained load test results for Adhesive A (load cell results).

Anchor	Load (lbf)	Percent Load (%)	Time to Failure (hours)	Type of Failure
A-07	11,017	76%	0.73	Partial Concrete
A-08	11,356	79%	12.80	Adhesive
A-09	11,162	77%	8.58	Partial Concrete
Mean	11,178	78%	7.37	
COV	2%	2%	83%	

Table 30. 75% sustained load test results for Adhesive A (spring stiffness results).

Anchor	Load (lbf)	Percent Load (%)	Time to Failure (hours)	Type of Failure
A-07	11,080	77%	0.73	Partial Concrete
A-08	11,122	77%	12.80	Adhesive
A-09	11,171	78%	8.58	Partial Concrete
Mean	11,125	77%	7.37	
COV	0%	0%	83%	

Adhesive B

Table 31 presents the loads calculated from the spring stiffness and displacement for the 75% sustained load (creep) test for Adhesive B. Table 32 presents the load cell results, and Table 33 presents the spring stiffness results for Adhesive B.

62% Sustained Load Test

The following sections present the results from the 62% sustained load (creep) test series. Stress versus time-to-failure graphs for each adhesive are presented later in this chapter, and the actual time-displacement test graphs can be found in Appendix B.

Slab Conditioning

The test slabs for the 62% sustained load (creep) tests were conditioned as discussed in Chapter 2. A chart of the temperature and humidity readings during the conditioning phase is presented in Appendix B.

Adhesive A

Table 34 presents the loads calculated from the spring stiffness and displacement for the 62% sustained load (creep) test for Adhesive A. Table 35 presents the load cell results, and Table 36 presents the spring stiffness results for Adhesive A. These results do not represent failure, but rather the loads

Table 31. Loads calculated from the spring stiffness and displacement for the 75% sustained load test (Adhesive B).

Anchor	Initial Load (lbf)	Spring Stiffness (lbf/in)	Position: End of Initial Loading (in)	Position: Initiation of Tertiary Creep (in)	Displacement (in)	Loss in Load (lbf)	Failure Load (lbf)
B-07	15,996	11,201	0.106	0.060	0.046	515	15,481
B-08	16,086	11,340	0.036	0.035	0.001	11	16,075
B-09	16,009	11,368	0.065	0.060	0.005	57	15,952

Table 32. 75% sustained load test results for Adhesive B (load cell results).

Anchor	Load (lbf)	Percent Load (%)	Time to Failure (hours)	Type of Failure
B-07	14,926	74%	0.60	Adhesive
B-08	17,310	86%	0.22	Adhesive
B-09	16,439	82%	0.13	Adhesive
Mean	16,225	81%	0.32	
COV	7%	7%	79%	

Table 33. 75% sustained load test results for Adhesive B (spring stiffness results).

Anchor	Load (lbf)	Percent Load (%)	Time to Failure (hours)	Type of Failure
B-07	15,481	77%	0.60	Adhesive
B-08	16,075	80%	0.22	Adhesive
B-09	15,952	79%	0.13	Adhesive
Mean	15,836	79%	0.32	
COV	2%	2%	79%	

Table 34. Loads calculated from the spring stiffness and displacement for the 62% sustained load test (Adhesive A).

Anchor	Initial Load	Spring Stiffness	Position: End of Initial Loading	Position: Initiation of Tertiary Creep	Displacement	Loss in Load	Failure Load
	(lbf)	(lbf/in)	(in)	(in)	(in)	(lbf)	(lbf)
A10 *	9,660	10,974	0.075	0.044	0.031	340	9,320
A11 *	9,632	10,300	0.084	0.062	0.022	227	9,405
A12 *	9,652	10,682	0.062	0.044	0.018	192	9,460

* Results at 3,026 hours – not failure

Table 35. 62% sustained load test results for Adhesive A (load cell results).

Anchor	Load (lbf)	Percent Load (%)	Time to Failure (hours)	Type of Failure
A-10 *	9,573	66%	3,026	No failure
A-11 *	9,301	65%	3,026	No failure
A-12 *	10,595	74%	3,026	No failure
Mean	9,823	68%	3,026	
COV	7%	7%	0%	

* Results at 3,026 hours – not failure

Table 36. 62% sustained load test results for Adhesive A (spring stiffness results).

Anchor	Load (lbf)	Percent Load (%)	Time to Failure (hours)	Type of Failure
A-10 *	9,320	65%	3,026	No failure
A-11 *	9,405	65%	3,026	No failure
A-12 *	9,460	66%	3,026	No failure
Mean	9,395	65%	3,026	
COV	1%	1%	0%	

* Results at 3,026 hours – not failure

and displacements at 3,026 hours in order to approximate these points on the stress versus time-to-failure graph (see Figure 46).

Adhesive B

Table 37 presents the loads calculated from the spring stiffness and displacement for the 62% sustained load (creep) test for Adhesive B. Table 38 presents the load cell results, and Table 39 presents the spring stiffness results for Adhesive B.

Recalculation for Adhesive B Based on Incremental Load Rate Tests

Because of the quick failure times in the sustained load (creep) tests for Adhesive B, the rate of the initial loading had much more of an effect on the time to failure for Adhesive B than for Adhesive A. The initial loading duration for these tests was more like the 10-min loading duration for the incremental load rate static load tests than it was like the 2-min loading duration for the continuous load rate static load test. Therefore, a new mean static load was calculated

Table 37. Loads calculated from the spring stiffness and displacement for the 62% sustained load test (Adhesive B).

Anchor	Initial Load (lbf)	Spring Stiffness (lbf/in)	Position: End of Initial Loading (in)	Position: Initiation of Tertiary Creep (in)	Displacement (in)	Loss in Load (lbf)	Failure Load (lbf)
B-10	13,468	9,975	0.082	0.037	0.045	449	13,019
B-11	13,507	10,770	0.100	0.058	0.042	452	13,055
B-12	13,500	11,201	0.117	0.062	0.055	616	12,884

Table 38. 62% sustained load test results for Adhesive B (load cell results).

Anchor	Load (lbf)	Percent Load (%)	Time to Failure (hours)	Type of Failure
B-10	13,023	65%	1.22	Adhesive
B-11	12,582	63%	3.55	Adhesive
B-12	14,334	71%	8.15	Adhesive
Mean	13,313	66%	4.31	
COV	6%	6%	82%	

Table 39. 62% sustained load test results for Adhesive B (spring stiffness results).

Anchor	Load (lbf)	Percent Load (%)	Time to Failure (hours)	Type of Failure
B-10	13,019	65%	1.22	Adhesive
B-11	13,055	65%	3.55	Adhesive
B-12	12,884	64%	8.15	Adhesive
Mean	12,986	65%	4.31	
COV	1%	1%	82%	

from the two incrementally loaded static load test samples, and the percentages were adjusted in the sustained load (creep) test based on the new mean static load. Adhesive A did have one specimen fail quickly (A-07 at 0.73 hours), but it was decided not to recalculate the results for Adhesive A because the majority of the anchors failed at times much longer than the loading times (greater than an order of magnitude).

Mean Static Load

The mean static load was calculated from the two incremental load rate tests. While two data points are not a sufficient statistical data set, it was decided to analyze these data points to investigate the effects of load rate. Table 40 presents the results from the two incrementally loaded tests for Adhesive B. The mean static load recalculated from the two incrementally loaded tests for Adhesive B was determined to be 16,473 lbf with a COV of 2%.

75% Sustained Load Test

The percent loads for the 75% sustained load (creep) test were recalculated based on the new mean static load calculated from the two incrementally loaded tests and are presented in Table 41.

Table 40. 110°F static load test results for Adhesive B (incremental load rate).

Anchor	Static Load Strength (lbf)	Static Bond Stress (psi)	Percent of Mean (%)	Failure Mode	Type of Failure
B-05	16,283	2,654	99%	Strength-controlled	Adhesive
B-06	16,663	2,716	101%	Strength-controlled	Adhesive
Mean	16,473	2,685			

Table 41. Adjusted 75% sustained load test results for Adhesive B.

Anchor	Load (lbf)	Percent Load (%)	Time to Failure (hours)	Type of Failure
B-07	15,481	94%	0.60	Adhesive
B-08	16,075	98%	0.22	Adhesive
B-09	15,952	97%	0.13	Adhesive
Mean	15,836	96%	0.32	
COV	2%	2%	79%	

62% Sustained Load Test

The percent loads for the 62% sustained load (creep) test were recalculated based on the new mean static load calculated from the two incrementally loaded tests and are presented in Table 42.

Stress versus Time to Failure

For each adhesive, 10 data points were plotted on the stress versus time-to-failure graph. These 10 points included data points from the four continuously loaded 110°F static load tests, the three 75% sustained load (creep) tests, and the three 62% sustained load (creep) tests. A logarithmic trendline was determined for each graph from these 10 data points. Figure 46 and Figure 47 present the stress versus time-to-failure graphs for Adhesives A and B, respectively. A stress versus time-to-failure graph was also plotted for Adhesive B using a mean static load based on the incrementally loaded anchors. These eight points as well as the logarithmic trendline are presented in Figure 47.

While the 62% sustained load (creep) tests for Adhesive A were not continued to failure, two curves were plotted: the first assumed a failure at 3,026 hours, and the second assumed a failure at 10,000 hours.

The R^2 values for the four trendline equations from Figures 46 and 47 (0.76, 0.75, 0.92, and 0.85) indicate that the trendlines are a good fit for the data. The resulting correlation coefficients (R) for the four data sets are 0.87, 0.87, 0.95, and 0.92. According to Wheeler and Ganji (*52*), for 10 samples, a correlation coefficient greater than 0.765 indicates that there is a 99% confidence level that a trend exists. For eight samples, a correlation coefficient greater than 0.834 indicates that there is a 99% confidence level that a trend exists.

Additionally, for a given time to failure, the percent difference was calculated between the measured percent load value and the percent load value expected from the trendline. The mean of the absolute value of the percent difference was determined for each data set (7%, 9%, 4%, and 15%, respectively), thereby providing an indication of the scatter of the data from the trendline and providing information that can be used to determine the spread on the stress level for a given time to failure.

The statistical information discussed above is summarized in Table 43. This simple statistical analysis indicates that the trendlines created from the stress versus time-to-failure graph provide reasonable estimations of time to failure.

A table of load levels for given structure lifetimes may be more useful to a designer than a stress versus time-to-failure graph. Table 44 presents the load levels for each adhesive for a given time to failure. The effect of load rate can be seen in the difference in the two columns for Adhesive B. Additionally, for the trendline equations determined for these adhesives, the unadjusted load levels for most structure lifetimes (100 years) are above 46% and 31% of mean static load for Adhesives A and B, respectively.

As discussed above, trendlines were created for Adhesive A assuming failure at 3,026 hours and at 10,000 hours for the 62% sustained load (creep) tests. It can be seen in the stress versus time-to-failure graph for Adhesive A (see Figure 46) as well as in Table 44 that a difference of almost 7,000 hours between these two assumed failure times does not affect the load levels at a given time to failure.

Table 42. Adjusted 62% sustained load test results for Adhesive B.

Anchor	Load (lbf)	Percent Load (%)	Time to Failure (hours)	Type of Failure
B-10	13,019	79%	1.22	Adhesive
B-11	13,055	79%	3.55	Adhesive
B-12	12,884	78%	8.15	Adhesive
Mean	12,986	79%	4.31	
COV	1%	1%	82%	

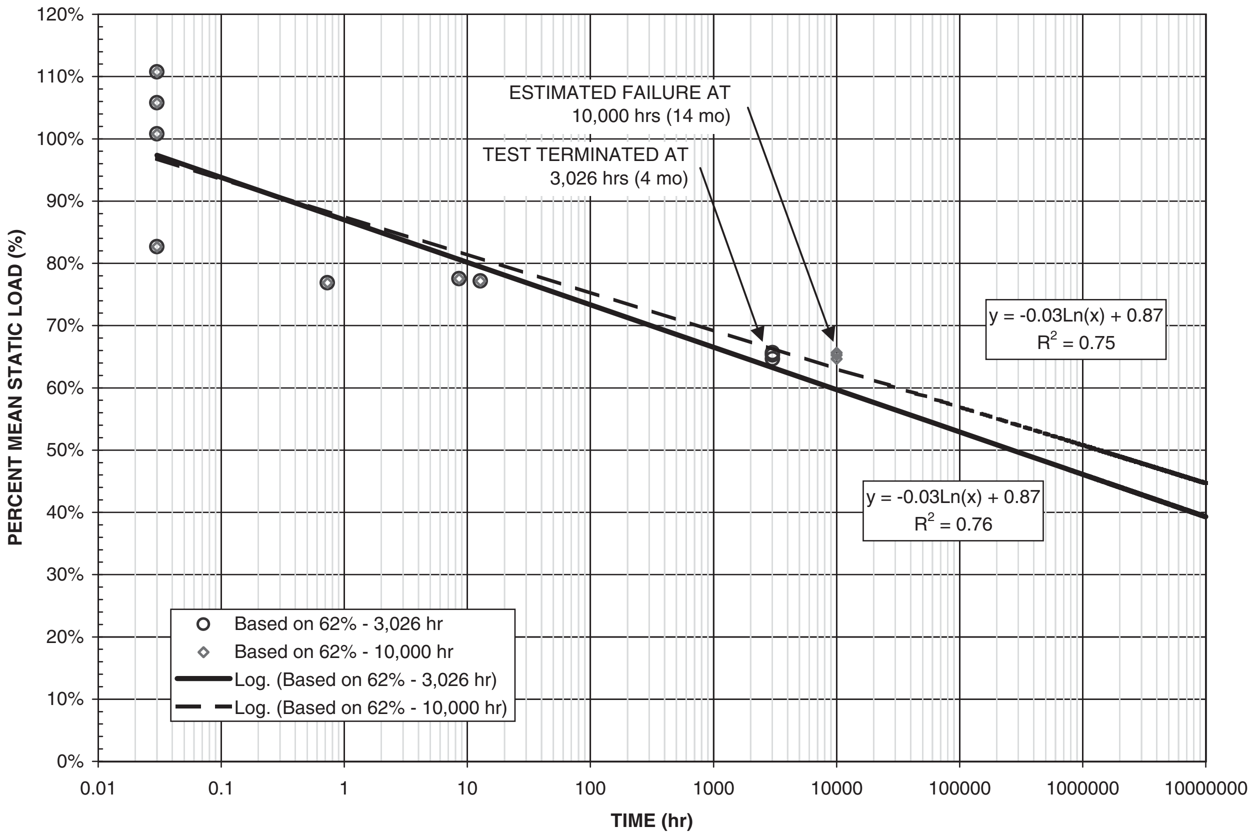


Figure 46. Stress versus time-to-failure graph for Adhesive A.

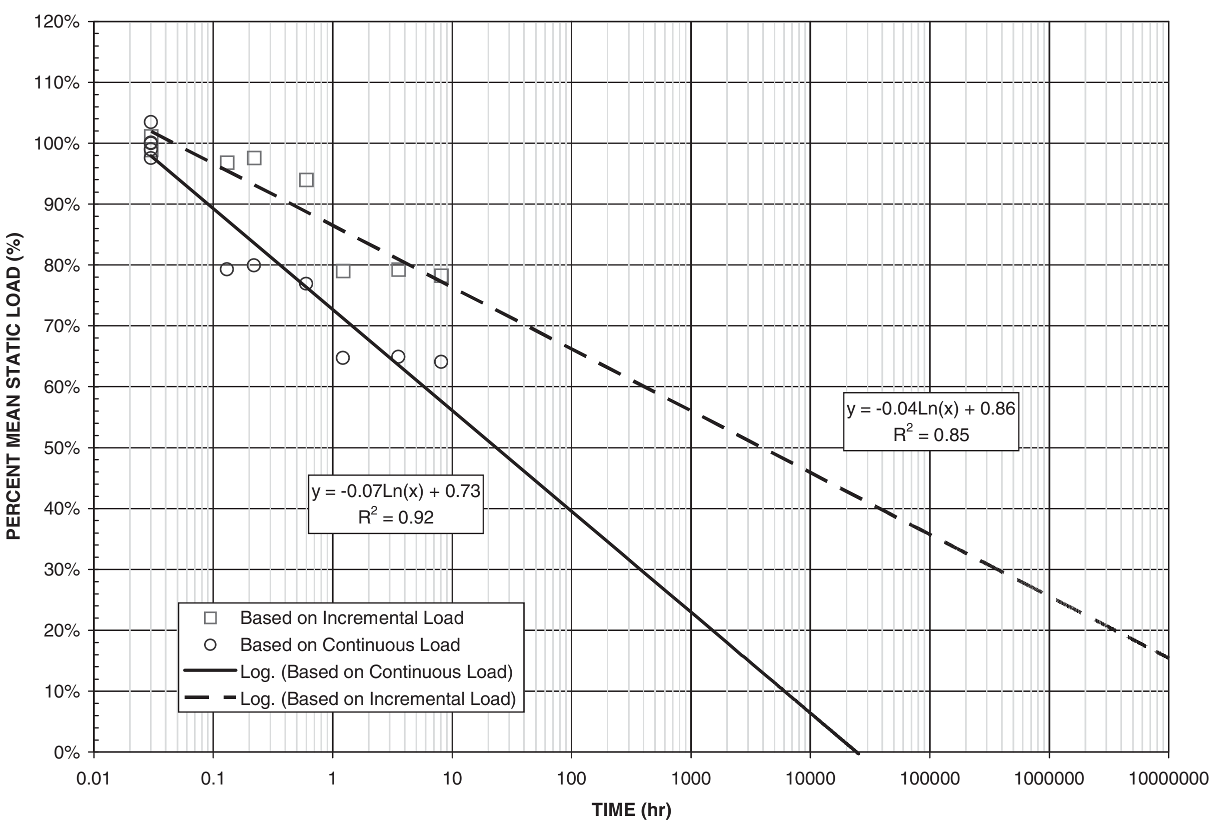


Figure 47. Stress versus time-to-failure graph for Adhesive B.

Table 43. Summary of statistical analysis.

Statistical Parameter	Adhesive A 62% - 3,026 hours	Adhesive A 62% - 10,000 hours	Adhesive B continuous load rate	Adhesive B incremental load rate
R^2 of trendline	0.76	0.75	0.92	0.85
Correlation coefficient (R)	0.87	0.87	0.95	0.92
Number of Samples	10	10	10	8
Confidence of Trend	99%	99%	99%	99%
Mean percent difference	7%	9%	4%	15%

Recommendations

As a result of the initial testing program, the following recommendations were identified to improve the test procedure and data analysis. These recommendations are included in the draft AASHTO test method. The recommendations are grouped into two groups: recommendations for the static load test and recommendations for the sustained load (creep) test.

Recommendations for the static load test are the following:

- Due to the scatter in the results, at least five specimens should be tested and their results averaged to determine the mean static load. This was the original intent of the research, but it was decided to use the results of the four continuously loaded specimens to test two at the incremental load rate to investigate its potential as an indicator of susceptibility to sustained load.
- The continuous load rate method should be the only method approved to determine the mean static load and incorporated into a stress versus time-to-failure graph. The purpose of the static load test is to determine the load level at "zero" time. Since zero does not exist on the log plot, and it is practically impossible to load at a "zero" time duration, the maximum static load value should be set at 2 min, as specified in the constraints on the continuous load rate.
- The incremental load rate method should not be used to calculate the mean static load because in this research this method introduced other parameters (load duration and adhesive composition) into the analysis. It was noticed that at an elevated temperature of 110°F, the static load tests for some adhesives were influenced by the rate of application of the load. Anchors that were loaded using the incremental load rate were subjected to a loading duration of around 10 min while anchors loaded under the continuous load rate were subjected to a loading duration of 2 min. For Adhesive B, specimens loaded under the incremental load rate test failed at a lower stress level than specimens loaded under the shorter, continuous load rate test. This trend was not noticed in the 75°F static load test. It is assumed that this difference at two temperature levels is due to adhesive chemistry.

Recommendations for the sustained load (creep) test are the following:

- Due to the scatter in the results, at least five specimens should be tested per series.
- It was originally thought that each sustained load (creep) test series would have samples at exactly the same load level. Due to difficulties in the loading procedure, this ideal condition was not met. Nonetheless, since the purpose is to create a trend of stress over time, it is not very important to have all percent load values for a series at a specific target value. It is more important that the percent load values for a series are located within a specified load range.
- Load ranges should be chosen so as to ensure failure at times greater than 1 hour. There was a lot of scatter and uncertainty in the specimens that failed in less than 1 hour. This is especially true for cases in which the initial loading duration was significantly long. To avoid this, it is suggested

Table 44. Load levels for given times to failure for Adhesives A and B.

Time to Failure (years)	Time to Failure (hours)	Adhesive A 62% - 3,026 hours	Adhesive A 62% - 10,000 hours	Adhesive B continuous load rate	Adhesive B incremental load rate
2	17,520	58%	58%	5%	47%
25	219,000	50%	50%	-	37%
50	438,000	48%	48%	-	34%
75	657,000	47%	47%	-	32%
100	876,000	46%	46%	-	31%

that load levels higher than 80% of mean static load not be chosen. In addition to avoiding rapid failure, setting this upper bound will ensure that the loads are well outside of any reasonable statistical variation on the mean static load.

- Load ranges should not be set too low because this will increase the testing time. Currently, products that pass *ICC-ES AC308* (*3*) do not fail prior to 1,000 hours (6 weeks) at a load level of 55% mean static load.
- It is suggested that Load Range 1 be from 70% to 80% of mean static load. Load Range 2 should be from 60% to 70% of mean static load. It is also recommended that the average of the two series be separated by 10%.
- Additionally, it was initially thought that the averages for the static load test and for each sustained load (creep) test series would be determined, and these three values would be plotted on the stress versus time-to-failure graph. However, since it is not necessary to load every anchor in a series at the same percent load, calculating averages is unnecessary.
- In the sustained load (creep) tests, the initial load should be applied to the anchor over the same duration as was used with the continuous load in the static load test. It is recommended that the load be applied within 2 min ±1 min.

CHAPTER 4

Conclusion and Recommendations

The objective of this research project was to develop a draft AASHTO standard test method to determine the ability of adhesive anchors to resist sustained tension load. The draft AASHTO test standard developed for this project is based on developing a stress versus time-to-failure interaction diagram for individual adhesive products. The interaction diagram (or simply a table) can be used to determine the percent of an adhesive's short-term design strength that is acceptable for use over the life of the structure. The project was divided into several phases: literature review, development of a testing procedure, demonstration and evaluation of the testing procedure, and conclusions and recommendations. The final product of this research is presented as Appendix A and entitled "Standard Method of Test for Evaluation of Adhesive Anchors in Concrete Under Sustained Loading Conditions."

Recommendations

It was determined that the stress versus time-to-failure method is a viable method to determine an adhesive anchor's ability to resist sustained tensile loads. It is a relatively simple test that builds upon established ASTM and ICC-ES test methods. The procedures included in the proposed test method use existing test procedures and apparatus. In other words, any laboratory that is equipped to conduct adhesive anchor tests under *ICC-ES AC308* (*3*) will generally be able to conduct this test. The stress versus time-to-failure method is different than the pass/fail method specified in *ASTM E1512-01* (*29*) and *ICC-ES AC308*, but it is an established analysis method found in other ASTM standards.

Listed below are specific changes from existing test methods (i.e., *ASTM E488-96* [*28*], *ASTM E1512-01* [*29*], and *ICC-ES AC308* [*3*]) as well as elements that are not specified in the existing test methods that have been incorporated into the draft AASHTO test method. Also included are suggestions developed during the validation of the test method that can improve the results of the tests. All of the following recommendations and suggestions have been incorporated into the draft AASHTO test method:

- The required sampling rate of 30 s for the static load test is faster than the 1-s sampling rate required for *ASTM E488-96* for better data resolution.
- Sampling for the sustained load (creep) test is more frequent than it is in *ASTM E1512-01* and *ICC-ES AC308*. The least frequent level of sampling in the AASHTO method is once per hour, and this level of sampling frequency begins 10 hours after loading.
- The incremental load rate, as mentioned in *ASTM E488-96*, is not used in the determination of mean static load. It was noted that load rates of longer duration, such as the incremental load rate, could produce lower static load strengths in an anchor.
- All baseline static and sustained load tests are restrained (confined) tests.
- All baseline test series of static and sustained load tests consist of a minimum of five specimens.
- The confining sheet thickness of 0.020 ±0.004 in. specified in *ICC-ES AC308* was considered to be too thin and was increased to a maximum of 0.06 in. thick.
- In the sustained load (creep) test, the initial load is to be applied for the same duration as it is applied in the static load test.
- The analysis of sustained load is not based on pass/fail criteria, as specified in *ICC-ES AC308,* but rather generates a stress versus time-to-failure relationship.
- The concrete strength requirement was changed from what was specified in *ASTM E1512-01* to what is specified in *ICC-ES AC308*.
- The recommended anchor diameter was increased to ⅝ in. from the ½ in. specified in *ASTM E1512-01* in order to avoid steel failure.
- A minimum embedment depth was specified, as found in *ICC-ES AC308,* in order to avoid steel failure. *ASTM E1512-01* specifies a 4.5-in. embedment depth.

- The static load tests are to be conducted at an elevated temperature of 110°F.
- All tests are to be conducted at a controlled humidity below 40%.
- The sustained load (creep) tests have at least two load level ranges within which the anchors are to be tested. It is not necessary that all specimens in a series be loaded at the same percent load; instead, they should be loaded within a specified load level range. It is suggested that the load levels be set below 80% of mean static load (1) to avoid early failures and (2) to lie outside a reasonable statistical variation of the mean static load. Additionally, to avoid long test durations, load levels should not be set too low. It is suggested that the two load level ranges should be 80% to 70% of mean static load and 70% to 60% of mean static load, with the average of each series separated by 10%.
- The load should be smoothly transferred during the sustained load (creep) test.
- The finish on the concrete member should be as smooth as possible to preclude surface spalling of the concrete during testing.

Benefits of the Stress versus Time-to-Failure Test Method

As discussed in Chapter 1 of this report, some of the benefits of the stress versus time-to-failure method are the following:

- Test results in the form of a stress versus time-to-failure graph or a table of stress values for given lifetimes of structures provide more useful design data for the practicing engineer than the pass/fail criteria in *ICC-ES AC308* (*3*).
- The reduction factor generated from the stress versus time-to-failure approach can easily be incorporated into an LRFD approach, which is in agreement with current AASHTO design philosophy.
- Existing data from *ICC-ES AC308* can be incorporated into stress versus time-to-failure graphs, which builds upon the database of current test results.
- The stress versus time-to-failure method allows manufacturers to qualify a product above the minimum pass/fail standard established by *ICC-ES AC308* in order to distinguish their product among the products of their competitors. For example, both Adhesive A and B passed *ICC-ES AC308* criteria, but Adhesive A performed significantly better in stress versus time-to-failure evaluation than Adhesive B.
- The stress versus time-to-failure method removes the uncertainty associated with the mathematical projection of displacement in the *ICC-ES AC308* approach.
- The stress versus time-to-failure method removes the uncertainty associated with establishing a limit on projected displacement in the *ICC-ES AC308* approach.
- The stress versus time-to-failure method provides a rational method of incorporating test results conducted at other temperatures.
- This test method creates a conservative stress versus time-to-failure relationship because it assumes that the anchor is exposed to an elevated temperature of 110°F for its lifetime.

Implementing the Test Method

It is recommended that this test method be provided to two or three independent laboratories qualified to conduct adhesive anchor tests in order to validate the approach and to test for precision and bias.

Further Research

Further research is needed to investigate this method and other factors that affect adhesive anchors. The following is a list of research needs:

- It is recommended that this test procedure be conducted on more specimens in order to see if the scatter in the results can be reduced and trendlines with higher R^2 values can be obtained.
- Due to project budget and timeline, the effect of in-service moisture was not investigated in this project. As discussed in Chapter 1, there are many factors that affect adhesive anchors. Currently, studies and tests have been conducted only to evaluate the effects on static load strength. Research is needed to investigate these varied effects on sustained load strength.
- The incremental load rate showed promise as a possible method to determine an adhesive anchor's sensitivity to creep at high load levels. Research should be conducted to investigate whether a method using an incremental load rate can be developed to evaluate an adhesive anchor's performance under sustained load. Alternatively, this could serve as a method to compare adhesives.
- Design standards for adhesive anchors appropriate for AASHTO applications and load conditions should be developed and incorporated into AASHTO's LRFD Design Specifications.
- Tests of the adhesive alone show promise as methods to prescreen or fingerprint adhesive anchor systems. Research could be conducted to see if a correlation can be made to actual sustained load test results.
- Stress versus time-to-failure tests should be conducted at other temperatures to investigate the change in slope of the time-to-failure curves at lower temperatures and the conservativeness of offsetting parallel lines.

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APPENDIX A

Draft AASHTO Test Method—Standard Method of Test for Evaluation of Adhesive Anchors in Concrete Under Sustained Loading Conditions

Standard Method of Test for

Evaluation of Adhesive Anchors in Concrete Under Sustained Loading Conditions

AASHTO Designation: T XXXX-XX

ASTM Designation: XXXX-XX

INTRODUCTION

Adhesive anchor systems have widespread use in transportation structures such as bridge widening, concrete repair and rehabilitation, barrier retrofitting, utility installation on existing structures, and tunneling. These systems are used to anchor threaded rod and reinforcing bars in concrete. This test method determines an adhesive anchor's ability to withstand sustained tensile loads under normal conditions.

1 SCOPE

1.1 This test method applies to structures used in AASHTO applications and is applicable to adhesive anchor systems with steel anchors in predrilled holes in concrete.

1.2 This test method determines the time to failure for adhesive anchors in concrete at various levels of sustained loading.

1.3 The static load test is developed from ASTM E 488 and the sustained load (creep) test is modified from ASTM E 1512 and ICC-ES AC308.

1.4 This test method only addresses the effect of sustained loads on adhesive anchors. There are numerous other factors that affect the load capacity of adhesive anchors and a complete battery of tests is essential to evaluate an adhesive anchor. Refer to ICC-ES AC308 for a listing of some of the many factors and related test methods that apply to adhesive anchors.

2 REFERENCED DOCUMENTS

2.1 *ASTM Standards:*

A 193, Standard Specification for Alloy-Steel and Stainless Steel Bolting Materials for High Temperature or High Pressure Service and Other Special Purpose Applications

C 31, Standard Practice for Making and Curing Concrete Test Specimens in the Field

C 39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

C 42, Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete

D 907, Standard Terminology of Adhesives

D 2990, Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics

E 488, Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements

E 1512, Standard Test Methods for Testing Bond Performance of Bonded Anchors

2.2 *Other Standards:*

ICC-ES AC308, Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete

3 TERMINOLOGY

3.1 Refer to ASTM D 907 for a complete listing of terminology related to adhesives.

3.2 *Adhesive anchor* – a post-installed anchor that transfers load to concrete through an adhesive compound embedded in a hole in hardened concrete. The adhesive materials used include epoxy, cementitious material, polyester resin, and others.

3.3 *Creep* – the deformation or displacement of an adhesive over time due to stress.

3.4 *Embedment depth* – distance from the surface of the structural member to the end of the installed anchor.

3.5 *LVDT* – Linear Variable Differential Transformer; an electronic instrumentation device used for measuring displacement.

3.6 *Static load test* – a test in which a load is slowly applied at a specified rate for one cycle until failure.

3.7 *Sustained load (creep) test* – a test in which a constant load is continuously applied until failure due to creep.

3.8 *Symbols*:

d = nominal anchor diameter, in (mm)

d_o = nominal diameter of drilled hole in concrete, in (mm)

f'_c = specified compressive strength of concrete, psi (MPa)

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

4 SIGNIFICANCE AND USE

4.1 Determination of mean static load of an adhesive anchor.

4.2 Determination of acceptable loads to apply to an adhesive anchor based on the lifetime of the structure.

4.3 Determination of an adhesive anchor's ability to endure sustained loads.

4.4 The Stress versus Time-to-Failure graph is useful to the practicing engineer in selecting and designing adhesive anchors.

4.5 A Stress versus Time-to-Failure graph can give an indication of the reduction in capacity of an adhesive anchor due to sustained load at a given design lifetime.

4.6 Means for comparing adhesive anchor products for sustained loading applications.

4.7 The test methods in this standard should be followed in order to ensure reproducibility of test results.

5 TEST APPARATUS

5.1 *Instrumentation and Data Collection:*

5.1.1 All laboratory instrumentation (electronic load, displacement, temperature, and humidity sensors, etc.) must be calibrated with certified equipment.

5.1.2 A load cell or other load measuring device must be able to measure forces to within ±1% of the anticipated peak load.

5.1.3 As an alternative, a load cell is not required for monitoring the sustained load (creep) test if the test apparatus has a stiffness that is sufficiently low to ensure accuracy of 1% of the applied sustained load at the maximum anchor creep displacement and a stiffness-displacement relationship can be established to determine the load applied with reasonable confidence.

5.1.4 Displacements should be measured continuously by LVDTs, linear potentiometers, or an equivalent device with an accuracy of at least 0.001 in. (0.025 mm).

5.1.5 The instrumentation must be placed in a way so as not to interfere with the anchor or testing apparatus. The instrumentation should measure the vertical displacement and load on the anchor relative to the test specimen. The instrumentation should be placed in such a way that it will remain parallel to the axis of the anchor and will not be affected by the deflection and/or failure of the anchor or test specimen.

5.1.6 Two displacement measuring devices shall be placed equidistant from the anchor and their values averaged to obtain the actual displacement. One displacement measuring device may be used if it is placed centered on the anchor’s axis and can be shown to produce acceptable confidence.

5.1.7 *Static Load Test:* The measuring devices and the data collection system must be able to gather data points at least twice per second for the static load test.

5.1.8 *Sustained Load (Creep) Test:* The measuring devices and the data collection system must be able to gather data points according to a progressively reducing frequency as discussed in section 9.4.6.2 of this standard.

5.2 *Test Apparatus:*

5.2.1 Examples of suitable test apparatus for static and sustained load (creep) tests are shown in Figure 1 and Figure 2, respectively.

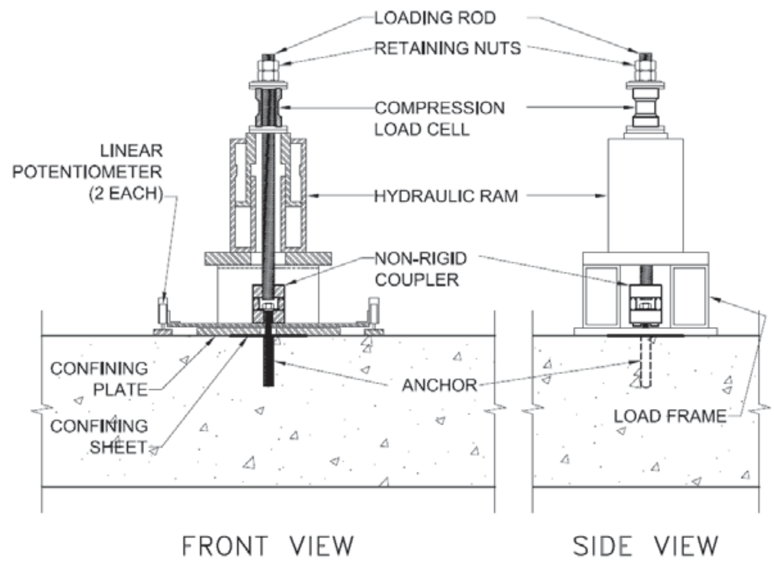

Figure 1: Static Load Test Apparatus

(Source: modified from Cook et al. [14.2])

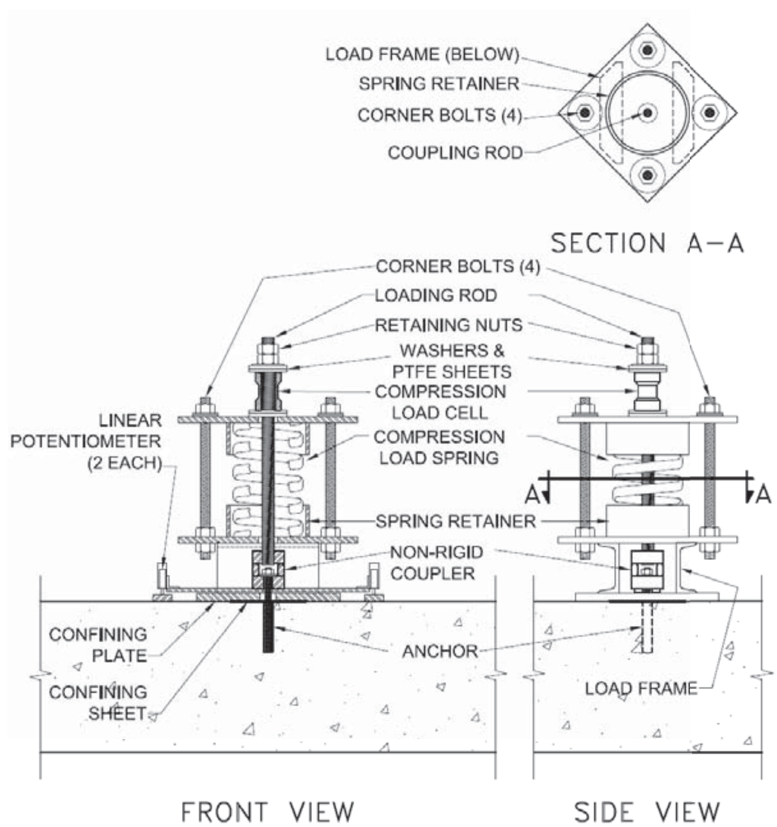

Figure 2: Sustained Load (Creep) Test Apparatus

(Source: modified from Cook et al. [14.2])

5.2.2 The test apparatus must be of sufficient capacity so as to not yield during testing.

5.2.3 *Coupler:* A coupler shall be used between the anchor and the test loading rod providing a non-rigid connection which does not transfer bending forces.

5.2.4 *Confining Plate:*

5.2.4.1 The thickness of the confining plate should be greater than or equal to the nominal anchor diameter ±1/16 in. (±1.5 mm).

5.2.4.2 In order to account for surface irregularities, a sheet of tetrafluoroethylene (TFE), polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), or perfluoroalkoxy (PFA) of up to 0.06 in (0.15mm) of the same shape and dimensions of the confining plate shall be placed between the confining plate and the surface of the concrete.

5.2.4.3 The confining plate and the confining sheet shall be large enough that the pressure on the concrete underneath the plate does not exceed $0.40f'_c$.

5.2.4.4 The hole in the confining plate and the confining sheet shall be $1.5d_o$ to $2.0d_o$. The initial shape of the hole shall match the anchor's cross-section. The size and shape of the hole shall be maintained in all tests.

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6 TEST SPECIMEN

6.1 *Anchorage System* - The anchorage system used in the tests should be representative of that used in the field.

6.2 *Anchor Placement* – Anchors shall be placed far enough apart so as to not interfere with the testing apparatus.

6.3 *Structural Member:*

6.3.1 The structural member used in the tests shall not have anchors located within $2h_{ef}$ of the edges and shall not cause early failure of the member or the anchor.

6.3.2 Reinforcing steel can be used but only what is necessary for handling and shall not interfere with the anchor. Reinforcing cannot be located within an imaginary cone projecting from the end of the embedded anchor to the loaded face of the structural member with an internal vertex angle of 120 degrees.

6.3.3 The depth of the structural member should be at least $1.5h_{ef}$ providing it is thick enough for installation and does not cause early failure of the member or the anchor.

6.3.4 The length and width of the structural member shall be large enough to ensure proper placement of the anchors in accordance with minimum spacing and edge distances.

6.3.5 The surface of the structural member shall be form-work or steel-trowel finish.

6.3.6 The concrete compressive strength at time of testing shall be from 2500 psi to 4000 psi (17 MPa to 28 MPa), unless otherwise specified. The aggregate should be of river gravel or crushed rock with a maximum aggregate size of ¾" or 1" (19mm or 24mm). The concrete mixture shall not include any materials such as blast furnace slag, fly ash, silica fume, limestone powder, or admixtures unless otherwise specified.

6.3.7 Cure the concrete for a minimum of 28 days ensuring proper moisture for hydration.

6.3.8 Concrete cylinders shall be made in accordance with ASTM C 31 and cured in similar conditions as the structural member. Cylinders shall be de-molded at the same time as form removal.

6.3.9 Test concrete compressive strength in accordance with ASTM C 39 for concrete cylinders or ASTM C 42 for concrete cores. Concrete strength at any point can be determined from a concrete strength-age relationship curve constructed from a sufficient number of compression tests conducted at regular intervals. It is also permitted, to linearly interpolate concrete strength from compression tests conducted at the beginning and end of a test series.

7 ADHESIVE AND ANCHOR INSTALLATION AND CURING

7.1 Prior to anchor installation, condition the test specimen to 75ºF ±10ºF (24ºC ±5ºC) and 50% ±10% relative humidity.

7.2 *Hole:*

7.2.1 Drill holes in accordance with the manufacturer's specifications and document any deviations. Drilled holes must be perpendicular (±6º) to the face of the concrete test specimen.

7.2.2 In order to more easily compare data – the embedment depth h_{ef} should be 4.5in. ±0.1in. (115mm ±2.5mm) unless otherwise specified. A shallower embedment depth may be used if it is determined that a steel failure would occur prior to bond failure.

7.2.3 For anchors with a diameter *d* the minimum embedment depth h_{ef} shall conform to Table 1.

Table 1: Minimum Embedment Depth

d	$h_{ef,min}$
1/2”	2 3/4”
5/8”	3 1/8”
3/4”	3 1/2”
≥ 1”	4d

7.2.4 Clean the holes in accordance with the manufacturer's specifications and document any deviations.

7.3 *Adhesive:*

7.3.1 Prepare and install the adhesive in accordance with the manufacturer's specifications and document any deviations.

7.3.2 Cure the adhesive according to the manufacturer's specifications and document any deviations.

7.4 *Anchor:*

7.4.1 Install the anchor in accordance with the manufacturer's specifications and document any deviations.

7.4.2 To ensure bond failure, use a high-strength steel (minimum strength equivalent to ASTM A 193 Grade B7).

7.4.3 In order to more easily compare data, anchors shall be 5/8” – 11 UNC (16mm) threaded rod unless otherwise specified. A larger anchor diameter may be used if it is determined that a steel failure would occur prior to bond failure.

8 SPECIMEN CONDITIONING

8.1 Begin conditioning of the test slabs to their final environmental condition upon completion of the manufacturer's specified curing time, and within 7 ±5 days.

8.2 Do not begin tests until the temperature and humidity of the test specimens have stabilized for at least 24 hours.

Note 1 – Depending on the size of the structural member it might take several days to raise and stabilize the concrete temperature to the final elevated temperature.

9 TEST PROCEDURE

9.1 The test procedure consists of two types of tests (Static Load Test and Sustained Load (Creep) Test). Static load tests are conducted initially to determine the *mean static load*. Subsequently, several sustained load (creep) tests are conducted at various percentages of the *mean static load*.

9.2 *General Requirements:*

9.2.1 All tests will be confined tests.

9.2.2 The tests will be conducted at specified temperature and humidity. The temperature shall be monitored via thermocouples or temperature sensors placed in the concrete test specimen. The thermocouples or temperature sensors can be either cast-in-place or installed in a maximum ½ in. (12mm) diameter hole and sealed to ensure accurate concrete temperature readings. The thermocouples or temperature sensors should ideally be placed at the mid-depth of the anchor but not deeper than 4.5 in. (114mm).

9.2.3 Alternatively, the temperature can be monitored daily by a temperature sensor located in the test chamber if a confident correlation can be shown between test chamber temperature and test specimen concrete temperature.

9.3 *Static Load Test:*

9.3.1 *Environmental Conditions* – Conduct the static load tests at a minimum temperature of 110ºF +10ºF/-0ºF (43ºC +5ºC/-0ºC) and below 40% relative humidity. Following the required adhesive curing time, raise the temperature to the minimum elevated temperature of 110ºF (43ºC). Do not begin testing until the temperature and humidity of the test specimen have stabilized for at least 24 hours.

9.3.2 *Number of Test Specimens* – A minimum of five (5) anchors shall be tested and their results averaged.

9.3.3 *Test Setup:*

9.3.3.1 Ensure that the test apparatus and instrumentation complies with the requirements of section 5 of this test method.

9.3.3.2 Ensure that the test apparatus is centered over the anchor and that the force applied is acting through the center of the anchor and perpendicular to the structural member.

9.3.3.3 Place the confining sheet around the anchor as discussed in section 5.2.4.2 of this standard.

9.3.3.4 Place the confining plate over the confining sheet assuring that there is full bearing with the structural member around the anchor.

9.3.3.5 Connect the loading rod to the anchor by means of a non-rigid connecting coupler and ensure that it is acting in-line with the anchor.

9.3.3.6 The amount of pre-tensioning to the apparatus during test setup shall be uniform for all samples.

9.3.4 *Loading:*

9.3.4.1 *Initial Load* – Apply an initial load not exceeding 5% of the estimated ultimate load capacity of the anchor system in order to bring all members of the test apparatus into bearing. Zero the displacement readings.

9.3.4.2 *Rate of Loading* – Two loading rates are allowed by ASTM E 488, the Continuous Load Rate and the Incremental Load Rate. The continuous load rate is the only load rate allowed in this test method for the calculation of *mean static load* and for inclusion in the Stress versus Time-to-Failure graph.

Note 2 - The incremental load rate can be used in optional additional tests as a method to (1) provide an indication of an adhesive's displacement sensitivity to load at the higher stress levels and (2) determine appropriate stress levels to test at for the sustained load (creep) tests. This method is discussed in further detail in Appendix X1.

9.3.4.2.1 *Continuous Load Rate* - Apply a uniform load rate such that failure will ideally occur at 2-min. Failure shall not occur in less than 1-min or greater than 3-min.

9.3.4.2.2 *Incremental Load Rate* - Apply the load in steps with the first increment not greater than 50% and each increment thereafter not exceeding 15% of the total expected load. Maintain each load increment within a tolerance of ±2% for 2 minutes.

9.3.5 *Data Collection* – Collect load and displacement readings according to section 5.1.7 of this standard.

9.3.6 *Determination of Failure* – See Appendix X2 for a description of the various failure modes and methods to determine static load strength.

9.3.7 *Calculations:* Determine and record the *mean static load* by averaging the individual static load strengths from each test series.

9.4 *Sustained Load (Creep) Test:*

9.4.1 *Environmental Conditions* – Conduct the sustained load (creep) tests at a minimum elevated temperature of 110ºF +10ºF/-0ºF (43ºC +5ºC/-0ºC) and below 40% relative humidity. Following the required curing time, raise the temperature to the minimum elevated temperature of 110ºF (43ºC). Do not begin the test until the temperature and humidity of the test specimen has stabilized for at least 24 hours.

9.4.2 *Test Series* – Conduct a minimum of two series of sustained load (creep) tests within two load ranges (PL1 and PL2) based on the *mean static load* from the static load test:

9.4.2.1 Percent load level range 1 (PL1) is suggested to be between 70% and 80% of *mean static load*.

9.4.2.2 Percent load level range 2 (PL2) is suggested to be between 60% and 70% of *mean static load*.

9.4.2.3 It is not necessary that all test specimens be tested at the same percent load level, but that they lie within the ranges and the averages of the two test series should vary by at lest 10%.

9.4.3 *Number of Test Specimens* – A minimum of five (5) anchors per series shall be tested.

9.4.4 *Test Setup:*

9.4.4.1 Ensure that the test apparatus and instrumentation complies with the requirements of section 5 of this test method.

9.4.4.2 Ensure that the test apparatus is centered over the anchor and that the force applied is acting through the center of the anchor and perpendicular to the structural member.

9.4.4.3 Place the confining sheet around the anchor as discussed in section 5.2.4.2 of this standard.

9.4.4.4 Place the confining plate over the confining sheet assuring that there is full bearing with the structural member around the anchor.

9.4.4.5 Connect the loading rod to the anchor by means of a non-rigid connecting coupler and ensure that it is acting in-line with the anchor.

9.4.4.6 The amount of pre-tensioning to the apparatus during test setup shall be uniform for all samples.

9.4.5 *Loading* – Apply an initial load not exceeding 5% of *mean static load* in order to bring all members of the test apparatus into bearing. Zero the displacement readings. Apply the remainder of the sustained load within 2-min ±1-min in as smooth a manner as possible.

Note 3 – A suggested modification to the sustained load (creep) test apparatus shown in Figure 2 is presented in Appendix X4 to provide for smooth load transfer.

9.4.6 *Data Collection:*

9.4.6.1 *Temperature* - Record the concrete specimen temperature at a maximum 1-hour interval. Alternatively, the concrete specimen temperature can be recorded at 24-hour intervals if the test chamber temperature is recorded at 1-hour intervals.

9.4.6.2 *Displacement* – The frequency of displacement readings can be reduced over time.

Note 4 - The following schedule is a suggestion: every three seconds during loading, every minute for the first hour following loading, every ten minutes for the next nine hours, and every hour thereafter.

9.4.7 *Determination of Failure:* Failure for the sustained load (creep) test will be determined as the onset of tertiary creep. A discussion of tertiary creep and a method to determine its onset can be found in Appendix X3.

9.4.8 *Calculations* - Determine and record the time to failure and load level at failure for each specimen.

10 CALCULATIONS AND INTERPRETATION OF RESULTS

10.1 Determine the five individual static load strengths from each static load test. Methods to determine the static load strength can be found in Appendix X2.

10.2 Determine the *mean static load* by averaging the individual values from the static load tests.

10.3 Determine the time to failure for each sustained load (creep) test series as the initiation of tertiary creep. A procedure to locate the onset of tertiary creep can be found in the Appendix X3.

10.4 Determine the failure load level for each sustained load (creep) test series at the initiation of tertiary creep.

10.5 Normalize the load levels for the sustained load (creep) test to a percent of the *mean static load* from the static load tests.

10.6 Plot the normalized values from the static load test and the sustained load (creep) test on a Stress versus log of Time-to-Failure graph.

10.7 Extend a linear trendline through the fifteen points plotted.

10.8 A Stress versus Time-to-Failure graph can give an indication of the reduction in capacity of an adhesive anchor due to sustained load at a given design lifetime.

11 REPORT

11.1 Data Collection: Report the type of test (static load or sustained load) and the following applicable information:

11.1.1 Date of test and date of report.

11.1.2 Test sponsor and test agency.

11.1.3 Anchor information: manufacturer, model, type, material, finish, shape, dimensions, and other relevant information.

11.1.4 Adhesive information: manufacturer, model, type, lot, material, application method, and other relevant information.

11.1.5 Structural member information: description, dimensions, reinforcing, mix design of concrete, aggregate type, curing method, strength at time of test, age of concrete at time of test.

11.1.6 Installation information: description of the procedure, tools, and methods used to install the adhesive anchor. Include the drilling and cleaning of the holes as well as the installation of the adhesive and anchor. Document any deviations from the manufacturer’s specifications.

11.1.7 Adhesive curing information: temperature and humidity conditions, length of cure, time when conditioning of test specimen began.

11.1.8 Temperature and humidity conditions at time of installation, and during adhesive cure, conditioning, and final testing.

11.1.9 Embedment depth and diameter of hole of installed anchors.

11.1.10 Test information: description of test method, amount of initial load, and actual rate of loading.

11.1.11 Number of samples tested per series.

11.1.12 Static Load Test Data:

11.1.12.1 Individual and average load values per anchor and COV.

11.1.12.2 Individual and average displacement values at maximum load

11.1.12.3 Load versus displacement curves per anchor.

11.1.12.4 Load versus time curves per anchor.

11.1.13 Sustained Load (Creep) Test Data:

11.1.13.1 Individual time-to-failure values per anchor.

11.1.13.2 Individual load values and percent *mean static load* values at failure per anchor.

11.1.13.3 Individual displacement values at failure per anchor.

11.1.13.4 Load versus displacement curves per anchor.

11.1.13.5 Displacement versus time curves per anchor.

11.1.13.6 Load versus time curves per anchor.

11.1.13.7 Stress versus Time-to-Failure curve.

11.1.14 Photographs, sketches and descriptions of failure modes observed.

11.1.15 Summary of findings

11.1.16 Listing of observers of tests and signatures of responsible persons.

12 PRECISION AND BIAS

12.1 *Precision* – No precision has been established for this test method.

12.2 *Bias* – No bias can be established because no reference material is available for this test.

13 KEYWORDS

13.1 adhesive anchors: anchors: bonded anchors: creep test: concrete: post-installed anchors: static load test: sustained load test: test methods: time to failure test

14 REFERENCES

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APPENDIXES

(Non-mandatory Information)

X1 INCREMENTAL LOAD RATE

X1.1 As discussed in 9.3.4.2.2 the incremental load rate is a method that applies the load in several load steps and holds the load for two minutes and then increases to the next load level.

X1.2 This method can provide an indication of an adhesive's sensitivity to sustained loading at higher load levels.

X1.3 Figure 3 shows a load versus displacement curve and a time versus displacement curve for an anchor under incremental loading.

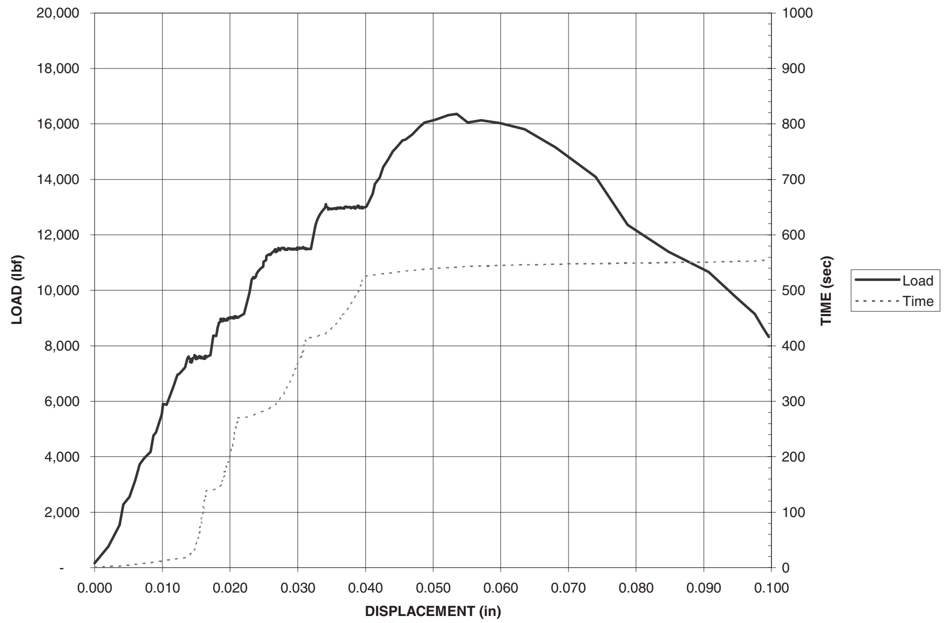


Figure 3: Load-Displacement and Time-Displacement Curves with Incremental Loading

X1.4 As shown in Figure 3, as the load is held constant, the anchor in this graph displays more displacement at the higher load steps.

X1.5 Figure 3 also shows that at the lower load levels, the displacement will tend to stabilize. Additionally, at the higher load levels, the anchor will continue to displace. This is indicated by the slope of the time-displacement curve.

X2 DETERMINING STATIC LOAD STRENGTH

X2.1 Cook and Konz [14.1] classify three types of load-displacement response (strength-controlled, stiffness-controlled, and displacement-controlled) for adhesive anchor systems. These three types of responses and methods of their analysis are summarized below:

X2.2 *Strength-controlled.* This failure mode is defined by a very sharp peak in the load-displacement curve. There is a drastic reduction in the stiffness of the adhesive anchor beyond the peak. The static load strength is determined to be at the peak on the load-displacement graph. Figure 4 shows a typical curve of a strength-controlled failure.

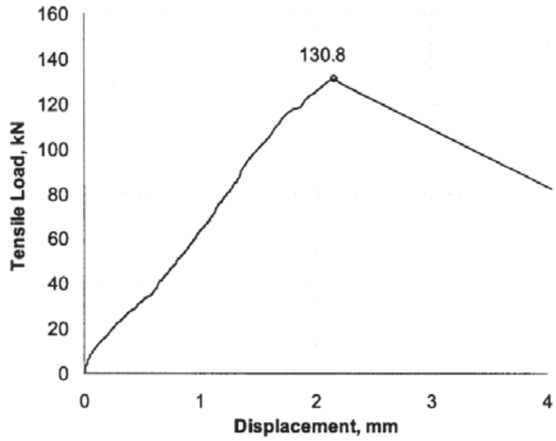


Figure 4: Typical Strength-controlled Failure

(Source: Cook and Konz [14.1])

X2.3 *Stiffness-controlled.* This failure mode is defined by a large initial stiffness and a drastic change in stiffness, which does not decrease but rather continues to increase at a lower slope. Due to the lack of "peak" in the curve, the static load strength is determined by finding the point at a tangent stiffness of 30 kip/in (5 kN/mm). The tangent stiffness (slope) at a given data point can be approximated by calculating the slope between a point five data points after and five data points before. Figure 5 shows a typical curve of a stiffness-controlled failure.

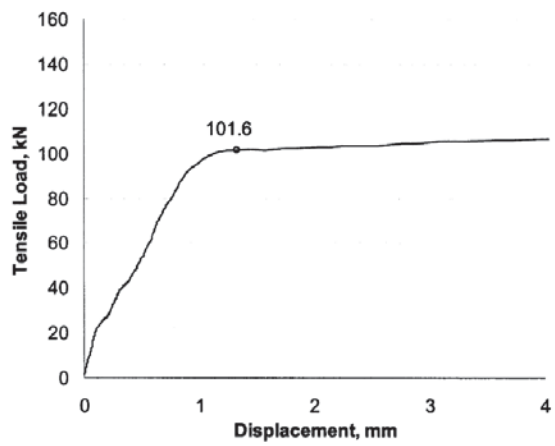


Figure 5: Typical Stiffness-controlled Failure

(Source: Cook and Konz [14.1])

X2.4 *Displacement-controlled.* This failure mode has a load-displacement curve with a relatively constant stiffness above the stiffness-controlled threshold of 30 kips/in. The maximum load occurs at very high, and impractical, displacements. In this case, the static load strength is set at a point with a displacement of 0.1 in (2.5mm). Figure 6 shows a typical curve of a displacement-controlled failure.

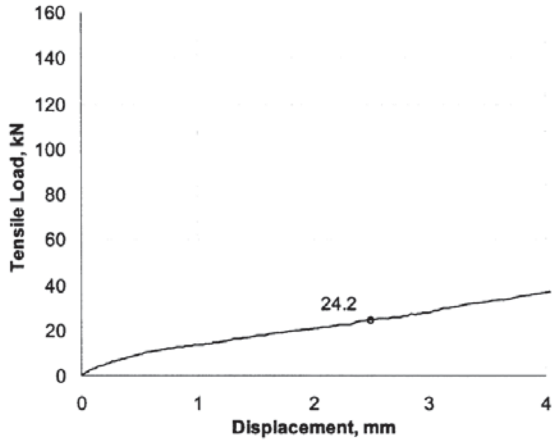


Figure 6: Typical Displacement-controlled Failure

(Source: Cook and Konz [14.1])

X3	**DETERMINING ONSET OF TERTIARY CREEP**

X3.1 As discussed in the appendix of ASTM D2990, the displacement versus time curve will display three regions. Region 1 is the primary creep region and is characterized by an initial rapid decrease in the creep rate. Region 2 is the secondary creep region and is characterized by a relatively steady slope. Region 3 is the tertiary creep region and is characterized by a rapid increase in creep ending in rupture. Figure 7 shows these three regions for a hypothetical sample.

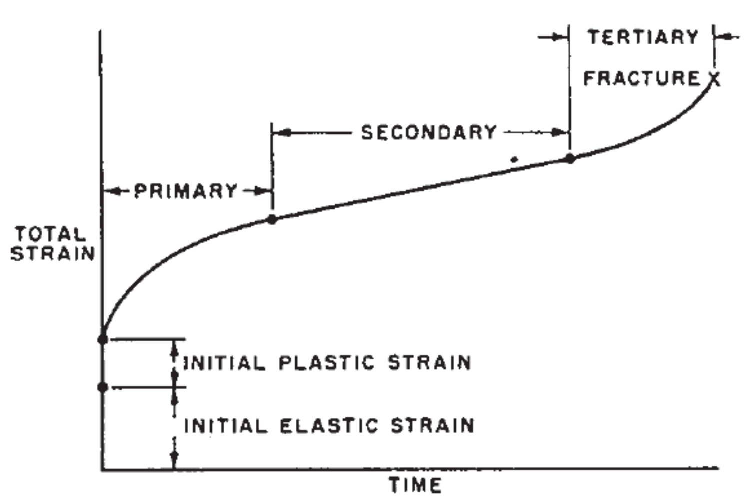


Figure 7: Regions on the Creep Curve

(Source: ASTM D 2990-01)

X3.2 The onset of tertiary creep is found by analyzing the change in the slope of the creep curve:

X3.2.1 This method calculates the slope at a given point as the slope between itself and the prior data point.

X3.2.2 The change in slopes between the given point and the following data point is plotted and examined over the region just prior to rupture. It is suggested that this examination be conducted on a normal graph (not log time). The rupture point is easily identified on the displacement vs. time graph. A suggested range for examining the change in slope is from 80% to 100% of time to rupture. Due to minor fluctuations in the displacement readings, the slope might change from positive to negative several times over this range.

X3.2.3 Tertiary creep is defined as the time the change in slope becomes positive for the last time prior to rupture. Figure 8 shows a sample graph for determining the initiation of tertiary creep.

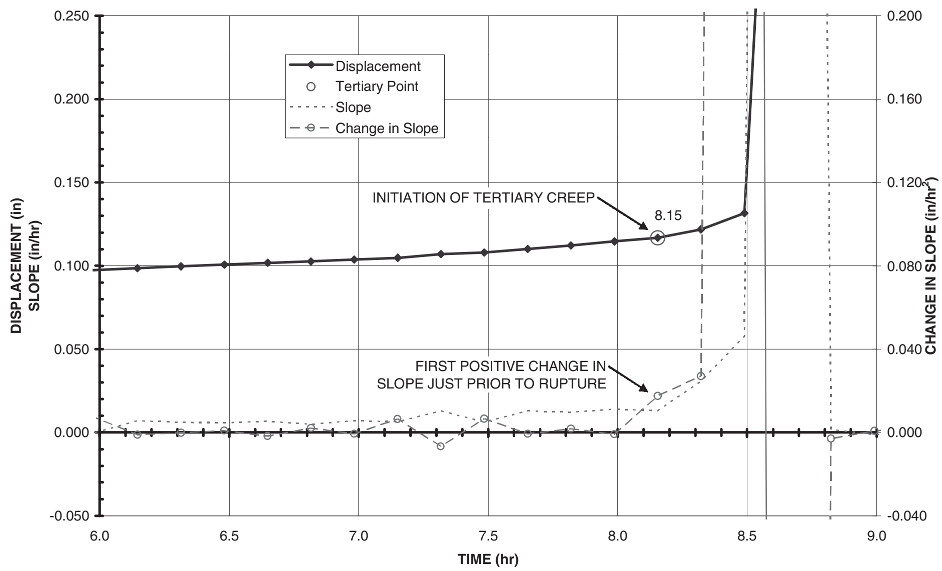


Figure 8: Sample Graph Showing Initiation of Tertiary Creep

X3.3 Failure for the sustained load is defined as the initiation of tertiary creep. The failure point for each sustained load test is plotted on the Stress versus Time-to-Failure graph. Figure 9 shows a sample Stress versus Time-to-Failure graph.

X3.4 A Stress versus Time-to-Failure graph can give an indication of the reduction in capacity of an adhesive anchor due to sustained load at a given design lifetime.

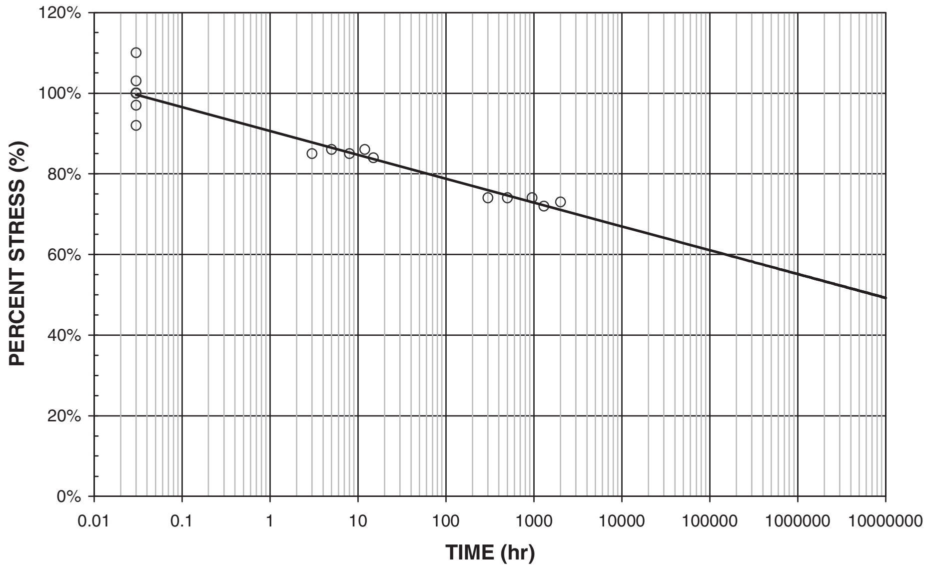


Figure 9: Sample Stress vs. Time-to-Failure Graph

X4 SUGGESTED SUSTAINED LOAD (CREEP) TEST APPARATUS FOR SMOOTH LOAD TRANSFER

X4.1 It is important that the load to the anchor be applied in a smooth manner. This can be accomplished with a hydraulic ram.

X4.2 Figure 10 shows a modified test apparatus for the sustained load (creep) test incorporating a hydraulic ram that reacts against a plate connected to the existing test apparatus by means of four threaded couplers. The ram and the upper plate can be removed following tightening of the loading rod nut.

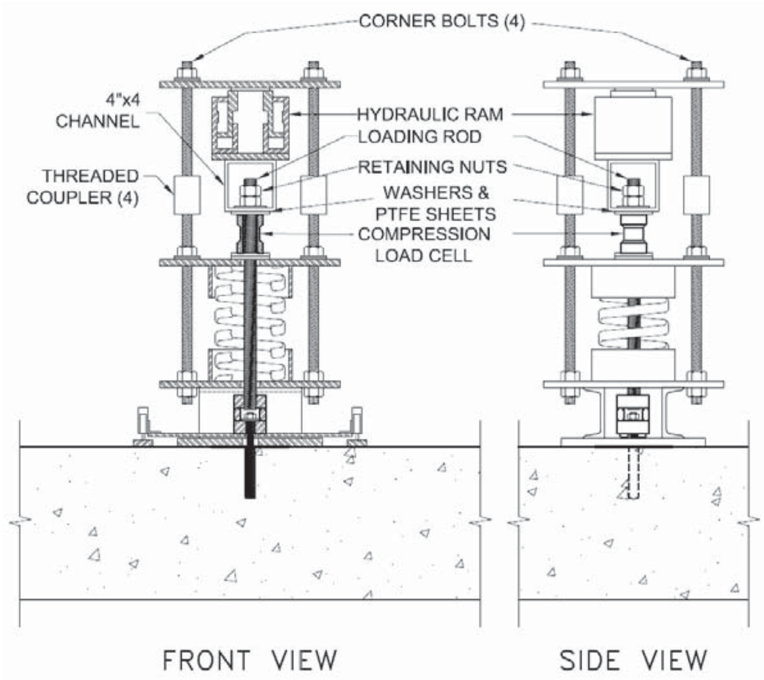


Figure 10: Suggested Load Transfer for Sustained Load (Creep) Tests

(Source: modified from Cook et al. [14.2])

APPENDIX B

Test Graphs

This appendix presents the graphs of the tests conducted during this research project. For interpretation of these graphs, refer to the body of this report.

The following abbreviations are used to describe the graphs contained within this appendix:

Abbreviation	Description
ST	Static Load Test
-75F	Test temperature of 75ºF for the static load test
-110F	Test temperature of 110ºF for the static load test
CT	Sustained Load (Creep) Test
-75%	Load level of 75% for the sustained load (creep) test
-62%	Load level of 62% for the sustained load (creep) test
LvD	Load versus Displacement graph
LvT	Load versus Time graph
TvD	Time versus Displacement graph
DvT	Displacement versus Time graph
PLvT	Percent Load versus Time graph
A-01	Anchor adhesive (A) and number (01)

110ºF Static Load Test Load vs. Displacement & Load vs. Time Graphs for Adhesive A

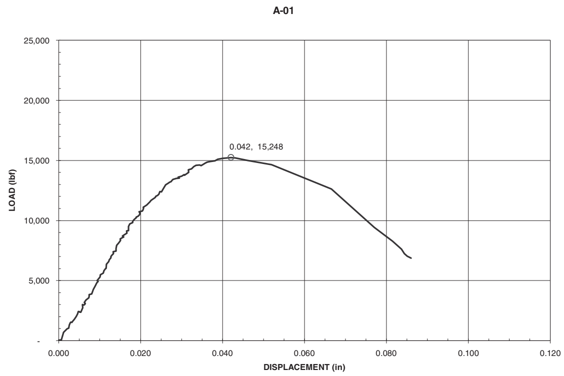


Figure 1: ST-110F LvD A-01

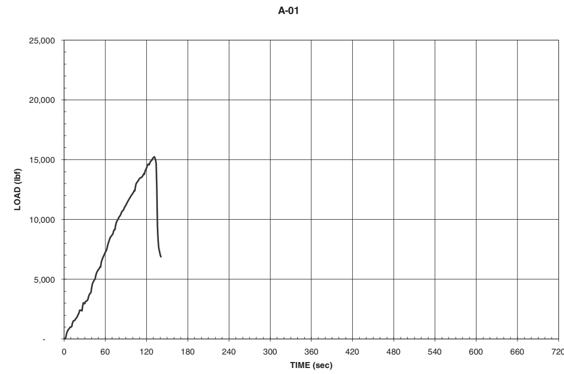


Figure 2: ST-110F LvT A-01

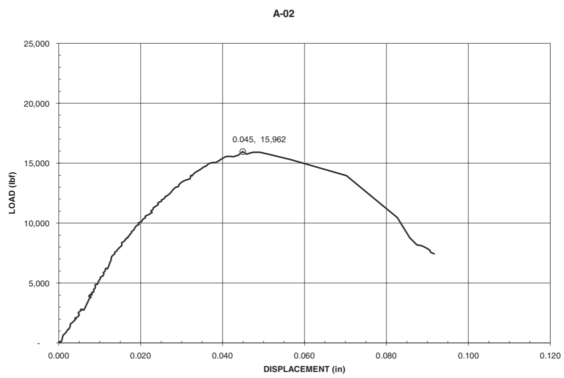


Figure 3: ST-110F LvD A-02

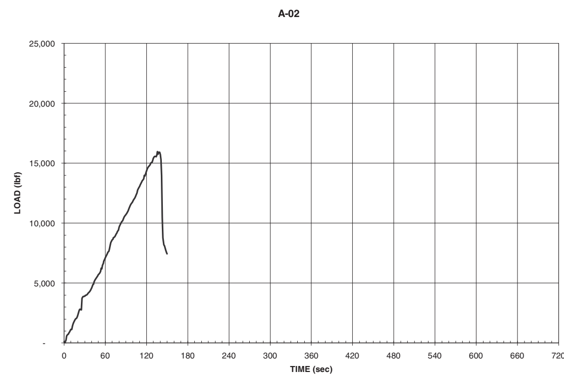


Figure 4: ST-110F LvT A-02

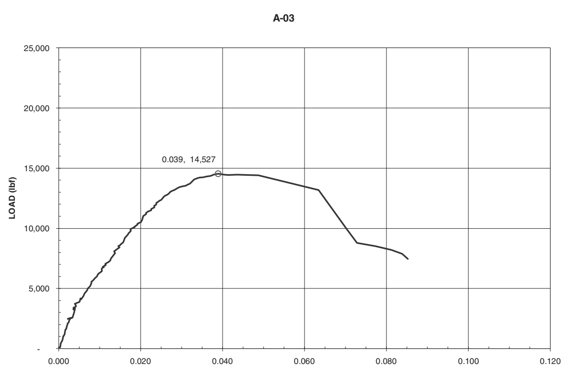


Figure 5: ST-110F LvD A-03

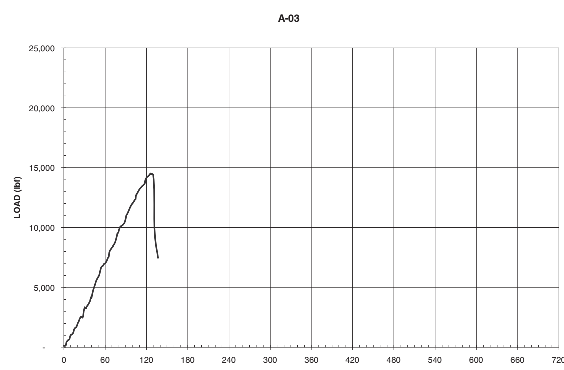


Figure 6: ST-110F LvT A-03

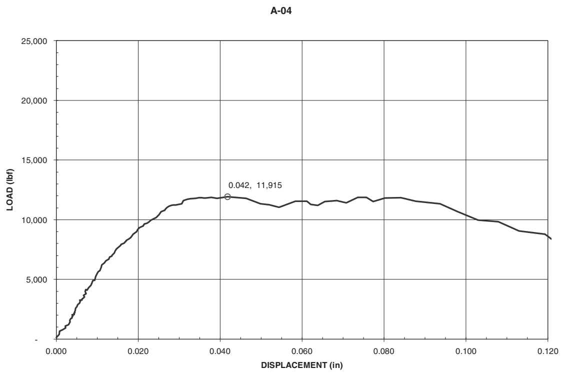


Figure 7: ST-110F LvD A-04

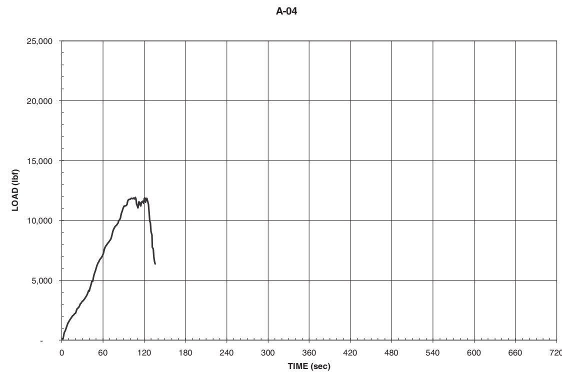


Figure 8: ST-110F LvT A-04

110ºF Static Load Test (incremental loading)

Load vs. Displacement, Time vs. Displacement, & Load vs. Time Graphs for Adhesive A

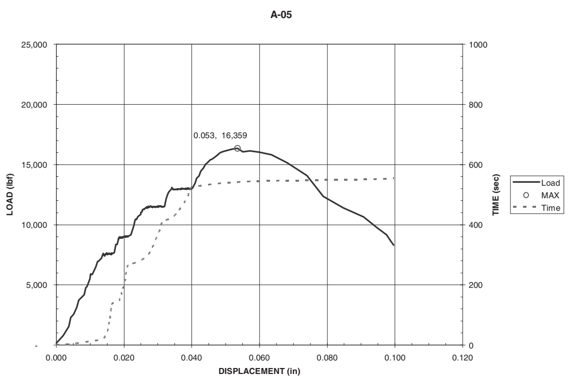


Figure 9: ST-110F LvD & TvD A-05

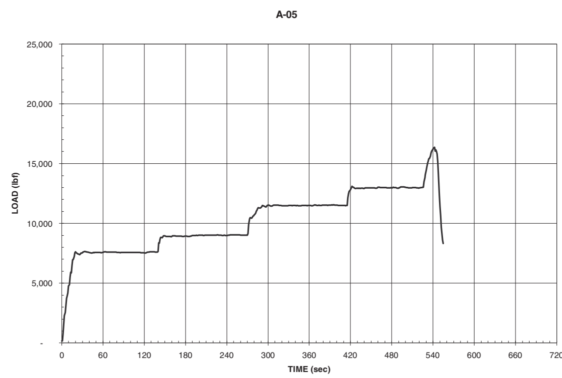


Figure 10: ST-110F LvT A-05

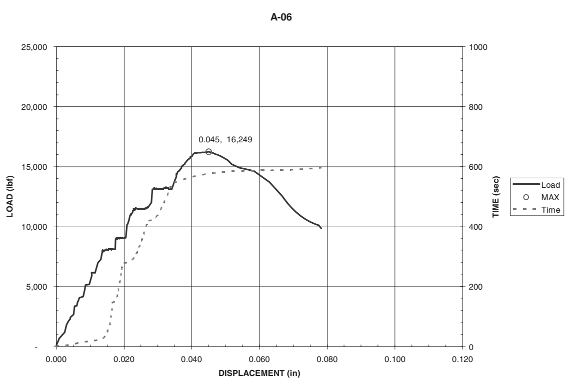


Figure 11: ST-110F LvD & TvD A-06

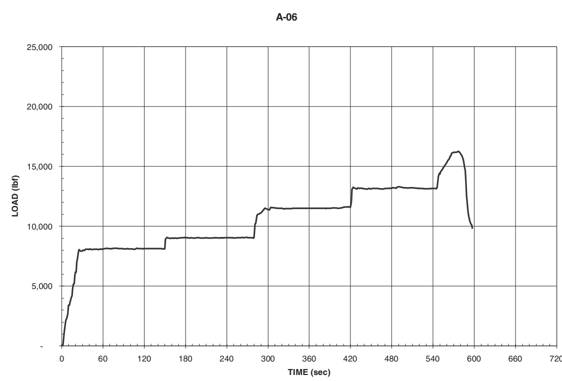


Figure 12: ST-110F LvT A-06

110ºF Static Load Test Load vs. Displacement & Load vs. Time Graphs for Adhesive B

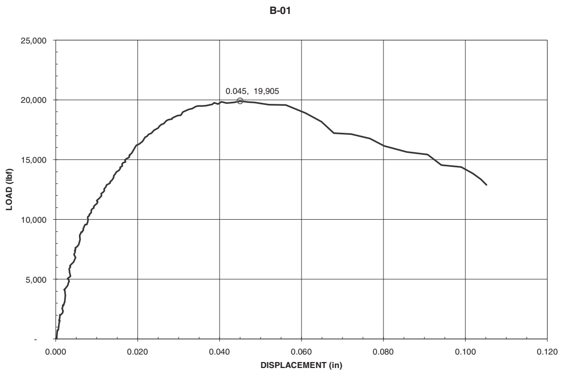


Figure 13: ST-110F LvD B-01

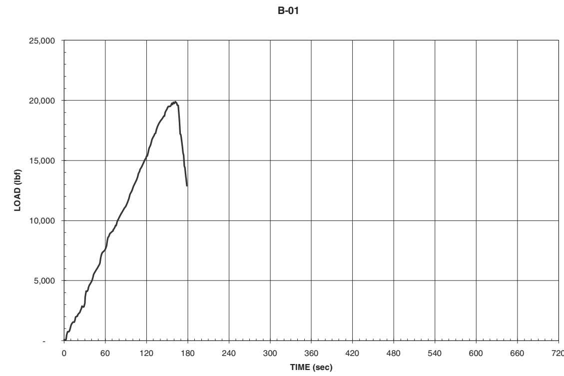


Figure 14: ST-110F LvT B-01

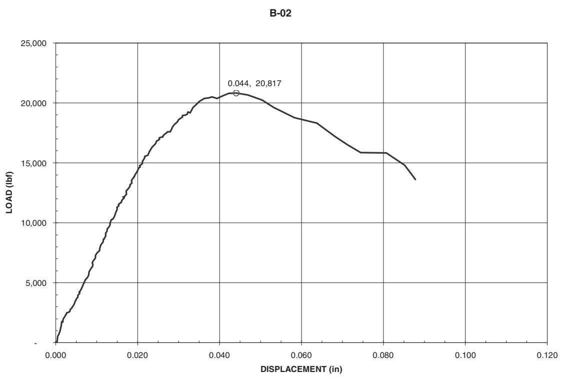


Figure 15: ST-110F LvD B-02

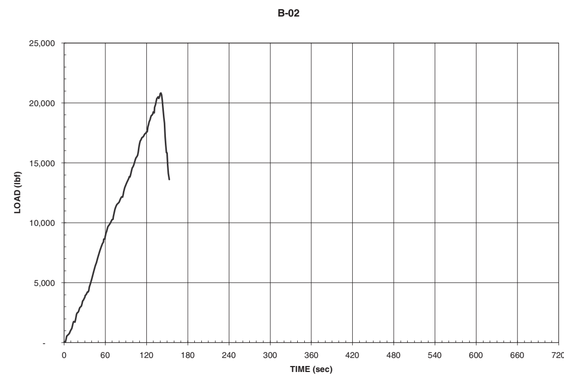


Figure 16: ST-110F LvT B-02

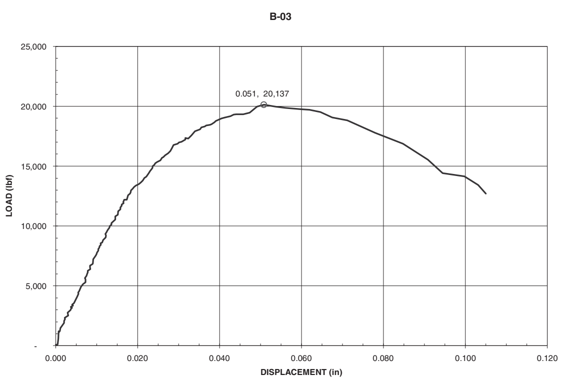


Figure 17: ST-110F LvD B-03

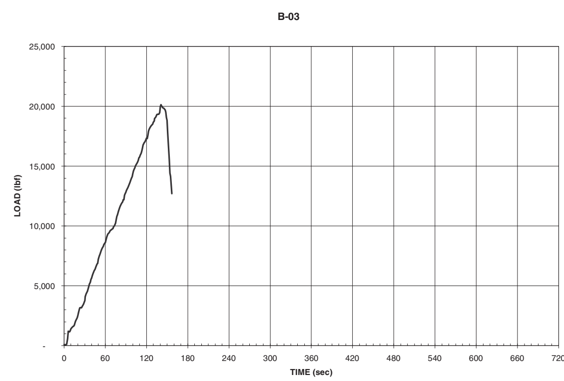


Figure 18: ST-110F LvT B-03

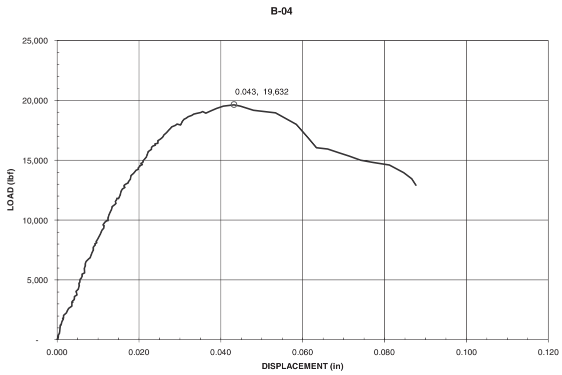


Figure 19: ST-110F LvD B-04

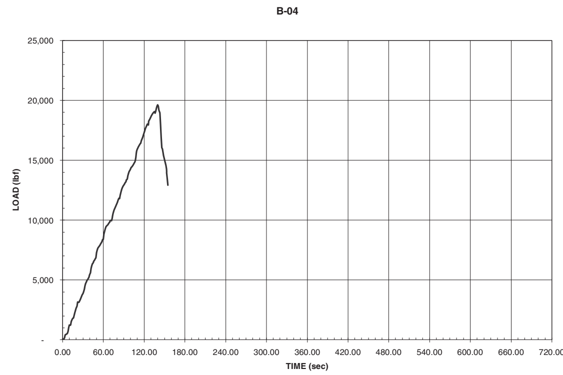


Figure 20: ST-110F LvT B-04

110ºF Static Load Test (incremental loading)

Load vs. Displacement, Time vs. Displacement, & Load vs. Time Graphs for Adhesive B

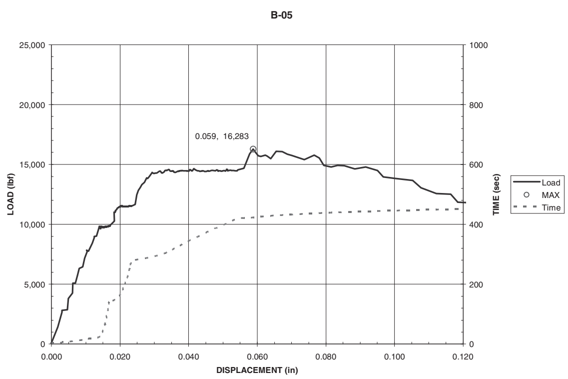


Figure 21: ST-110F LvD & TvD B-05

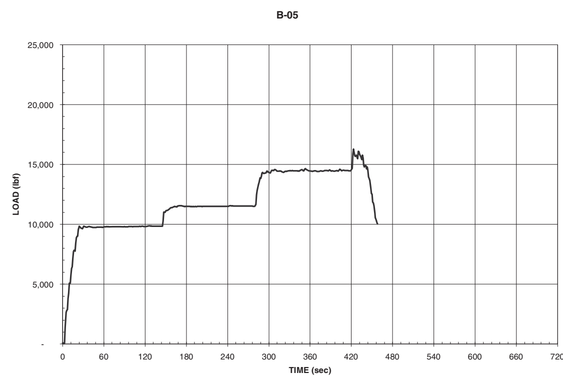


Figure 22: ST-110F LvT B-05

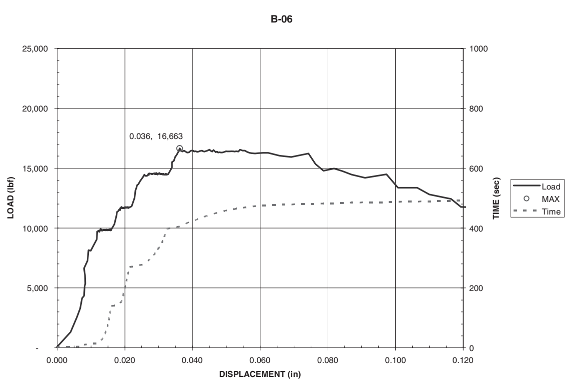


Figure 23: ST-110F LvD & TvD B-06

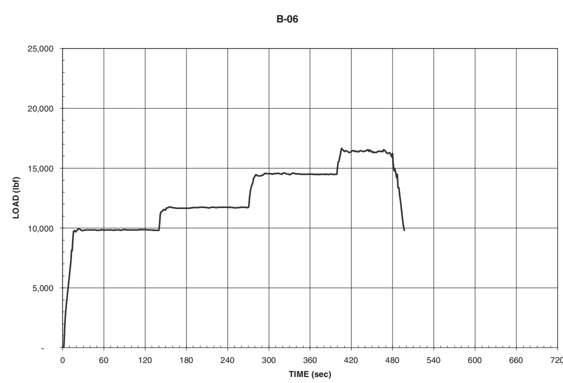


Figure 24: ST-110F LvT B-06

110ºF Static Load Test Load vs. Displacement & Load vs. Time Graphs for Adhesive C

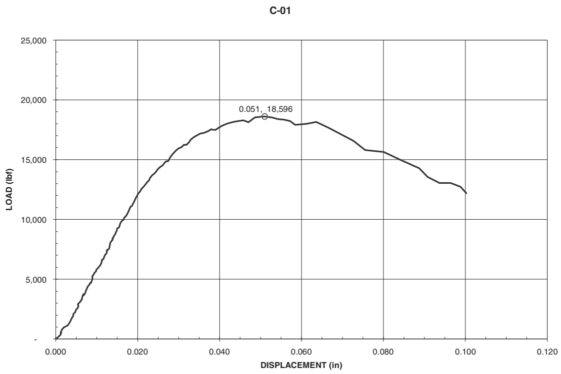


Figure 25: ST-110F LvD C-01

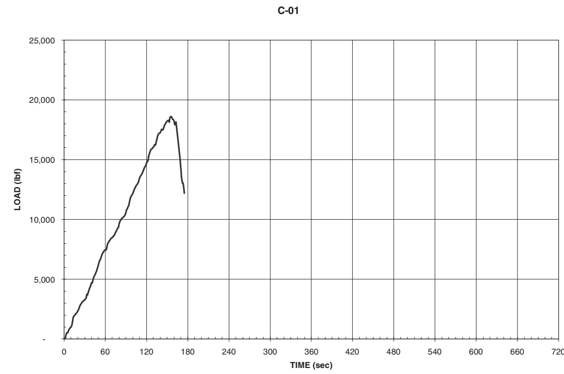


Figure 26: ST-110F LvT C-01

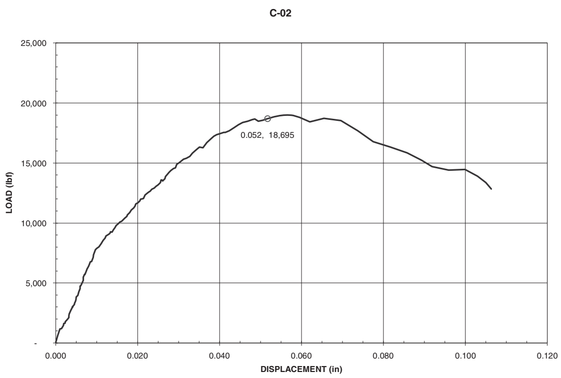


Figure 27: ST-110F LvD C-02

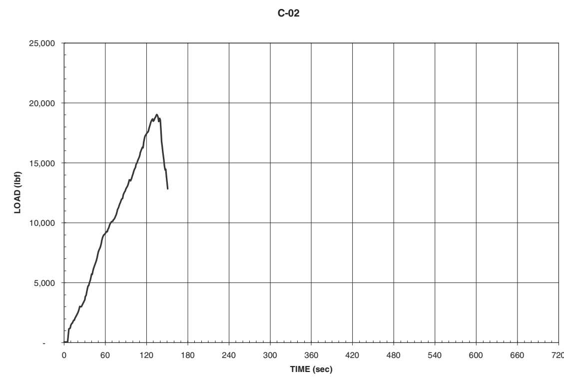


Figure 28: ST-110F LvT C-02

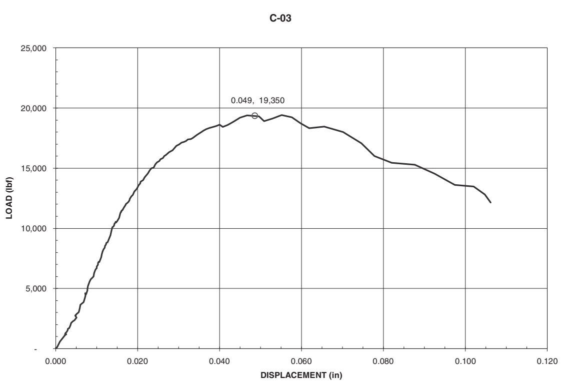


Figure 29: ST-110F LvD C-03

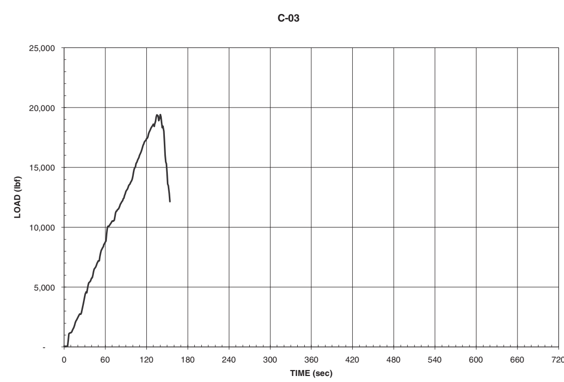


Figure 30: ST-110F LvT C-03

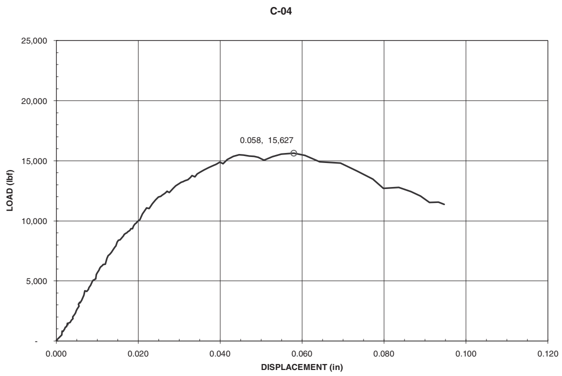


Figure 31: ST-110F LvD C-04

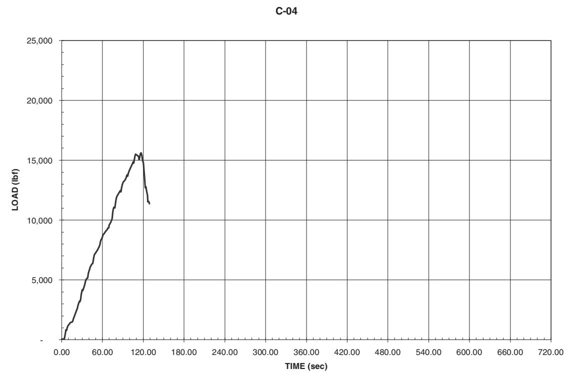


Figure 32: ST-110F LvT C-04

110ºF Static Load Test (incremental loading)

Load vs. Displacement, Time vs. Displacement, & Load vs. Time Graphs for Adhesive C

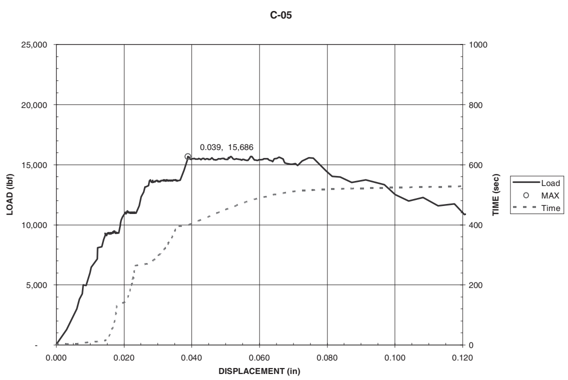


Figure 33: ST-110F LvD & TvD C-05

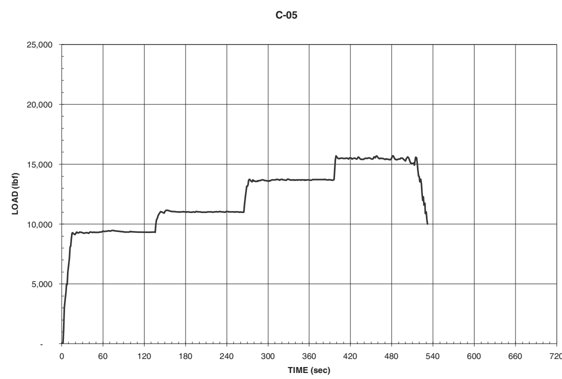


Figure 34: ST-110F LvT C-05

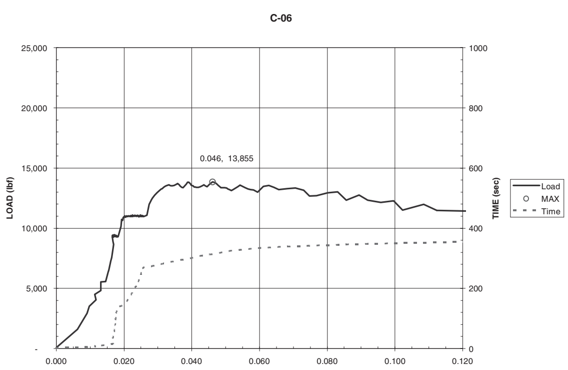


Figure 35: ST-110F LvD & TvD C-06

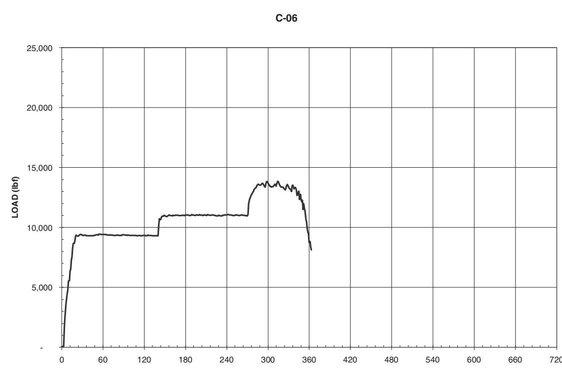


Figure 36: ST-110F LvT C-06

75ºF Static Load Test Load vs. Displacement & Load vs. Time Graphs for Adhesive A

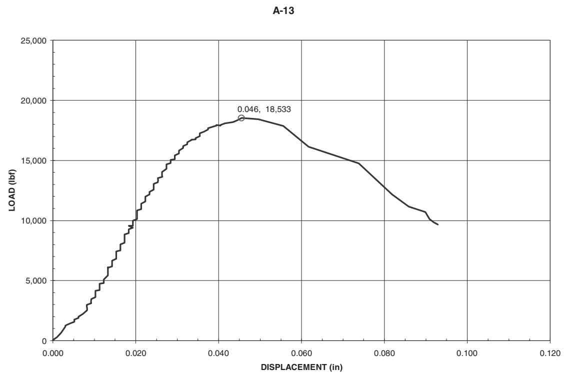


Figure 37: ST-75F LvD A-13

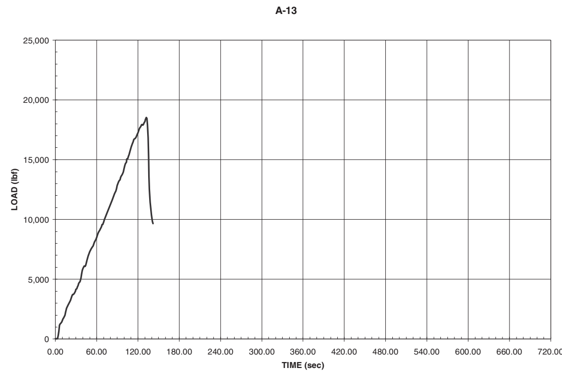


Figure 38: ST-110F LvT A-13

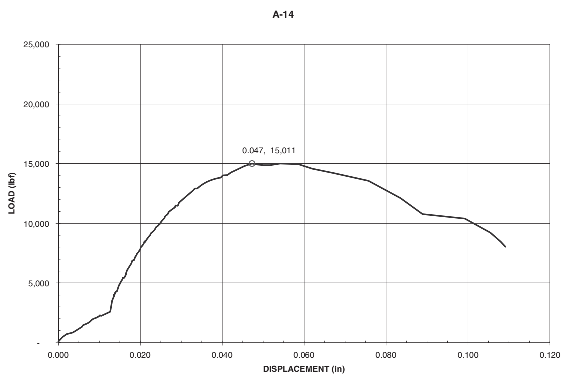


Figure 39: ST-75F LvD A-14

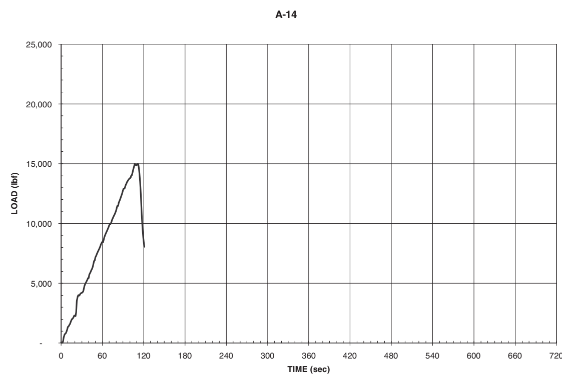


Figure 40: ST-110F LvT A-14

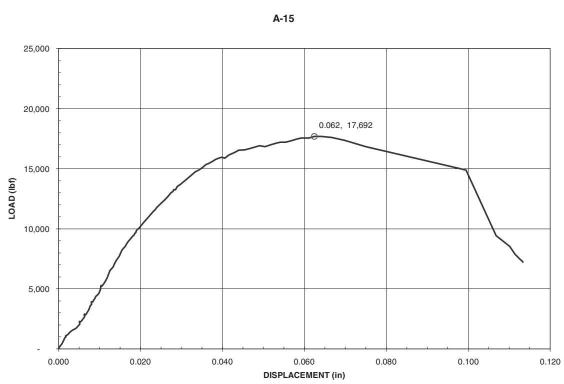


Figure 41: ST-75F LvD A-15

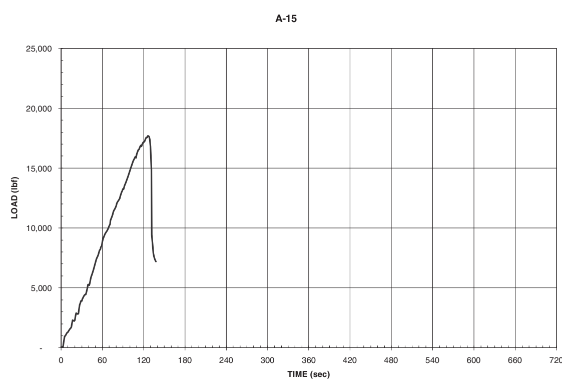


Figure 42: ST-110F LvT A-15

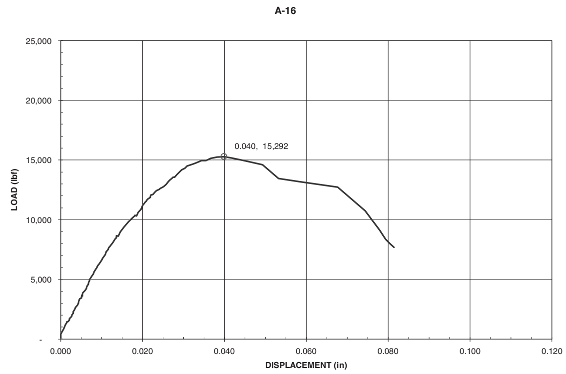


Figure 43: ST-75F LvD A-16

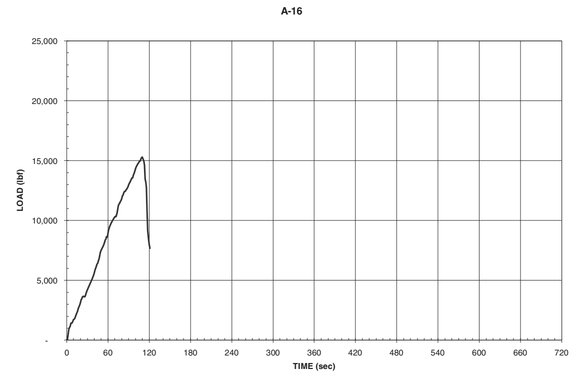


Figure 44: ST-110F LvT A-16

75ºF Static Load Test (incremental loading)

Load vs. Displacement, Time vs. Displacement, & Load vs. Time Graphs for Adhesive A

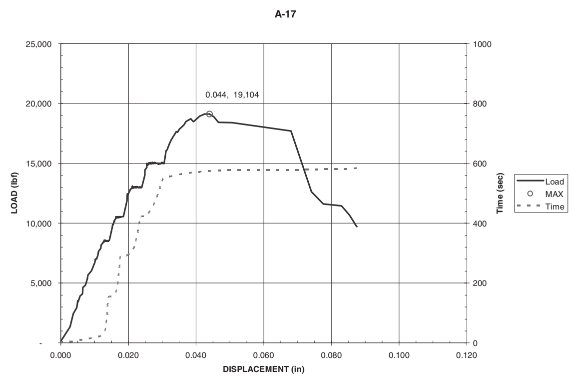


Figure 45: ST-75F LvD & TvD A-17

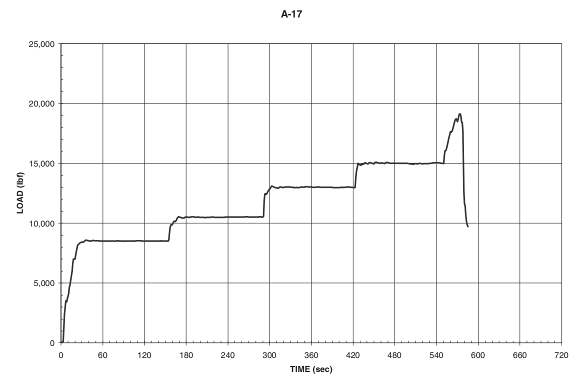


Figure 46: ST-110F LvT A-17

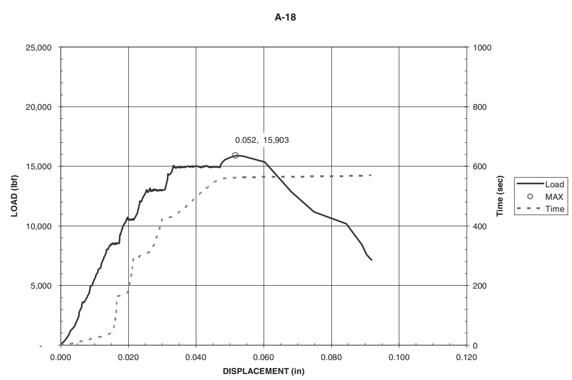


Figure 47: ST-75F LvD & TvD A-18

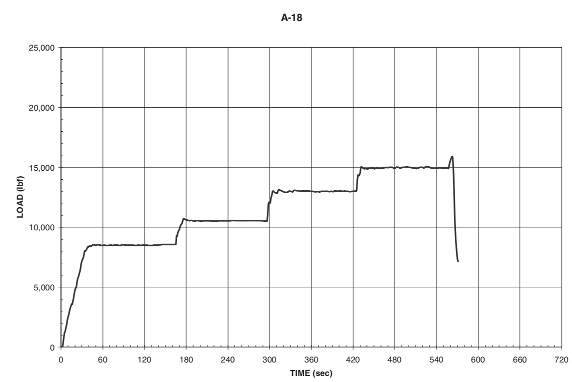


Figure 48: ST-110F LvT A-18

75ºF Static Load Test Load vs. Displacement & Load vs. Time Graphs for Adhesive B

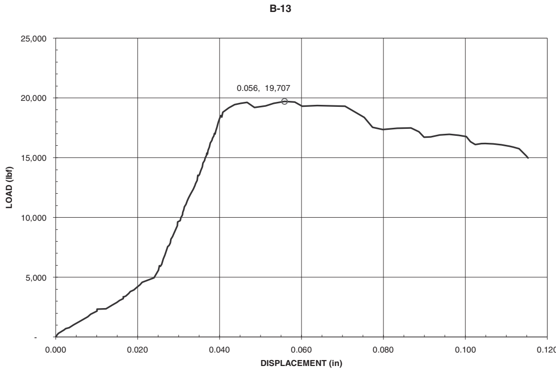


Figure 49: ST-75F LvD B-13

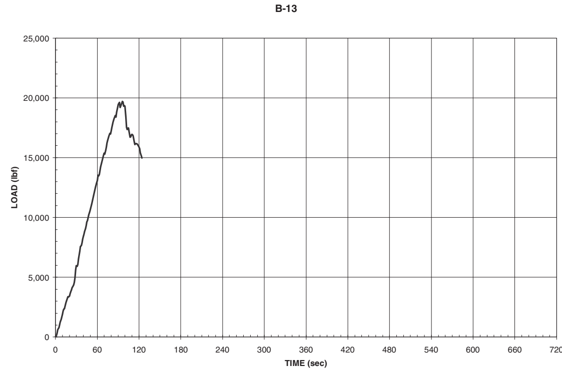


Figure 50: ST-110F LvT B-13

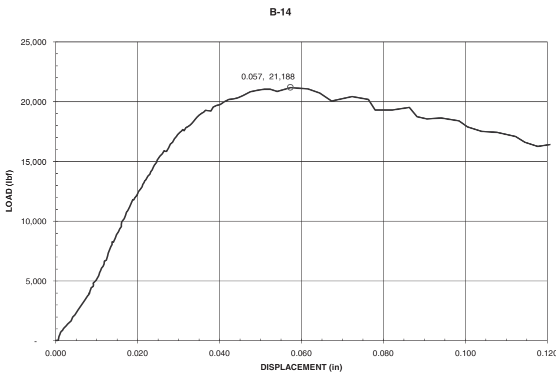


Figure 51: ST-75F LvD B-14

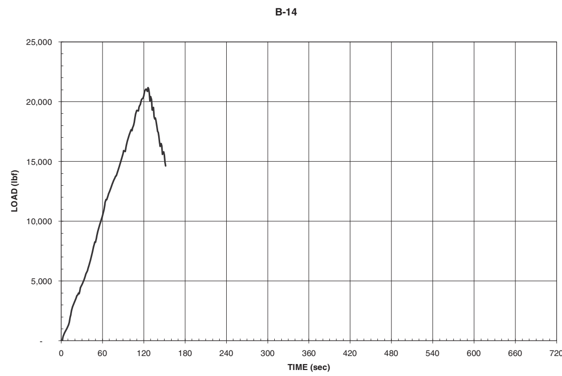


Figure 52: ST-110F LvT B-14

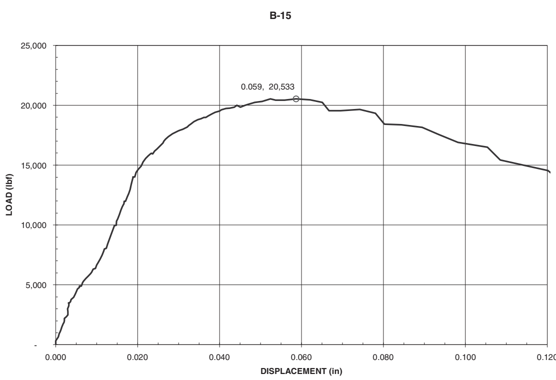


Figure 53: ST-75F LvD B-15

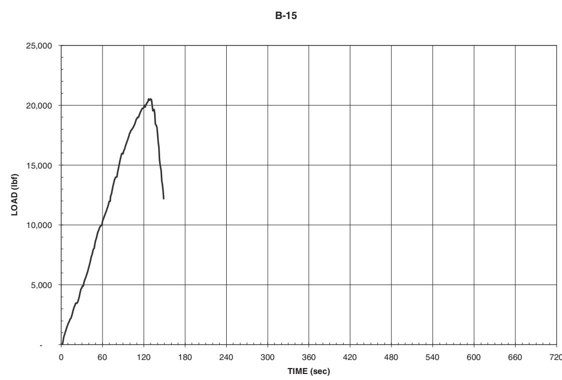


Figure 54: ST-110F LvT B-15

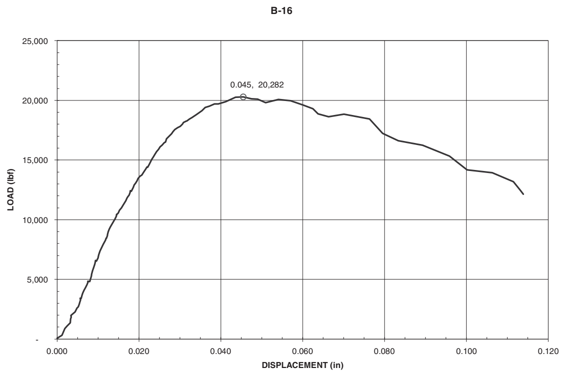


Figure 55: ST-75F LvD B-16

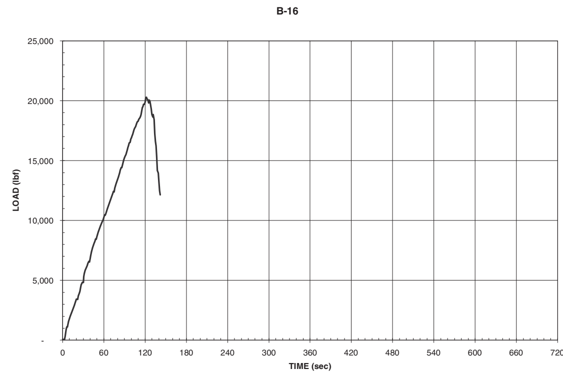


Figure 56: ST-110F LvT B-16

75ºF Static Load Test (incremental loading)

Load vs. Displacement, Time vs. Displacement, & Load vs. Time Graphs for Adhesive B

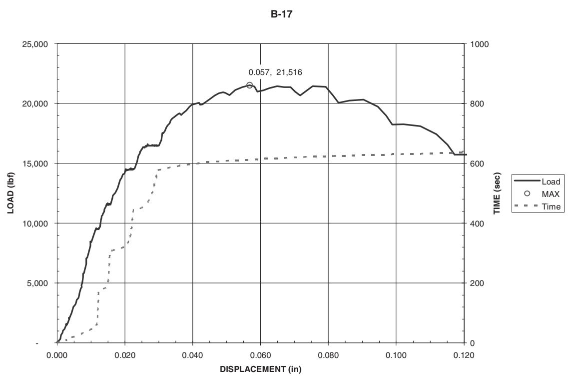


Figure 57: ST-75F LvD & TvD B-17

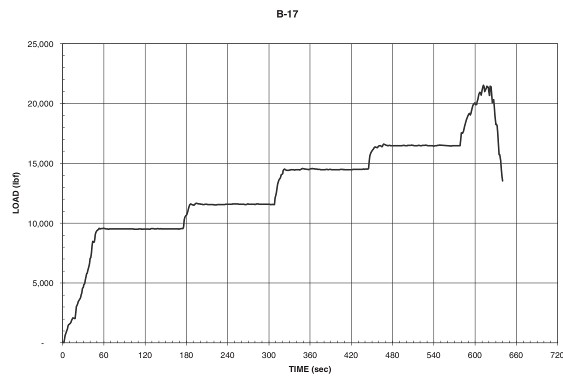


Figure 58: ST-110F LvT B-17

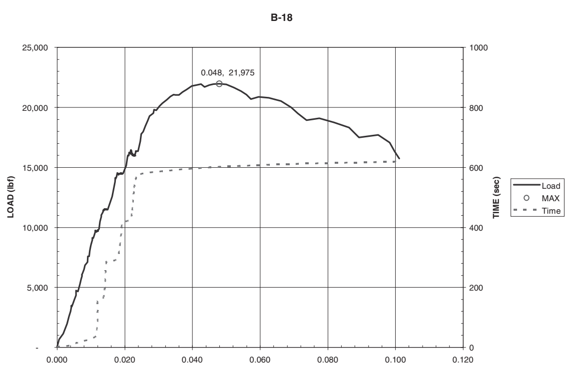


Figure 59: ST-75F LvD & TvD B-18

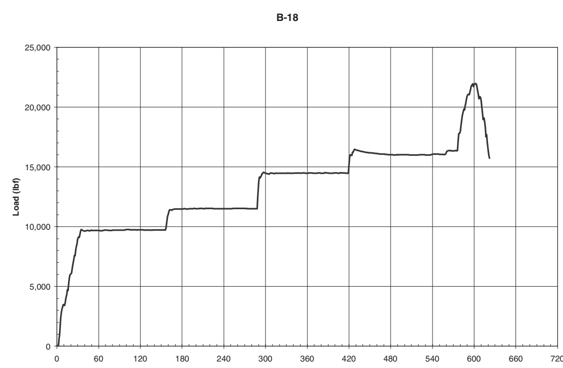


Figure 60: ST-110F LvT B-18

75ºF Static Load Test Load vs. Displacement & Load vs. Time Graphs for Adhesive C

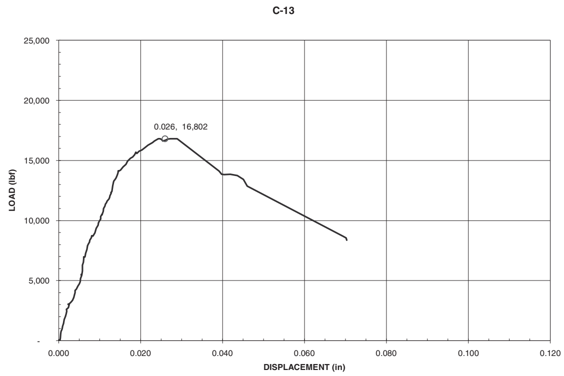


Figure 61: ST-75F LvD C-13

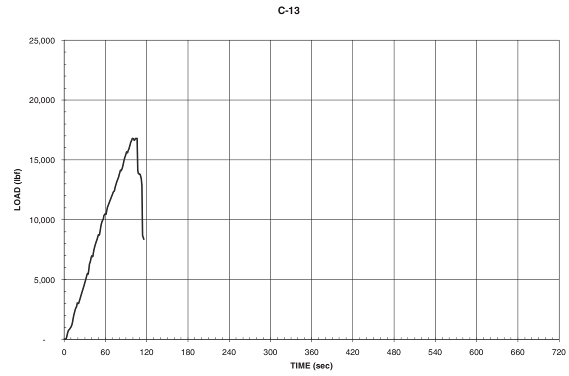


Figure 62: ST-110F LvT C-13

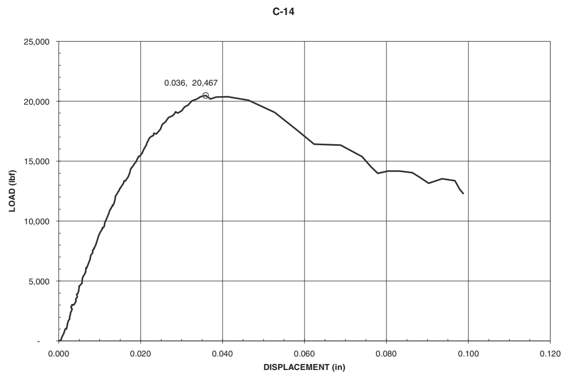


Figure 63: ST-75F LvD C-14

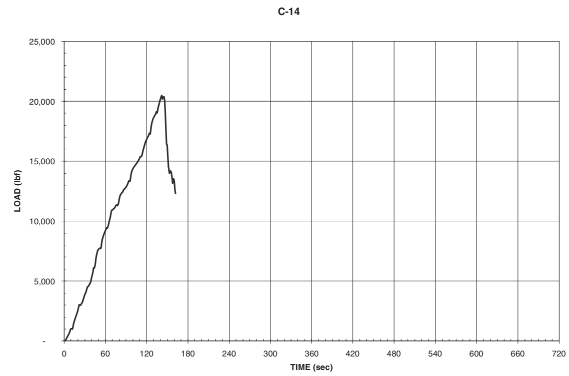


Figure 64: ST-110F LvT C-14

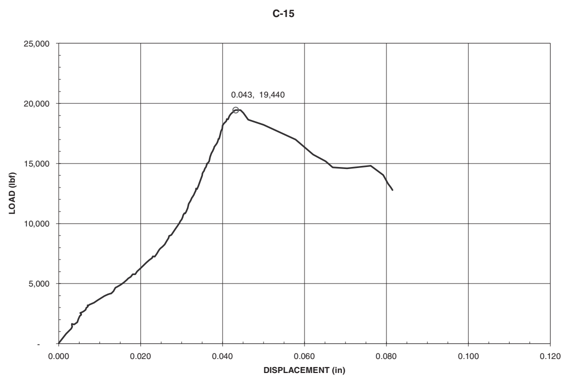


Figure 65: ST-75F LvD C-15

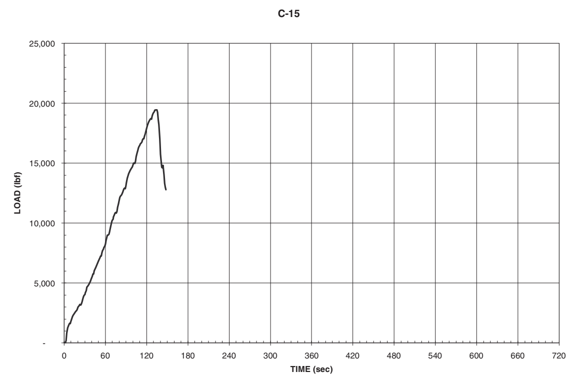


Figure 66: ST-110F LvT C-15

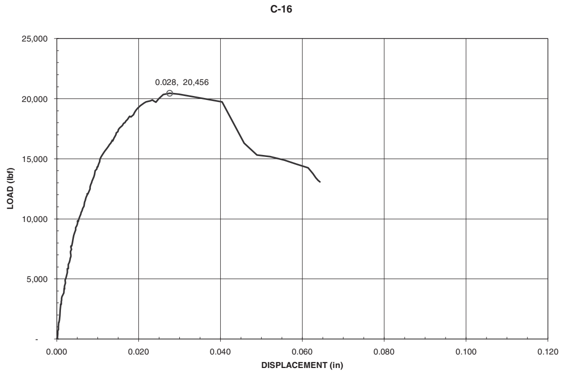


Figure 67: ST-75F LvD C-16

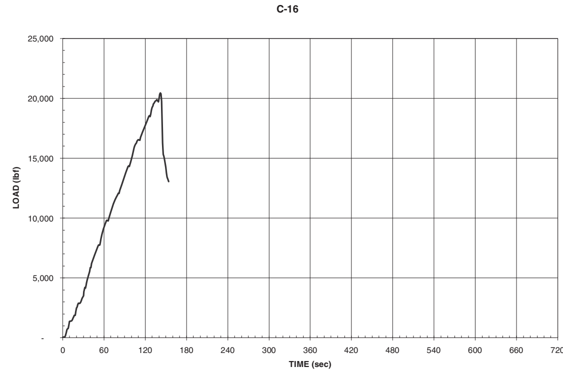


Figure 68: ST-110F LvT C-16

75ºF Static Load Test (incremental loading)

Load vs. Displacement, Time vs. Displacement, & Load vs. Time Graphs for Adhesive C

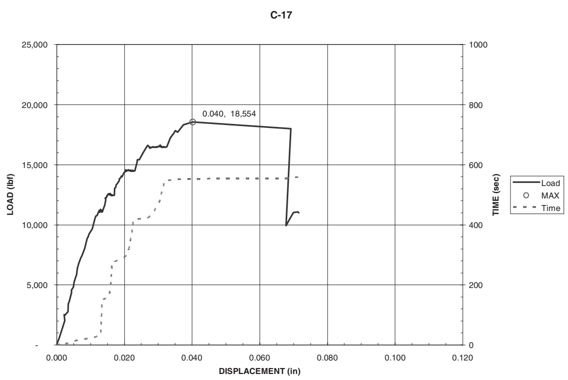


Figure 69: ST-75F LvD & TvD C-17

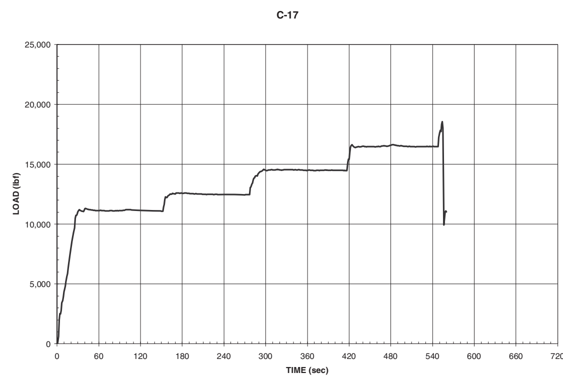


Figure 70: ST-110F LvT C-17

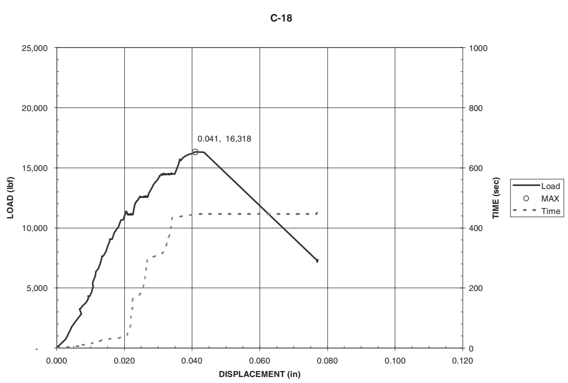


Figure 71: ST-75F LvD & TvD C-18

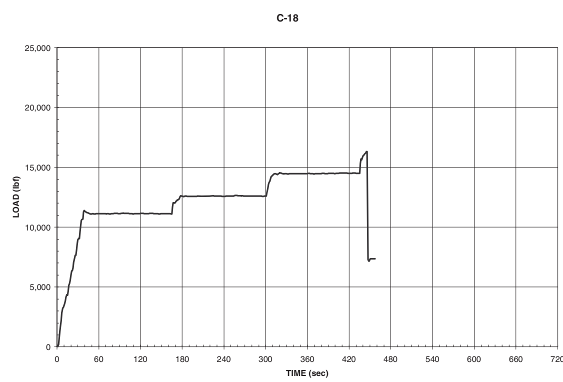


Figure 72: ST-110F LvT C-18

110ºF Static Load Test Combined Load vs. Displacement Graphs for Adhesive A

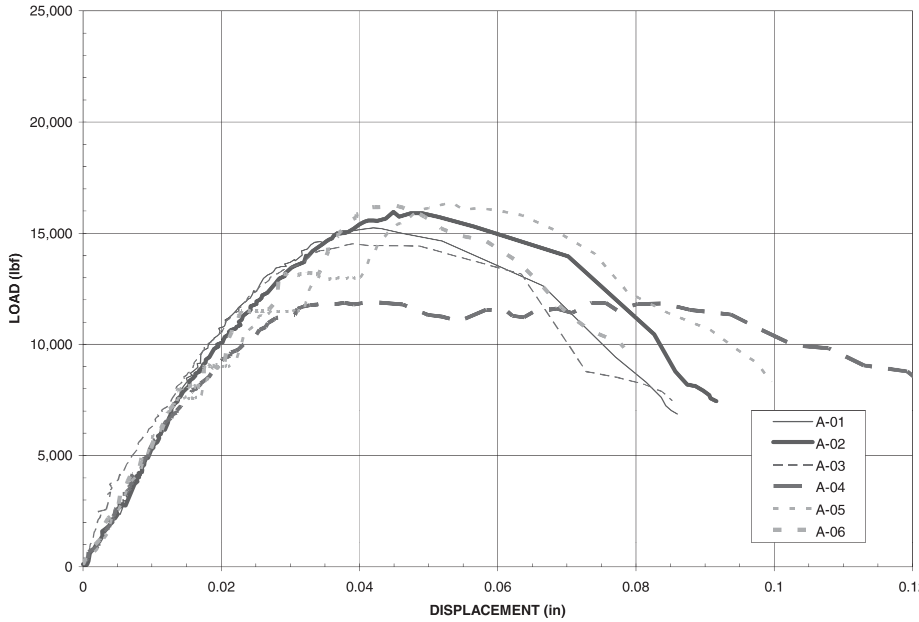


Figure 73: ST-110F LvD A-01 - A-06

75ºF Static Load Test Combined Load vs. Displacement Graphs for Adhesive A

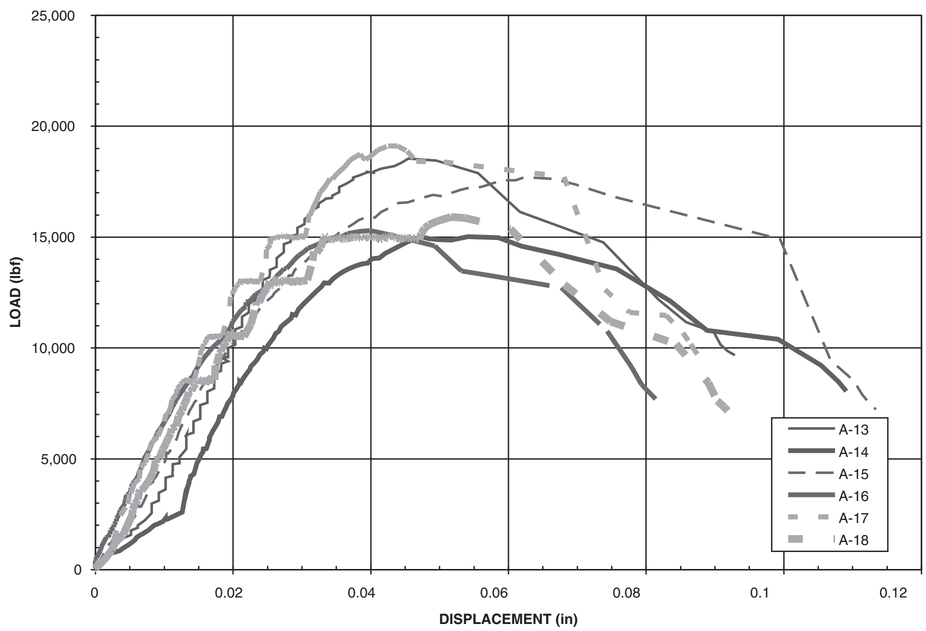


Figure 74: ST-75F LvD A-13 - A-18

110ºF Static Load Test Combined Load vs. Displacement Graphs for Adhesive B

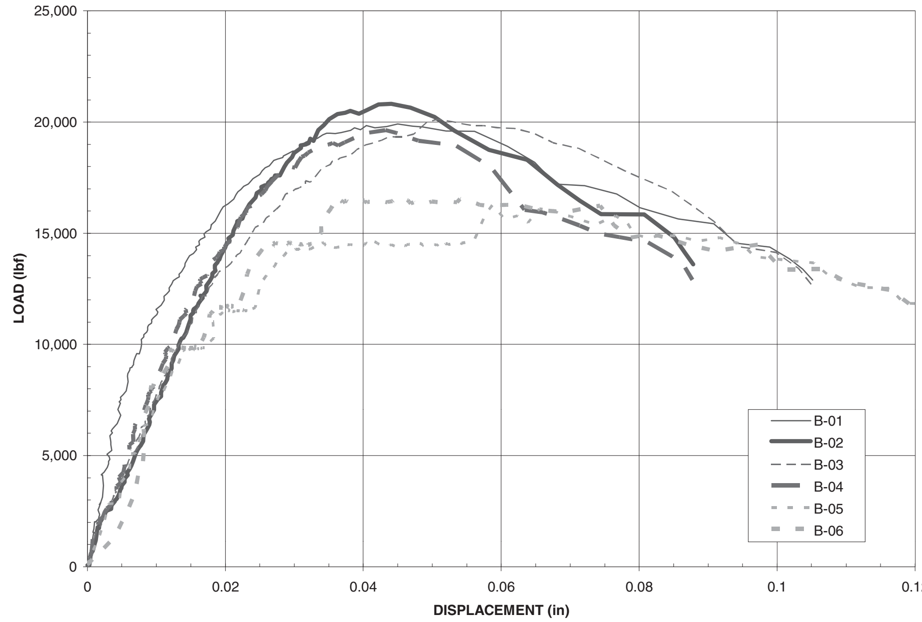


Figure 75: ST-110F LvD B-01 - B-06

75ºF Static Load Test Combined Load vs. Displacement Graphs for Adhesive B

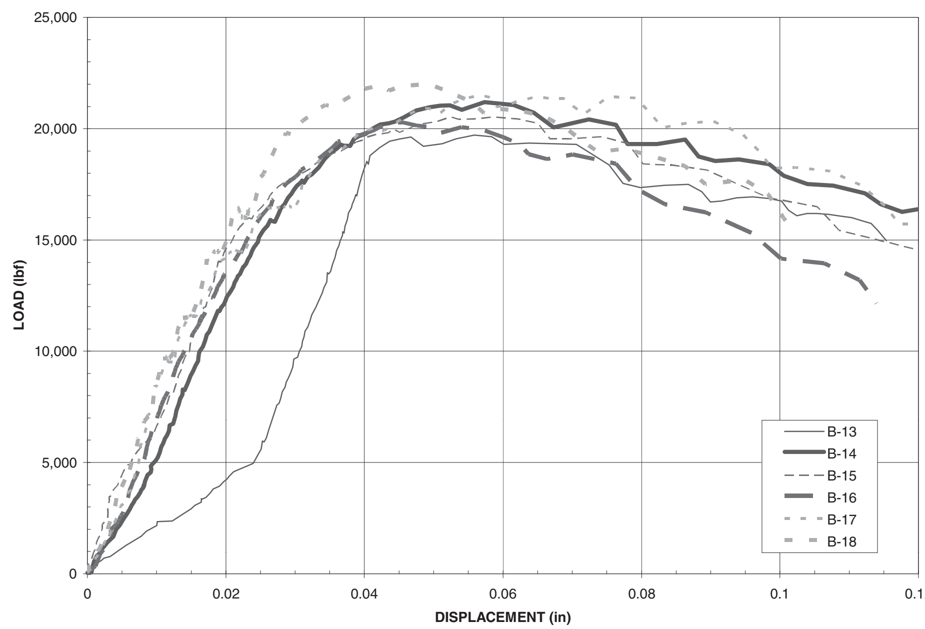


Figure 76: ST-75F LvD B-13 - B-18

110°F Static Load Test Combined Load vs. Displacement Graphs for Adhesive C

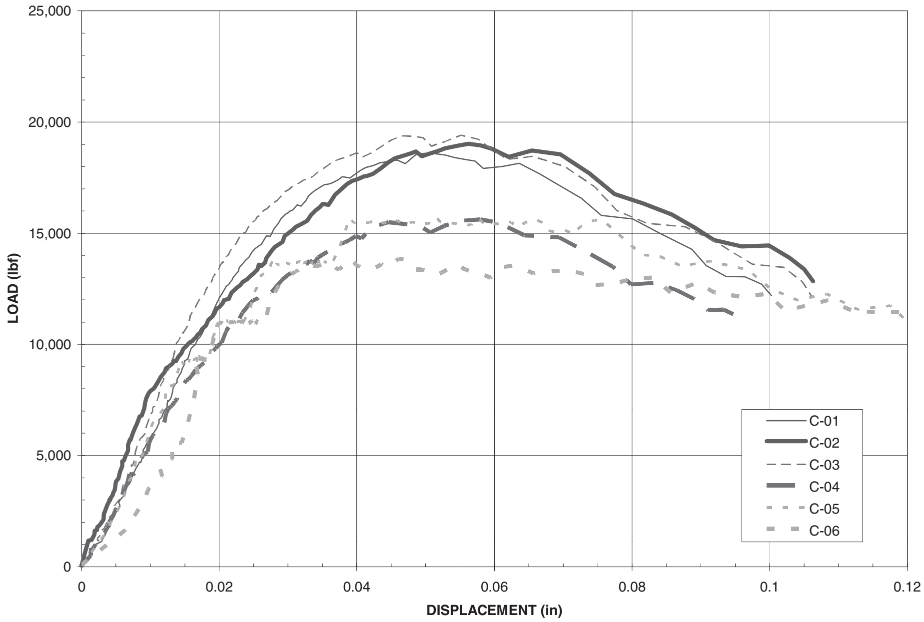


Figure 77: ST-110F LvD C-01 - C-06

75°F Static Load Test Combined Load vs. Displacement Graphs for Adhesive C

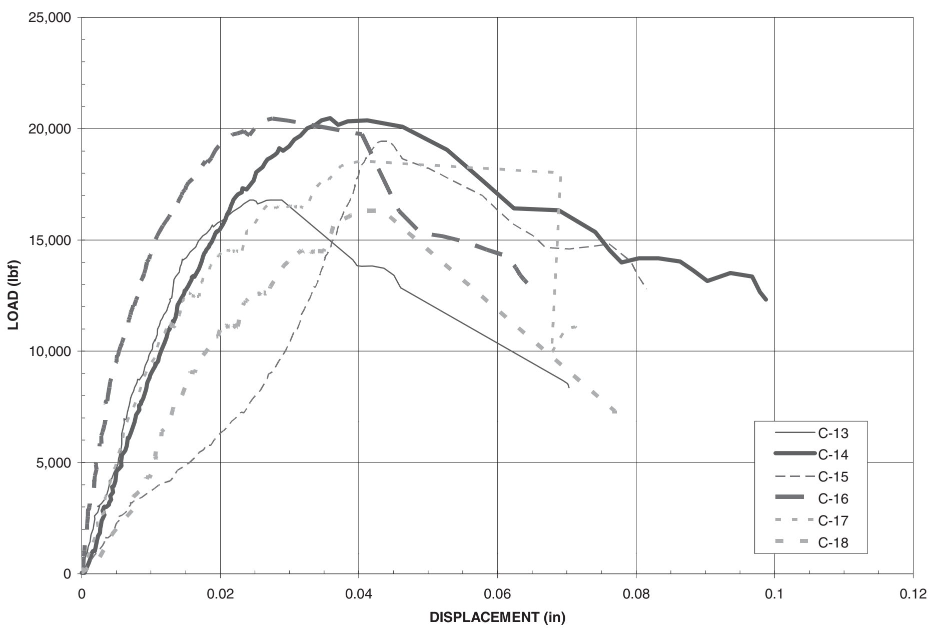


Figure 78: ST-75F LvD C-13 - C-18

75% Sustained Load (Creep) Test

Displacement vs. Time & Load vs. Displacement Graphs for Adhesive A

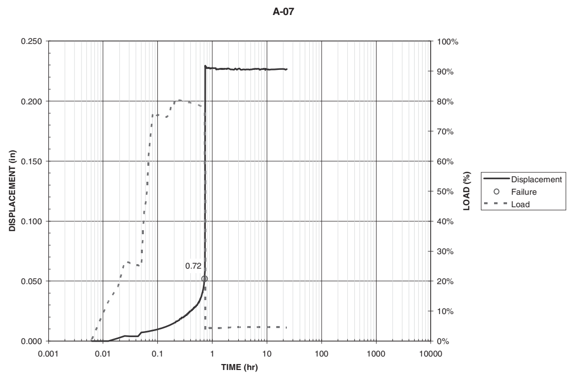


Figure 79: CT-75% DvT & PLvT A-07

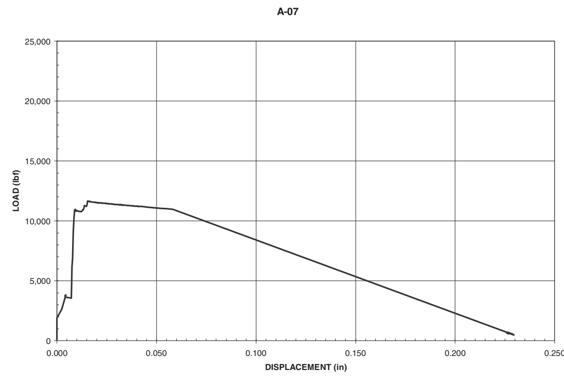


Figure 80: CT-75% LvD A-07

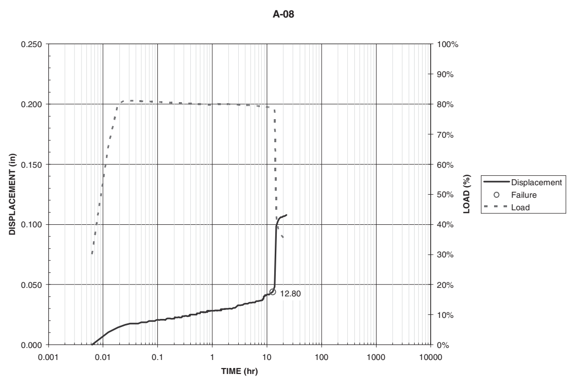


Figure 81: CT-75% DvT & PLvT A-08

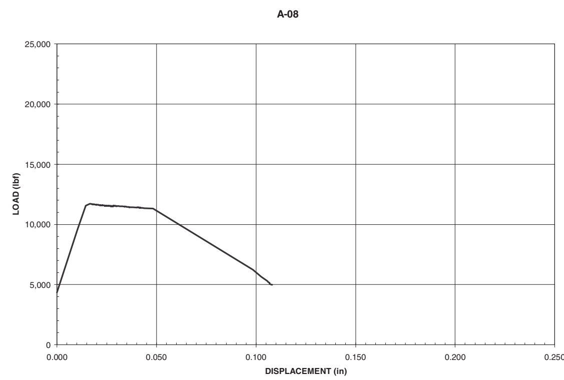


Figure 82: CT-75% LvD A-08

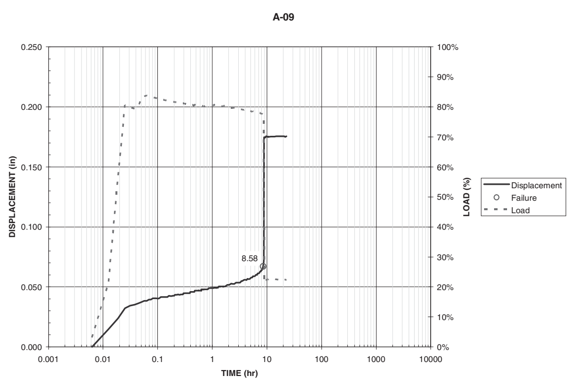


Figure 83: CT-75% DvT & PLvT A-09

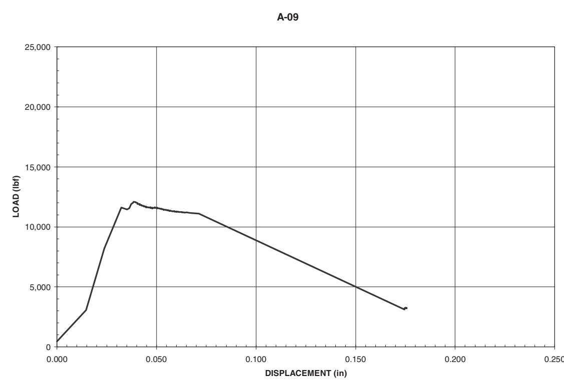


Figure 84: CT-75% LvD A-09

62% Sustained Load (Creep) Test

Displacement vs. Time & Load vs. Displacement Graphs for Adhesive A

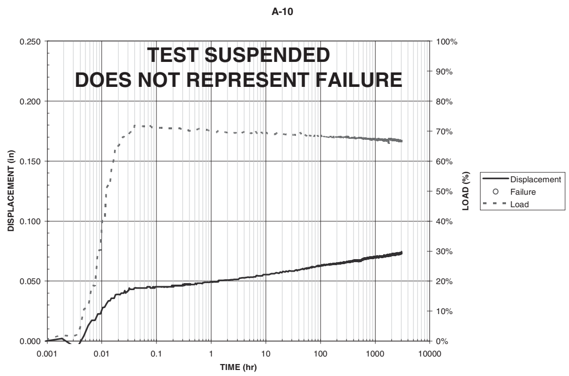


Figure 85: CT-62% DvT & PLvT A-10

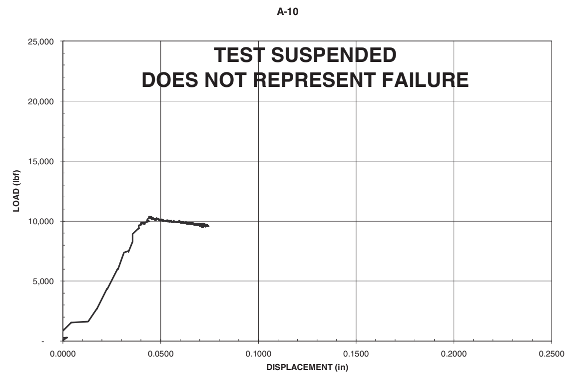


Figure 86: CT-62% LvD A-10

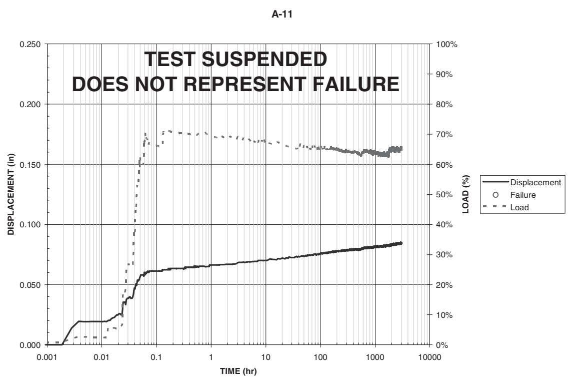


Figure 87: CT-62% DvT & PLvT A-11

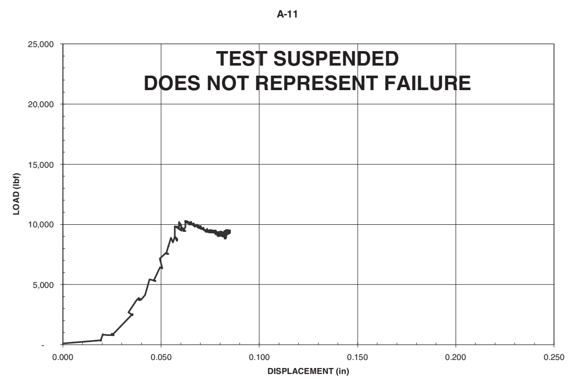


Figure 88: CT-62% LvD A-11

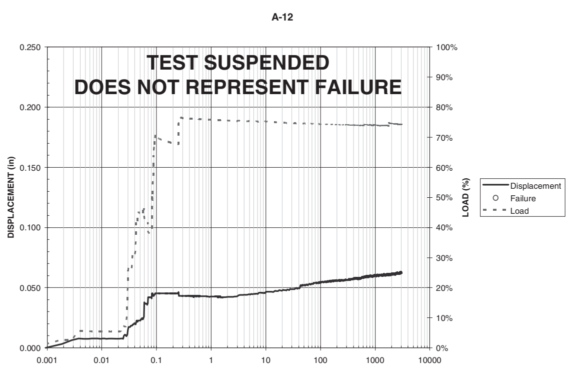


Figure 89: CT-62% DvT & PLvT A-12

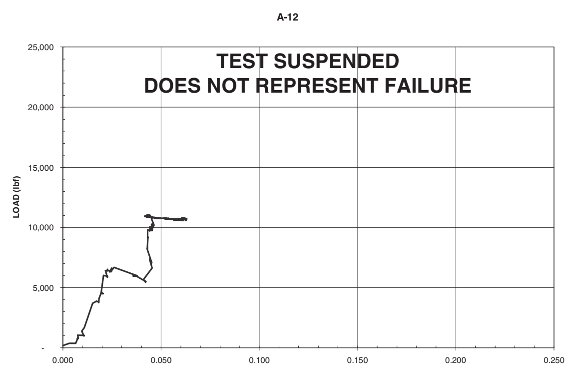


Figure 90: CT-62% LvD A-12

75% Sustained Load (Creep) Test

Displacement vs. Time & Load vs. Displacement Graphs for Adhesive B

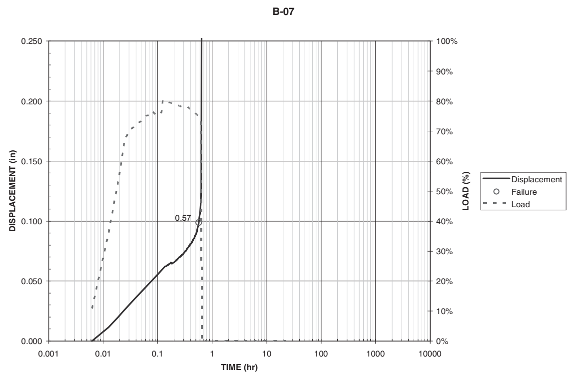


Figure 91: CT-75% DvT & PLvT B-07

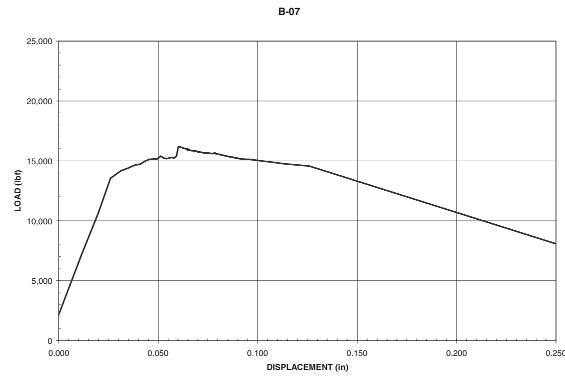


Figure 92: CT-75% LvD B-07

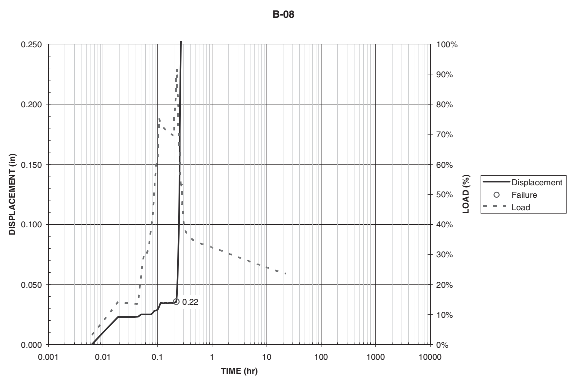


Figure 93: CT-75% DvT & PLvT B-08

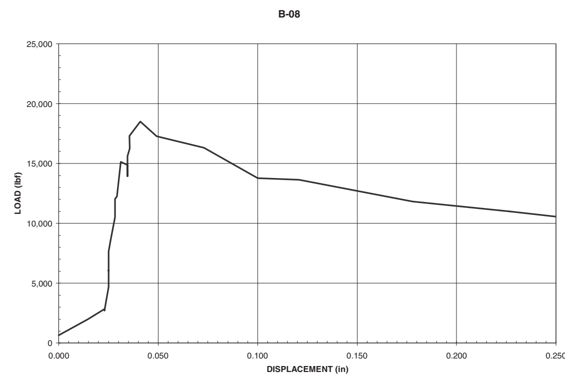


Figure 94: CT-75% LvD B-08

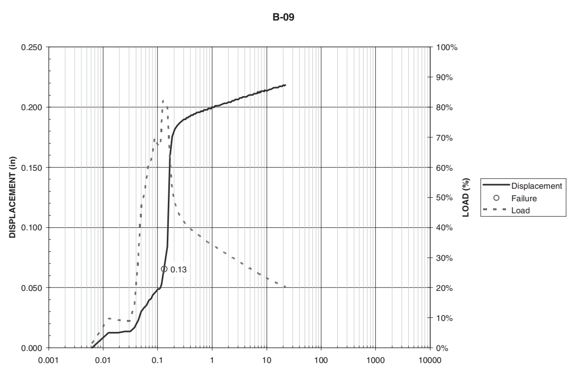


Figure 95: CT-75% DvT & PLvT B-09

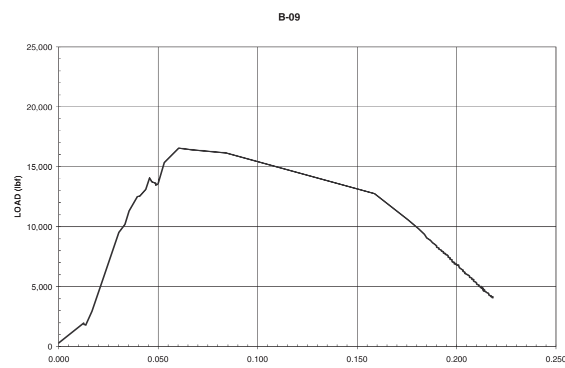


Figure 96: CT-75% LvD B-09

62% Sustained Load (Creep) Test

Displacement vs. Time & Load vs. Displacement Graphs for Adhesive B

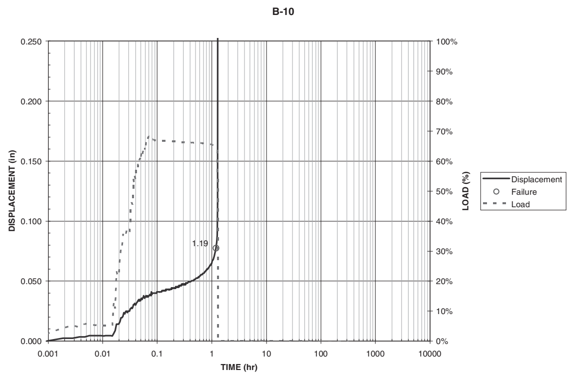


Figure 97: CT-62% DvT & PLvT B-10

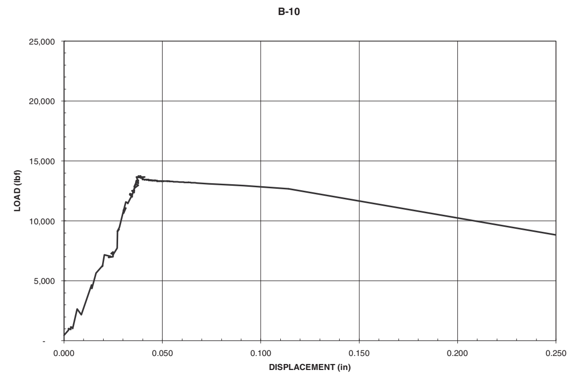


Figure 98: CT-62% LvD B-10

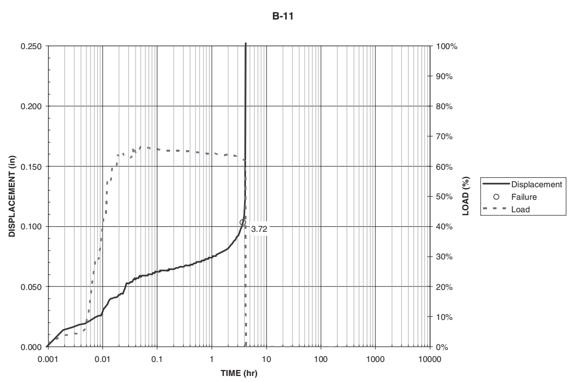


Figure 99: CT-62% DvT & PLvT B-11

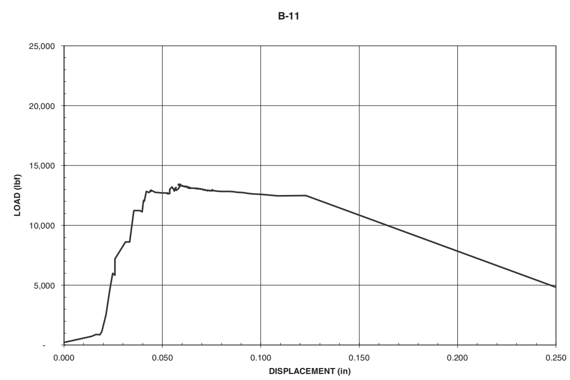


Figure 100: CT-62% LvD B-11

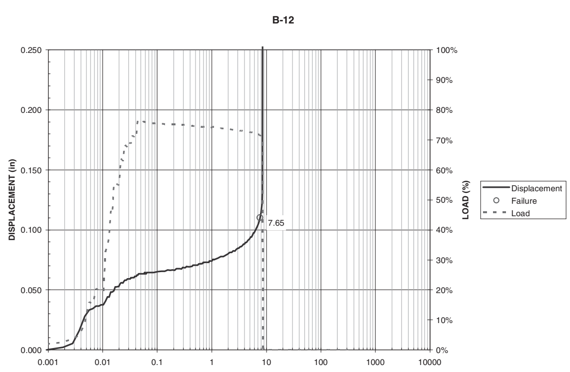


Figure 101: CT-62% DvT & PLvT B-12

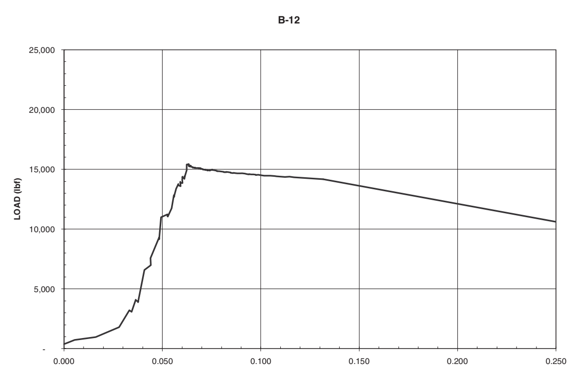


Figure 102: CT-62% LvD B-12

Slab & Chamber Conditioning Logs (Temperature and Humidity)

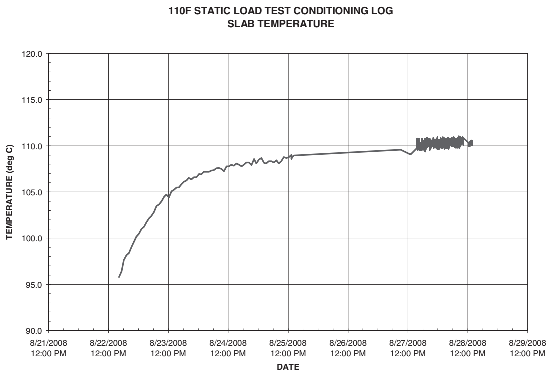


Figure 103: ST-110F Conditioning Log - Temperature

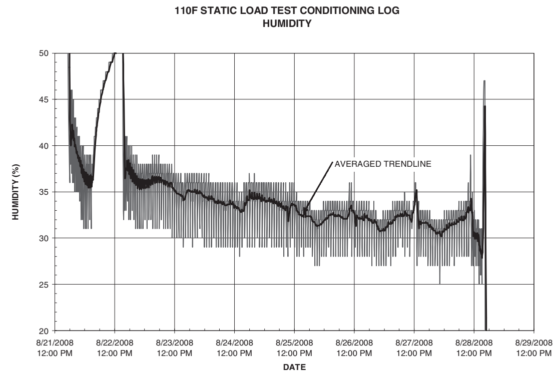


Figure 104: ST-110F Conditioning Log - Humidity

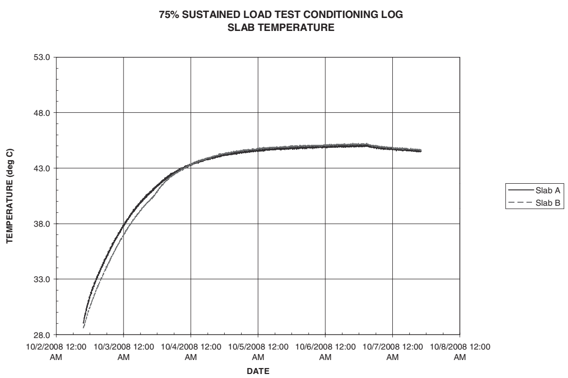


Figure 105: CT-75% Conditioning Log - Temperature

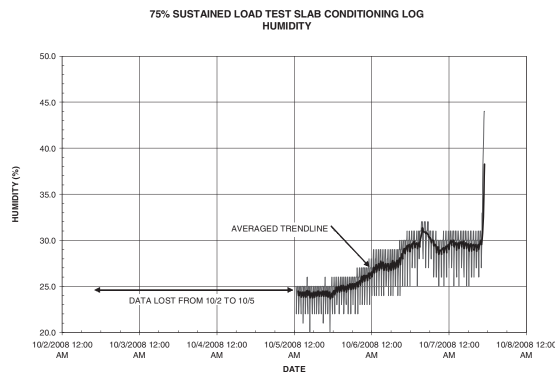


Figure 106: CT-75% Conditioning Log - Humidity

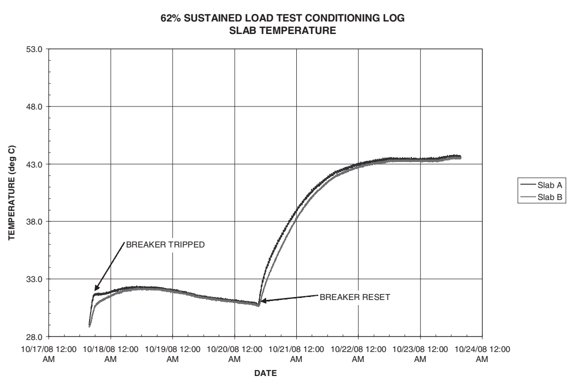


Figure 107: CT-62% Conditioning Log - Temperature

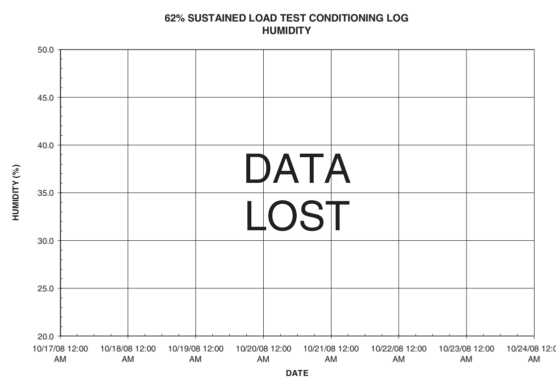


Figure 108: CT-62% Conditioning Log - Humidity

Anchor Testing Environmental Logs (Temperature and Humidity)

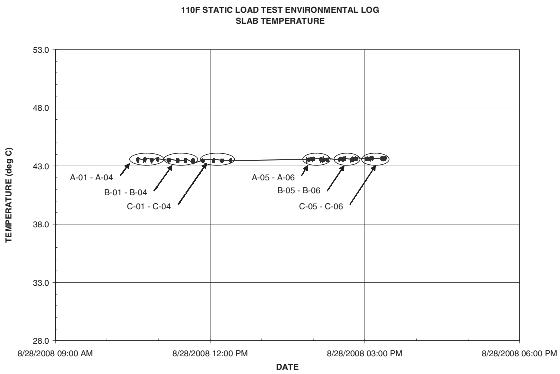


Figure 109: ST-110F Environmental Log - Temperature

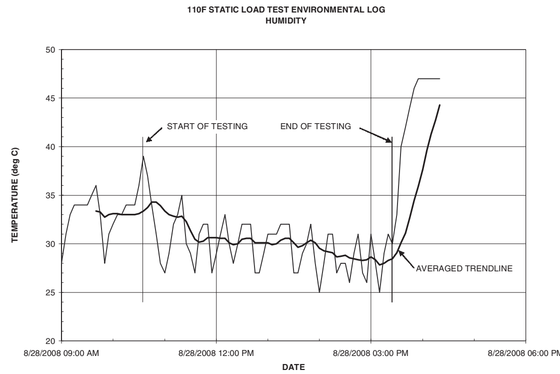


Figure 110: ST-110F Environmental Log - Humidity

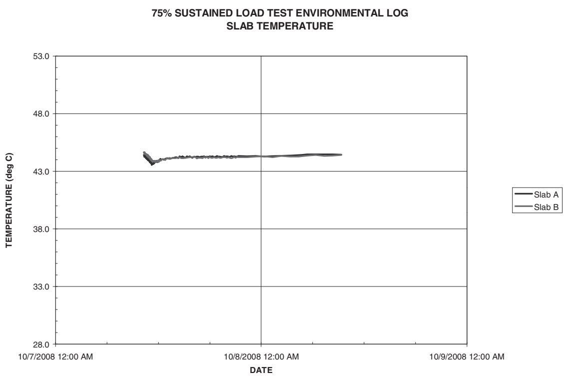


Figure 111: CT-75% Environmental Log - Temperature

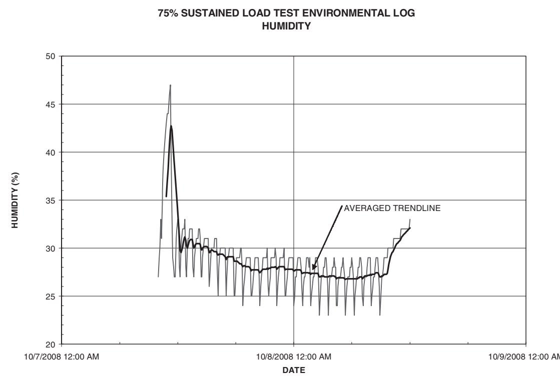


Figure 112: CT-75% Environmental Log - Humidity

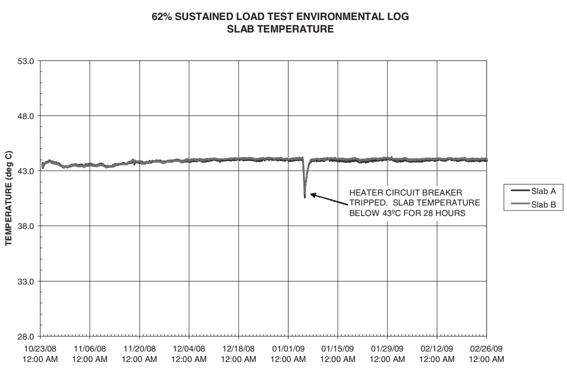


Figure 113: CT-62% Environmental Log - Temperature

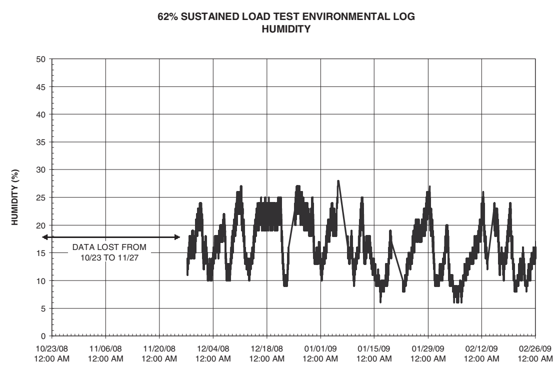


Figure 114: CT-62% Environmental Log - Humidity

APPENDIX C

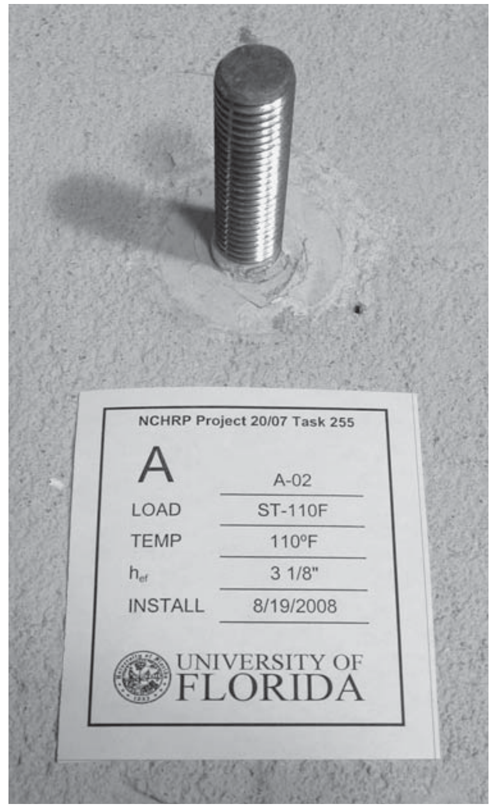
Photographs

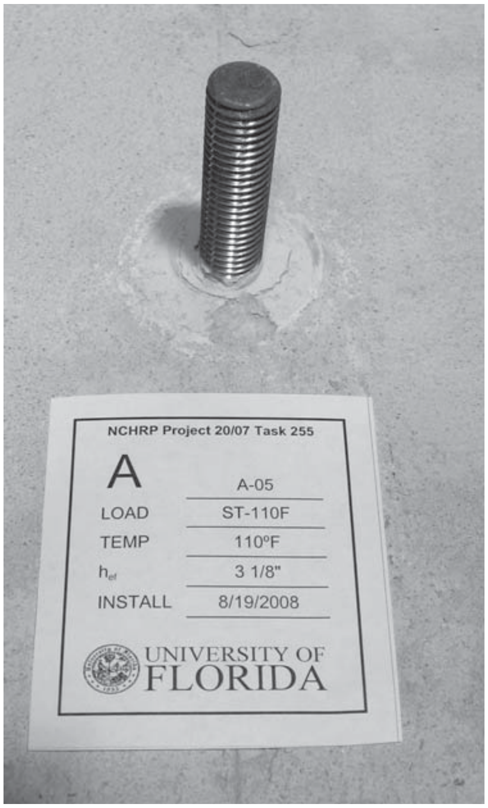
This appendix presents the photographs of the tests specimens taken during this research project. For interpretation of these photographs, refer to the body of this report.

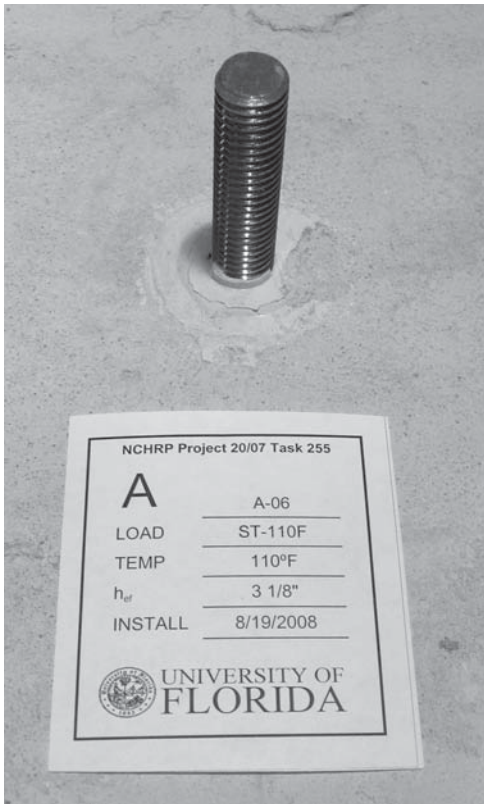
The following abbreviations are used to describe the photographs contained within this appendix:

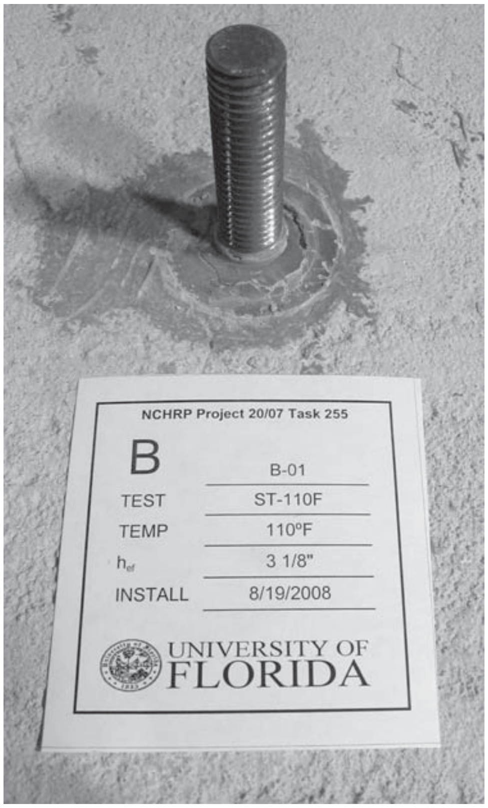
Abbreviation	Description
ST	Static Load Test
-75F	Test temperature of 75ºF for the static load test
-110F	Test temperature of 110ºF for the static load test
CT	Sustained Load (Creep) Test
-75%	Load level of 75% for the sustained load (creep) test
-62%	Load level of 62% for the sustained load (creep) test
A-01	Anchor adhesive (A) and number (01)

110ºF Static Load Test Photographs

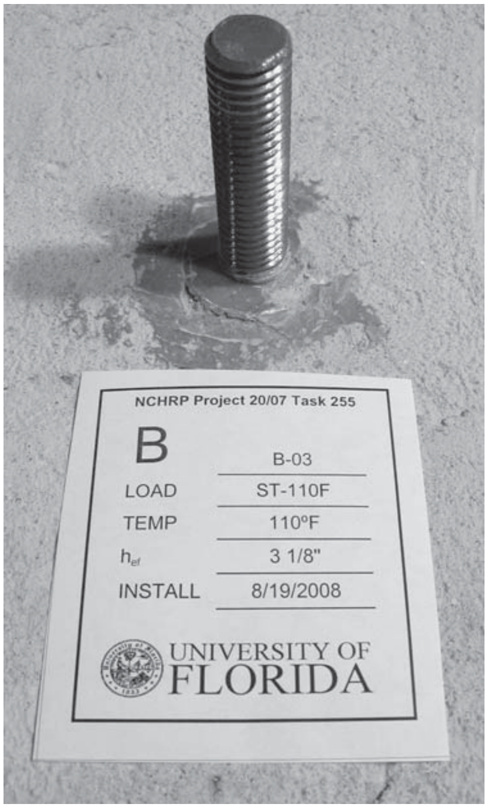



NCHRP Project 20/07 Task 255
A
A-05
LOAD
ST-110F
TEMP
110ºF
hef
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA


NCHRP Project 20/07 Task 255
A
A-06
LOAD
ST-110F
TEMP
110ºF
hef
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA


NCHRP Project 20/07 Task 255
B
B-01
TEST
ST-110F
TEMP
110ºF
hef
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

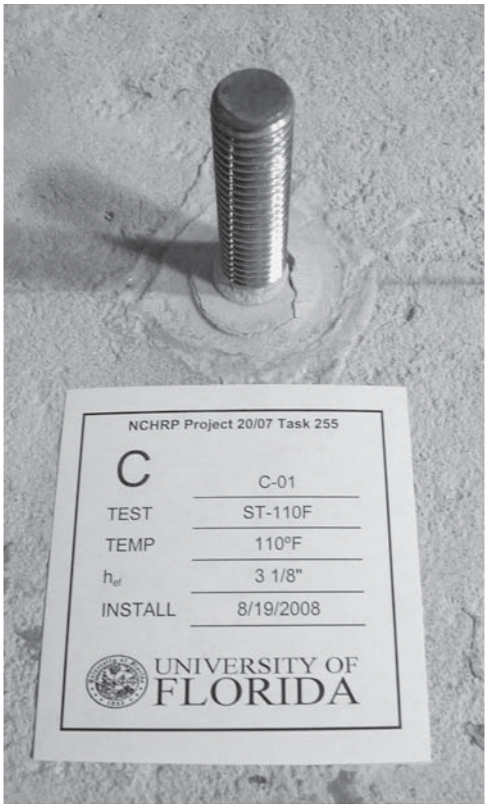

NCHRP Project 20/07 Task 255
B
B-02
LOAD
ST-110F
TEMP
110ºF
hef
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

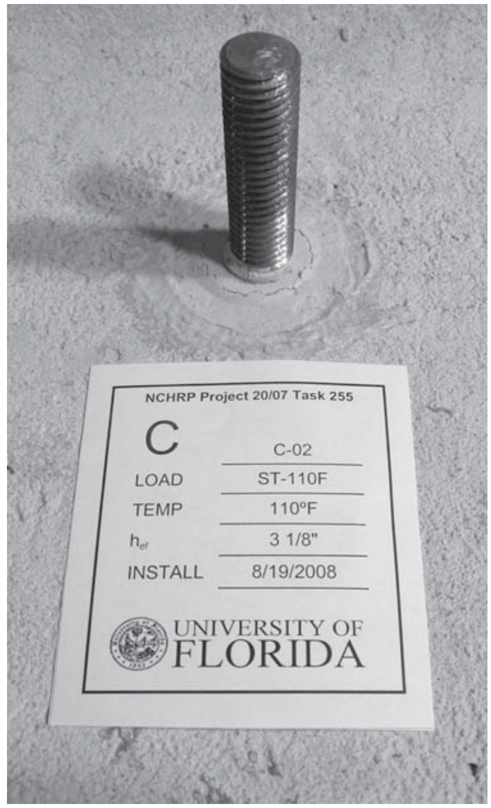

NCHRP Project 20/07 Task 255
B
B-03
LOAD
ST-110F
TEMP
110ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA


NCHRP Project 20/07 Task 255
B
B-04
TEST
ST-110F
TEMP
110ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

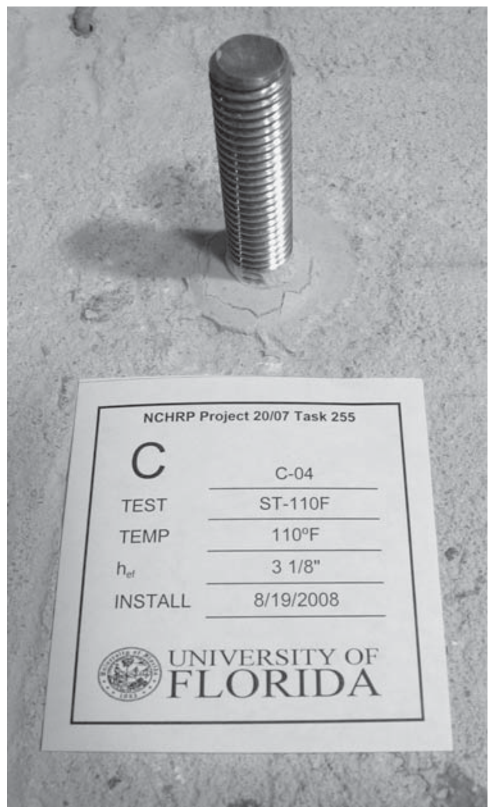

NCHRP Project 20/07 Task 255
B
B-05
LOAD
ST-110F
TEMP
110ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA


NCHRP Project 20/07 Task 255
B
B-06
LOAD
ST-110F
TEMP
110ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

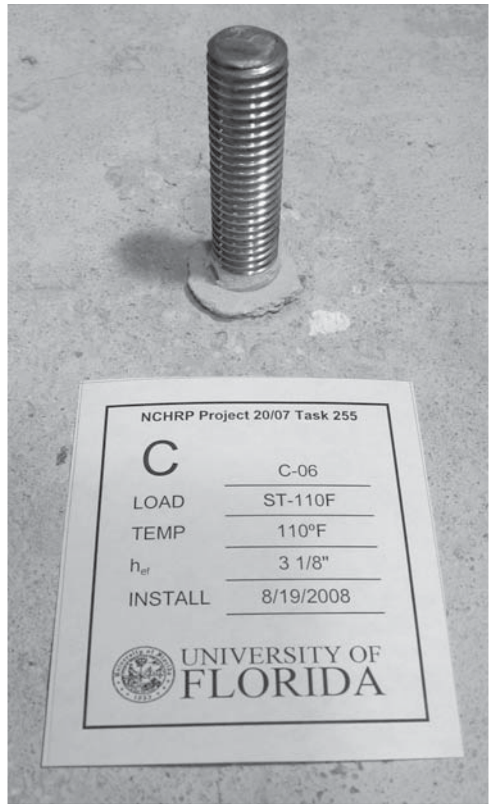

NCHRP Project 20/07 Task 255
C
C-01
TEST
ST-110F
TEMP
110ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF FLORIDA


NCHRP Project 20/07 Task 255
C
C-02
LOAD
ST-110F
TEMP
110ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF FLORIDA

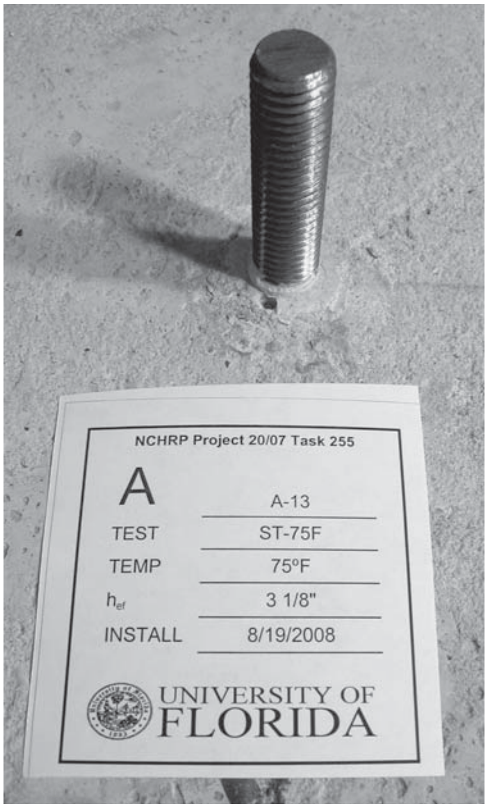

NCHRP Project 20/07 Task 255
C
C-03
LOAD
ST-110F
TEMP
110ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF FLORIDA

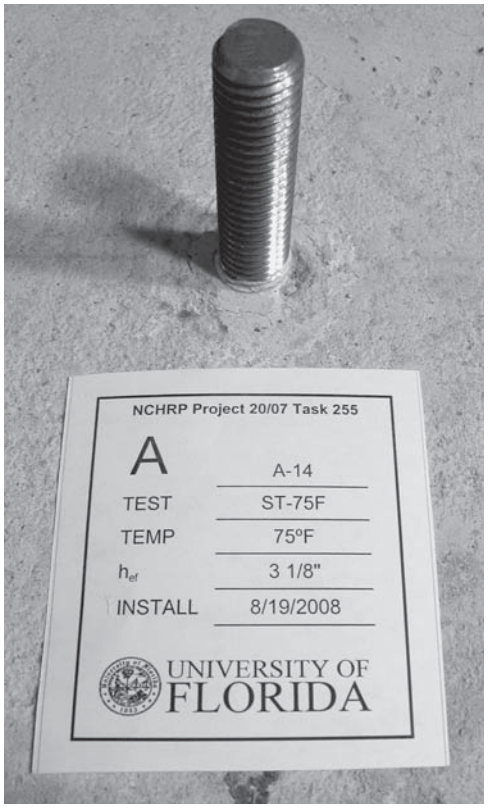

NCHRP Project 20/07 Task 255
C
C-04
TEST
ST-110F
TEMP
110ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF FLORIDA

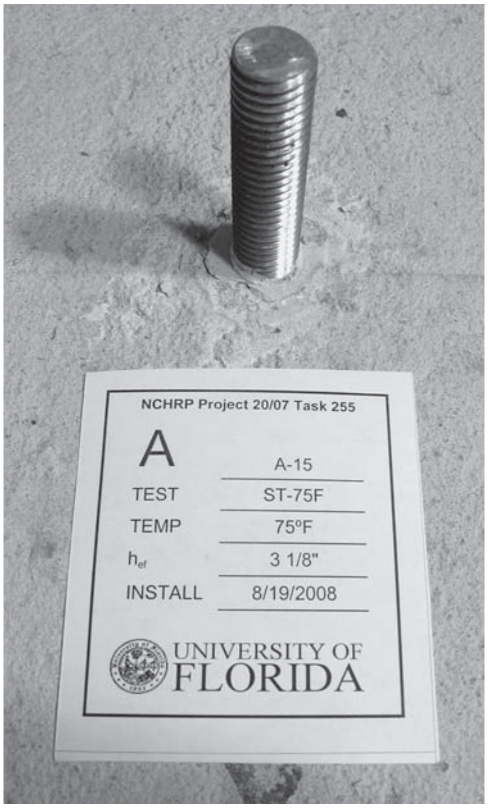

NCHRP Project 20/07 Task 255
C
C-05
LOAD
ST-110F
TEMP
110ºF
h_ef
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

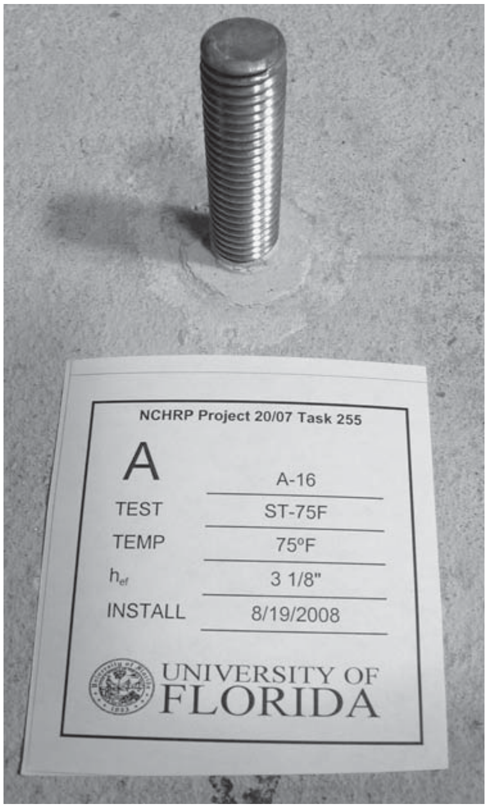

NCHRP Project 20/07 Task 255
C
C-06
LOAD
ST-110F
TEMP
110ºF
h_ef
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

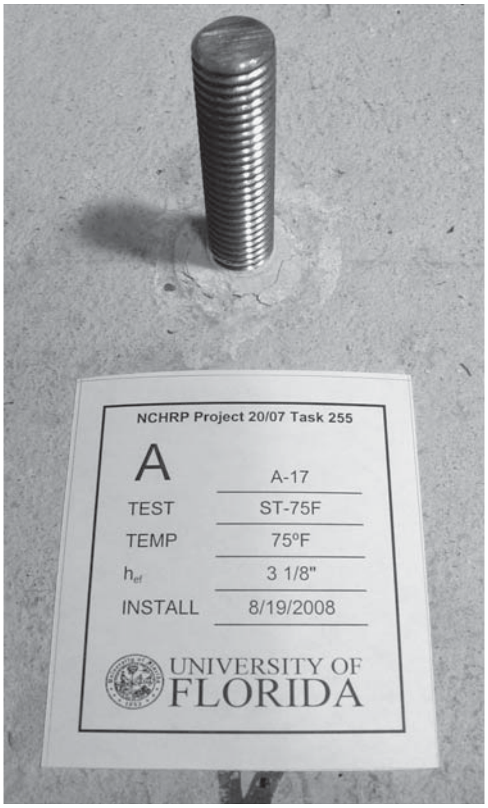
75ºF Static Load Test Photographs

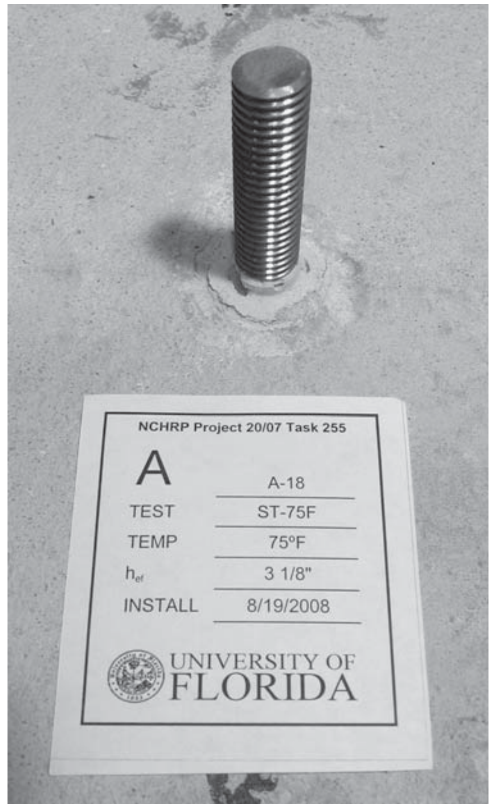


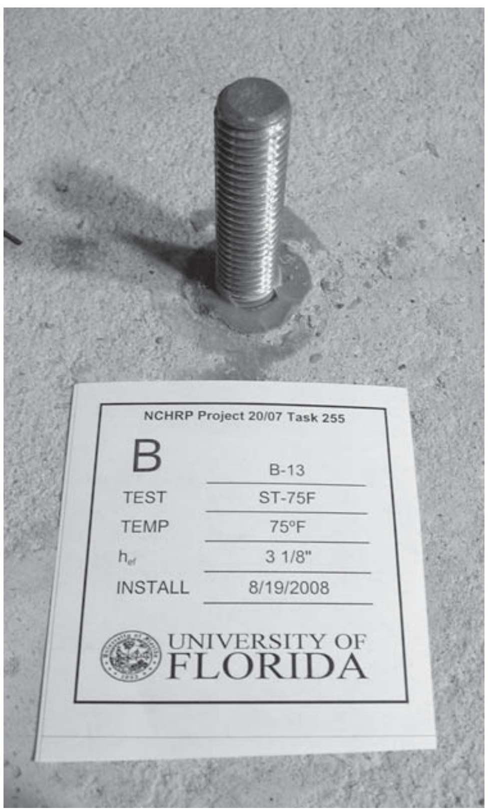


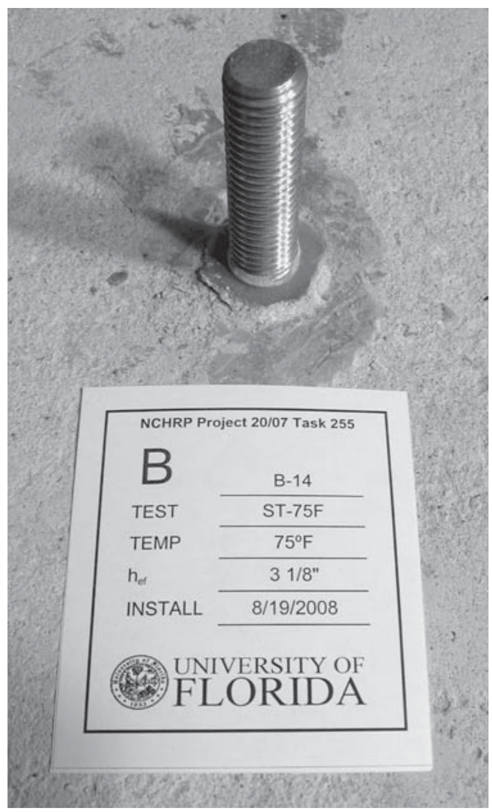


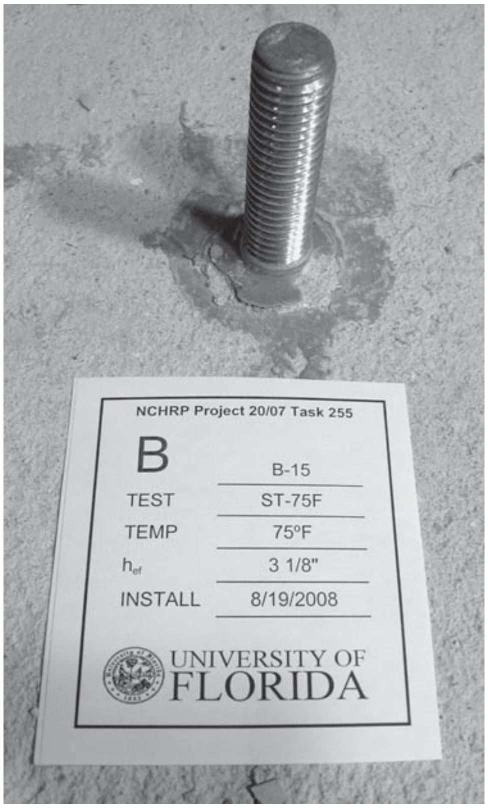


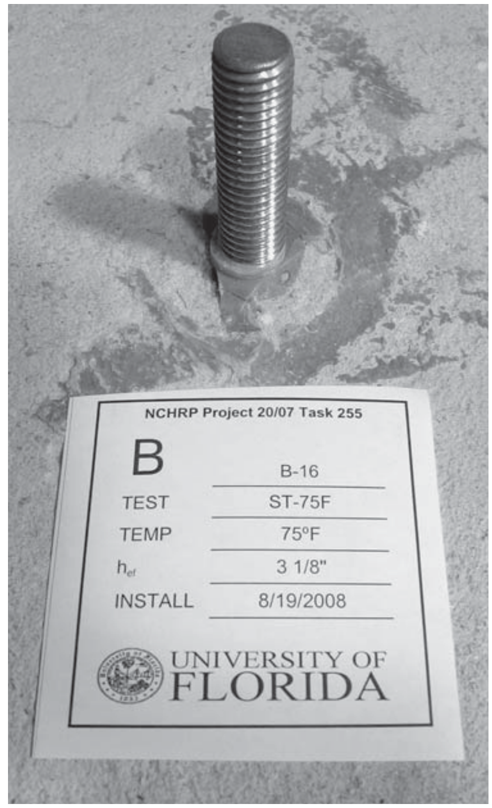

NCHRP Project 20/07 Task 255
A
A-17
TEST ST-75F
TEMP 75°F
h_{ef} 3 1/8"
INSTALL 8/19/2008
UNIVERSITY OF FLORIDA


NCHRP Project 20/07 Task 255
A
A-18
TEST ST-75F
TEMP 75°F
h_{ef} 3 1/8"
INSTALL 8/19/2008
UNIVERSITY OF FLORIDA


NCHRP Project 20/07 Task 255
B
B-13
TEST ST-75F
TEMP 75°F
h_{ef} 3 1/8"
INSTALL 8/19/2008
UNIVERSITY OF FLORIDA

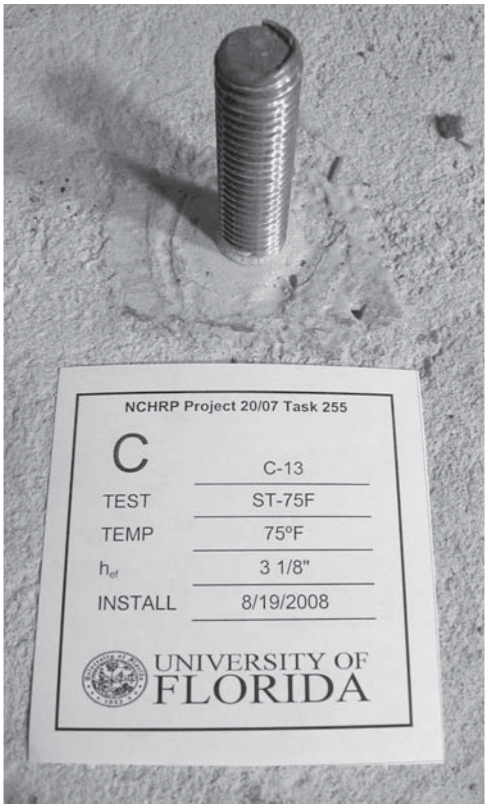

NCHRP Project 20/07 Task 255
B
B-14
TEST ST-75F
TEMP 75°F
h_{ef} 3 1/8"
INSTALL 8/19/2008
UNIVERSITY OF FLORIDA


NCHRP Project 20/07 Task 255
B
B-15
TEST
ST-75F
TEMP
75ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

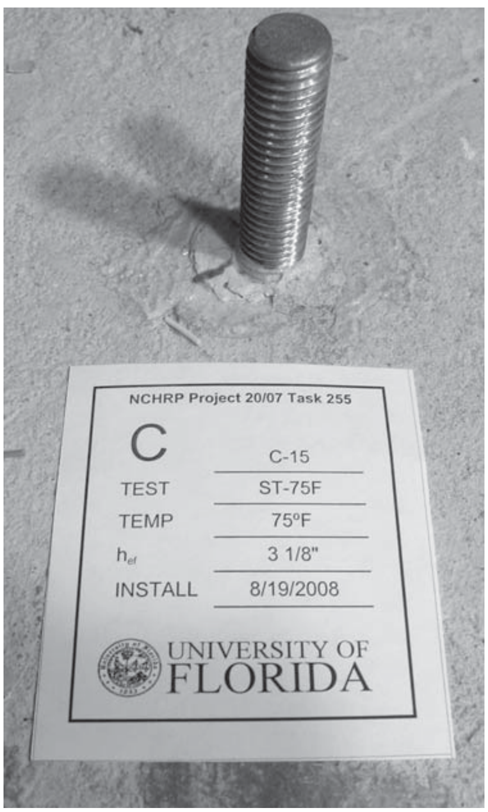

NCHRP Project 20/07 Task 255
B
B-16
TEST
ST-75F
TEMP
75ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA


NCHRP Project 20/07 Task 255
B
B-17
TEST
ST-75F
TEMP
75ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

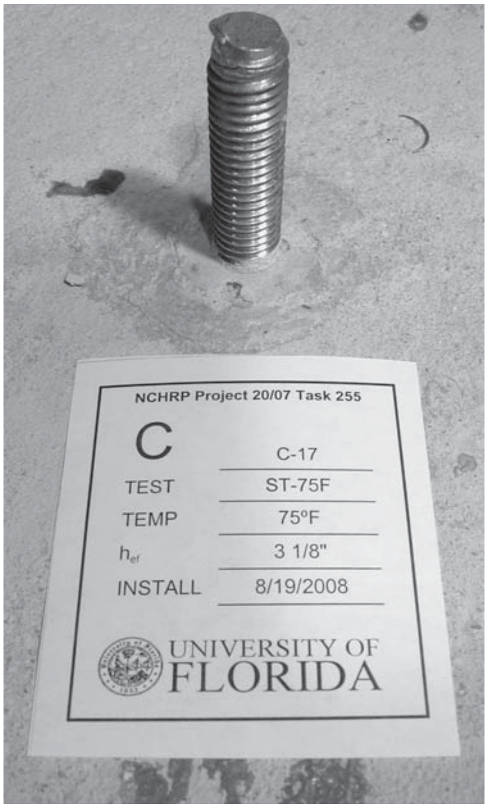

NCHRP Project 20/07 Task 255
B
B-18
TEST
ST-75F
TEMP
75ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA


NCHRP Project 20/07 Task 255
C
C-13
TEST
ST-75F
TEMP
75ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA


NCHRP Project 20/07 Task 255
C
C-14
TEST
ST-75F
TEMP
75ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

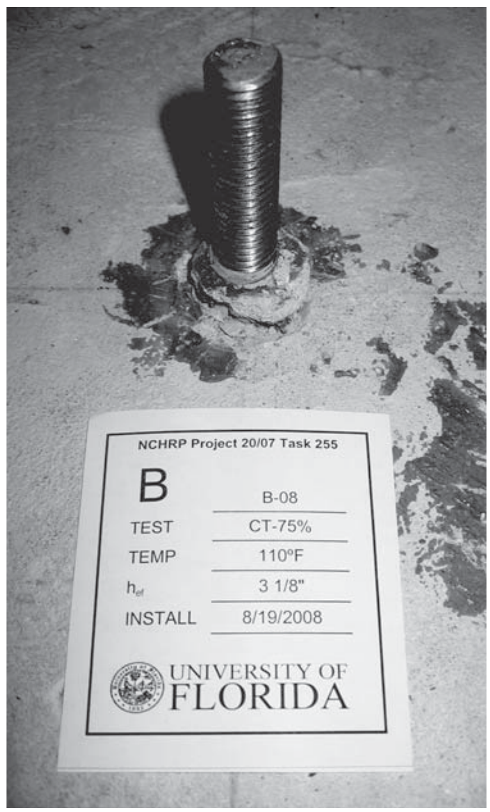

NCHRP Project 20/07 Task 255
C
C-15
TEST
ST-75F
TEMP
75ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

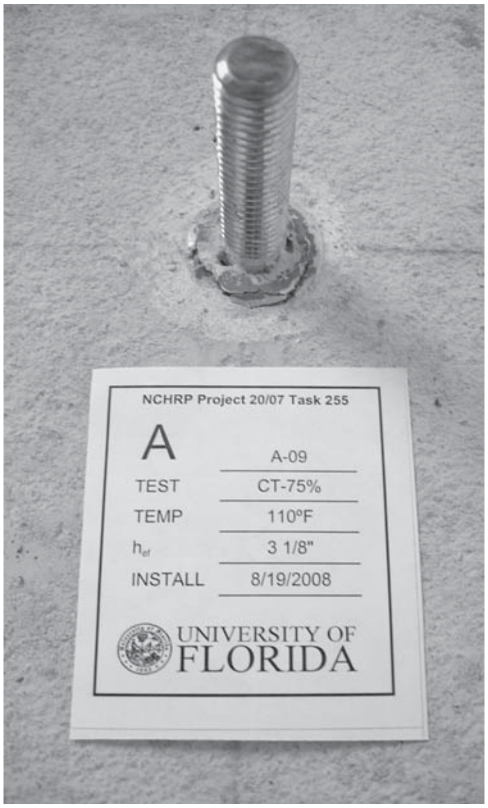

NCHRP Project 20/07 Task 255
C
C-16
TEST
ST-75F
TEMP
75ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

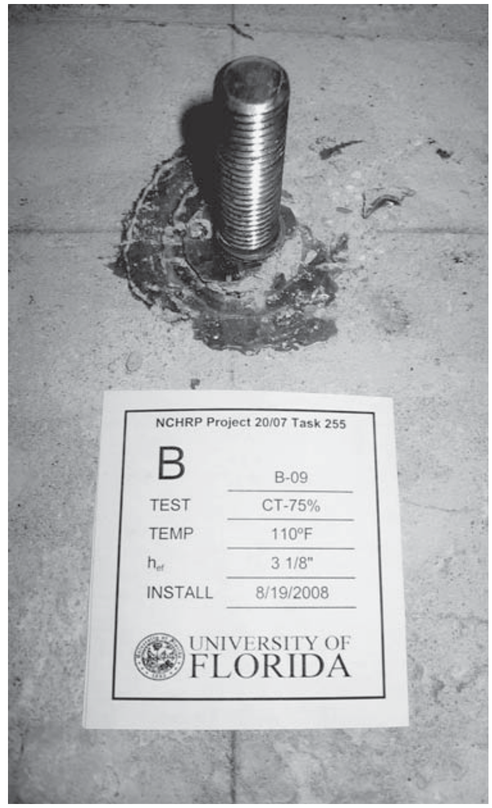

NCHRP Project 20/07 Task 255
C
C-17
TEST
ST-75F
TEMP
75ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA


NCHRP Project 20/07 Task 255
C
C-18
TEST
ST-75F
TEMP
75ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

75% Sustained Load (Creep) Test Photographs




NCHRP Project 20/07 Task 255
A
A-09
TEST
CT-75%
TEMP
110ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

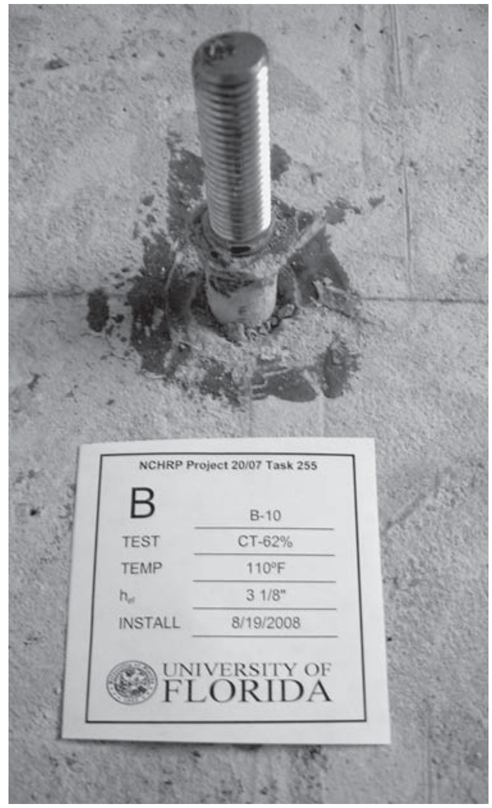

NCHRP Project 20/07 Task 255
B
B-09
TEST
CT-75%
TEMP
110ºF
h_{ef}
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF
FLORIDA

62% Sustained Load (Creep) Test Photographs

A-10

NO FAILURE

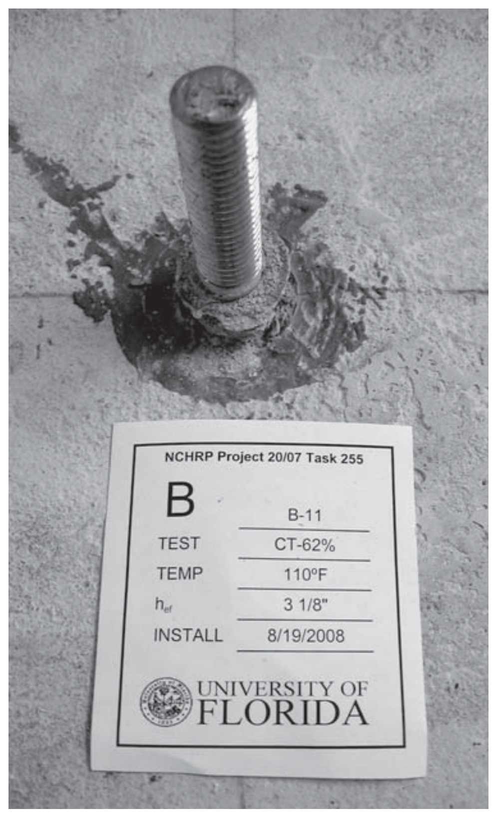
TEST SUSPENDED



A-11

NO FAILURE

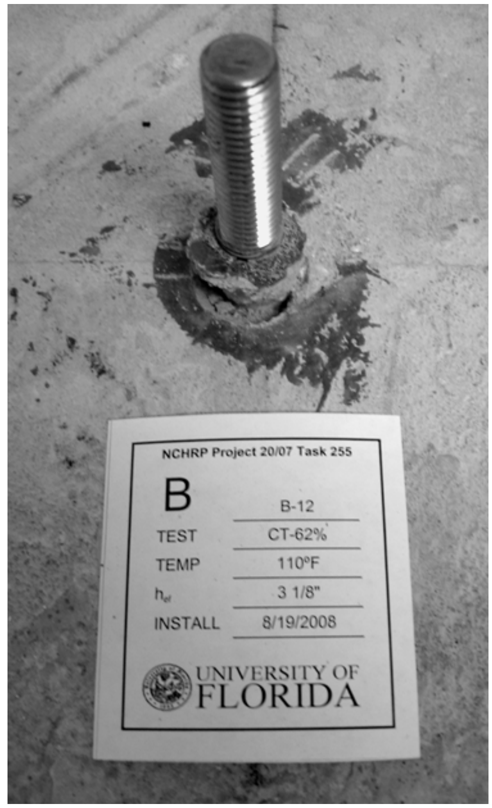
TEST SUSPENDED



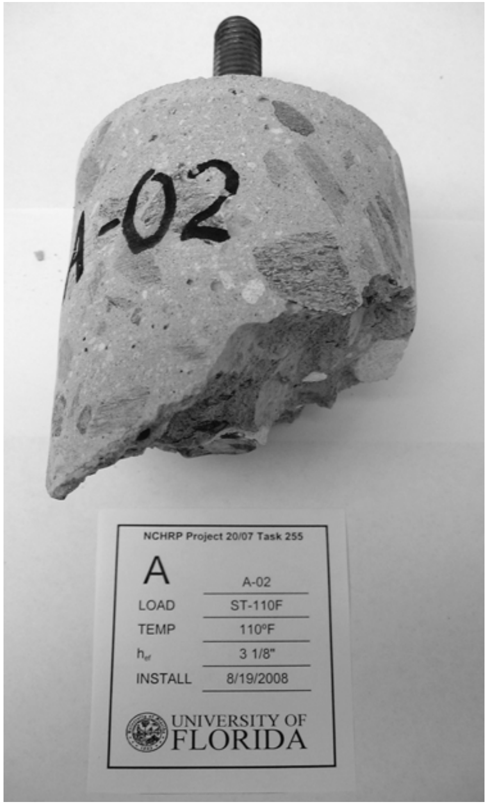
A-12

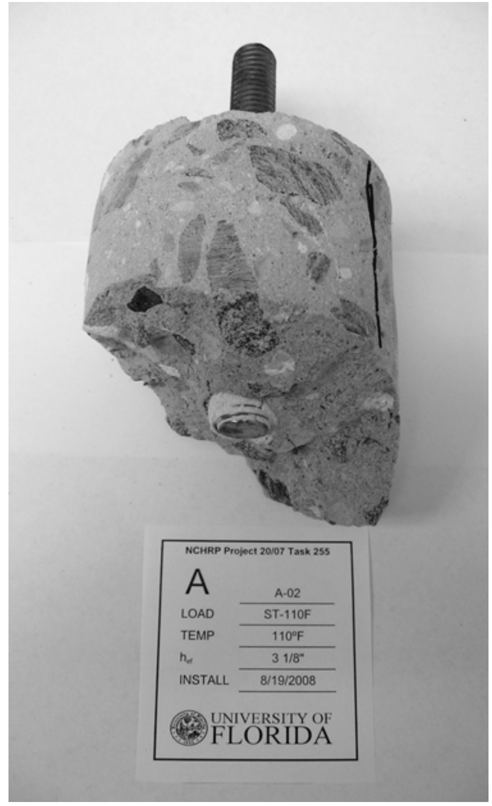
NO FAILURE

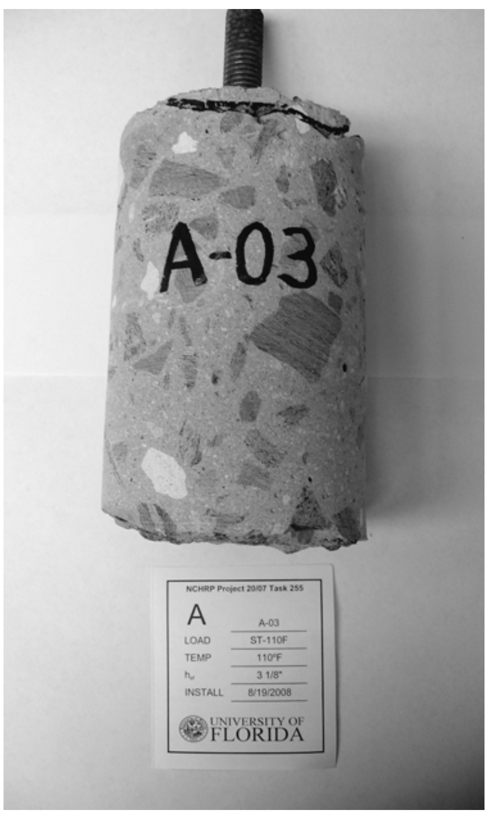
TEST SUSPENDED



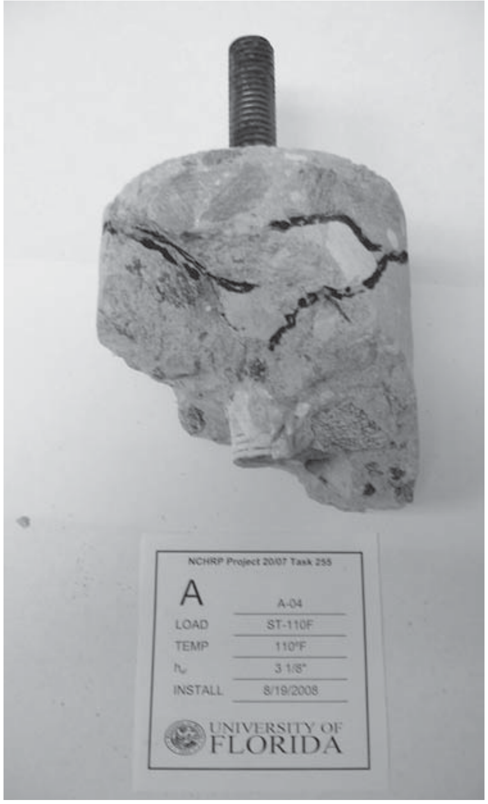
Photographs of Failure Surface from Core Samples

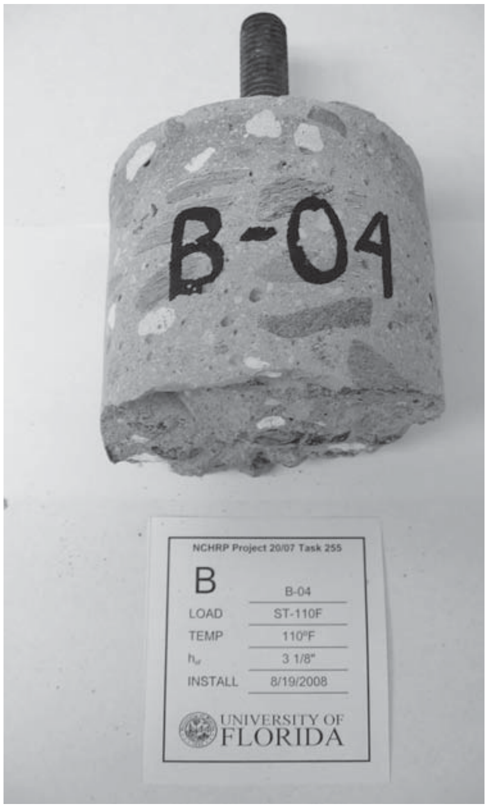






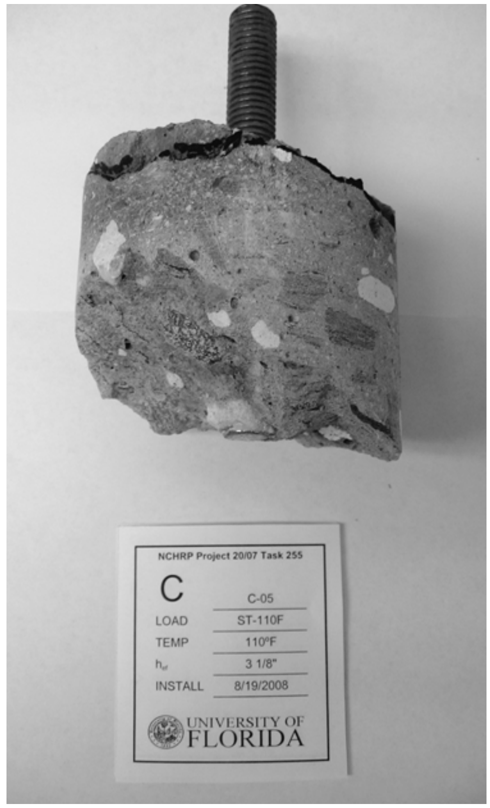

A-04
NCHRP Project 20/07 Task 255
A
A-04
LOAD ST-110F
TEMP 110°F
3 1/8"
INSTALL 8/19/2008
UNIVERSITY OF FLORIDA


NCHRP Project 20/07 Task 255
A
A-04
LOAD ST-110F
TEMP 110°F
3 1/8"
INSTALL 8/19/2008
UNIVERSITY OF FLORIDA


B-04
NCHRP Project 20/07 Task 255
B
B-04
LOAD ST-110F
TEMP 110°F
3 1/8"
INSTALL 8/19/2008
UNIVERSITY OF FLORIDA


NCHRP Project 20/07 Task 255
B
B-04
LOAD ST-110F
TEMP 110°F
3 1/8"
INSTALL 8/19/2008
UNIVERSITY OF FLORIDA


C-05
NCHRP Project 20/07 Task 255
C
C-05
LOAD
ST-110F
TEMP
110ºF
h_ef
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF FLORIDA


NCHRP Project 20/07 Task 255
C
C-05
LOAD
ST-110F
TEMP
110ºF
h_ef
3 1/8"
INSTALL
8/19/2008
UNIVERSITY OF FLORIDA

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation