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TENSILE BEHAVIOR AND DESIGN OF SINGLE, ADHESIVE ANCHORS

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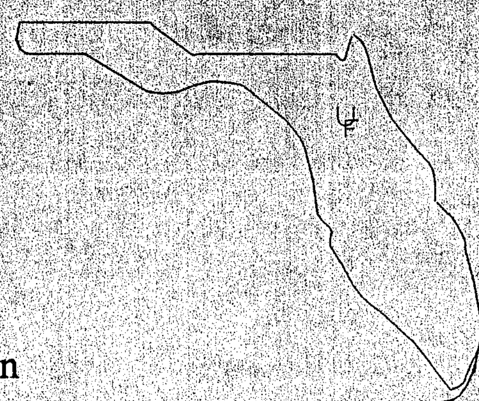
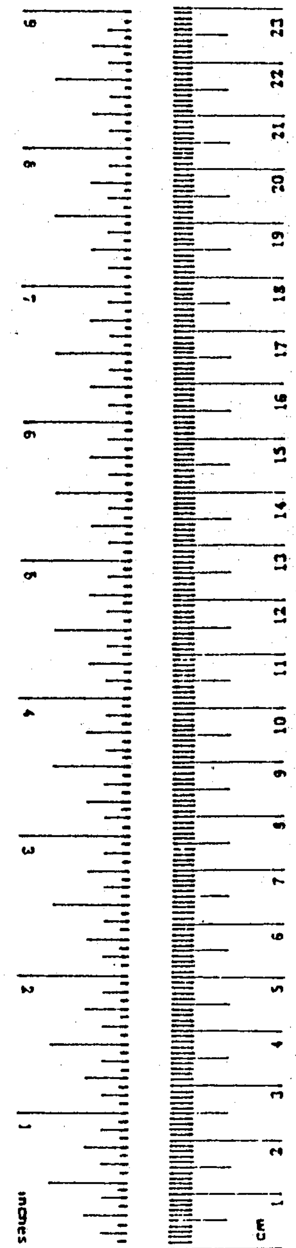


Engineering and Industrial Experiment Station

Approximate Conversions to Metric Measures

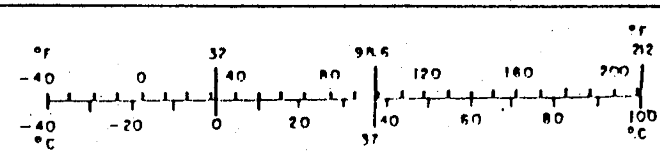
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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16. Abstract

The purpose of this project was to study the tensile behavior of adhesive bonded anchors subjected to static loading. A total of 167 tests were performed involving three rod diameters and 16 adhesives. Load-displacement data was collected for each test.

A series of confined, fully-bonded baseline tests were used to determine the basic behavior of the adhesive anchor system. Failure of the confined, fully-bonded anchors was characterized by the pullout of an adhesive core along the concrete-adhesive interface.

Other tests were performed for comparison with the baseline tests. These consisted of unconfined tests with both fully and partially-bonded anchors and confined tests with partially-bonded anchors. All tests involving partially-bonded anchors experienced failures characterized by the pullout of an adhesive core along the concrete-adhesive interface. The unconfined tests with fully-bonded anchors experienced a shallow concrete cone failure coupled with the pullout of an adhesive core along the concrete-adhesive interface.

The test results were used to evaluate two bond stress models for the adhesive anchor system. One model was based on a bond stress distribution obtained from an elastic analysis of the anchor system. The second model was based on a uniform bond stress distribution.

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CHAPTER 1 INTRODUCTION

1.1 Problem Statement

The Florida Department of Transportation (FDOT) presently does not have standard specifications for adhesive-bonded anchors in structural applications. An adhesive-bonded anchor is a reinforcing bar or threaded rod inserted into a drilled hole in hardened concrete with a structural adhesive acting as a bonding agent between the concrete and the steel. Such adhesives are packaged as two component units comprised of an epoxy, polyester, or vinylester resin and a catalyst or curing agent.

These anchors provide a viable, economical method for adding new concrete sections or attaching steel members to existing concrete structures. Presently, most designers follow the adhesive manufacturer's recommendations which are based on laboratory testing specific to individual products and applications. The increasing amount of retrofit and rehabilitation work encountered today exemplifies the need for a standard specification for this type of anchor.

1.2 Scope and Objectives

1.2.1 Scope

The purpose of this project was to study the tensile behavior of adhesive-bonded anchors when subject to static loading and to identify parameters specific to each adhesive. Previous research (Klingner et al., 1982) has shown that if a structural anchor has been sufficiently embedded for tension, it will also be adequate for shear. Therefore, the tensile behavior should provide the information necessary to describe the bond failure of an adhesive anchor.

The adhesives tested were all self-mixing and intended for structural applications. The diameters and embedment lengths of the anchors were varied to provide a broad range of contact surface areas and length-to-diameter ratios. The embedment lengths were chosen as to prevent steel failure and concentrate on the bond strengths of the individual adhesives.

A series of baseline tests was used to determine bond and stiffness characteristics that are specific to each adhesive. These properties were utilized to develop a design equation for structural adhesive anchors.

Other tests were performed to confirm the results from the baseline tests.

1.2.2 Objectives

Experimental data will be employed to develop a qualification specification that can be used to establish the basic parameters necessary to design a structural adhesive bonded anchor.

CHAPTER 2

BACKGROUND

2.1 Behavior of Adhesive Anchors

The main function of a structural adhesive is to transfer load from the steel anchor to the surrounding concrete. Daws (1978) suggests four factors that contribute to the load transfer capability of an adhesive anchor: Mechanical interlock on the adhesive-concrete interface, chemical bond along the adhesive-concrete interface, mechanical interlock on the adhesive-steel interface, and chemical bond along the adhesive-steel interface. The actual failure mode of an adhesive anchor is often a combination of mechanical interlock and chemical bond failure.

The quantity of documented research pertaining to the behavior and the bond stress distribution of structural adhesive anchors is currently limited. One study at the University of Texas at Austin (Collins et al., 1989) investigated the load-deflection behavior of retrofit and cast-in-place anchors. Five-eighths inch diameter ASTM A193 Grade B7 threaded rods were installed in concrete with a specified compressive strength of 3600 psi (actua1 4500-6750 psi). The embedment lengths ranged from 7 to 12 in. and the anchors were allowed to cure for either 7 days or 24 hours.

The adhesive anchors were subject to unconfined testing (the reaction forces were kept away from the anchor).

During the testing, four failure modes were experienced: yield and fracture of the steel with anchor slip, yield and fracture of the steel without anchor slip, failure of the bond between the adhesive and the concrete, and the failure of the bond between the adhesive and the steel.

Just before failure, the anchors apparently resisted the loading until it reached a level of maximum bond stress. Beyond that point, the anchor and adhesive began to slip out as a unit. Little or no anchor slip was detected before bond failure. After bond failure, residual anchor strength was apparently due to mechanical interlock between the adhesive and the concrete.

Failure of the bond between the adhesive and the concrete occurred at loads ranging from about one-third of the anchor steel capacity to the full capacity of the anchor steel.

Another study at the University of Texas at Austin (Doerr et al., 1989) also investigated the behavior of structural adhesive anchors. Data from these experiments was used to develop a design equation that, given certain characteristics of the anchoring system, predicts anchor capacity. Five-eighths inch diameter ASTM A193 Grade B7 threaded rods were installed in 3600 psi concrete and subject to unconfined testing. The anchors tested were either fully bonded (adhesive covered the entire embedded portion of anchor) or partially bonded (top 2 in. of the embedded portion of the anchor treated with a debonding agent) and embedment depths ranged from 4 to 8 in.

During the testing, the fully bonded anchors failed either by fracture of the steel or by the formation of a shallow (about 1 to 2 in.) concrete cone accompanied by pullout of the adhesive. The partially bonded anchors failed either by fracture of the steel or by the pullout of an adhesive core. Concrete cone failures did not occur with the partially bonded anchors. Test data revealed that fully bonded anchors had only slightly higher capacities than the partially bonded anchors of the same embedment length.

The following equation for anchor strength was found using an elastic analysis:

$$p_{\max} = \frac{\pi u_{\max} d^{1.5}}{\lambda'} \tanh\left(\frac{\lambda' \ell}{\sqrt{d}}\right)$$

where P_{max} is the maximum tensile force, u_{max} is the maximum bond stress, λ' is a stiffness parameter of the adhesive (exp erimentally determined), d is the hole diameter, and ℓ is the embedment length. This model provided the best fit for the test data.

For each adhesive, a value for u_{max} and λ' was calculated based on the experimental results. Load resistance factors, based on the asymptotic nature of the equation were suggested for design use.

$$asymptote = \frac{\pi u_{\max} d^{1.5}}{\lambda'}$$

If P is within 95% of the asymptotic value, Φ=0.80. Otherwise, Φ=0.60.

The study (1989b) also found that a uniform bond stress distribution serves as a reasonable approximation of the load capacity of an adhesive anchor.

$$P_{\max} = u_{\max} \pi d \ell$$

2.2 Other Factors Affecting Adhesive Anchor Behavior

Structural adhesives are sensitive to several factors. Misproportioning the resin and curing agent, even by a slight amount, may affect curing time and bond strength. The wetting characteristics (ability of the adhesive to coat the entire surface of the embedded portion of the anchor) of each adhesive affect the ability of the adhesive to distribute bond stress to the surrounding concrete along the bonded length of the anchor.

Other factors that may affect adhesive behavior include hot temperatures often experienced during the summer months in warmer climates, high lime concentrations, moisture, and ultraviolet light. Testing under such conditions is beyond the scope of this project and is recommended for further research.

2.3 Current Qualification Specifications

The Florida Department of Transportation (FDOT) does not currently have a specification for adhesive anchors in structural applications. Section 460-30 of the current FDOT code (1986) contains specifications pertaining to setting and furnishing anchor bolts (i.e. bolt composition, cleaning and drilling holes, etc.). Classification of each type of adhesive compound is listed in Section 926-1. A Type J adhesive is "an epoxy for anchor bolts where strength of the overall structure is not a factor such as for hanging telephone lines or other utility attachments" (1986, p. 644). Section 926-2 lists specifications for each type of adhesive and makes a reference to the FDOT *Qualified Products List* (1990).

One current qualification test for structural adhesive anchors is specified by the Missouri Highway and Transportation Department (MHTD). Section 1039.3 and T49-2-90 in MHTD *Standard Specifications* (1990) specifies a pull-out test for chemical bonding agents. Given a standardized concrete compressive strength, hole depth and diameter, anchor diameter, anchor length, adhesive curing time, and loading rate, the adhesive anchor must withstand a specified minimum load.
The method of testing (confined or unconfined) is not specified.

CHAPTER 3

DEVELOPMENT OF EXPERIMENTAL PROGRAM

3.1 General

The test program consisted of baseline tests that were performed on each of 16 adhesives. The purpose of these tests was to determine bond and stiffness properties specific to each adhesive. These characteristics were utilized to develop a design equation for adhesive anchors. Additional tests were used to verify the results of the baseline tests.

3.2 Test Specimens

The structural adhesive anchors tested were ASTM A193 Grade B7 threaded rods. The anchor diameters were ½", 5/8", and ¾" and their respective embedment lengths were 5", 3.5", and 7": These combinations of dimensions were chosen to provide a wide range in the specimens $\ell/\sqrt{d}$ ratio. This relationship was determined to be important in modeling the behavior of adhesive anchors (see Chapter 6).

High strength (minimum specified tensile strength of 125 ksi) threaded rod was used to ensure that the bond would fail before the steel began to yield under tensile loading. The adhesives tested are intended to be used in structural applications. Many of the products are currently included in the FDOT *Qualified Products List (1990)*.

3.3 Test Methods

Static tensile tests were performed two ways--confined and unconfined. A confined test requires that the reaction force be kept close to the anchor. An unconfined test requires the reaction force to be kept away from the anchor. For both testing methods, the adhesive anchors were either fully bonded or partially bonded. The fully-bonded anchors had the adhesive over the entire embedded length of the steel. Partially-bonded anchors were debonded at the top 2 in. of the embedded length.

The baseline tests involved confined testing with fullybonded anchors. The tests were performed in accordance with ASTM Z1706z *(1991)*. This method of testing prevented spalling at the surface of the concrete. By eliminating concrete cone formations, confined testing allowed for the study of the bond strength while neglecting the tensile strength of the concrete.

Unconfined tests were performed in accordance with ASTM E488. Fully bonded anchors were studied under this loading condition since it is often encountered in many engineering applications. Since concrete cone formation is possible with unconfined testing, concrete tensile strength may be a factor.

The results of these tests are compared with the baseline tests.

Partially bonded anchors were studied under both confined and unconfined testing. Previous tests (Doerr et al., 1989) have shown that the depth of a typical concrete cone formed during failure is about 2 in. To avoid cone formation, these anchors were debonded along the top 2 in. of the embedded length. The strength of the partially-bonded anchors were compared to that of the fully-bonded anchors of the same diameter and embedment depth. Design equations, derived using results of the baseline tests, were used to predict the capacity of the debonded anchors. The accuracy of the design equation was investigated by comparing the calculated values with the actual test data.

CHAPTER 4

IMPLEMENTATION OF TEST PROGRAM

4.1 Design and Construction of Concrete Test Slabs

4.1.1 Formwork

As shown in Figure 4-1, the formwork was designed so that two slabs could be cast at once. The center divider was permanently attached to the base. Removable side panels were employed for both easy stripping and reuse.

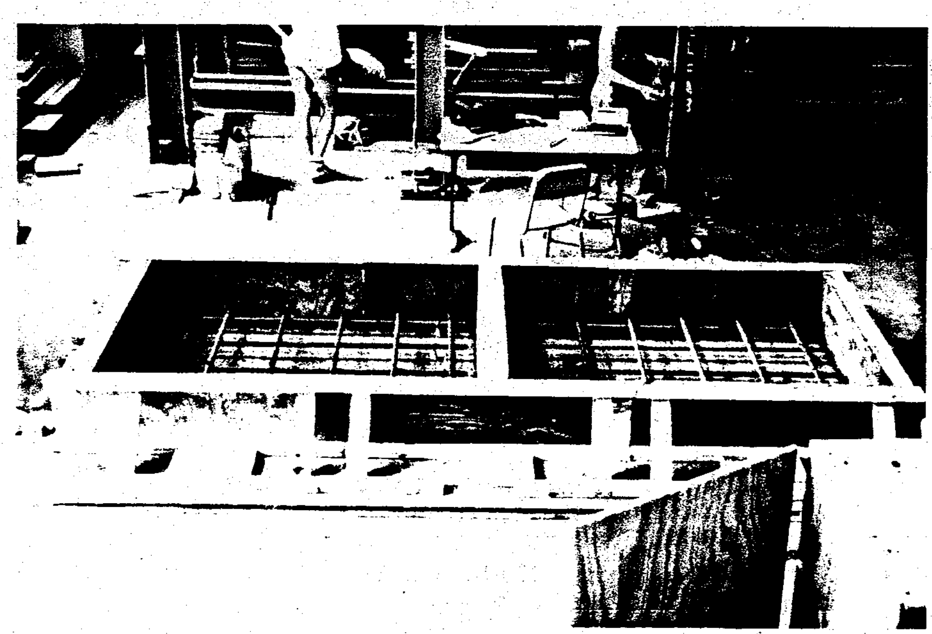


Figure 4-1 Formwork with steel reinforcement

4.1.2 Test Slab

The concrete slabs measured 72 x 54 x 15 in. They were reinforced at the bottom to control cracking and' shrinkage (Figure 4-1). The reinforcing bars were spaced at 12in. in both the longitudinal and transverse directions. Bent #3 bars were used for lifting hooks.

The slabs were cast using readymix 3500 psi FDOT Class II concrete. Test beams and cylinders cured along the sides of the forms under the same atmospheric conditions as the slabs.

Results of the cylinder tests show the compressive strength of the concrete to be well over the minimum specified strength of 3500 psi at the time of testing. The compressive strengths were `all above 5000 psi ('see table 4-1). This was the same as that in the tests performed at the University of Texas (Doerr et al., 1989). The concrete tensile strength

Table 4-1 Concrete strength at time of testing

Pour #	Compressive Strength (psi)	Modulus of Rupture (psi)
1	5175	603
2	5220	471
3	5719	624

(modulus of rupture) ranged from about 471 to 624 psi. Since the baseline anchor pull-out tests were designed to study bond strength (in the absence of concrete cone formation), the tensile strength of the concrete should not affect test results.

4.2 Anchor Installation

4.2.1 Anchor Bolt Preparation

ASTM A193 Grade B7 threaded rods were used for all of the adhesive anchors. The rods were cut to their desired length using a horizontal band saw. Sharp edges were removed with a grinding wheel. The rods were then soaked in paint thinner and wiped clean to rid the steel of any oily residue. Duct tape served as a bond-breaker for the partially-bonded adhesive anchors. The tape was wrapped around the top 2 in. of the embedded length.

4.2.2 Hole Preparation

The procedure presented in this section was consistent for each individual test. Drill bits were measured with a micrometer before and after each series of tests to detect any trace of deterioration. No deterioration was detected.

Holes were drilled into the concrete using a rotary hammer drill (Figure 4-2). Laboratory assistants observed the drilling to ensure proper alignment. The holes were then cleaned out with compressed air. A plastic tube enabled the compressed air to clean the bottoms and sides of the holes until residual dust leaving the holes was no longer noticeable. A stiff bottle brush connected to an electric drill (Figure 4-3) was used to loosen dust along the sides of the holes. Afterwards, compressed air was again used to remove any residual dust.

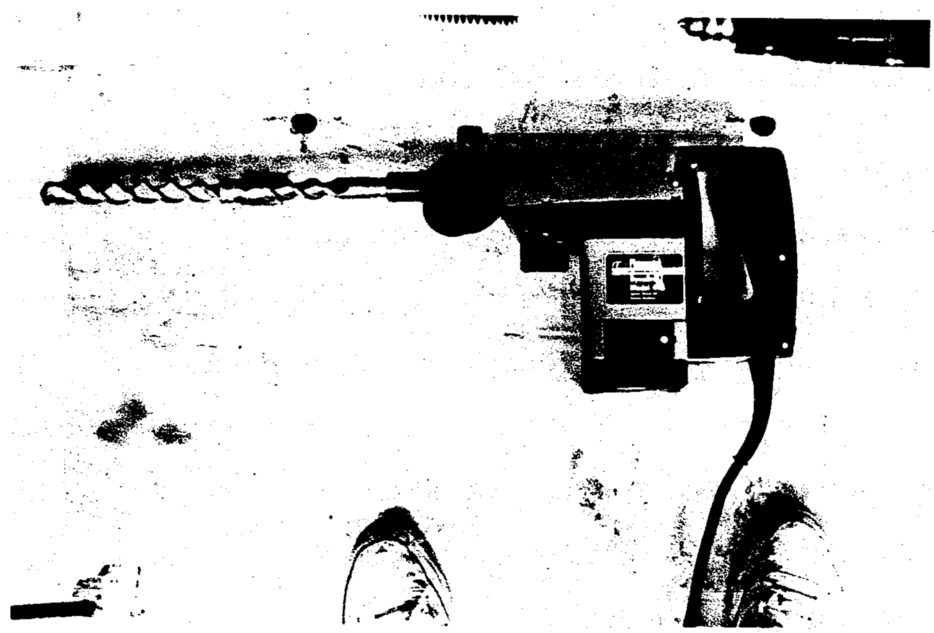


Figure 4-2 Rotary hammer drill

4.2.3 Anchor Installation

Adhesive anchors were installed using the manufacturer's recommendations. For typical injection applicators (Figure 44), the adhesive product was initially discharged onto a paper towel until a uniform color was observed. This ensured a

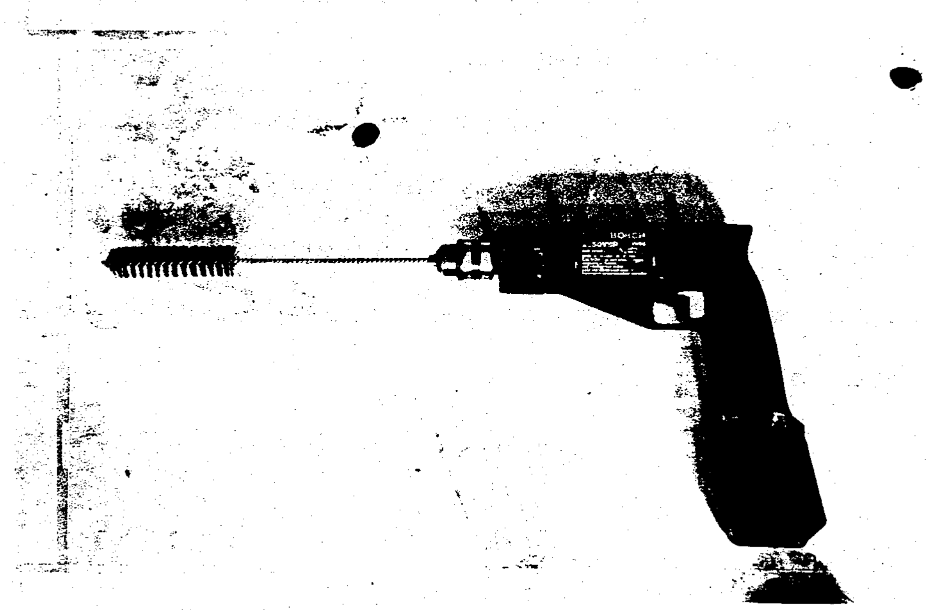


Figure 4-3 Stiff bottle brush connected to an electric drill

proper mixture. Holes were then filled about 1/2 full with the adhesive. To avoid air pockets, the applicator was placed at the bottom of the hole and slowly moved upward as the adhesive was discharged. The bolts were then slowly inserted into the adhesive-filled hole. The bolts were rotated slowly as they were inserted into the holes.

To install an anchor with a glass capsule adhesive (Figure 4-5), the capsule was placed into the hole. A chisel-pointed rod was then inserted into an attachment that connected to the rotary hammer drill. The anchor was then drilled through the capsule and down into the hole to its desired embedment length. The motion of the drill enabled the bolt to break the capsule and mix the resin and catalyst components of the adhesive.

At least 7 in. of edge distance and space between consecutive bolts ensured that individual tests were not affected by other influences. After curing for approximately 24 hours, excess adhesive was removed from the concrete with a hammer and chisel.

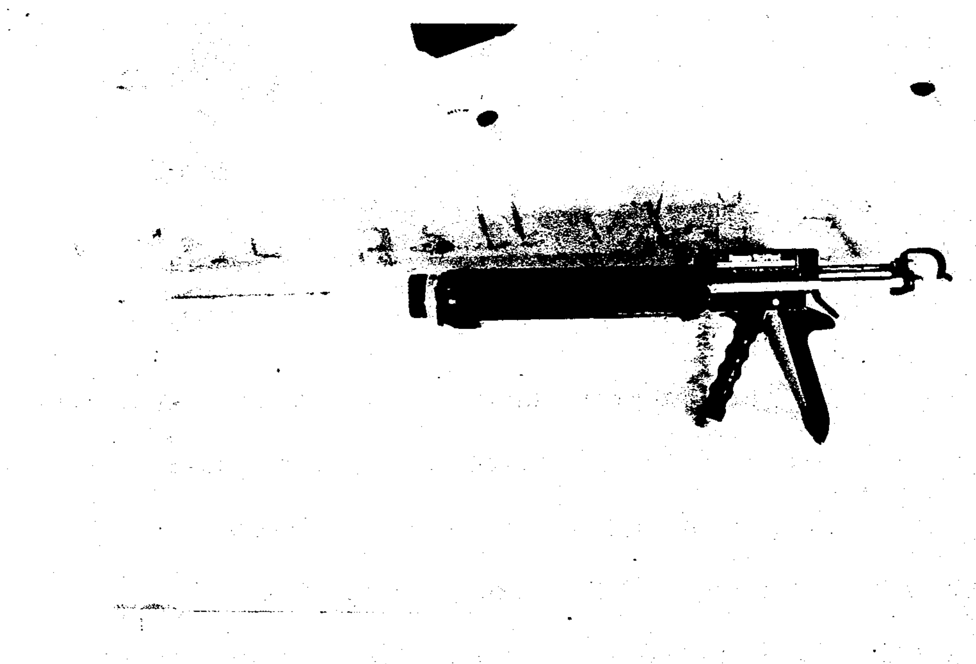


Figure 4-4 Injection type adhesive applicator

4.3 Test Equipment and Procedure

4.3.1 Confined Testing

The objective of the confined testing was to keep the reaction force close to the adhesive anchor. This was

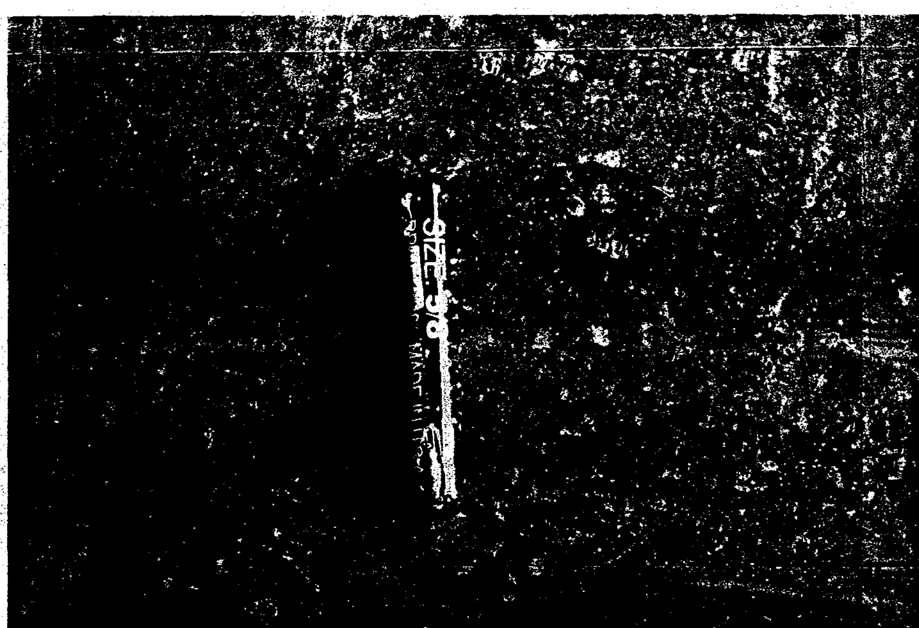


Figure 4-5 Glass capsule adhesive

accomplished by the use of confining plates. Confining plates were 1/2 in. thick steel plates with a hole diameter 1/2 in. greater than the anchor diameter. These were placed over the anchor and onto the surface of the concrete.

A 200 kip center-hole hydraulic ram was then placed over the anchor and on top of the confining plate. A pulling rod extended through the center of the hydraulic ram and supplied the load to the adhesive anchors. Two pulling rods were used during the testing program. These rods were of ASTM A193 Grade B7 steel and had diameters of 7/8 and 1-3/8 in. They were connected to the adhesive anchors by means of high strength steel couplers.

The hydraulic ram was connected by hydraulic hoses to a hand pump. Load was applied at a constant rate of 0.25 in/min to the adhesive anchors until the bond between the adhesive and the concrete was well beyond failure. Figure 4-6 illustrates the confined test getup.

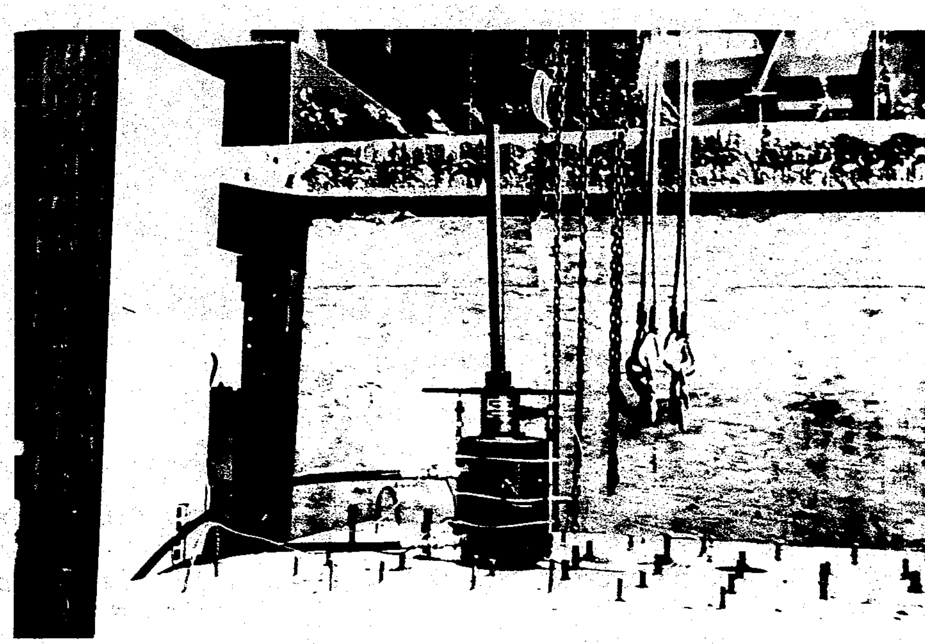


Figure 4-6 Confined test setup

4.3.2 Data Acquisition

Load was measured using an HSI 3500 Series compression load cell. This load cell contained four strain gages in a full bridge that measured voltage excitation due to loading. The load cell was mounted on top of the ram as shown in Figure 4-7. As load was applied to the anchor, the inner cylinder of the ram lifted upward. This exerted a bearing reaction on the upper, end of the pulling rod. The load cell served as a medium between the ram and the upper end of the pulling rod thus enabling it to measure this bearing reaction.

The displacement of the loaded anchor was measured with a pair of DC-operated linear variable differential transformers (LVDTs). As shown in Figure 4-7, the LVDTs were mounted on the sides of the hydraulic ram. As the inner cylinder of the ram moved upward, the LVDTs measured displacement relative to a steel plate mounted on top of the load cell.

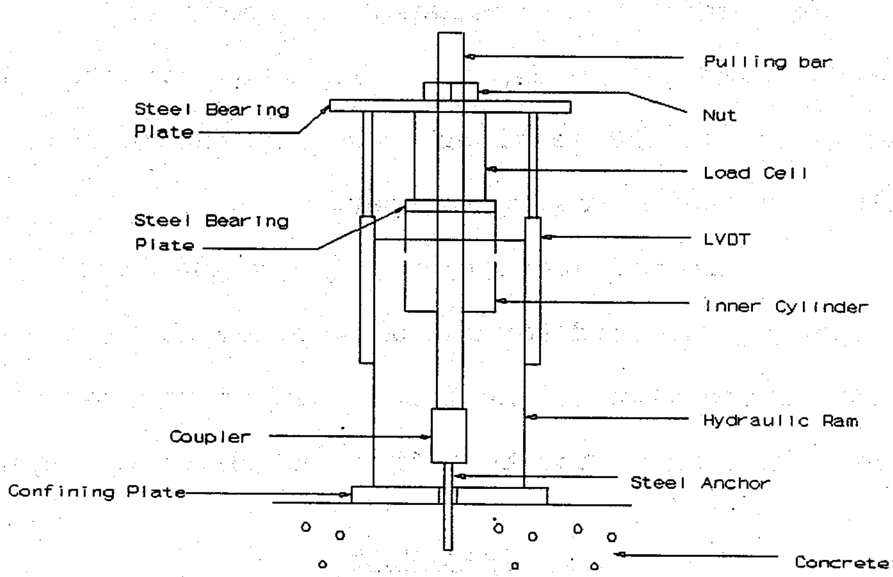


Figure 4-7 Schematic of loading apparatus

Voltages from the load cell and LVDTs were read and recorded by a Hewlett Packard 3497A data acquisition system.

This was connected to a Club 386 personal computer equipped with a Hewlett Packard I/O interface card. A computer program written in Hewlett Packard Basic stored the voltage readings from the data acquisition system in an ASCII file. The ASCII file was read by a spreadsheet program to average the readings from the LVDTs and produce load-deflection plots.

4.3.3 Unconfined Testing

The purpose of unconfined testing was to keep the reaction force away from the adhesive anchor. This was accomplished by the use of an ASTM E488 (1984) type test frame. The frame was designed to support a 100 kip concentrated load at midspan. It was composed of two stiffened 36 in. 12x30 sections acting as the base and two 49in. C10x30 sections as the main span.

The same instrumentation and procedure used for the confined testing was used for the unconfined testing. Instead of using confining plates, the loading apparatus was placed on top of the main span of the test frame as shown in Figure 4-8.

4.4 Test Matrix

A total of 16 adhesives were tested. Each adhesive was subjected to nine confined tests with fully-bonded anchors. These tests served as the baseline tests. Three tests were performed for each anchor diameter. Anchor diameters of 1/2, 5/8, and 3/4 in. were used for each adhesive.

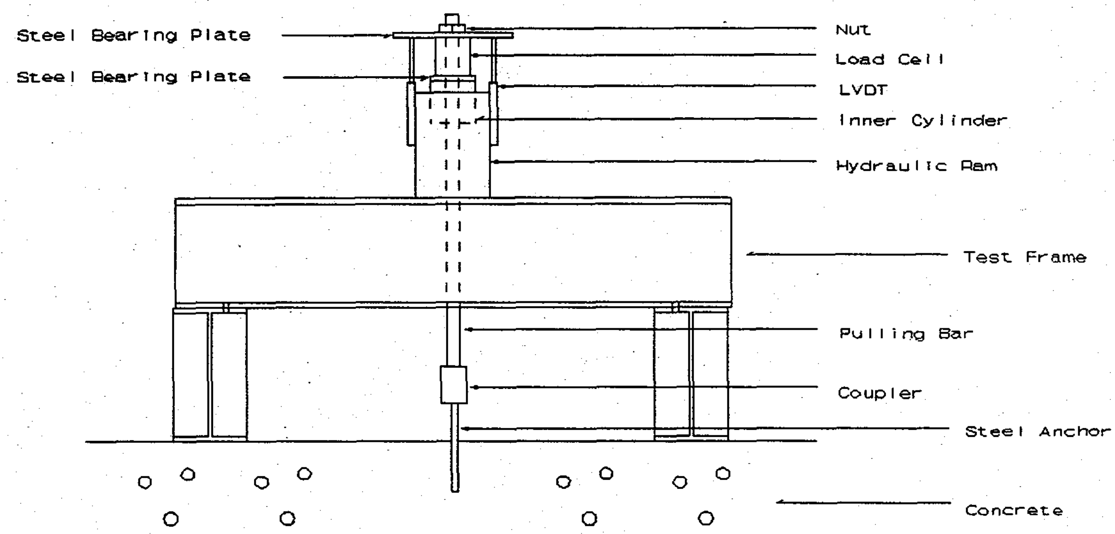


Figure 4-8 Unconfined test setup

Confined testing with partially bonded anchors and unconfined testing with both fully and partially-bonded anchors were performed to compare with the baseline tests.

Individual tests were designated as shown in Figure 4-9. Appendices B and C show the load-displacement plots for all tests.

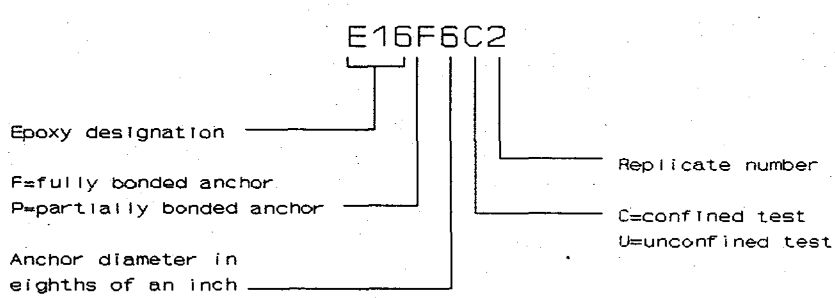


Figure 4-9 Test designation

CHAPTER 5

TEST RESULTS

5.1 General

In this chapter, the failure modes for the adhesive anchors are presented. Comparisons are made between the failure characteristics of the baseline and the non-baseline tests.

5.2 Failure Modes

5.2.1 Confined Testing and Fully-Bonded Anchors

Fully-bonded adhesive anchors subject to confined testing usually experienced a pull-out failure along the concrete adhesive interface. Characteristics of this type of failure consist of an adhesive core without cone formation (Figure 51). Two tests out of the 144 experienced fracture of the steel anchor. In both of these cases, the anchor was 1/2in. in diameter and no displacement of the adhesive was noticeable at the surface of the concrete. Both of these tests were both repeated.

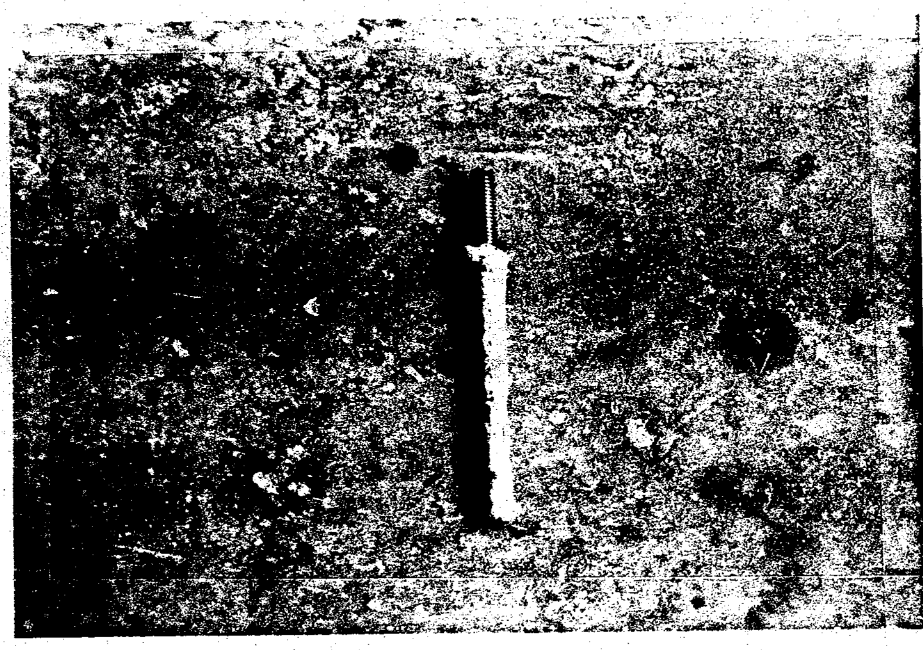


Figure 5-1 Confined test with a fully bonded anchor

5.2.2 Testing with Partially-Bonded Anchors

Nine partially-bonded anchors were subjected to confined testing and compared to the baseline tests. All specimens experienced a pull-out failure along the concrete-adhesive interface (Figure 5-2). As a result of debonding the top 2 in. of the embedded length, the anchor experienced a 19% decrease in tensile strength compared to a fully-bonded anchor of the same length.

Three partially-bonded anchors (3/4 in. diameter) were subjected to unconfined testing. In all 3 cases, the debonding agent was successful in preventing the formation of a concrete cone. These anchors failed along the concrete adhesive interface with the pullout of an adhesive core.

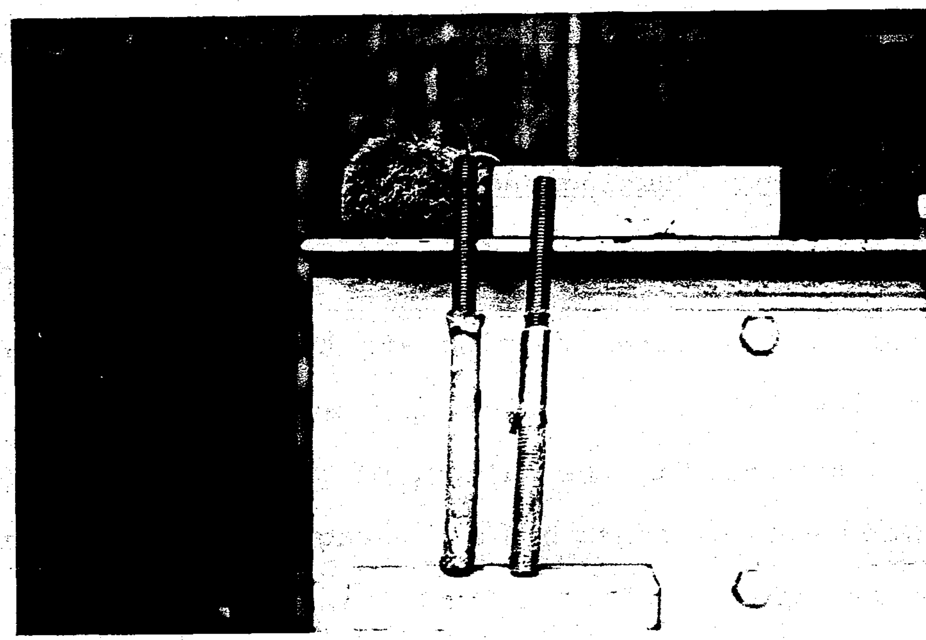


Figure 5-2 Fully-bonded (left) and partially-bonded (right) anchors subject to confined testing

since a cone did not form, the tensile strength of these anchors was most likely due to the bond strength between the adhesive and the concrete. As a result, these anchors were about 6% stronger in tensile loading than fully-bonded anchors subject to unconfined testing.

Both sets of tests involving partially bonded anchors (confined, and unconfined testing) share two important similarities. Neither of the tests experienced the formation of a concrete cone at failure. As a result, the tensile strength of both types of anchors should be governed, by the bond strength of the adhesive. Also, both types of anchors had the same effective embedment length. Test results showed that there was essentially no difference (within 1.5%) in tensile strength between partially bonded anchors subject to confined and unconfined testing.

5.2.3 Unconfined Testing and-Fully-Bonded Anchors

Five fully-bonded anchors (3/4 in. diameter) were subjected to unconfined testing and the results compared to the baseline tests. All five specimens experienced a cone failure accompanied by the pullout of an adhesive core (Figure 5-3). The concrete cones had an average diameter of 8 in. and an average depth of about 1.5 in. The adhesive core failed along the concrete-adhesive interface

As a result of unconfined testing, the tensile strength of the concrete becomes a factor. A 22% decrease in tensile strength (with respect to the baseline tests) was experienced with these tests. Note that this decrease is nearly identical

Figure 5-3 Unconfined testing with a fully bonded anchor

to that obtained with a partially-bonded anchor of the same length.

This agrees with the Texas tests (Doerr et al., 1989) which showed that the strength of a partially-bonded anchor (top 2 in. debonded) is essentially the same as a fully-bonded anchor of the same embedment length.

5.3 Description of Test Data

Data for each test performed was recorded in the form of a load-displacement graph. An example is shown in Figure 5-4. It is important to note that the recorded displacements consist of those due to the test system. The test system includes the adhesive anchor-and the steel pulling rod that it is connected to. The slope of the initial straight line portion of the graph (the region between the circled points on the graph) represents the stiffness of the test system. It was calculated using the regression analysis feature of the spreadsheet. In the example, the stiffness was determined to be 326 kip/in. The linear elastic range of the vinylester based adhesives was not as well defined as with the other products.

The failure load is at the point where the stiffness of the test system begins to decrease (denoted by a circle at the top of the straight line portion of the graph). It can be found by manually extending the straight line portion of the graph for use as a tangent line. The failure load is where

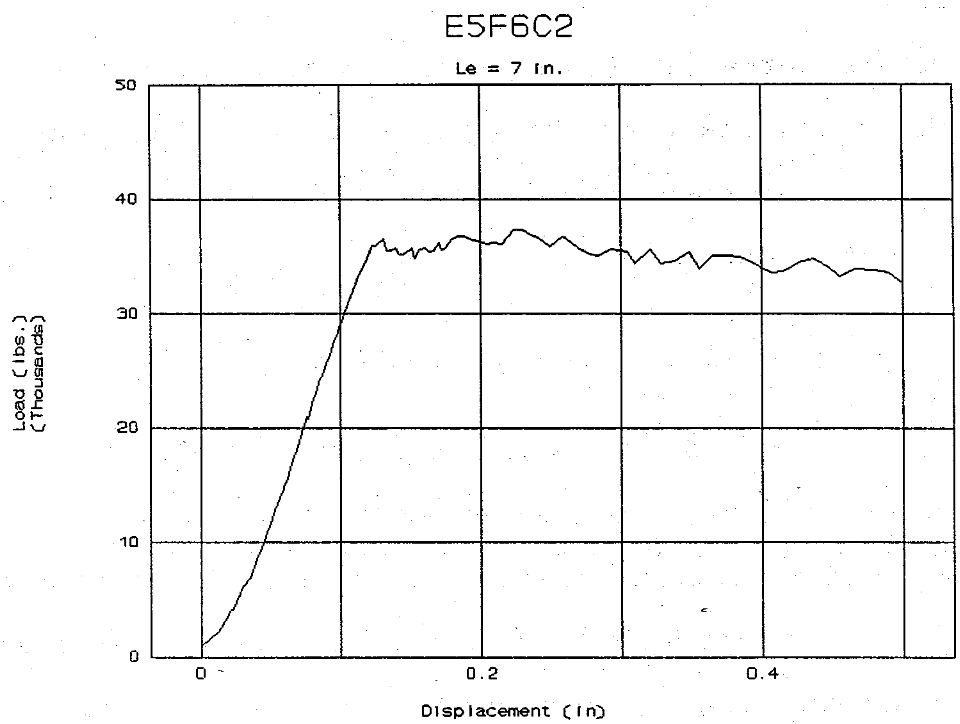


Figure 5-4 Sample load-displacement graph

the slope of graph begins to deviate from the tangent line. In the example, the failure load was determined to be 36 kips. After the failure load, the graph shows additional increases and decreases in tensile strength. Some cases show this strength to increase and some show this strength to decrease. This is a random phenomenon and is mainly due to mechanical interlock of the adhesive anchor and the surrounding concrete. The results for all of the tests are shown in both graphical and tabular form in Appendices B and

CHAPTER 6

BEHAVIORAL MODELS FOR ADHESIVE ANCHORS

6.1 General

Several models have been suggested (Collins et al., 1989) to describe the distribution of bond stress along adhesive anchors. Two such models are the elastic model and the uniform bond stress model. The elastic model satisfies both the compatibility of displacements at the anchor/adhesive interface and equilibrium. The uniform bond stress model is an assumed distribution that only satisfies equilibrium.

6.2 Elastic Model for Adhesive Anchors 6.2.1 Development of Model

The derivation of the elastic solution is based on minimizing of the total energy of the system shown in Figure 6-1. The net energy in the adhesive anchor system is equal to the total internal energy (the strain energy due to both the steel and the adhesive) less the external energy (work due to the applied loading).

The internal energy in the steel is given by

$$II_s = \int_v \sigma\varepsilon dv = \frac{1}{2}\int_0^{\ell}\int_{A_s} \sigma\varepsilon dA dz$$

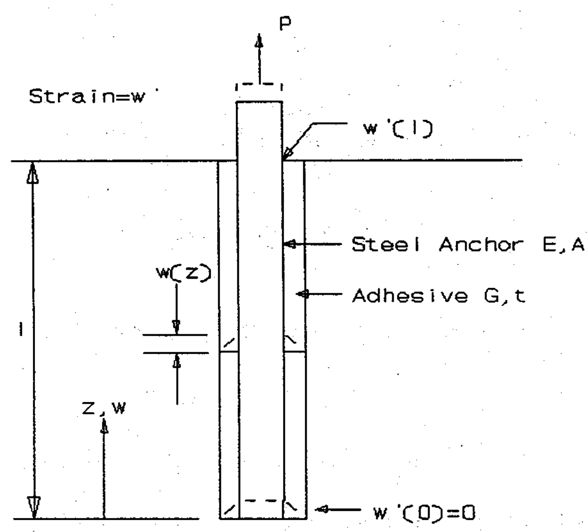


Figure 6-1 Model of adhesive anchor system

where

$$\int_A dA = A$$
$$\varepsilon = w'$$
$$\sigma = \varepsilon E = w' E$$

Therefore, the internal energy of the steel can be expressed as

$$II_s = \frac{1}{2}\int_0^{\ell} EA(w')^2 dz \qquad \text{Eq. 6-1}$$

where

ℓ = embedded length of anchor

E = modulus of elasticity of anchor

A = cross-sectional area of anchor

w' = axial strain in anchor

The internal energy, due to the adhesive is given by

$$\Pi_a = \frac{1}{2}\int_V \tau\gamma dV = \frac{1}{2}\int_0^{\ell}\int_A \tau\gamma dA dz$$

where $$\int_A dA = A_e \cong \pi dt$$

$$\gamma = \frac{w}{t}$$

$$\tau = \gamma G = \frac{w}{t}G$$

Therefore, the internal energy due to the adhesive can be *expressed* by

$$\Pi_a = \frac{1}{2}\int_0^{\ell}\frac{\pi dG}{t}w^2 dz \qquad \text{Eq. 6-2}$$

where

ℓ= embedded length of the adhesive anchor

d = hole diameter

G = shear modulus of the anchor

t = thickness of the adhesive layer

w = axial displacement of the anchor

The external energy of the adhesive anchor system is the work applied to pull the anchor out of the concrete and is given by

$$\Pi_{ext} = Pw(\ell) \qquad \text{Eq. 6-3}$$

where

P = axial load applied to the adhesive anchor

$w(\ell)$ = displacement of the adhesive anchor relative to the surface of the concrete

Therefore, the net energy of the system can be expressed by

$$\Pi_{net} = \frac{1}{2}\int_0^{\ell} EA(w')^2 dz + \frac{1}{2}\int_0^{\ell} \frac{\pi dG}{t} w^2 dz - Pw(\ell)$$

Minimizing the net energy with respect to displacement w yields the controlling differential equation

$$w'' - \frac{\pi dG}{tEA} w = 0$$

Eq. 6-5

By substituting

$$\lambda^2 = \frac{\pi dG}{tEA}$$ Eq.6-6

Eq. 6-5 can be rewritten as

$$w'' - \lambda^2 w = 0$$ Eq. 6-7

Applying boundary conditions and solving Eq. 6-7, yields the following solution:

$$w(z) = \frac{P}{AE\lambda} \frac{\cosh(\lambda z)}{\sinh(\lambda \ell)}$$ Eq. 6-8

The adhesive bond stress at any point *z* along the length of the anchor $\tau(z)$ is related to the anchor displacement *w(z)* by the following equation:

$$\tau(z) = \frac{G}{t} w(z)$$ Eq. 6-9

Substituting Eq. 6-9 into Eq. 6-8 yields the following equation relating axial load and the maximum bond stress at z=1:

$$P = \tau(\ell)\frac{\pi d}{\lambda}\tanh(\lambda\ell) \qquad \text{Eq.6-10}$$

To make Eq.6-10 dependent on the properties of a given adhesive, λ will be replaced with λ', a stiffness parameter which is independent of anchor diameter and specific to the given adhesive. Substituting the net tensile stress area (approximately 75% of the cross-sectional area of the anchor) into Eq.6-6 yields

$$\lambda = \sqrt{\frac{16G}{3tEd}} = \sqrt{C\frac{G}{d}} = \frac{1}{\sqrt{d}}\sqrt{CG} \qquad \text{Eq.6-11}$$

$$\lambda' = \sqrt{CG}$$

$$\lambda = \frac{\lambda'}{\sqrt{d}}$$

Substituting Eq.6-11 into Eq.6-10 and, denoting the maximum bond stress τ (ℓ) as u_{max} results in the final equation relating axial load with the maximum adhesive bond stress.

$$P = u_{\max}\frac{\pi d^{\frac{3}{2}}}{\lambda'}\tanh\left(\frac{\lambda'\ell}{\sqrt{d}}\right) \qquad \text{Eq.6-12}$$

6.2.2 Application of Model to Test Data

Eq.6-12 contains parameters, λ' and u_{max}' that are specific to each adhesive. The two variables were calculated using the data from the baseline (confined and fully bonded) tests for each adhesive.

The variable λ' is a stiffness characteristic specific to each adhesive. Stiffness is the relationship between axial load and displacement of the adhesive anchor and is denoted by

$$k = \frac{P}{w(\ell)}$$

Substituting equations 6-8 and 6-11 yields the following equation:

$$k = \frac{AE\lambda'}{\sqrt{d}} \tanh \frac{\lambda' \ell}{\sqrt{d}} \qquad \text{Eq. 6-13}$$

where

k = stiffness of adhesive anchor

A = effective net tensile area of adhesive anchor

E = modulus of elasticity of anchor

d = hole diameter

ℓ = embedment length (bonded) of adhesive anchor

The product AE was experimentally determined for each anchor diameter. A specimen of each bolt size was axially loaded until failure using a Tinius Olsen testing machine. Load-displacement data was recorded for each test. The displacement was measured over a gage length ℓ_g equal to 2 inches. Noting that the slope of the elastic range in the test data represents the stiffness of the anchor steel, the following equation was used to calculate AE:

$$k = \frac{AE}{\ell_g}$$

The same testing procedure was used to determine the stiffness of the pulling bar k_{pbar}'

The stiffness values

calculated from the baseline test data were the total stiffnesses k_{tot} that included the effects of both the adhesive anchor and the pulling bar. The desired stiffness k could have been determined directly from the test data if anchor displacement had been measured at the surface of the concrete. The following relationship was used to calculate the stiffness of the adhesive anchor k:

$$\frac{1}{k_{tot}} = \frac{1}{k} + \frac{1}{k_{pbar}}$$

where

k_{tot} = stiffness including effects of adhesive anchor and pulling bar

k = stiffness of adhesive anchor

k_{pbar} = stiffness of pulling bar

For each adhesive, an average k value was calculated for each anchor diameter. These values are shown in Table 6-1. Individual values for k_{tot} and k_{pbar} are tabulated in Appendices B and D respectively. The corrected k values were then substituted into Eq. 6-13 to solve for λ' (one value for each anchor diameter). For each adhesive, the values of A' for each-anchor diameter were approximately equal (see Appendix D).

Therefore, an average value of λ' represents each adhesive. The values of λ' for each adhesive: are tabulated in Table 6-1.

These values along with the baseline test data for the maximum axial load P were then substituted into Eq.6-12 to

Table 6-1 Values for k, λ', u_0, and u_{max} for baseline tests

Adh. #	Corrected Stiffness k (kip/in)			λ'	Maximum Bond Stress (ksi)	
	1/2"	5/8"	3/4"		Uniform u_0	Elastic u_{max}
E1	119.6	145.2	220.7	0.0629	1.185	1.244
E2	175.1	174.3	299.0	0.0730	1.451	1.548
E3	145.1	112.7	252.2	0.0634	0.928	0.973
E4	197.7	137.8	271.0	0.0705	1.357	1.445
E5	188.6	294.7	342.8	0.0842	2.123	2.305
E6	216.3	269.7	327.2	0.0840	1.755	1.904
E7	204.0	184.0	286.9	0.0754	1.753	1.881
E8	129.9	161.1	217.7	0.0650	0.907	0.954
E9	150.8	222.5	386.3	0.0780	1.293	1.388
E10	133.0	178.7	280.1	0.0693	1.339	1.419
E11	179.9	282.7	496.6	0.0881	1.972	2.158
E12	229.8	314.1	477.1	0.0930	1.905	2.101
E13	99.5	105.7	132.0	0.0530	1.253	1.273
E14	84.8	69.5	78.6	0.0443	1.153	1.168
E15	268.3	296.6	490.0	0.0949	1.795	1.984
E16	182.6	228.9	286.4	0.0772	1.287	1.379

determine the values for each adhesive's maximum bond stress u_{max} (one value for each anchor diameter). As shown in Appendix D, the values of u_{max} for' each anchor diameter were approximately equal for a given adhesive. Therefore, an average value of u_{max} represents each adhesive. The values of u_{max} for each adhesive are tabulated in Table 6-1.

6.3 Uniform Bond Stress Model

6.3.1 Development of Model

A uniform bond stress distribution relates a tensile load to the product of a bond stress and a surface area. This relation is given by the following equation:

$$P = u_o \pi d \ell \qquad \text{Eq.6-14}$$

where:

P = maximum axial load applied to adhesive anchor at failure

u_o = maximum bond stress of adhesive based on the uniform distribution

d = hole diameter

ℓ = embedment length of adhesive anchor

Values: of u_o were determined from the maximum load P obtained before anchor slip (:see Table 6-1).

6:3.2 Application of Model to Test Data

In order to verify that the uniform bond stress model is acceptable, the elastic analysis of Section 6.2 was used to compute the ratio of the bond stress at the bottom of the adhesive anchor u (O) at failure to u_{max}. By substituting Eqs.6-8 and 6-11 into Eq.6-9, the following equation is obtained to calculate u(0):

$$u(o) = \frac{P\lambda'}{\pi d^{\frac{3}{2}}} \frac{1}{\sinh\left(\frac{\lambda' \ell}{\sqrt{d}}\right)} \qquad \text{Eq.6-15}$$

Dividing Eq.6-15 by- Eq.6-12 yields the following relationship between u(0) and u_{max}

$$\frac{u(o)}{u_{\max}} = \frac{1}{cash\left(\frac{\lambda' \ell}{\sqrt{d}}\right)} \qquad \text{Eq.6-16}$$

where the variables are as defined in Section 6.2.

Calculating the- ratios of u(0) to u_{max} revealed that the bond stresses of the adhesive anchors approximate a uniform distribution. Values are shown in Table 6-2. Substituting values for f, d, and A into Eq.6-16 reveals that u(0) /u_{max} ≥ 0.80 for $\ell/\sqrt{d} \leq$ 10. The bond stress distribution becomes closer to a pure uniform distribution as $\ell / \sqrt{d}$ decreases.

6.4 Comparison of: Models: to Test Results

6.4.1 Elastic Model

Equation 6-12 was able to -calculate the anchor capacities of the baseline tests within an average of 11.6% of the experimental values. A summary of results is presented in Table 6-3. This accuracy should be no surprise since the values of λ' and u_{max} are based on the data from the baseline tests.

Table 6-2 Ratio of u(0) to u_{max} obtained from the elastic model for baseline tests

Adhesive Desig.	$u(0)/u_{max}$		
	1/2"	5/8"	3/4"
E1	0.92	0.97	0.90
E2	0.89	0.96	0.87
E3	0.92	0.97	0.90
E4	0.90	0.96	0.88
E5	0.86	0.94	0.83
E6	0.86	0.94	0.83
E7	0.88	0.96	0.86
E8	0.91	0.97	0.89
E9	0.88	0.95	0.85
E10	0.90	0.96	0.88
E11	0.85	0.94	0.82
E12	0.83	0.93	0.80
E13	0.97	0.99	0.97
E14	0.98	0.99	0.97
E15	0.83	0.93	0.79
E16	0.88	0.95	0.85

other tests were performed that were not associated in the determination of λ' and u_{max}. These tests implemented different embedment lengths, fully and partially bonded anchors, and both confined and unconfined testing. Eq.6-12 calculated the capacity of these anchors within an average of

7.2% of the experimental values. The results of these tests are summarized in Tables 6-4, 6-5, 6-6, and 6-7.

It is apparent from these results that the elastic model can be used to predict the tensile capacity of any adhesive anchor regardless of anchor diameter and embedment length.

6.4.2 Uniform Bond Stress Model

The uniform bond stress distribution (Eq.6-14) was able to calculate the anchor capacities of the baseline tests within an average of 13.1% of the experimental values. A summary of results is presented in Table 6-3. This correlation could be due to the fact that the values of u_o are based on the data from the baseline tests.

Other tests were performed that were not associated in the determination u_o. These tests implemented different embedment lengths, fully and partially bonded anchors, and both confined and unconfined testing. Eq.6-14 calculated the capacity of these anchors within an average of 12.2% of the experimental values. The results of these tests are summarized in Tables 6-4, 6-5, 6-6, and-6-7.

Table 6-3 Experimental vs. calculated anchor capacities for baseline tests

Adhes. Desig.	Anchor Dia. (in.)	Embed. Length (in.)	P_{calc}/P_{exp} Uniform	P_{calc}/P_{exp} Elastic
E1	0.5	5	1.10	1.09
	0.625	3.5	0.95	0.97
	0.75	7	0.97	0.95
E2	0.5	5	0.86	0.86
	0.625	3.5	1.01	1.05
	0.75	7	1.17	1.14
E3	0.5	5	1.14	1.13
	0.625	3.5	0.82	0.84
	0.75	7	1.12	1.09
E4	0.5	5	0.78	0.78
	0.625	3.5	1.19	1.24
	0.75	7	1.14	1.11
E5	0.5	5	1.14	1.13
	0.625	3.5	0.84	0.88
	0.75	7	1.06	1.02
E6	0.5	5	0.89	0.88
	0.625	3.5	0.89	0.93
	0.75	7	1.32	1.27
E7	0.5	5	1.03	1.02
	0.625	3.5	1.00	1.05
	0.75	7	0.93	0.90
E8	0.5	5	0.84	0.83
	0.625	3.5	0.93	0.96
	0.75	7	1.36	1.33

Table 6-3--continued

Adhes. Desig.	Anchor Dia. (in.)	Embed. Length (in.)	P_{calc}/P_{exp} Uniform	Elastic
E9	0.5	5	1.10	1.09
	0.625	3.5	0.85	0.88
	0.75	7	1.09	1.06
E10	0.5	5	1.14	1.13
	0.625	3.5	0.88	0.91
	0.75	7	1.01	0.99
E11	0.5	5	1.12	1.10
	0.625	3.5	0.86	0.90
	0.75	7	1.06	1.02
E12	0.5	5	1.07	1.05
	0.625	3.5	0.83	0.88
	0.75	7	1.16	1.11
E13	0.5	5	1.02	1.02
	0.625	3.5	0.98	0.99
	0.75	7	1.00	0.99
E14	0.5	5	0.94	0.94
	0.625	3.5	0.99	1.00
	0.75	7	1.08	1.07
E15	0.5	5	1.08	1.06
	0.625	3.5	0.80	0.84
	0.75	7	1.22	1.16
E16	0.5	5	1.51	1.49
	0.625	3.5	0.79	0.82
	0.75	7	0.92	0.89

Table 6-4 Experimental vs. calculated capacities for unconfined testing with fully-bonded anchors

Adhes. Desig.	Anchor Dia. (in.)	Embed. Length (in.)	P_{calc}/P_{exp}	
			Uniform	Elastic
E1	0.75	7	0.87	0.87
E2	0.75	7	1.08	1.09

Table 6-5 Experimental vs. calculated capacities for unconfined testing with partially-bonded anchors (2 in. bond-breaker)

Adhes. Desig.	Anchor Dia. (in.)	Embed. Length (in.)	P_{calc}/P_{exp}	
			Uniform	Elastic
E2	0.75	5	1.02	1.03

Table 6-6 Experimental vs. calculated capacities for confined testing with partially-bonded anchors (2 in. bond-breaker)

Adhes. Desig.	Anchor Dia. (in.)	Embed. Length (in.)	P_{calc}/P_{exp}	
			Uniform	Elastic
E2	0.5	5	0.76	0.78
E2	0.625	6	1.00	1.03
E2	0.75	7	1.10	1.12

Table 6-7 Experimental vs. calculated capacities for confined testing with fully-bonded anchors (not included in baseline tests)

Adhes. Desig.	Anchor Dia. (in.)	Embed. Length (in.)	P_{calc}/P_{exp}	
			Uniform	Elastic
E2	0.625	6	1.17	1.15
E3	0.625	6	0.88	0.85

CHAPTER 7 DISCUSSION OF RESULTS

7.1 General

In actual situations, the adhesive anchors will not be fully confined. Therefore, the results of the baseline tests need to be adjusted for unconfined loading in practical applications.

7.2 Design Procedures

7.2.1 Effective Embedment Length

Fully-bonded adhesive anchors subject to unconfined loading were among the tests, that were not included in the baseline tests. This situation represents that which is most commonly experienced in practical use. The failure mode of these anchors consisted of the formation of a concrete cone with an average depth of approximately 2 in. followed by the pullout of an adhesive core. This was the same result as observed in the tests performed at the University of Texas (1989b).

As a result, an effective bond length ℓ_e equal to the total embedment length ℓ minus 2 in. should be substituted into Eqs.6-12 and 6-14 for ℓ.

By making this substitution, both Eqs.6-12 (the elastic model) and 6-14 (the uniform bond stress model) were able to predict the tensile capacity of the unconfined, fully-bonded anchors within average of 11% of their experimental values.

7.2.2 Bond Stress Distribution

The elastic solution given by Eq.6-12 provided the best prediction of adhesive anchor capacity. However, the uniform bond stress distribution (Eq.6-14) predicted anchor capacities that were extremely close to those calculated with the elastic solution

As discussed in Chapter 6, an elastic analysis revealed that the bond: stress of the adhesive anchor approximately followed a uniform distribution for $\ell / \sqrt{d} \leq 10$. Therefore, the uniform bond stress distribution given by Eq.6-14 is recommended for design purposes (when applicable) due to its ease of use.

7.2.3 Capacity Reduction Factors

For design purposes, reduction factors should be used with Eqs.6-12 and 6-14 to ensure that the calculated anchor capacity does not exceed the actual anchor capacity. Data from 144 baseline tests was used to investigate Φ factors.

For Φ=0.80, 92% of the experimental capacities exceed their respective calculated capacities for both the elastic and uniform solutions. When Φ=0.75, 98% of the experimental capacities for the elastic model and 96% of those for the uniform bond stress model exceed their respective calculated capacities. For design, Φ=0.80 is recommended. This is the same as that recommended by the results of the tests performed at the University of Texas (Doerr et al., 1989).

7.3 Qualification of Products

A qualification specification based on static testing of fully-bonded confined adhesive anchors can be used not only to determine which products should be accepted or rejected but also to determine structural properties specific to each adhesive. Therefore, the designer will be able to specify an adhesive product for structural anchors based on either a lower-bound bond stress that all qualified products must achieve or a higher bond stress that only certain products can achieve.

The qualification specification for structural adhesives requires that values for u_o, u_{max}, and λ' be determined for each product. Based on the value of u_a, the adhesive will fall into one of four classes. The classes are arranged as follows: Class I for $u_o \geq$ 1700 psi (upper 25% of products tested, mean + 0.67 standard deviations), Class II for $u_o \geq$ 1450 psi (upper 50% of products tested), Class III for $u_o \geq$ 1200 psi (upper 75% of products tested, mean - 0.67 standard deviations), and Class IV for u_o $\geq$ 900 psi. An adhesive shall be rejected if u_o < 900 psi.

Use of a qualified product would guarantee a value of u_o greater than or equal to 900 psi. If a higher maximum bond stress is required, an adhesive with the appropriate classification may be used to meet the design criteria. Higher bond strengths may be specified if required.

A sample qualification specification is given in Appendix E. Note that this specification does not include other factors that need to be incorporated. Such factors include the effects of confinement, hole orientation, elevated temperatures, wet installation, concrete strength, different aggregates, and long term loading.

CHAPTER 8

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

8.1 Summary

The purpose of this project was to study the tensile behavior of adhesive bonded anchors subjected to static loading. A total of 167 tests were performed involving three rod diameters and 16 adhesives. Load-displacement data was collected for each test.

A series of confined, fully-bonded baseline tests were used to determine the basic behavior of the adhesive anchor system Failure of the confined, fully-bonded anchors was characterized by the pullout of an adhesive core along the concrete-adhesive interface.

Other tests were performed for comparison with the baseline tests. These consisted of unconfined tests with both fully and partially-bonded anchors and confined tests with partially-bonded anchors. All tests involving partially bonded anchors experienced failures characterized by the pullout of an adhesive core along the concrete-adhesive interface. The unconfined tests with fully-bonded anchors experienced a shallow concrete cone failure coupled with the pullout of an adhesive core along the concrete-adhesive interface.

The test results were used to evaluate two bond stress models for the adhesive anchor system. One model was based on a bond stress distribution obtained from an elastic analysis of the anchor system. The second model was based on a uniform bond stress distribution.

8.2 Design Recommendations

For the typical condition of an unconfined fully-bonded anchor, the design capacity can be determined by the following equations based on the value of $\ell / \sqrt{d}$.

For $\ell / \sqrt{d} \leq 10$, the following equation may used to calculate anchor capacity:

$$P = \Phi u_o \pi d(\ell - 2)$$

For $\ell / \sqrt{d} > 10$, the following equation may used to calculate anchor capacity:

$$P = \Phi u_{\max} \frac{\pi d^{\frac{3}{2}}}{\lambda'} \tanh\left(\frac{\lambda'(\ell - 2)}{\sqrt{d}}\right)$$

where:

ℓ = embedded length of the adhesive anchor (in.)

d = diameter of hole (not to exceed anchor diameter + 1/8 in.) In both cases, $\Phi = 0.80$.

The properties u_o, u_{max}, and λ’ are determined from tests as instructed in the Qualification Specification (Appendix E).

less than 3 in. should be avoided. Also, to prevent splitting, adhesive anchors should be installed at least 3 in. from the edge of the concrete.

8.3 Conclusions

Based on the results reports herein, the' following conclusions have been drawn:

1) Tensile capacities predicted by the elastic solution (Eq.6-1,2) best fit the test data, but the uniform bond stress distribution (Eq.6-14) also provides acceptable results.
2) The elastic solution demonstrated that the actual adhesive bond -stress follows an approximate uniform distribution for typical anchor diameters and embedment lengths.
3) Anchor capacities fell short of those recorded from comparable tests performed at the University of Texas (Doerr et al., 1989). Both sets of tests used concrete of the same specified and actual compressive strengths. Therefore, other factors relating to the concrete mix (such as the aggregate) may influence the behavior of adhesive anchors in concrete. It should be noted that the Texas tests recorded ultimate tensile loads as opposed to the failure-loads described in Chapter 5. In many cases these are not the same:
4) Variations- in maximum bond stress exist among the various adhesive products.

5) A sample product qualification specification based on the results of this study is contained in Appendix E. It is recommended that all products tested during the course of this research project be accepted as qualified products. The parameters u_o, u_{max}, and λ' for each product are given in Table 6-1.

8.4 Recommendations for Further Research

The following research is recommended to be performed and compared to the results of this project:

1) Investigate the effects of using a different concrete mix design with the same compressive strength (i.e. use different types of aggregate).
2) Investigate the effects of using concrete mixes with higher and lower compressive strengths¯ and different aggregates.
3) Test larger diameter anchors.
4) Investigate the effects of confining the adhesive anchors.
5) Investigate the effects of moisture in the drilled holes prior to anchor installation.
6) Investigate the effects of different hole orientations (i.e. horizontally installed anchors).
7) Investigate the effects of elevated temperatures.
8) Investigate the effects of long term loading.

APPENDIX A

LIST OF ADHESIVES USED FOR TESTING

The following adhesives (with their respective designations) were tested in this project:

El Covert Operations, Covert Injection Adhesive Gel (CIA Gel, epoxy-amine based)

E2 ITW-Ramset, Epcon C6 Injection System (epoxymercaptan based)

E3 ITW-Ramset, Epcon G4 Injection System (epoxyamine based)

E4 Molly Parabound Capsule System (polyester based)

E5 Molly Paramount HVC Injection System (epoxymercaptan based)

E6 Molly Parapoxy Injection System (epoxy-amine based)

E7 Hilti HEA Capsule System (vinylester based) E8 Gunnebo (U.S.E. Diamond) 392T Grout Pump (polyester based)

E9 Gunnebo (U.S.E. Diamond) 392 Grout Pouch (polyester based)

E10 Gunnebo (U.S.E. Diamond) 392E Epoxy (epoxyamine based)

Ell Ackerman-Johnson, Poly-All PAC 12 (epoxymercaptan based)

E12 Ackerman-Johnson, Poly-All PAC 24 (epoxy-amine based)

E13 Hilti HIT C-100 (vinylester based)

E14 Rawl, Chem-Fast Injection (vinylester based)

E15 Sika-Ravel, Foil-Fast Slow Set (epoxy-amine based)

E16 Sika-Ravel, Foil-Fast Fast Set (epoxy-amine based)

APPENDIX B

TABULATION AND-GRAPHS-FOR BASELINE TEST DATA

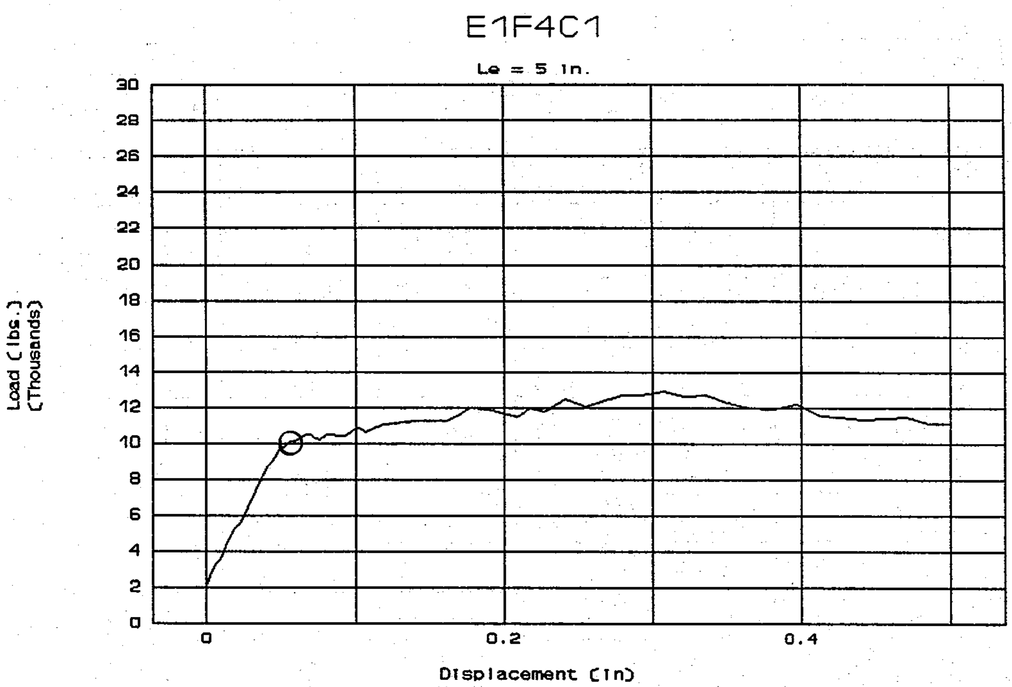
The baseline tests consist of fully-bonded anchors subjected to confined testing. The tests are designated as described in Chapter 4.

Table B-1 Tabulation of baseline test results

Adh. #	Anch. Dia. (in)	P_{exp} (kips) Trial Desig. 1	2	3	k (kips/in) Trail Desig. 1	2	3
E1	1/2	10.13	8.99	9.43	149.67	90.08	112.75
	5/8	12.36	8.52	10.12	127.00	126.68	172.80
	3/4	25.21	24.61	20.90	214.76	211.97	214.42
E2	1/2	14.77	14.95	14.74	189.67	176.52	145.95
	5/8	11.47	12.55	11.53	161.46	205.45	142.97
	3/4	25.20	23.56	22.72	287.80	291.49	279.76
E3	1/2	5.58	8.02	7.94	105.41	163.37	157.43
	5/8	5.51	6.44	9.43	75.75	92.59	164.33
	3/4	14.51	13.28	20.07	230.17	240.59	258.49
E4	1/2	16.89	15.75	13.38	206.07	180.63	189.66
	5/8	8.69	9.17	10.32	142.24	113.50	149.42
	3/4	25.86	21.44	21.70	277.56	252.97	251.01
E5	1/2	15.97	16.96	16.25	176.01	174.87	199.44
	5/8	21.35	20.64	20.33	297.83	244.54	304.78
	3/4	39.43	35.89	39.92	328.34	326.21	324.23
E6	1/2	17.38	17.64	17.16	183.71	232.29	212.71
	5/8	15.34	13.20	20.01	252.44	228.94	296.75
	3/4	25.55	27.15	24.37	308.59	296.08	331.68
E7	1/2	13.59	13.88	15.70	170.54	212.75	210.74
	5/8	12.29	13.88	16.96	143.23	182.81	211.40
	3/4	38.18	36.30	34.37	281.87	295.02	248.75
E8	1/2	10.00	9.76	8.31	118.93	134.66	128.87
	5/8	7.68	9.01		158.82	155.85	
	3/4		12.99	12.07		173.67	256.24

Table B-1--continued

Adh. #	Anch. Dia. (in)	P_{exp} (kips) Trial Desig. 1	2	3	k (kips/in) Trail Desig. 1	2	3
E9	1/2	9.01	9.95	12.05	142.43	146.97	153.21
	5/8	10.30	13.33	14.16	219.25	235.22	191.67
	3/4	23.29	21.74	23.19	332.65	382.14	418.26
E10	1/2	10.26	11.68	9.19	136.96	148.78	105.56
	5/8	13.52	11.14	12.99	184.41	159.43	178.55
	3/4	26.40	25.76	24.14	272.49	228.13	306.14
E11	1/2	15.64	14.60	16.47	201.59	155.77	176.59
	5/8	18.35	19.36	18.97	276.33	268.75	289.05
	3/4	35.07	36.76	35.73	485.65	497.18	464.40
E12	1/2	15.25	14.24	15.77	338.73	257.22	196.32
	5/8	19.35	18.71	18.57	265.67	316.90	342.60
	3/4	32.88	32.04	29.87	527.99	468.04	396.05
E13	1/2	12.50	9.55	10.56	52.51	42.71	31.03
	5/8	9.16	11.12	11.28	32.86	48.52	41.51
	3/4	20.61	32.05	19.76	41.81	90.58	83.09
E14	1/2	12.10	10.22	10.15	44.59	41.28	26.04
	5/8	9.07	10.19	9.62	21.80	25.07	36.46
	3/4	19.64	17.09	24.92	57.19	72.95	70.08
E15	1/2	15.31	15.00	13.72	346.35	288.52	181.85
	5/8	20.47	18.16	17.09	279.68	303.25	302.74
	3/4	32.14	23.28	29.61	472.27	427.02	529.29
E16	1/2	7.30	7.22	8.08	139.43	179.57	223.06
	5/8	8.09	16.19	15.92	176.45	289.59	211.48
	3/4	26.00	25.14	28.75	243.18	345.49	256.35


E1F4C1
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
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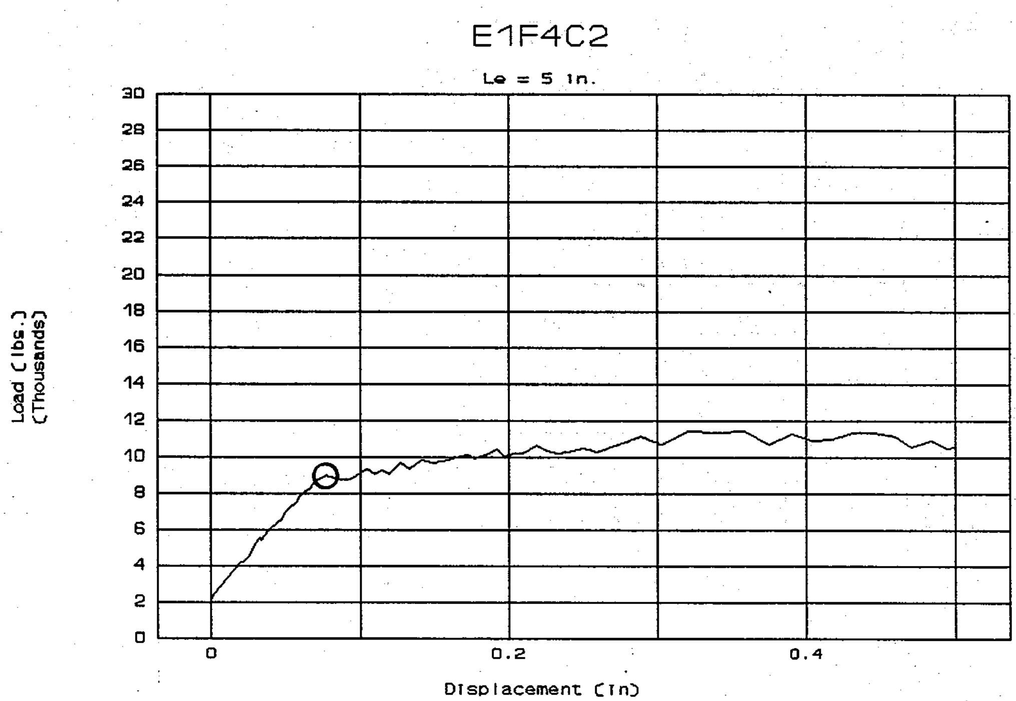
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)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Load (lbs.)
(Thousands)
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10
8
6
4
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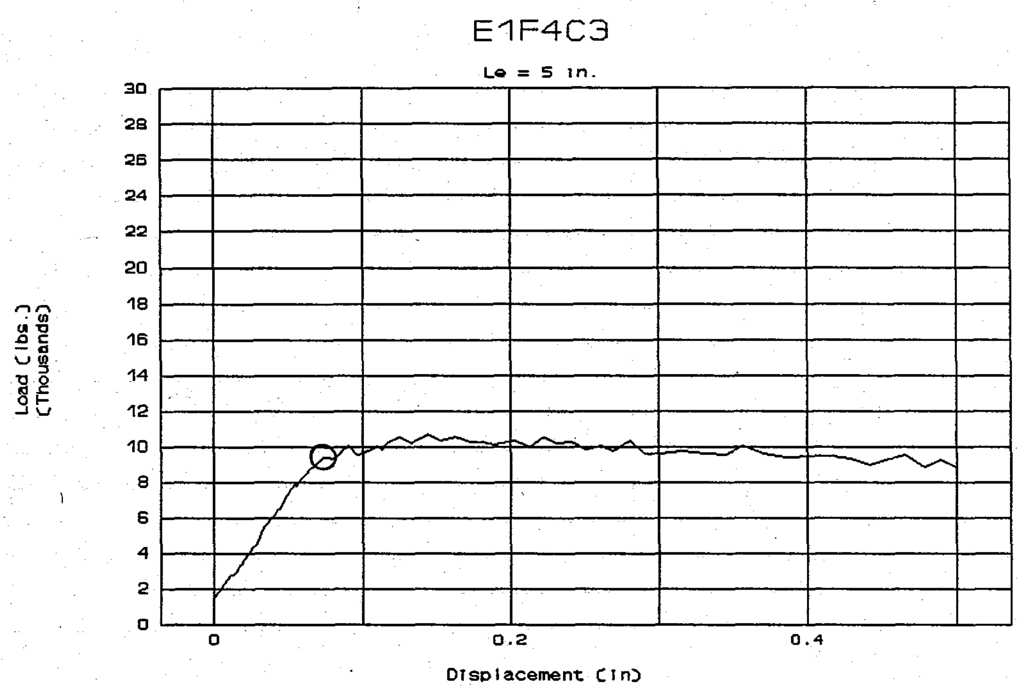
0
0.2
0.4
Displacement (in)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(Thousands)
Displacement (in)
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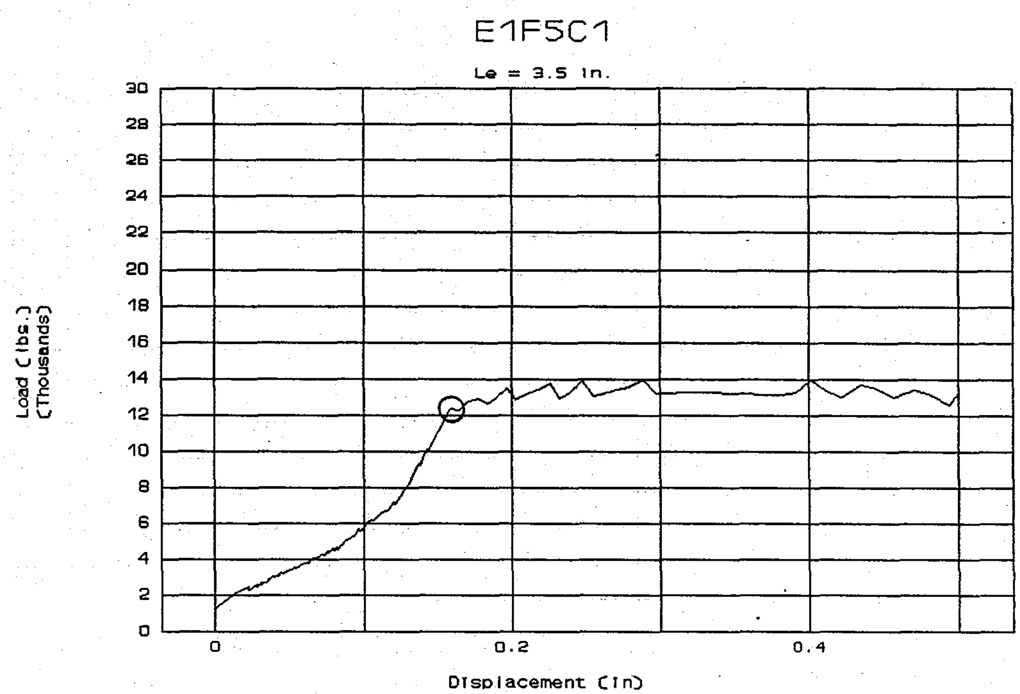
8
6
4
2
0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Load (lbs.)
(Thousands)
Displacement (in)
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0.2
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22
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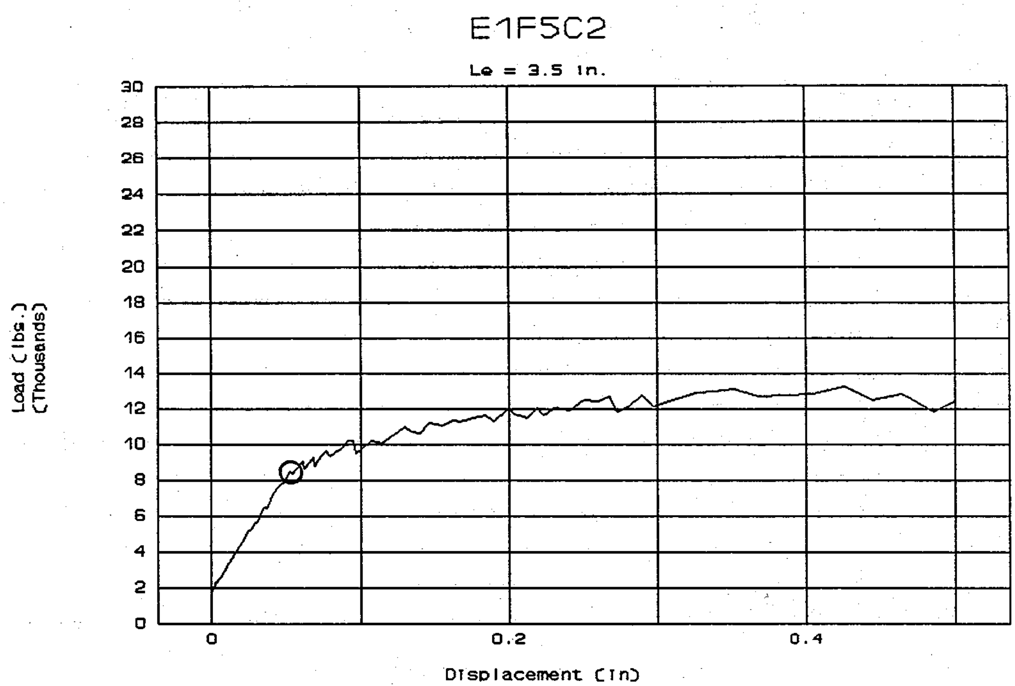
6
4
2
0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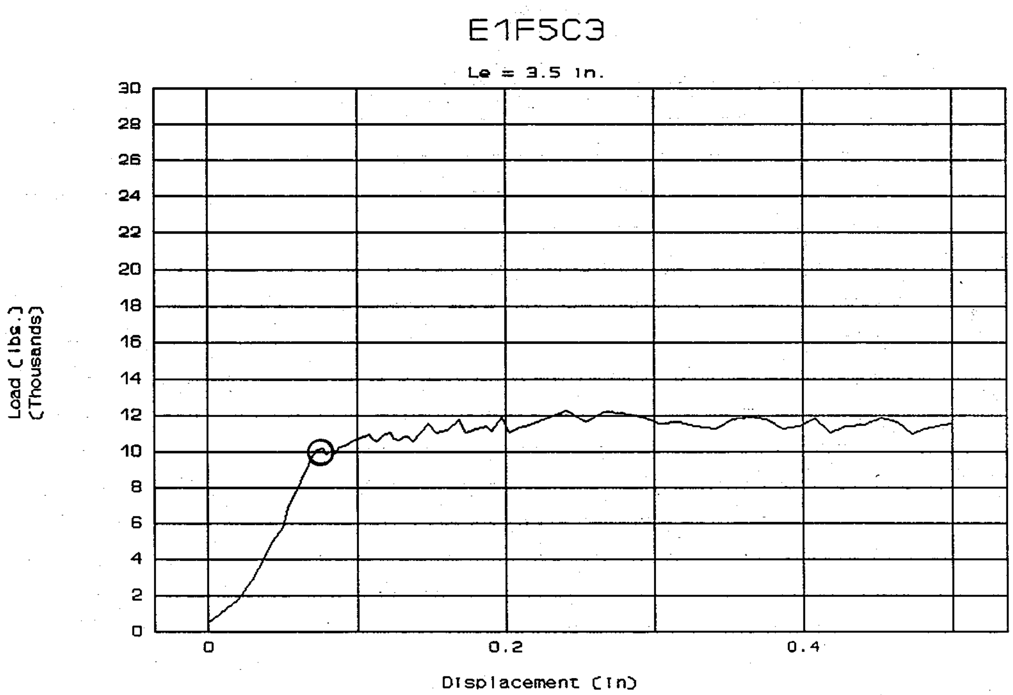
0.4
Displacement (in)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(Thousands)
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8
6
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2
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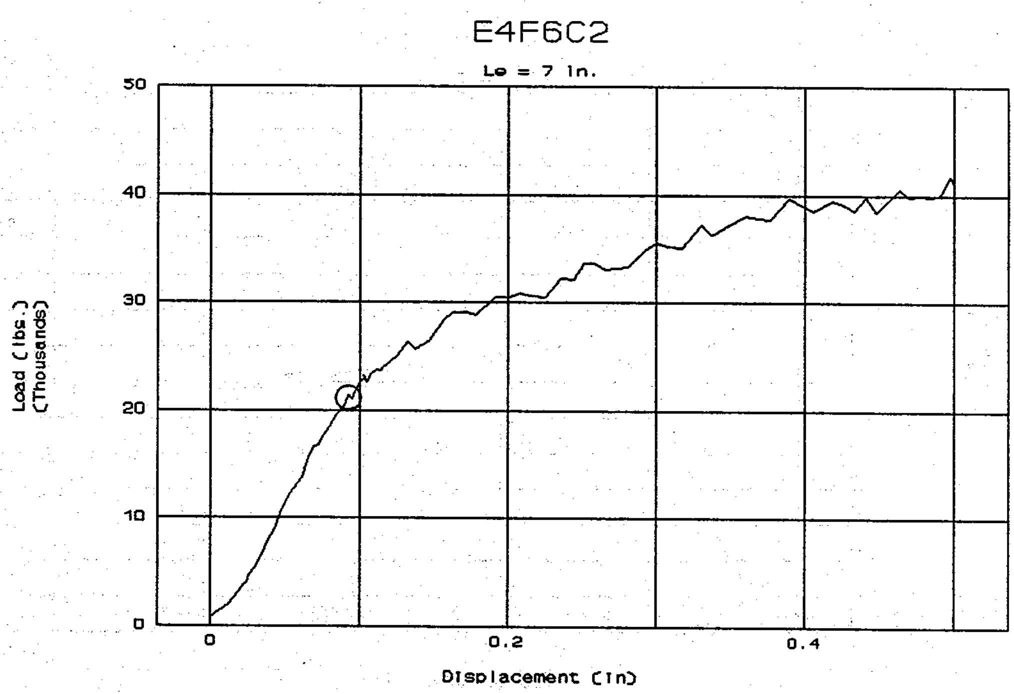
0.2
0.4
Displacement (in)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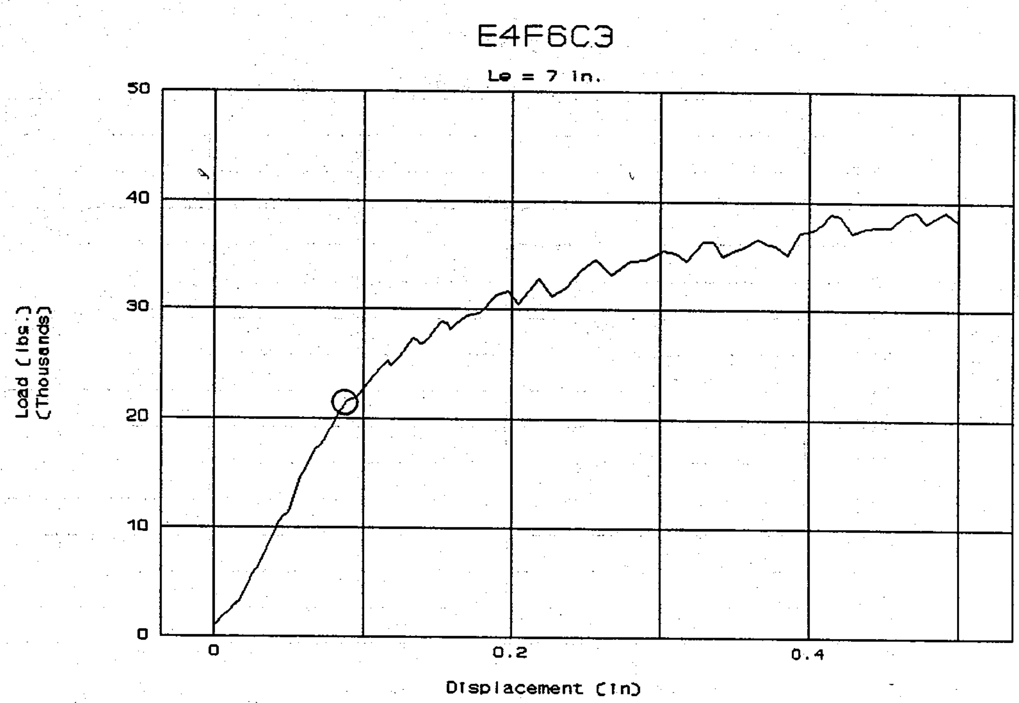
0.4
Displacement (in)


E4F6C3
Le = 7 in.
Load (lbs.)
(Thousands)
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10
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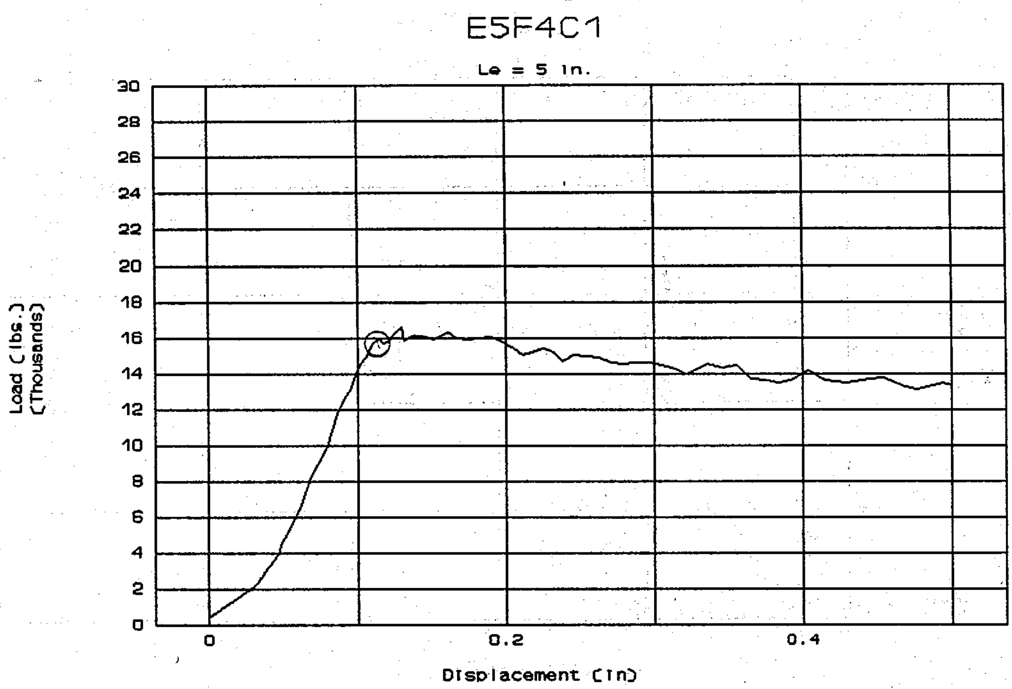
0.2
0.4
Displacement (in)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Displacement (in)
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0.4
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26
24
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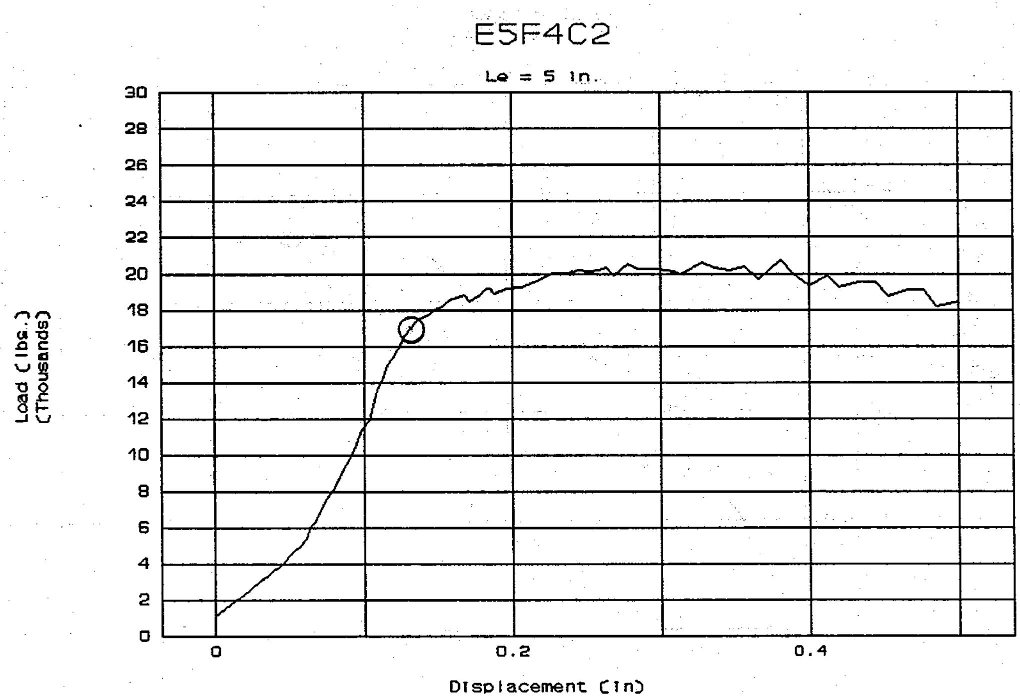
6
4
2
0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Load (lbs.) (Thousands)
Displacement (in)
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0.4
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24
22
20
18
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14
12
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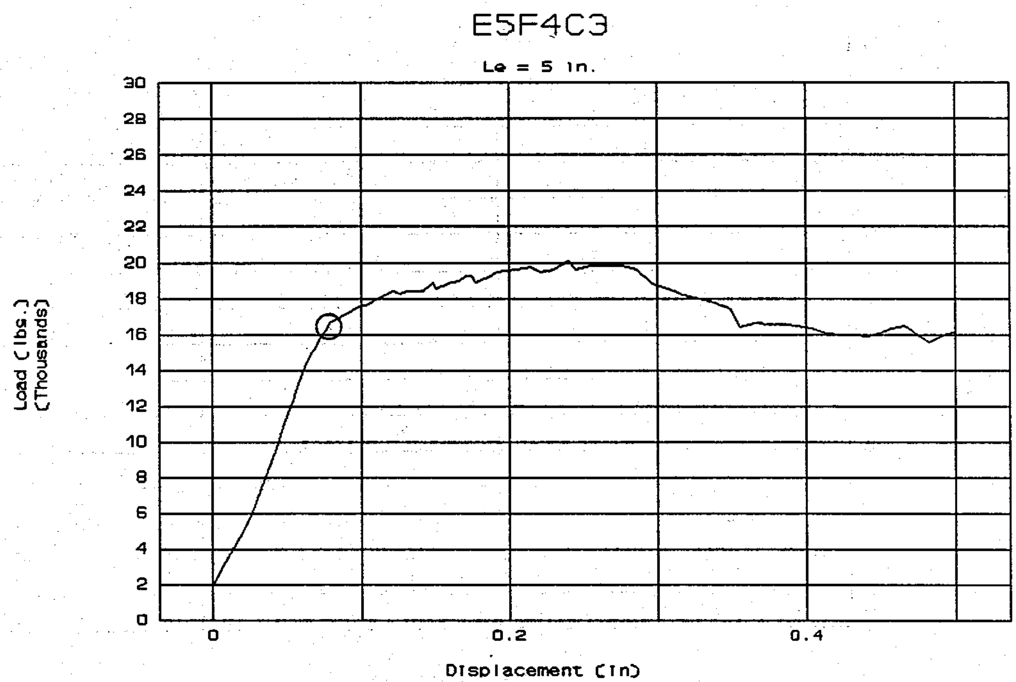
2
0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Load (lbs.)
(Thousands)
Displacement (in)
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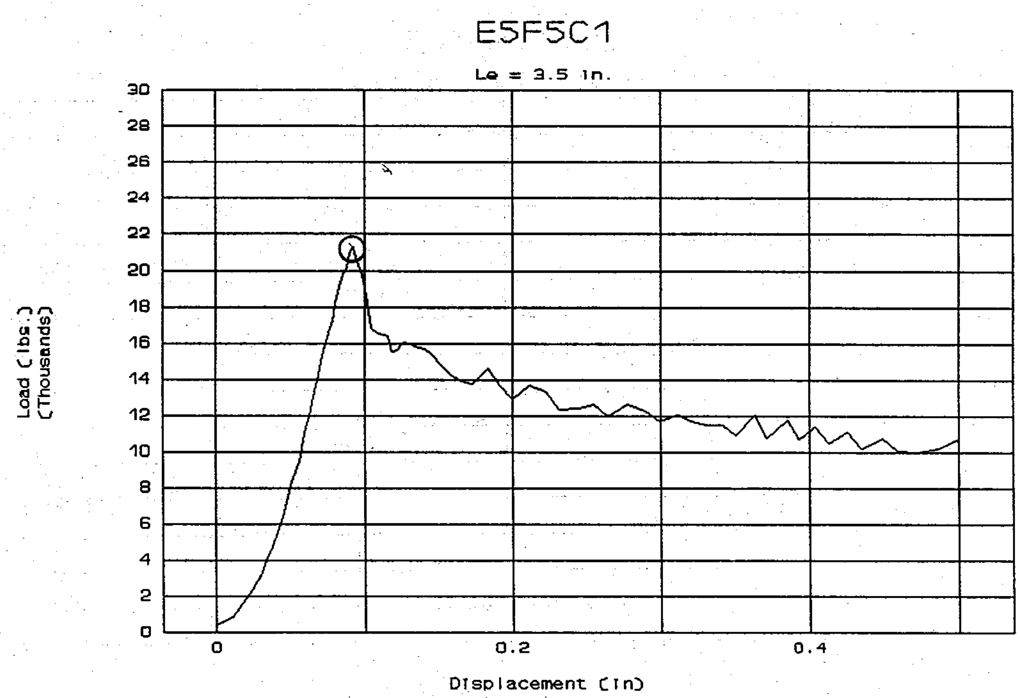
6
4
2
0


E5F5C1
Le = 3.5 in.
Load (lbs.)
(Thousands)
Displacement (in)
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0.4
30
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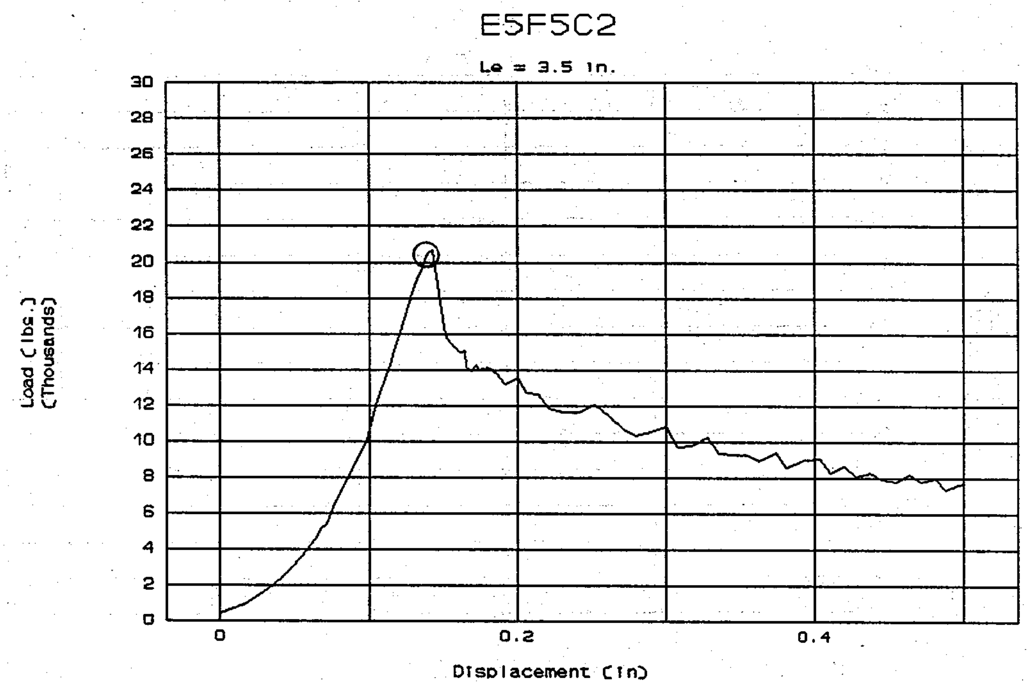
0


E5F5C2
Le = 3.5 in.
Load (lbs.)
(Thousands)
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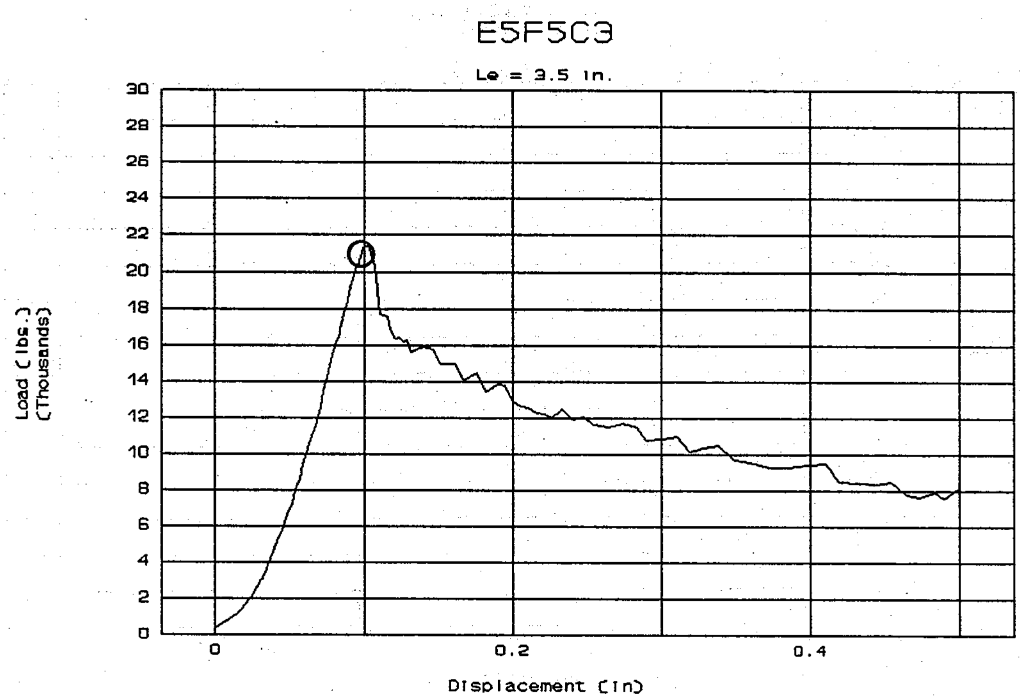
0
0.2
0.4
Displacement (in)


E5F5C3
Le = 3.5 in.
Load (lbs.)
(Thousands)
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28
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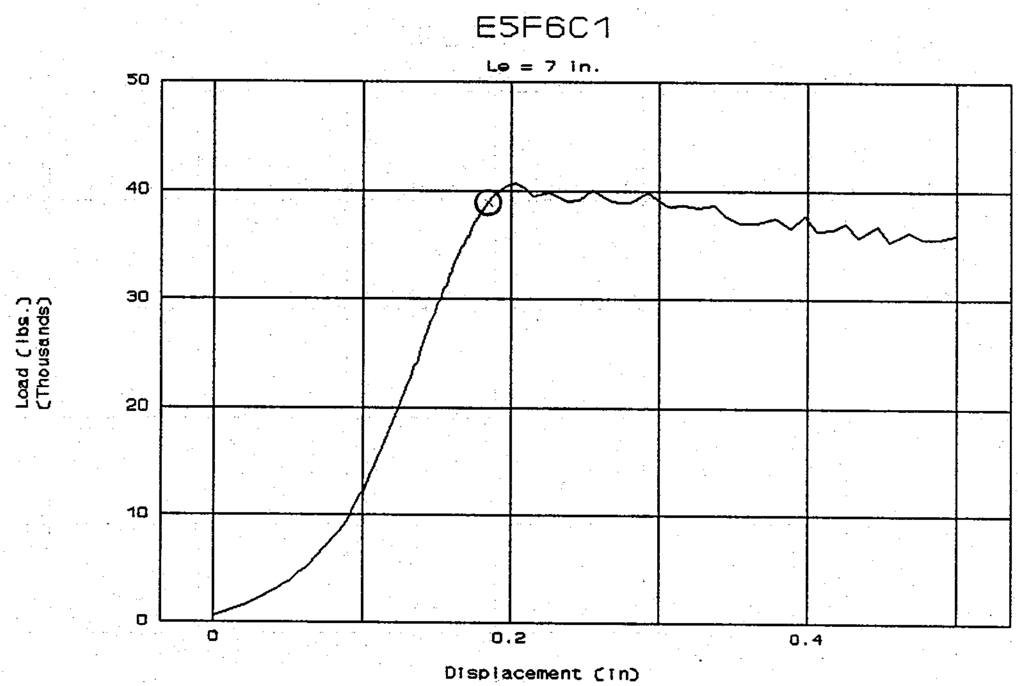
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E5F6C1
Le = 7 in.
Load (lbs.) (Thousands)
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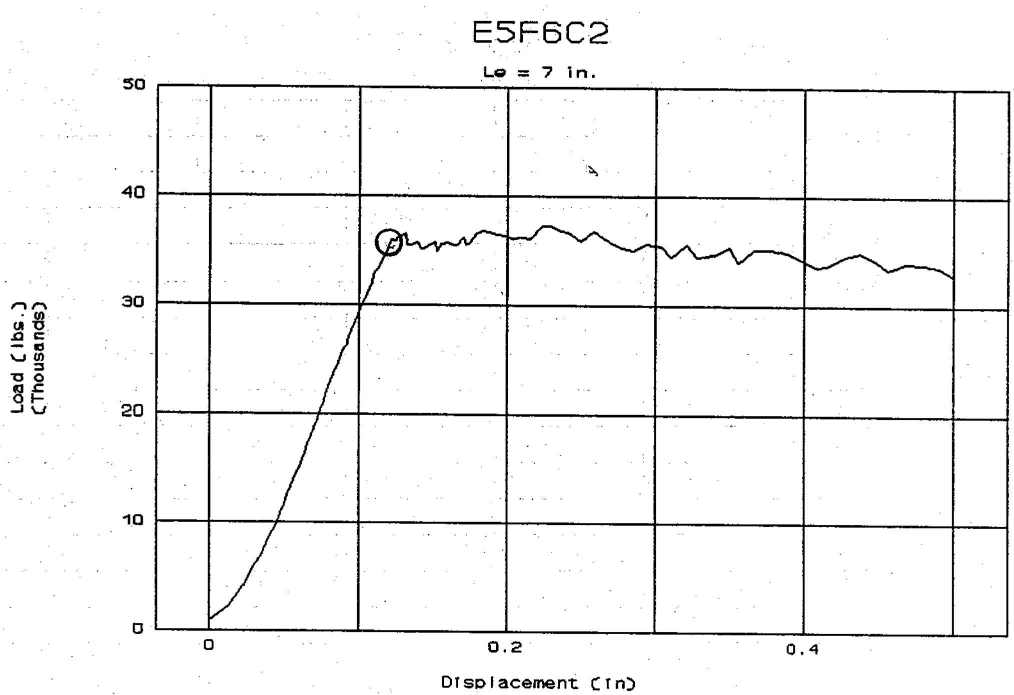
10
20
30
40
50
0
0.2
0.4
Displacement (in)


E5F6C2
Le = 7 in.
Load (lbs.) (Thousands)
0
10
20
30
40
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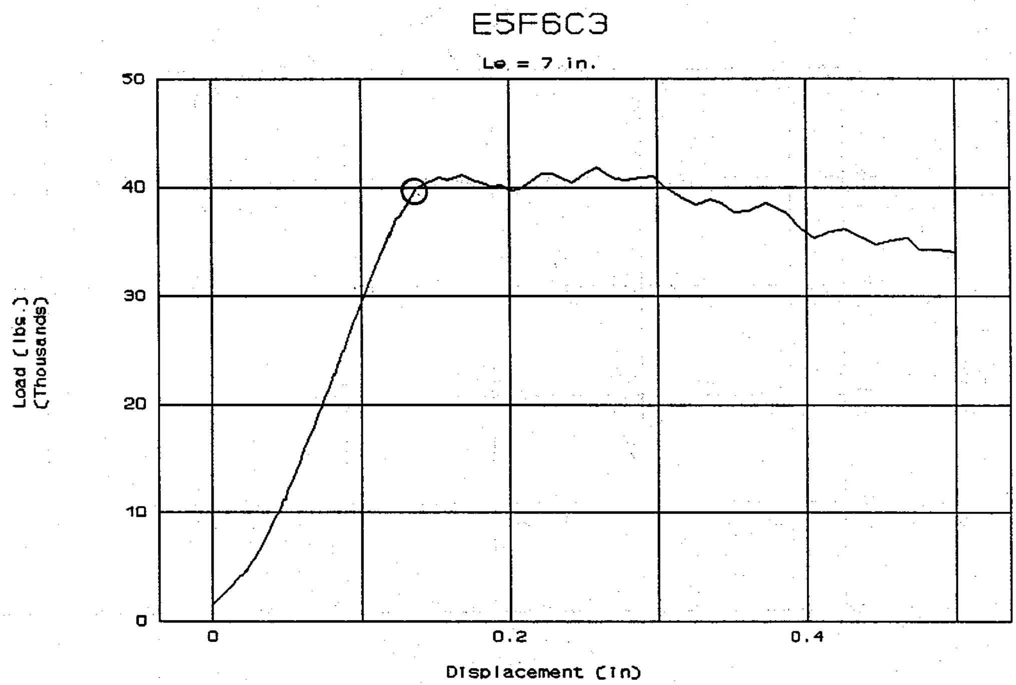
0.4
Displacement (in)


E5F6C3
Le = 7 in.
Load (lbs.)
(Thousands)
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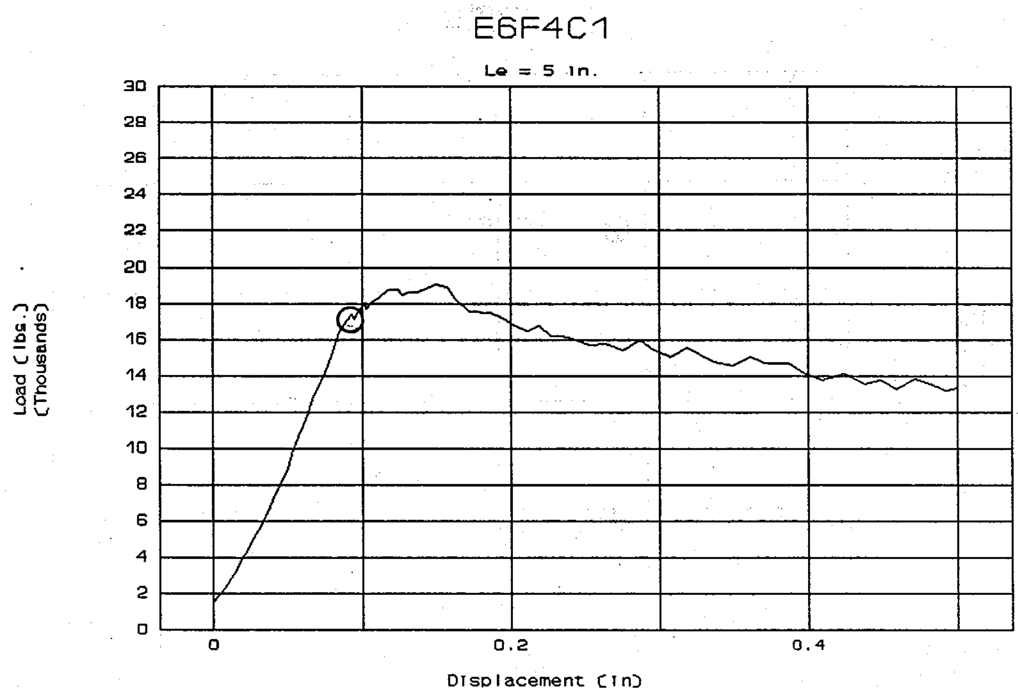
0.4
Displacement (in)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Le = 5 in.
Load (lbs.)
(Thousands)
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8
6
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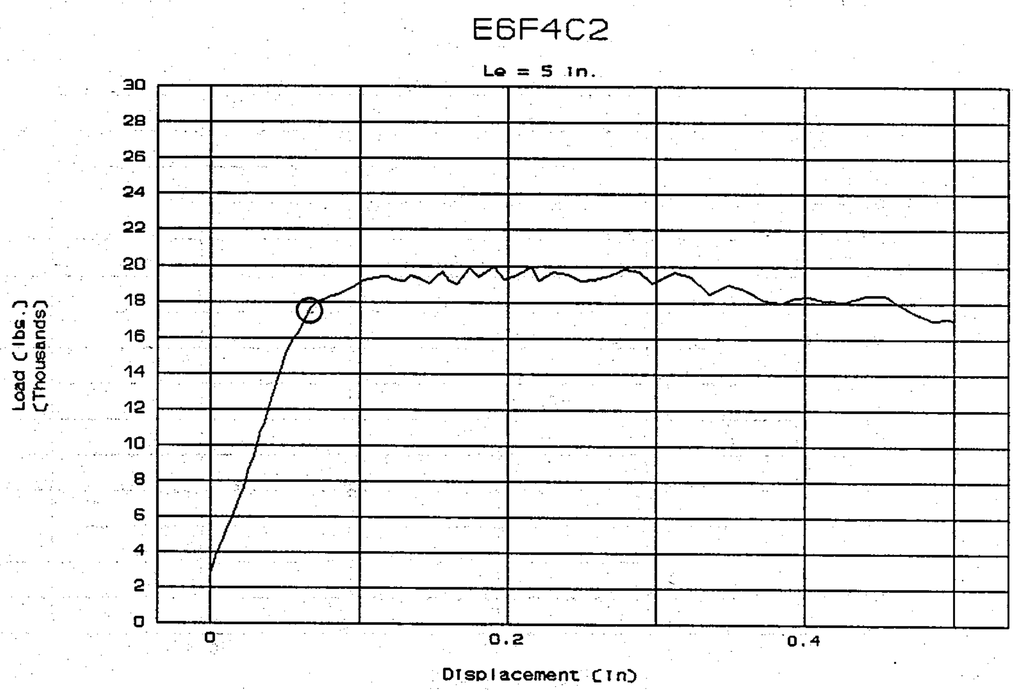
2
0
0
0.2
0.4
Displacement (in)


E6F4C2
Le = 5 in.
Load (lbs.) (Thousands)
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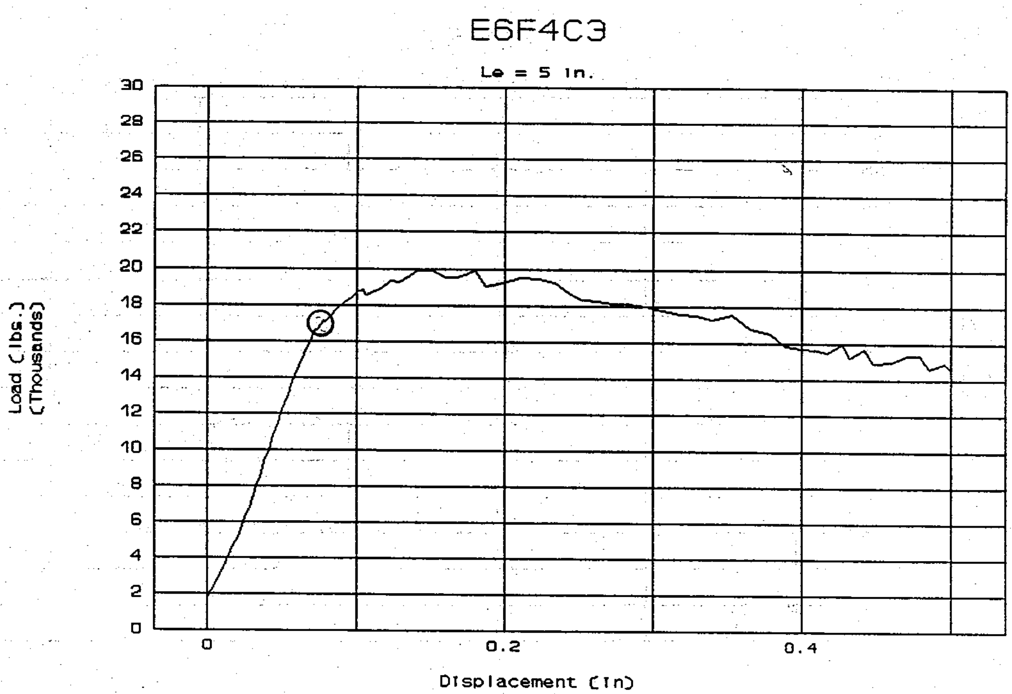
6
4
2
0
0
0.2
0.4
Displacement (in)


E6F4C3
Le = 5 in.
Load (lbs.) (Thousands)
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28
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4
2
0
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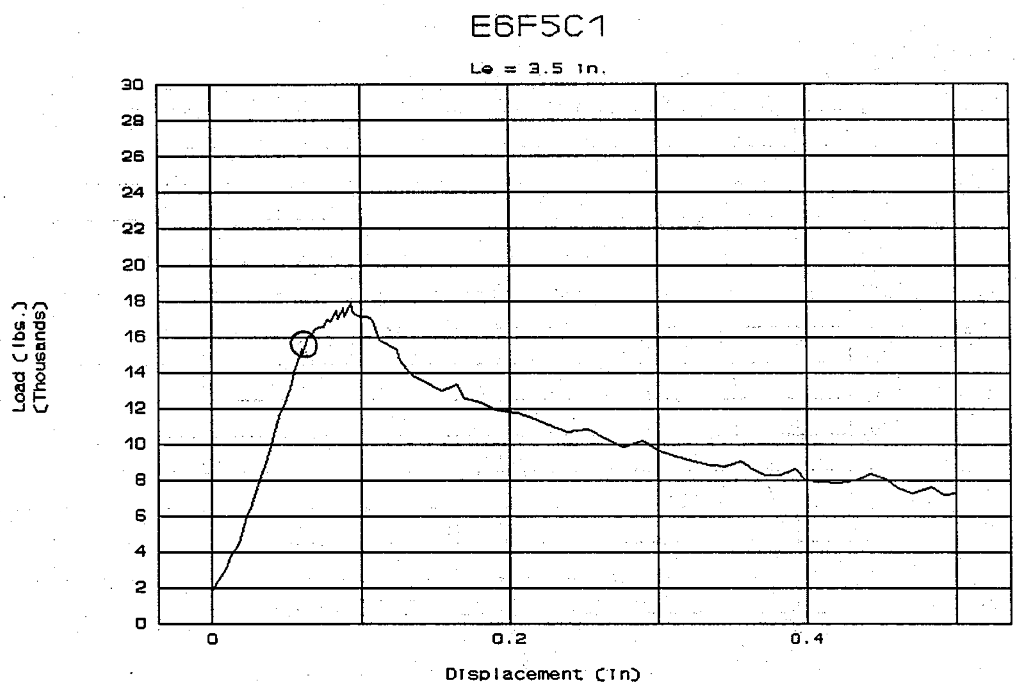
0.4
Displacement (in)


E6F5C1
Le = 3.5 in.
Load (lbs.)
(Thousands)
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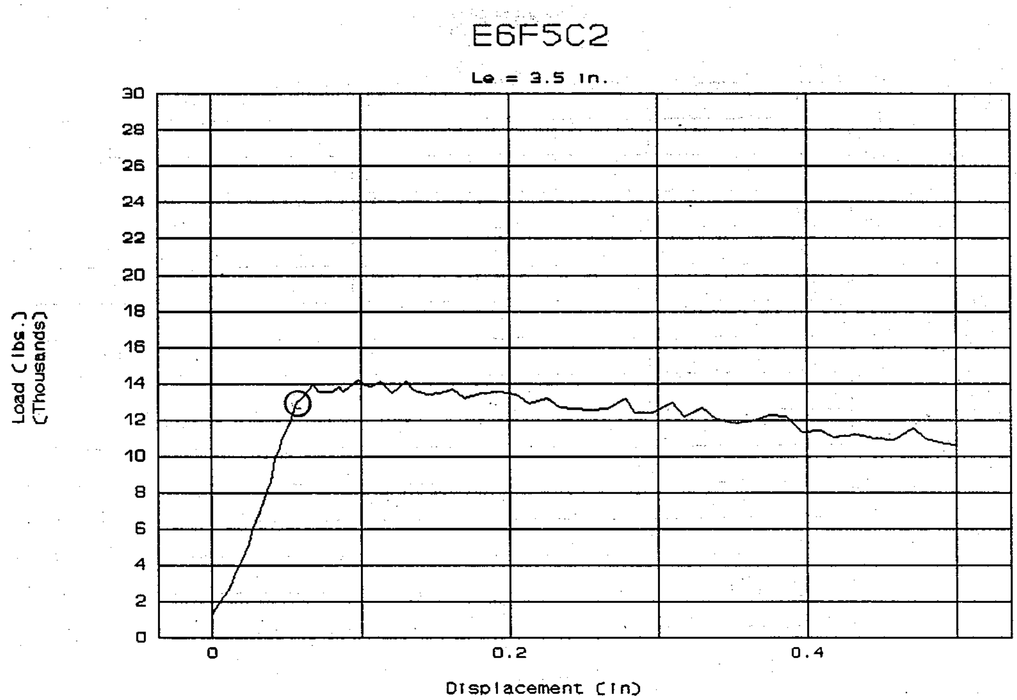
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)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Le = 3.5 in.
Load (lbs.)
(Thousands)
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28
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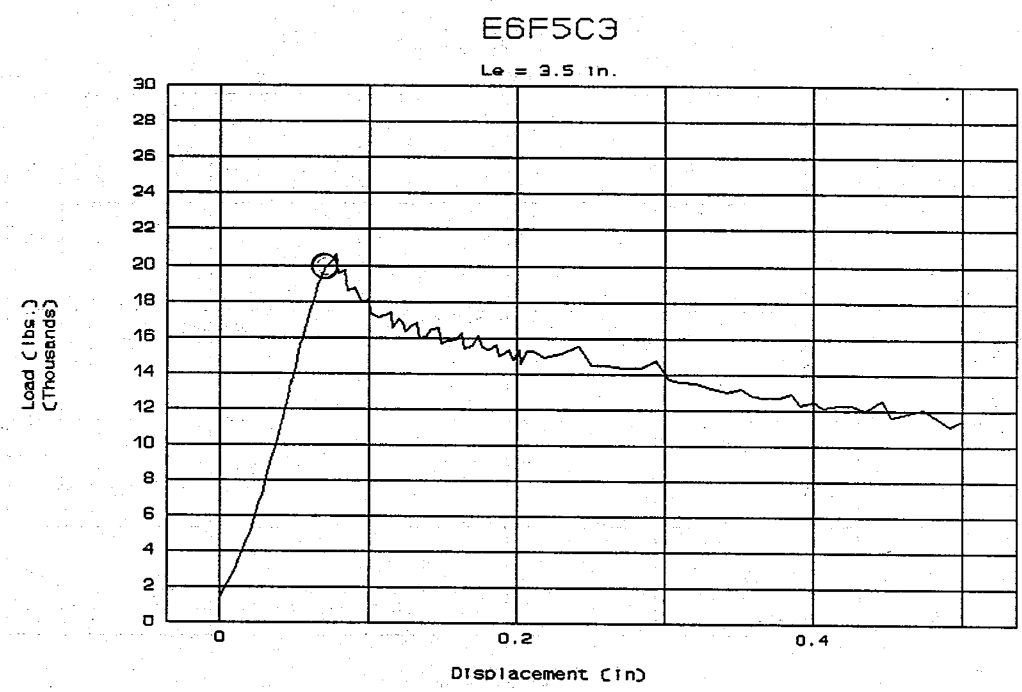
6
4
2
0
0
0.2
0.4
Displacement (in)


E6F5C3
Le = 3.5 in.
Load (lbs.) (Thousands)
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2
4
6
8
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28
30
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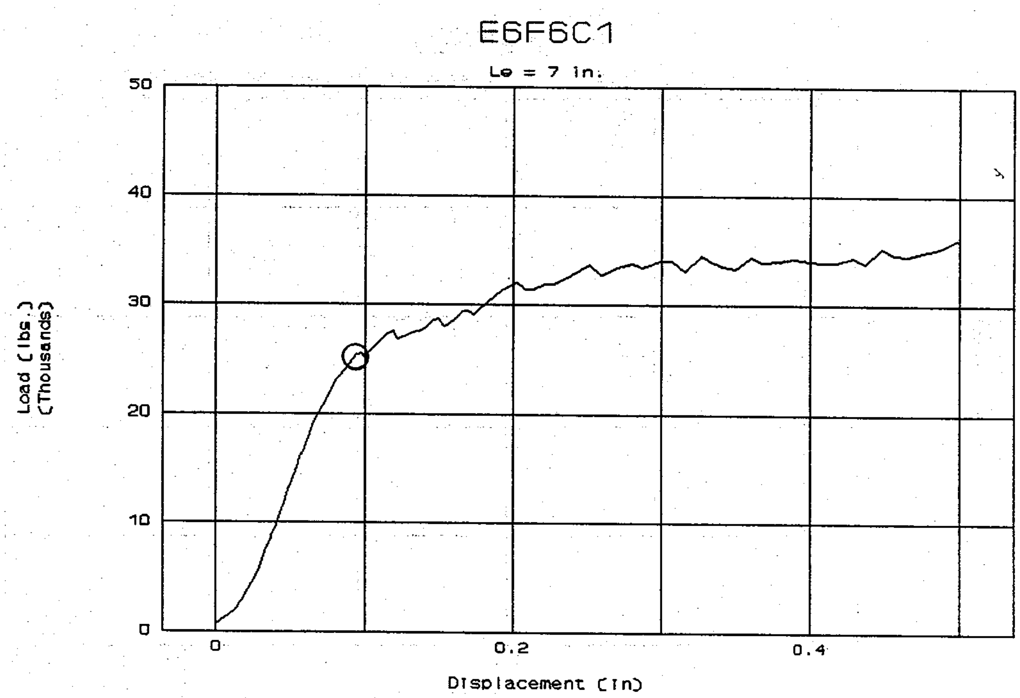
0.4
Displacement (in)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Load (lbs.) (Thousands)
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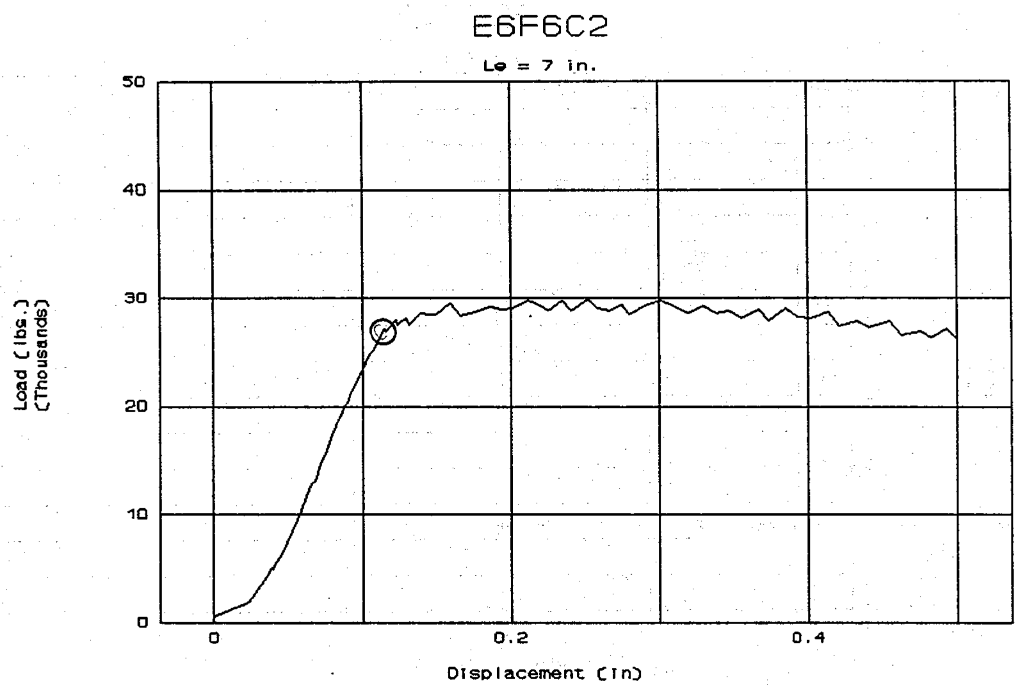
10
20
30
40
50
0
0.2
0.4
Displacement (in)


E6F6C2
Le = 7 in.
Load (lbs.)
(Thousands)
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40
30
20
10
0
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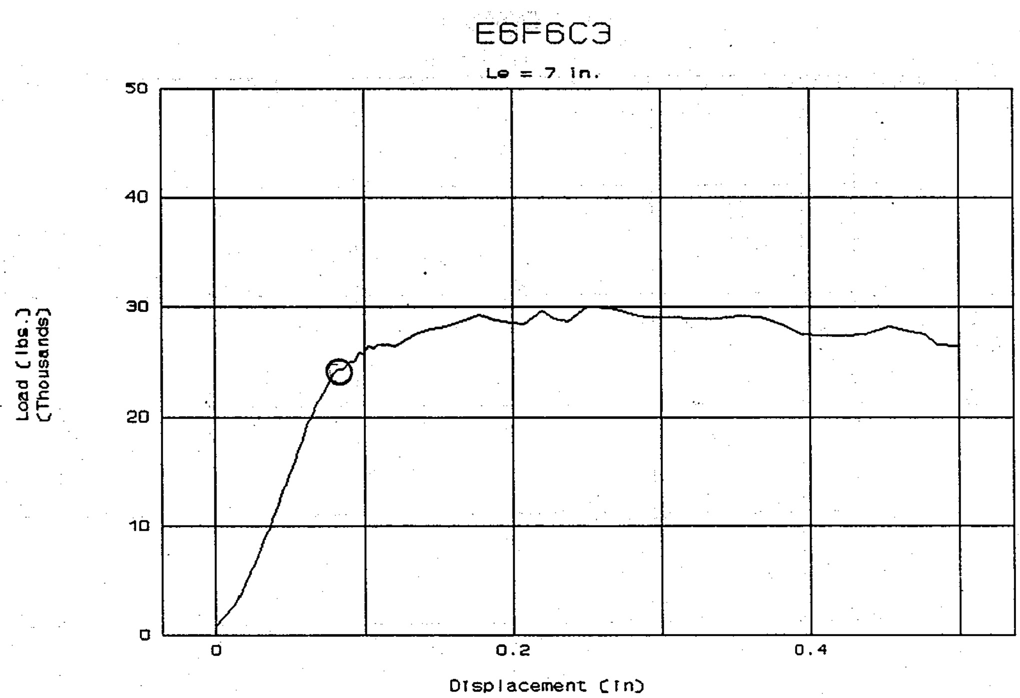
0.2
0.4
Displacement (in)


E6F6C3
Le = 7 in.
Load (lbs.)
(Thousands)
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30
20
10
0
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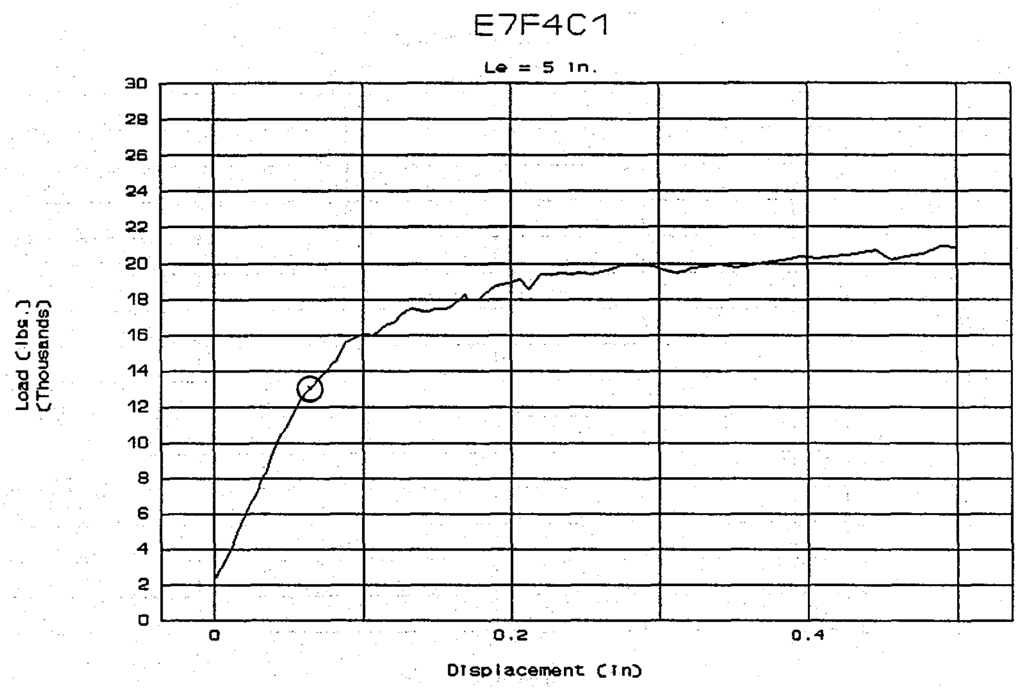
0.2
0.4
Displacement (in)


E7F4C1
Le = 5 in.
Load (lbs.) (Thousands)
30
28
26
24
22
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18
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14
12
10
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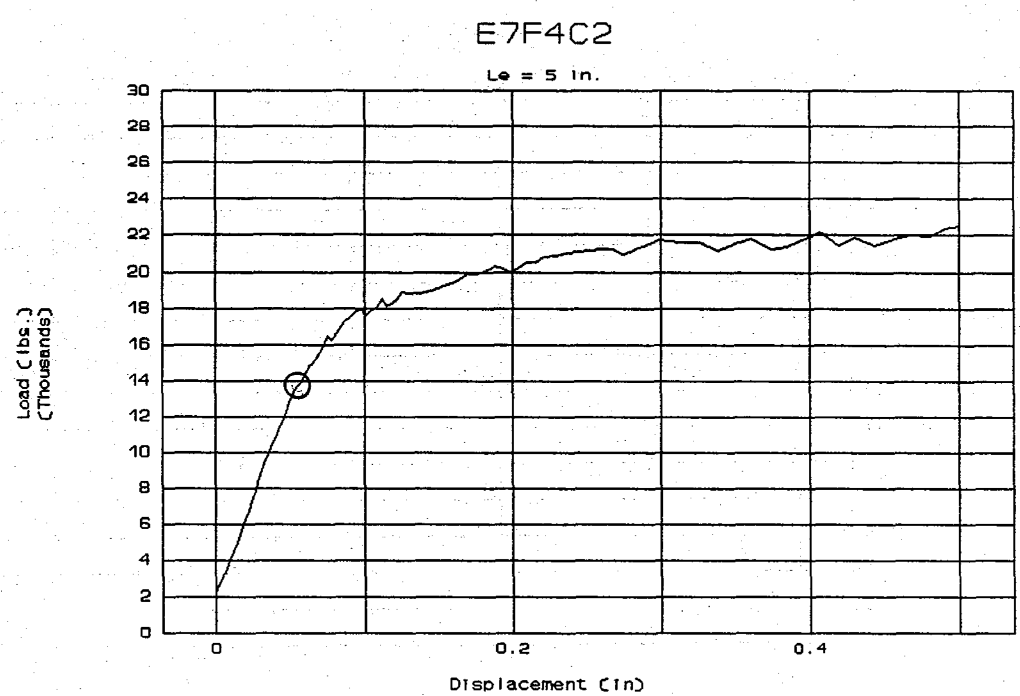
6
4
2
0
0
0.2
0.4
Displacement (in)


E7F4C2
Le = 5 in.
Load (lbs.) (Thousands)
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28
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14
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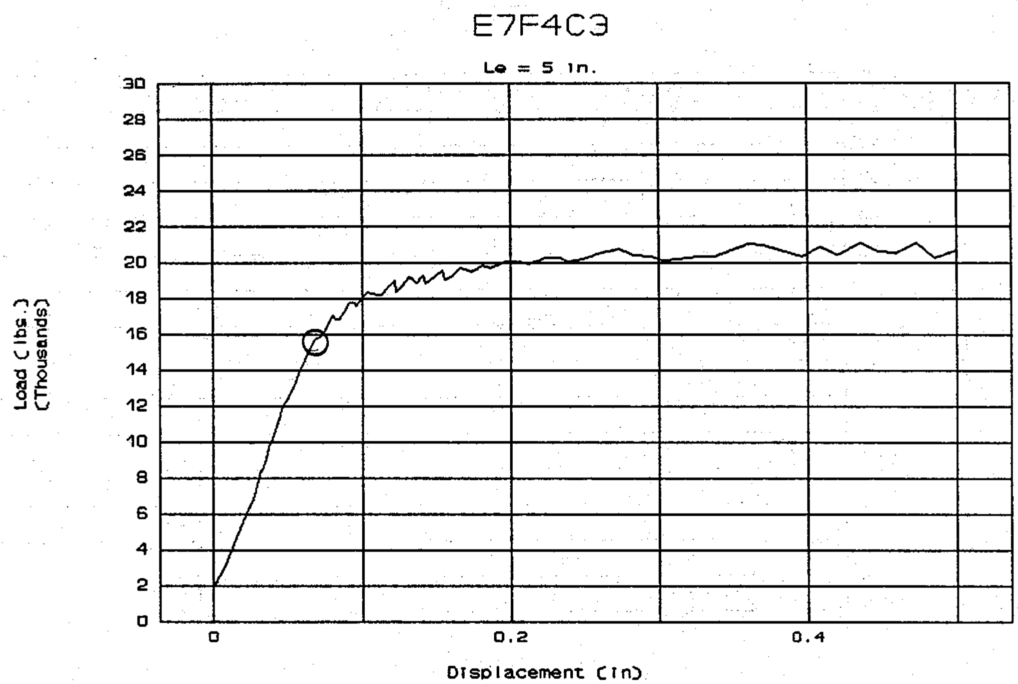
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E7F4C3
Le = 5 in.
Load (lbs.) (Thousands)
30
28
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14
12
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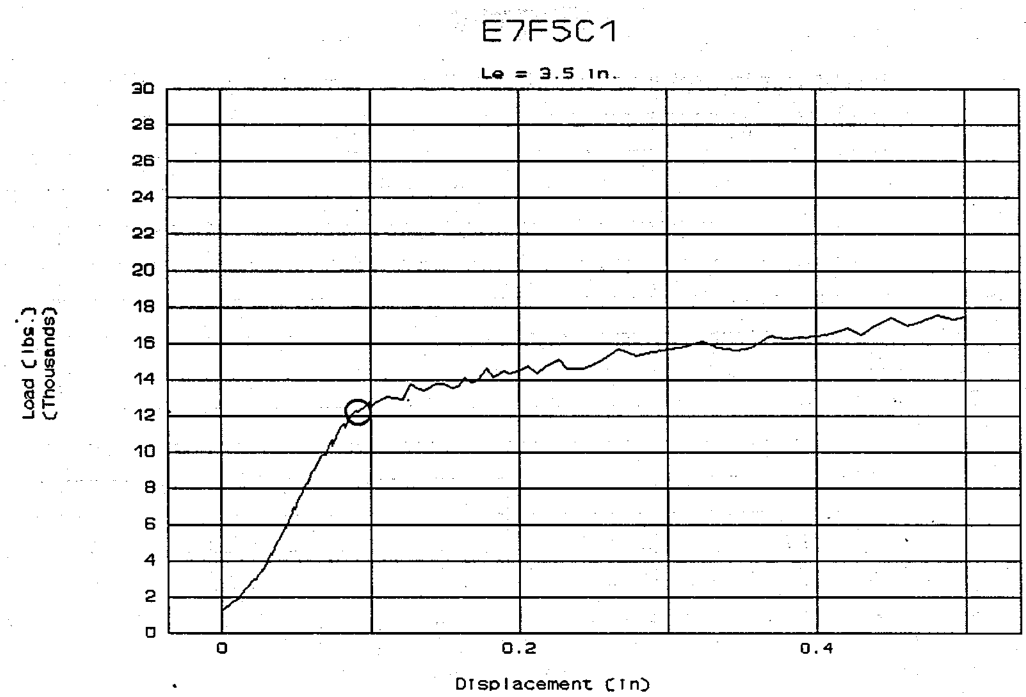
6
4
2
0
0
0.2
0.4
Displacement (in)


E7F5C1
Le = 3.5 in.
Load (lbs.) (Thousands)
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28
26
24
22
20
18
16
14
12
10
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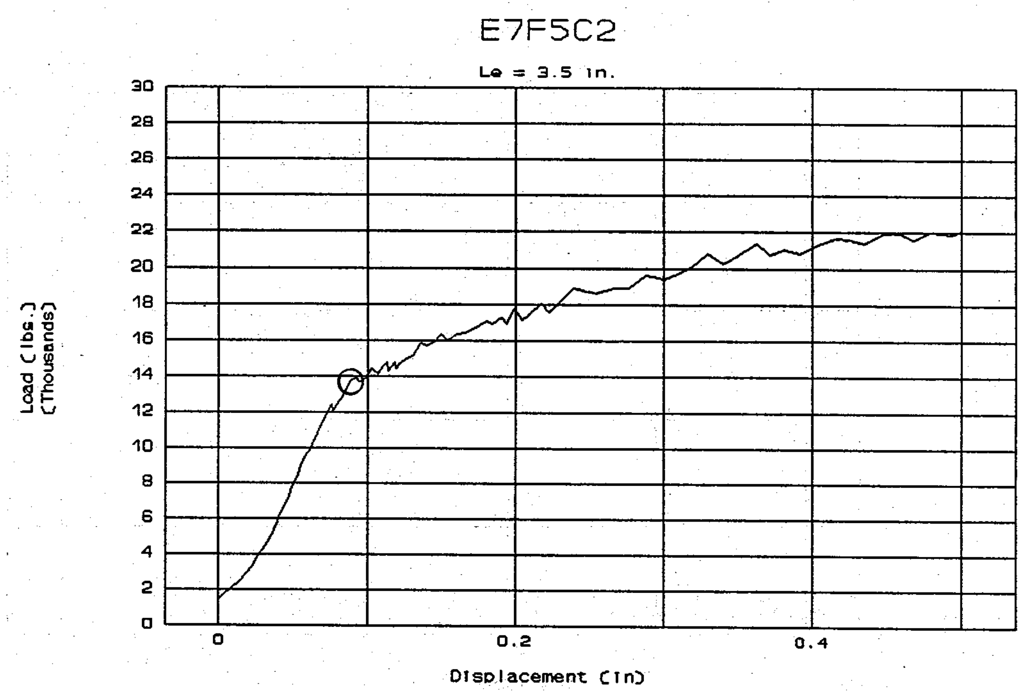
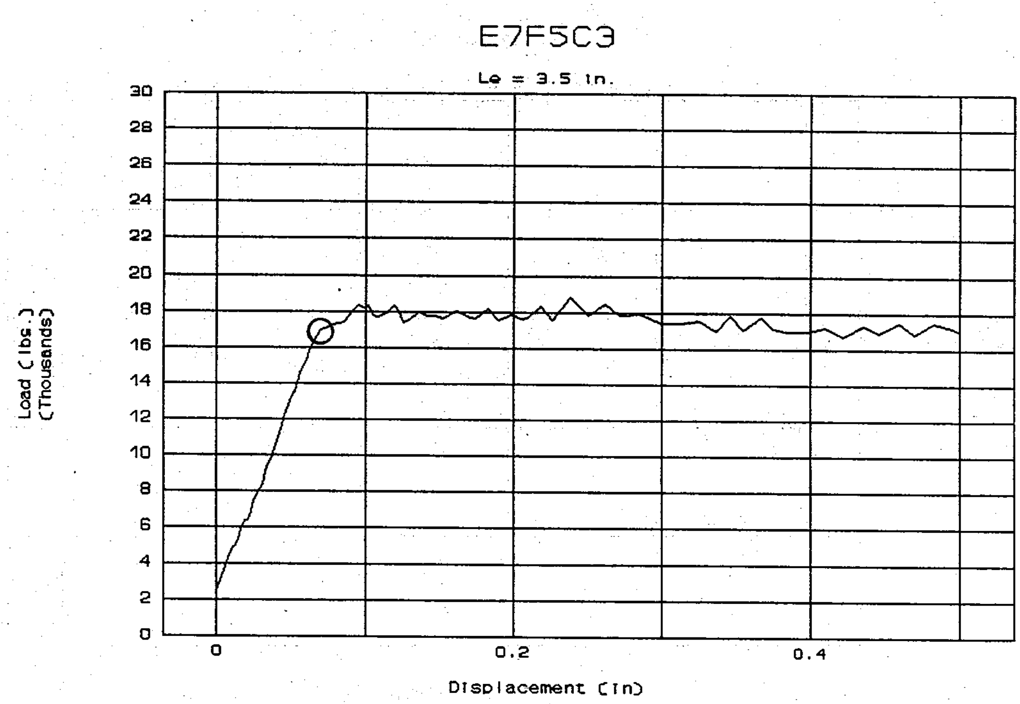
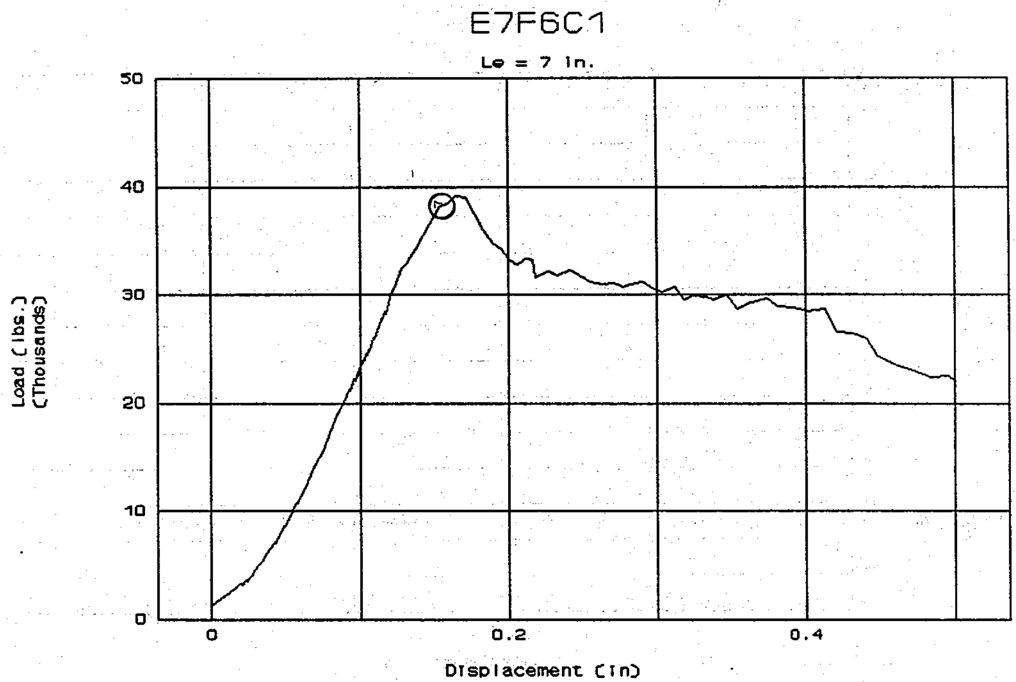
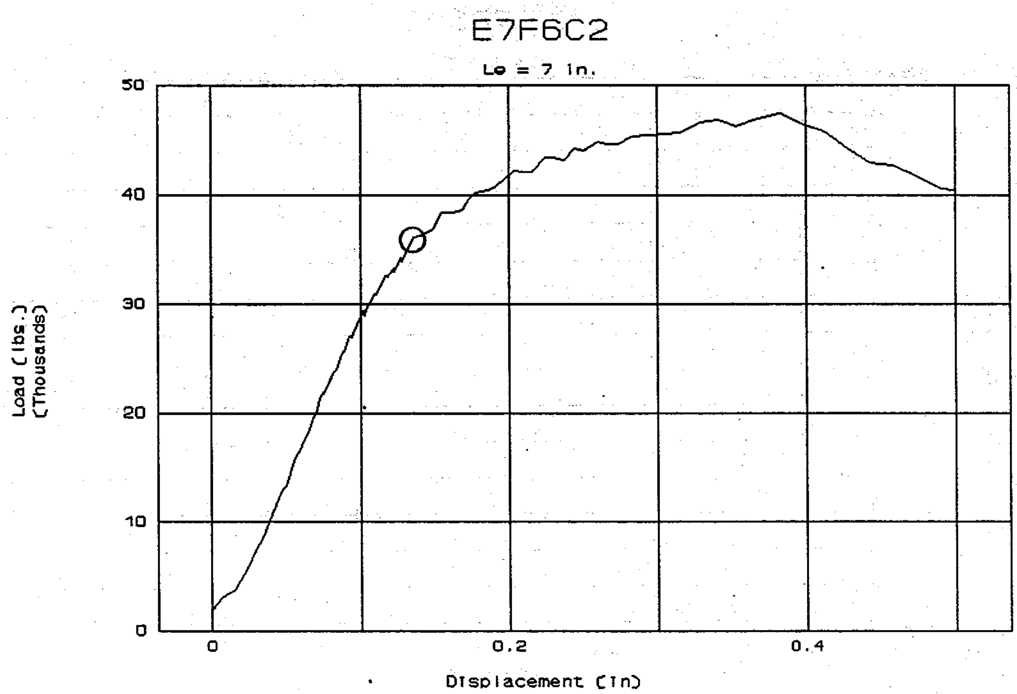
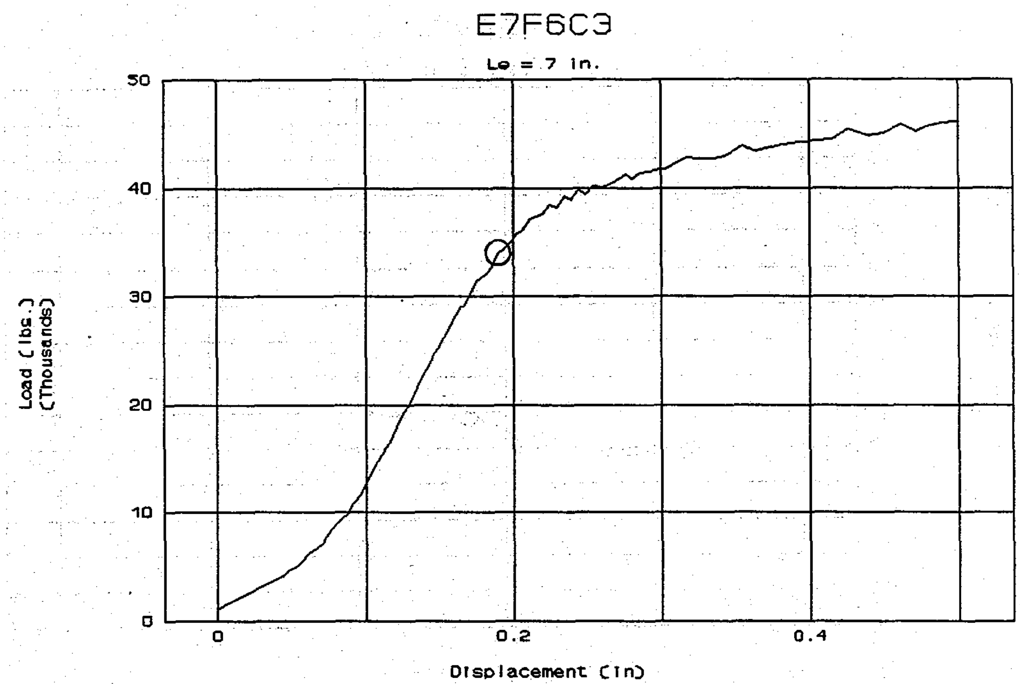
6
4
2
0
0
0.2
0.4
Displacement (in)

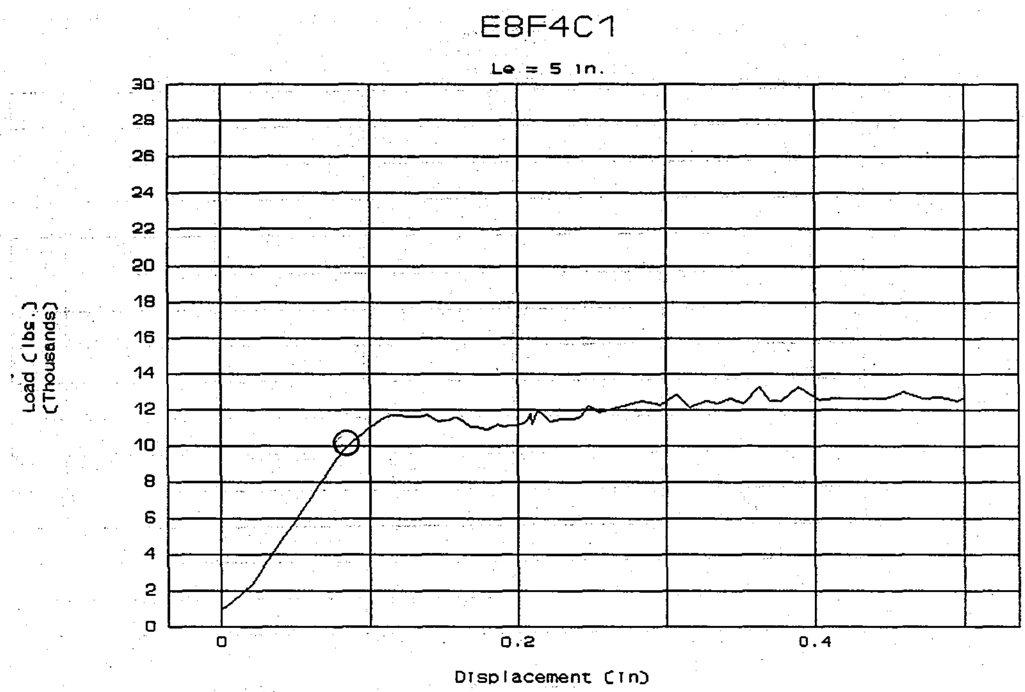

E7F5C2
Le = 3.5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

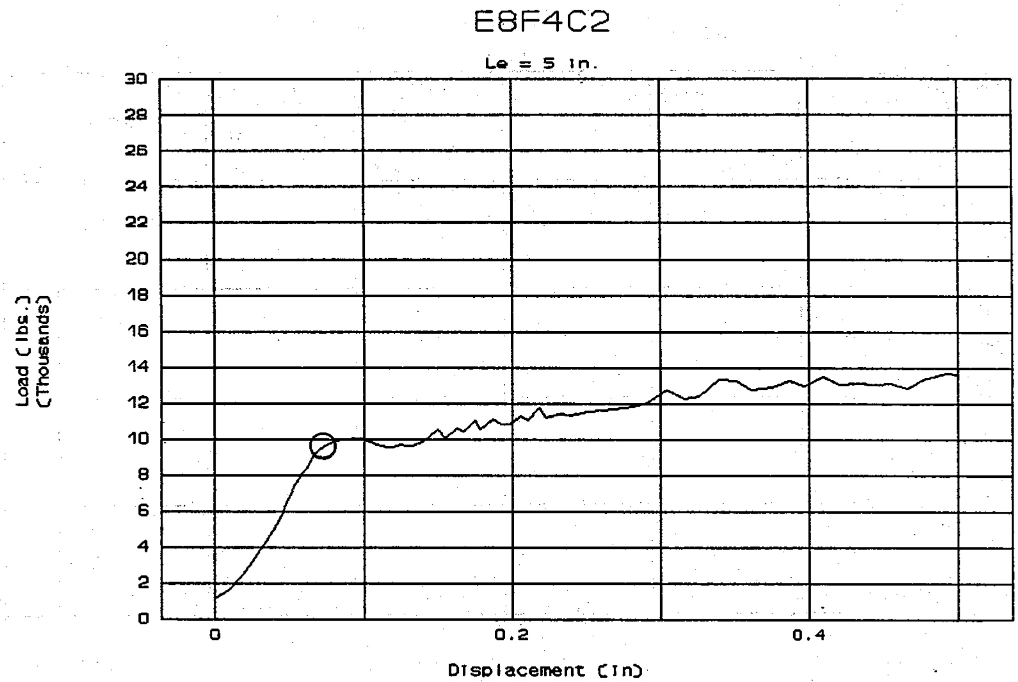

E7F5C3
Le = 3.5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

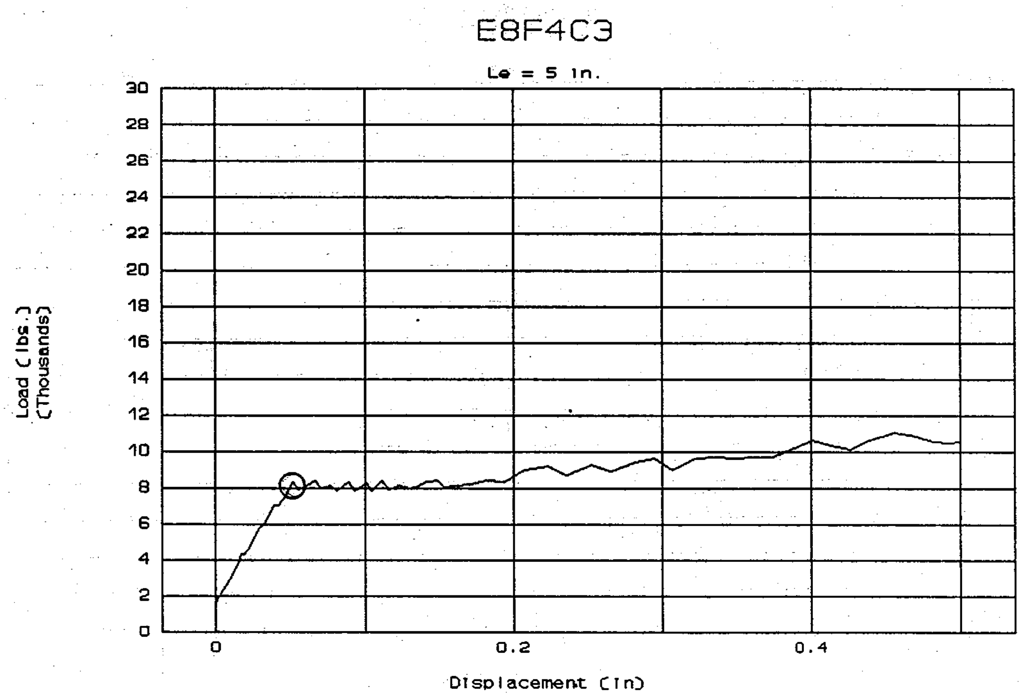

E7F6C1
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

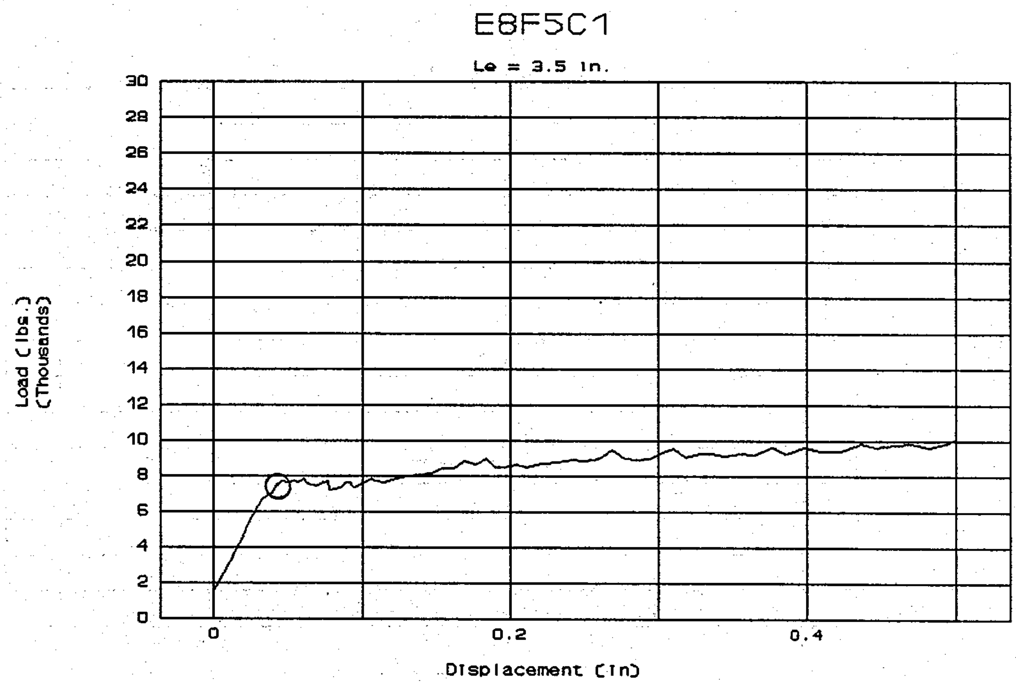

E7F6C2
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

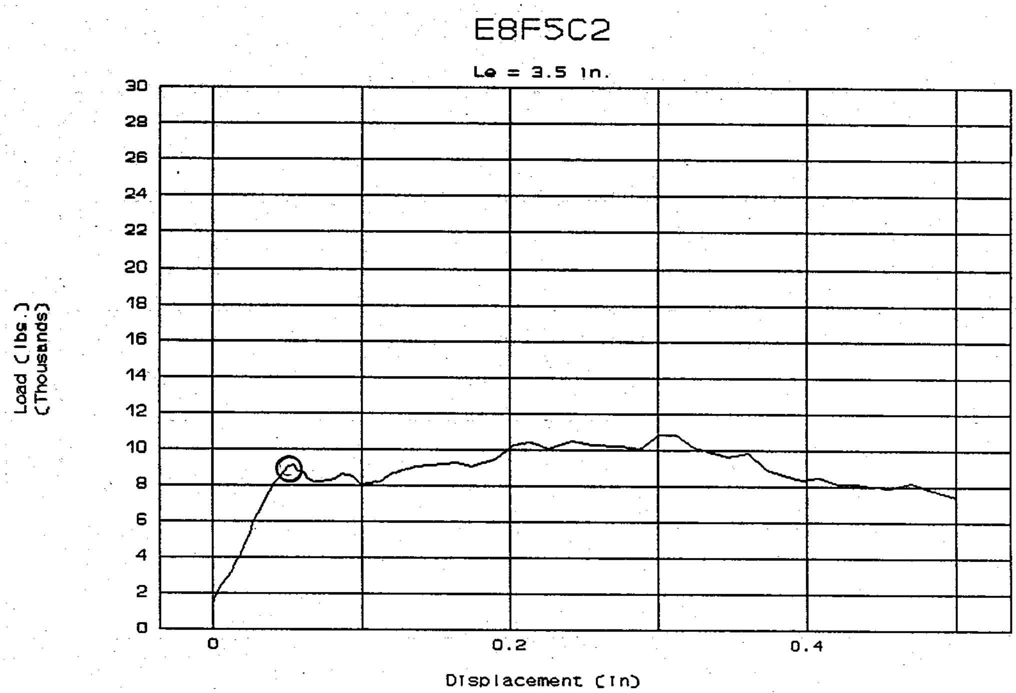

E7F6C3
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

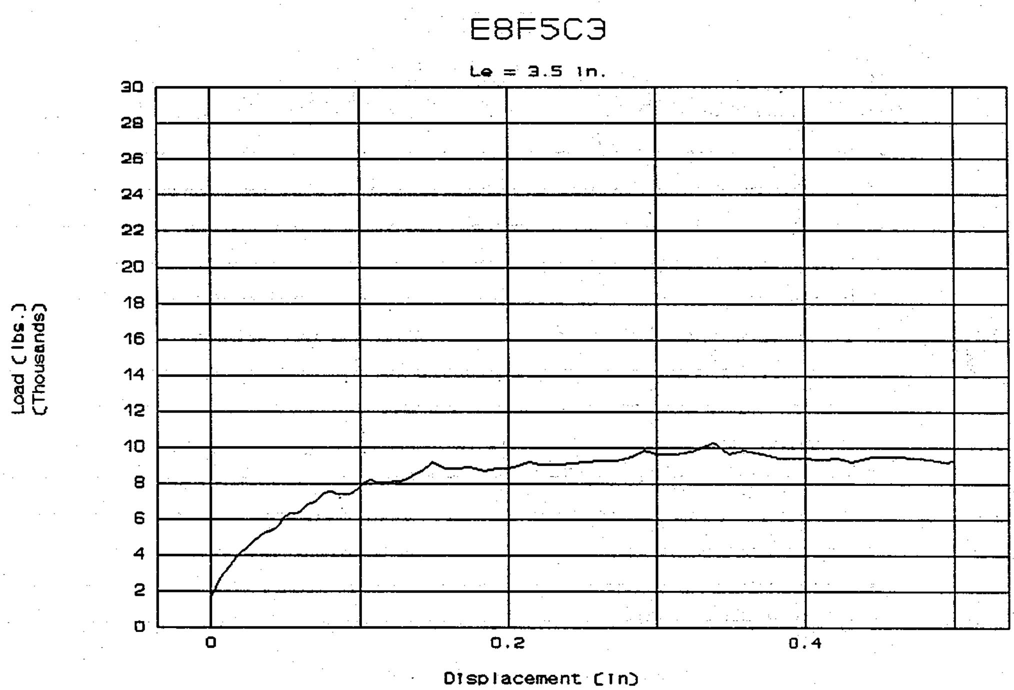

E8F4C1
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

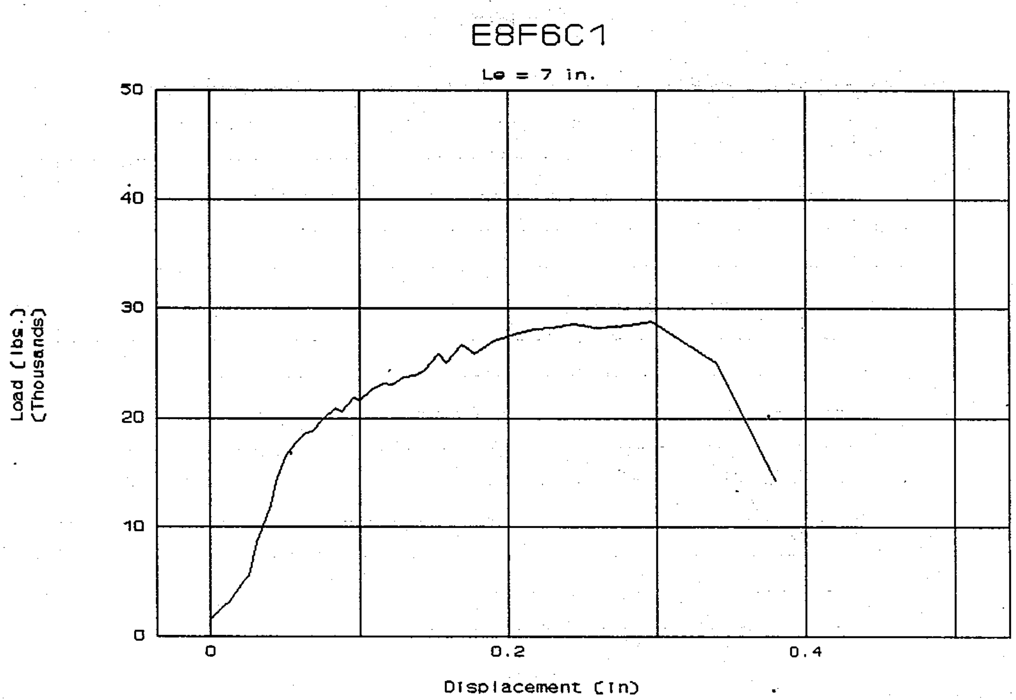

E8F4C2
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

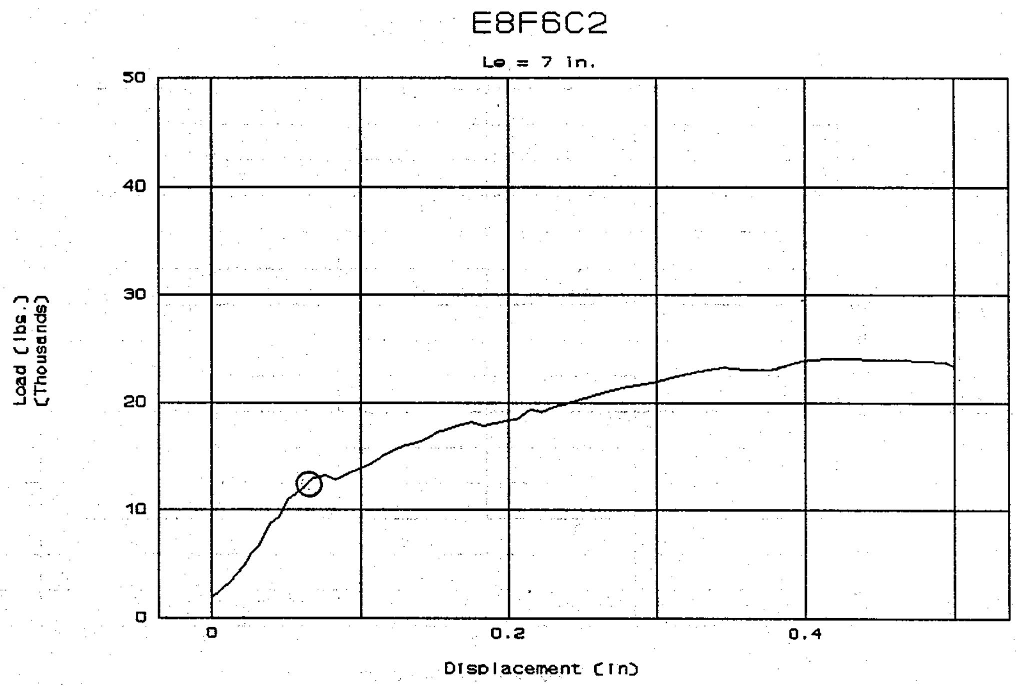

E8F4C3
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

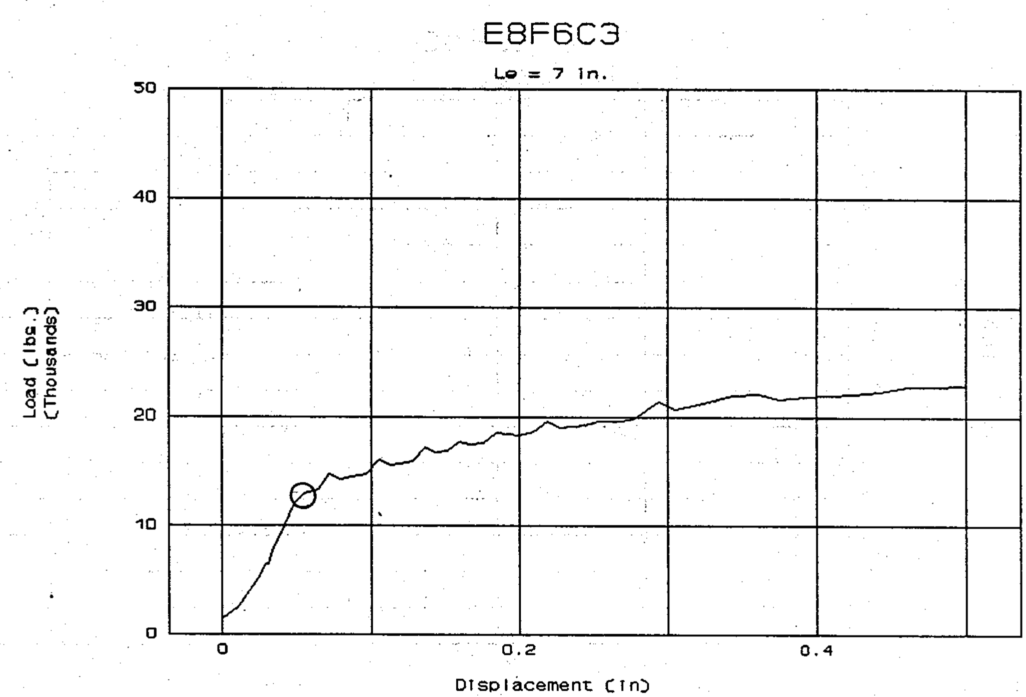

E8F5C1
Le = 3.5 in.
Load (lbs.) (Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

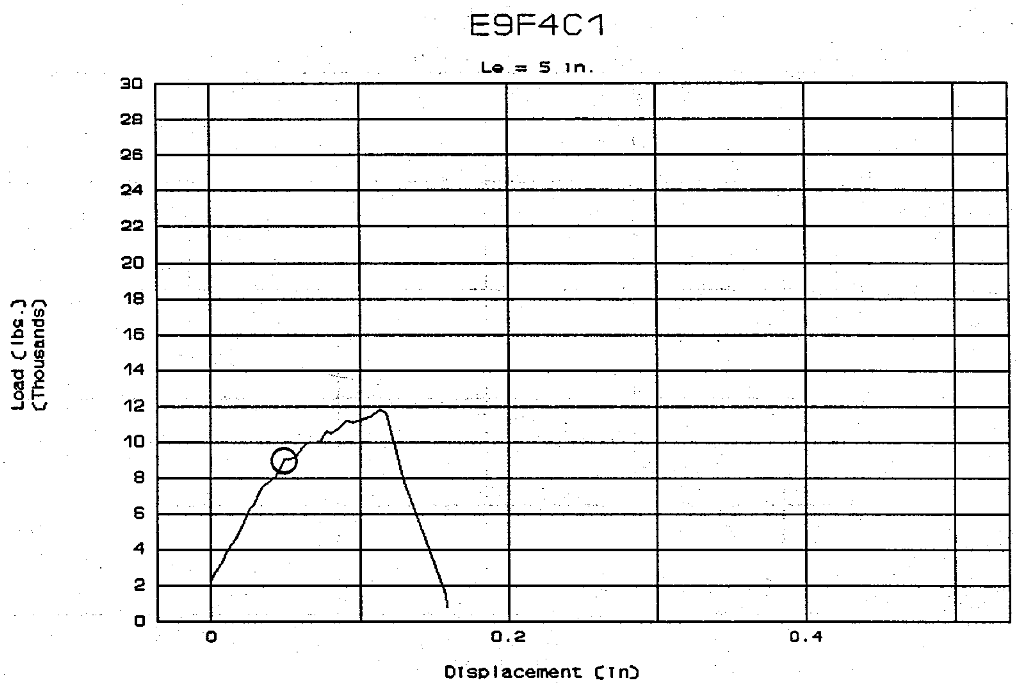

E8F5C2
Le = 3.5 in.
Load (lbs.) (Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

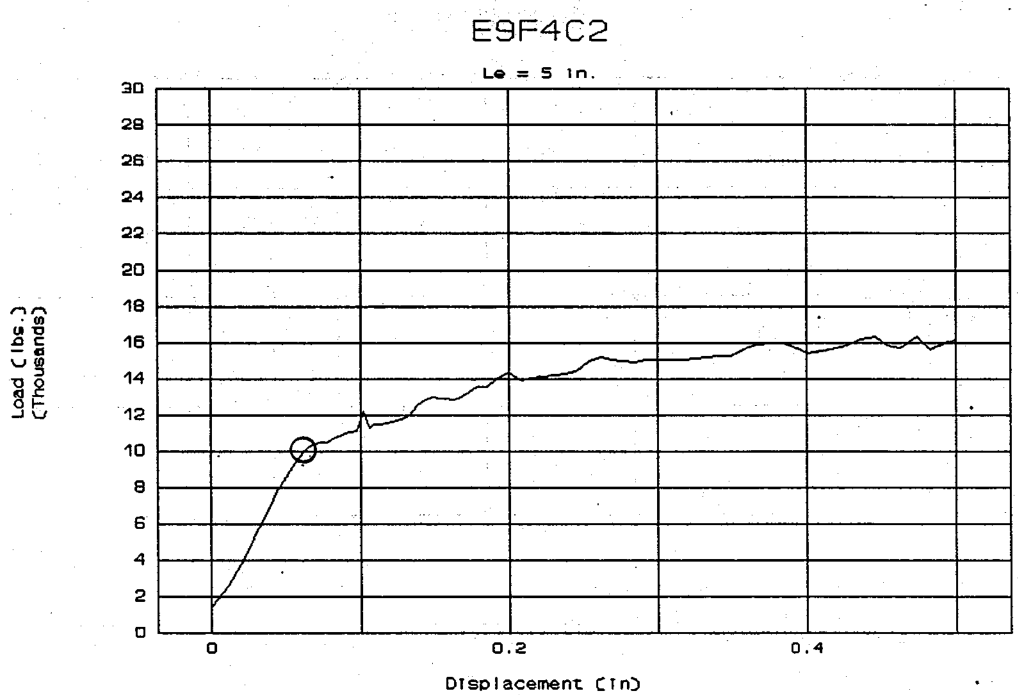

E8F5C3
Le = 3.5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

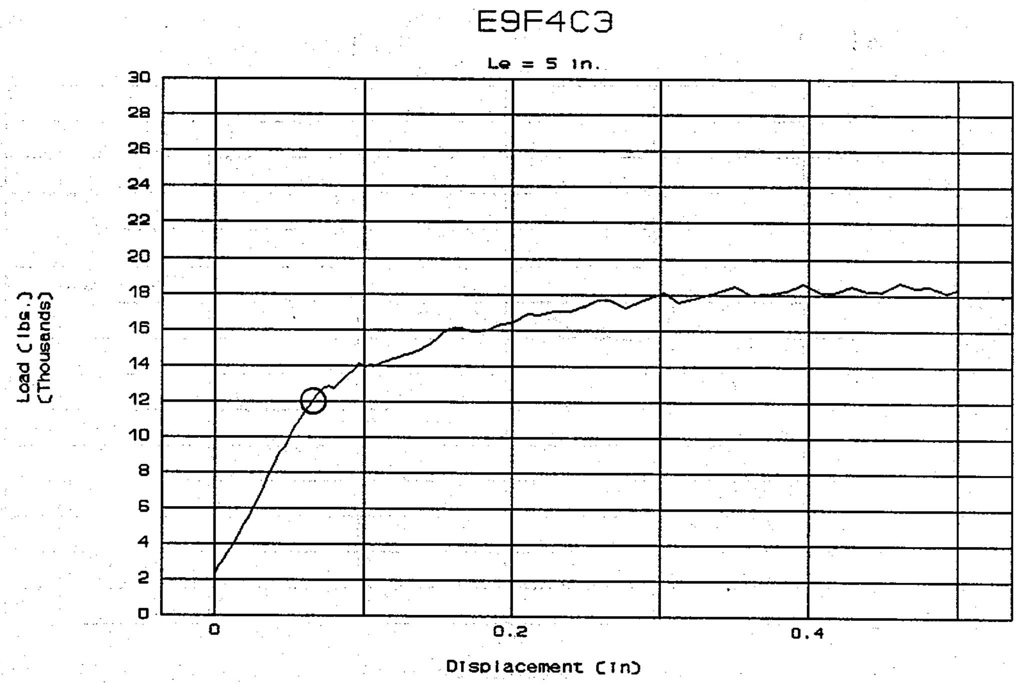

E8F6C1
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

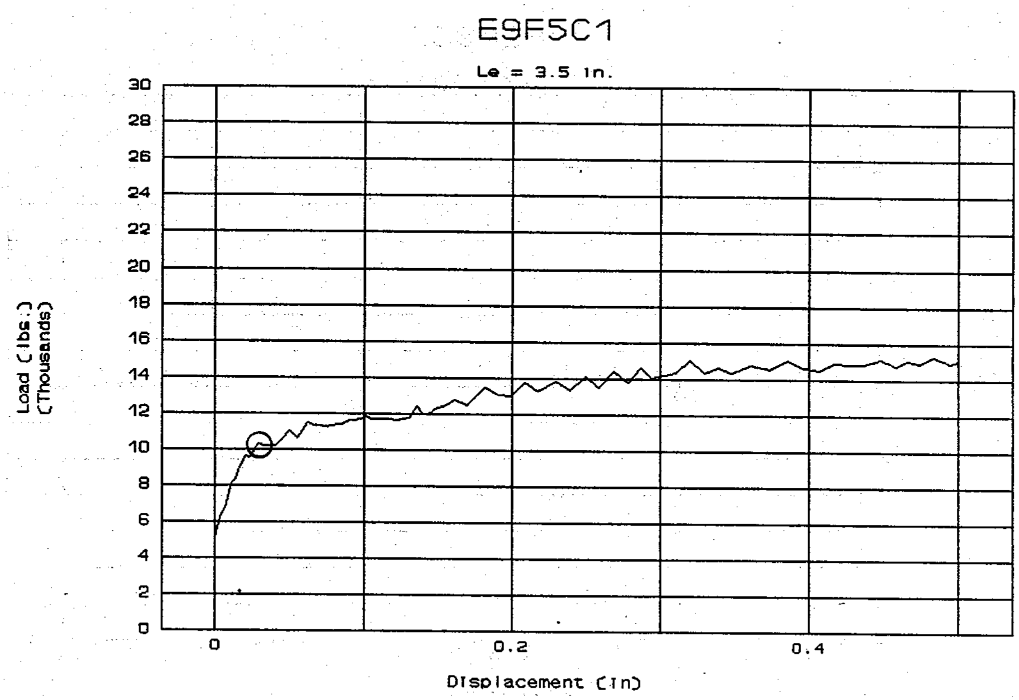

E8F6C2
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)


E8F6C3
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

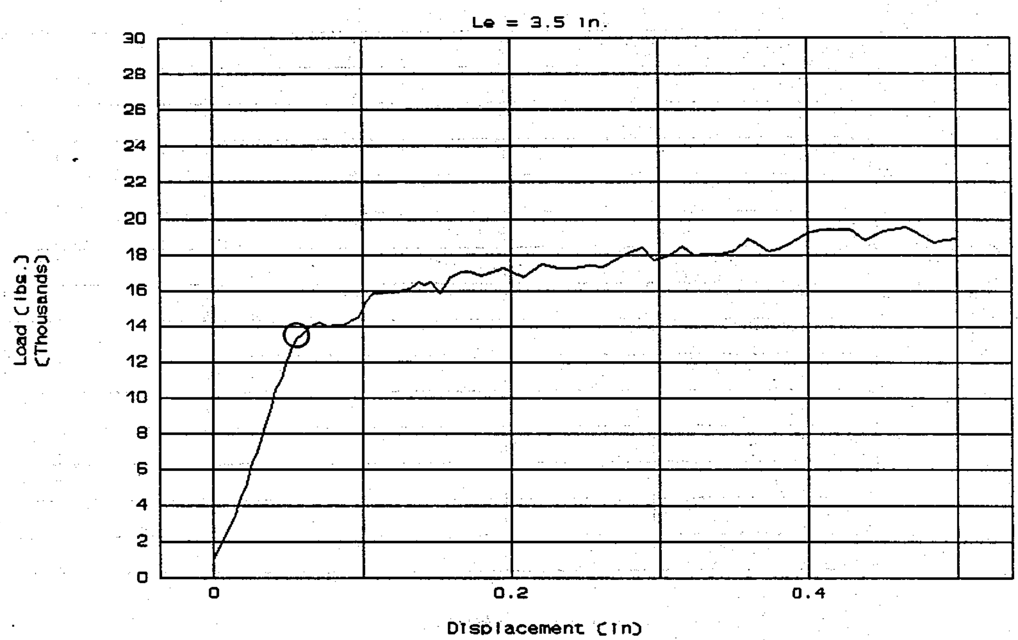

E9F4C1
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E9F4C2
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

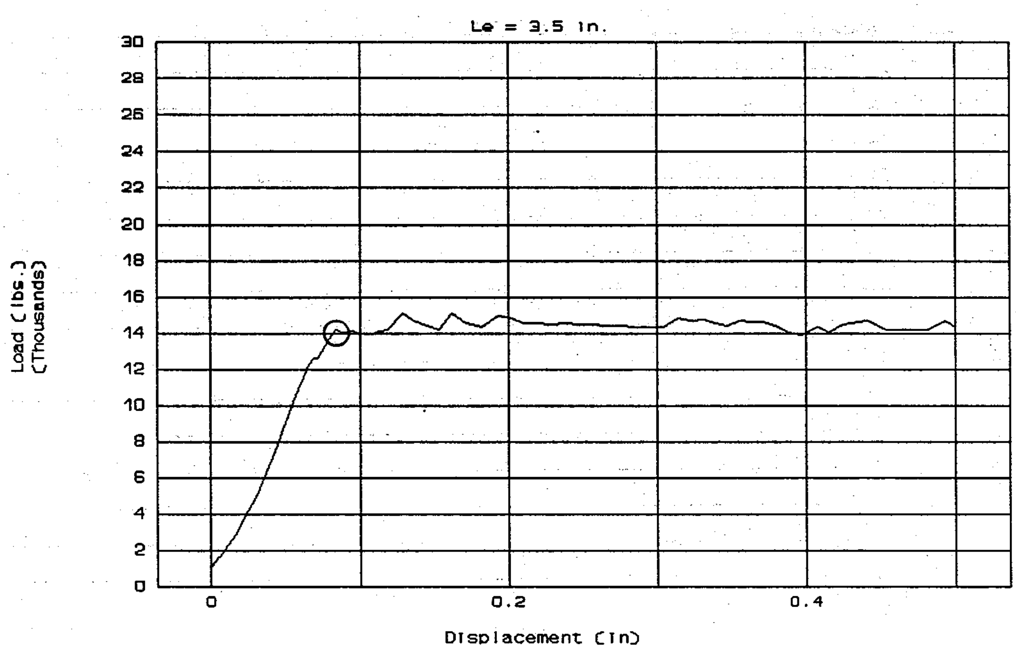

E9F4C3
Le = 5 in.
Load (lbs.)
(Thousands)
Displacement (in)
0
0.2
0.4
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0

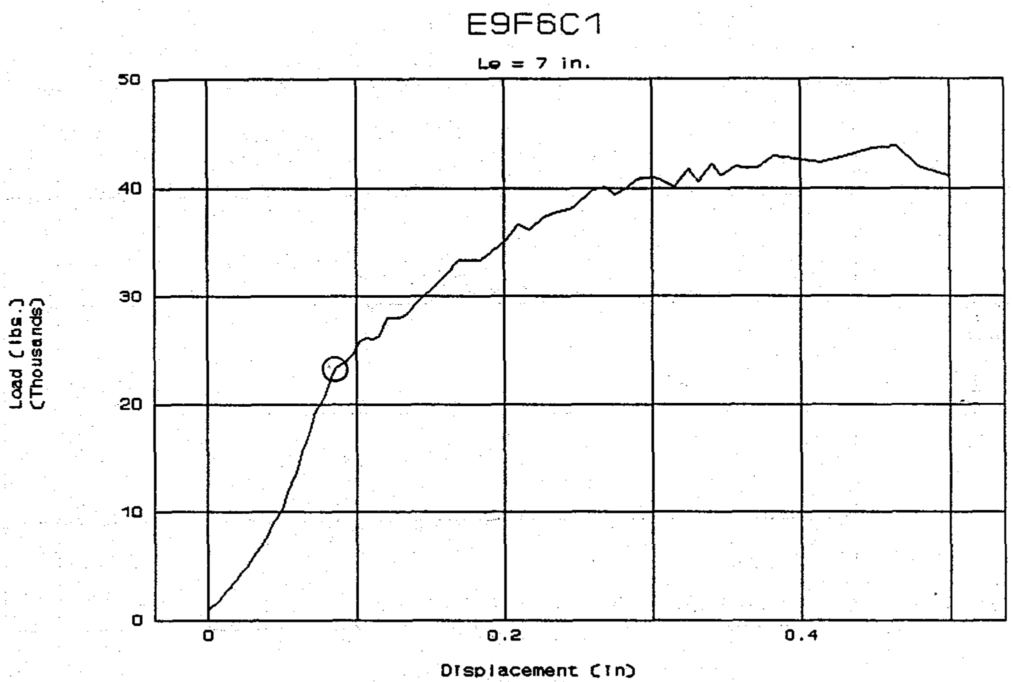

E9F5C1
Le = 3.5 in.
Load (lbs.)
(Thousands)
Displacement (in)
0
0.2
0.4
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0

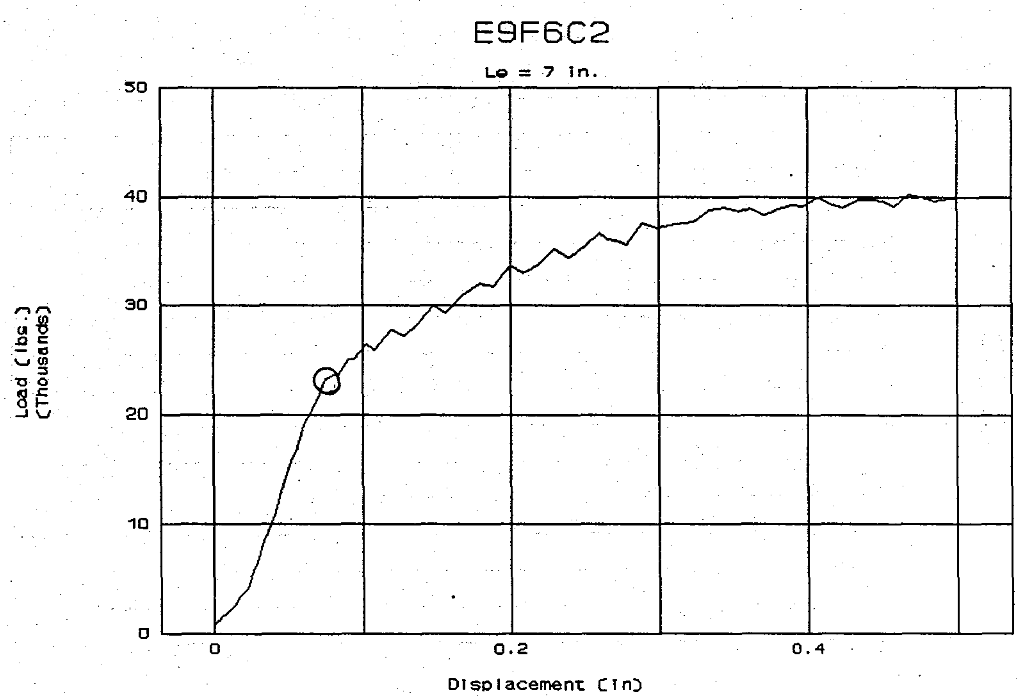
E9F5C2

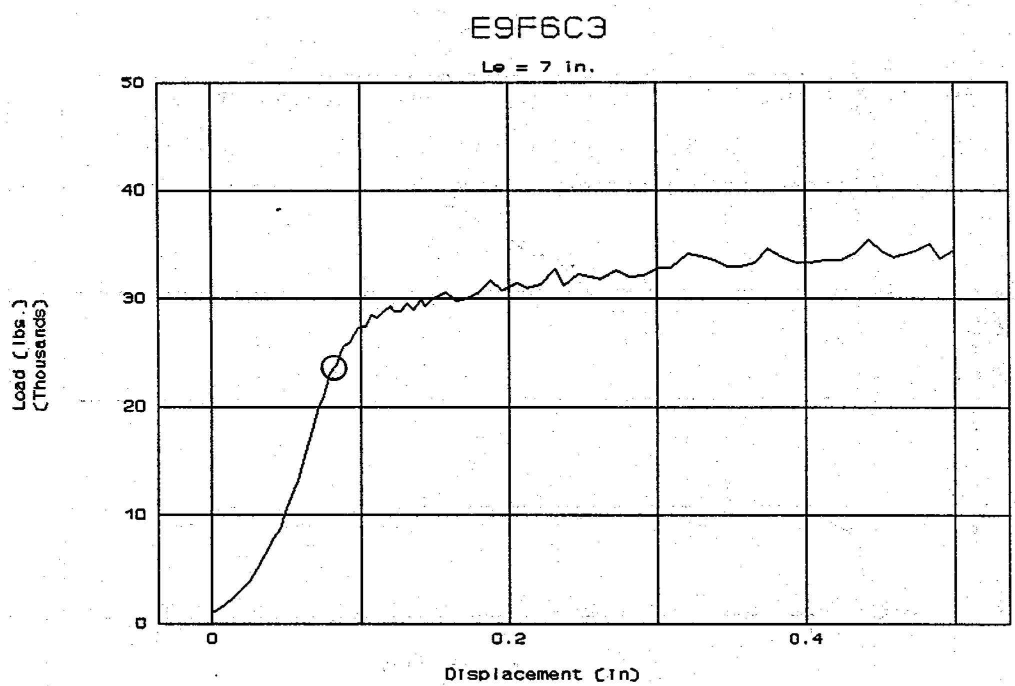


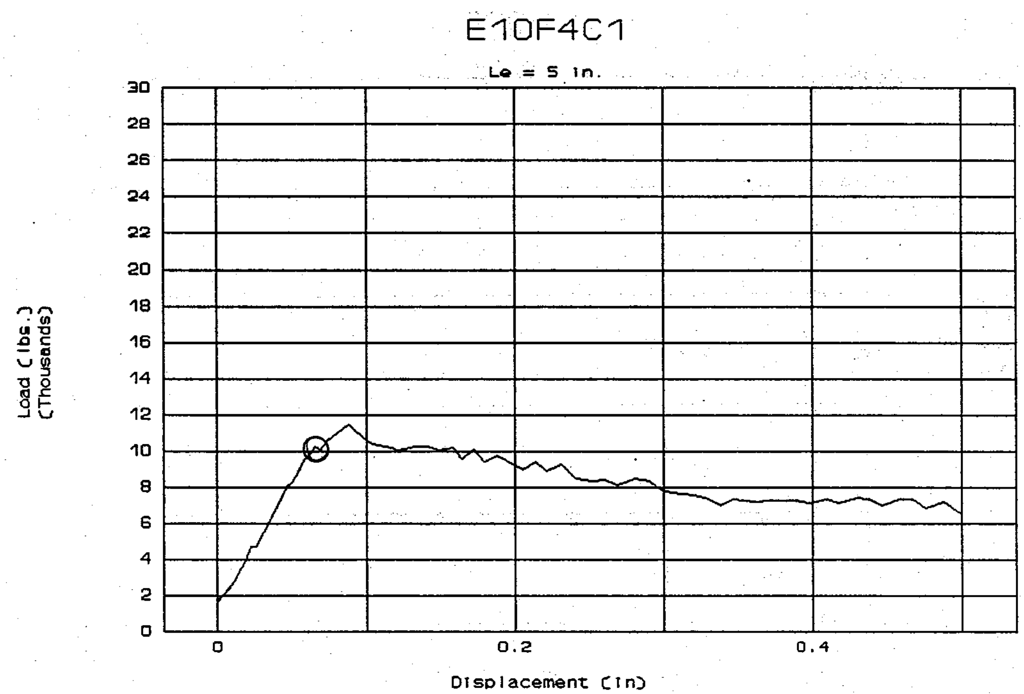
E9F5C3

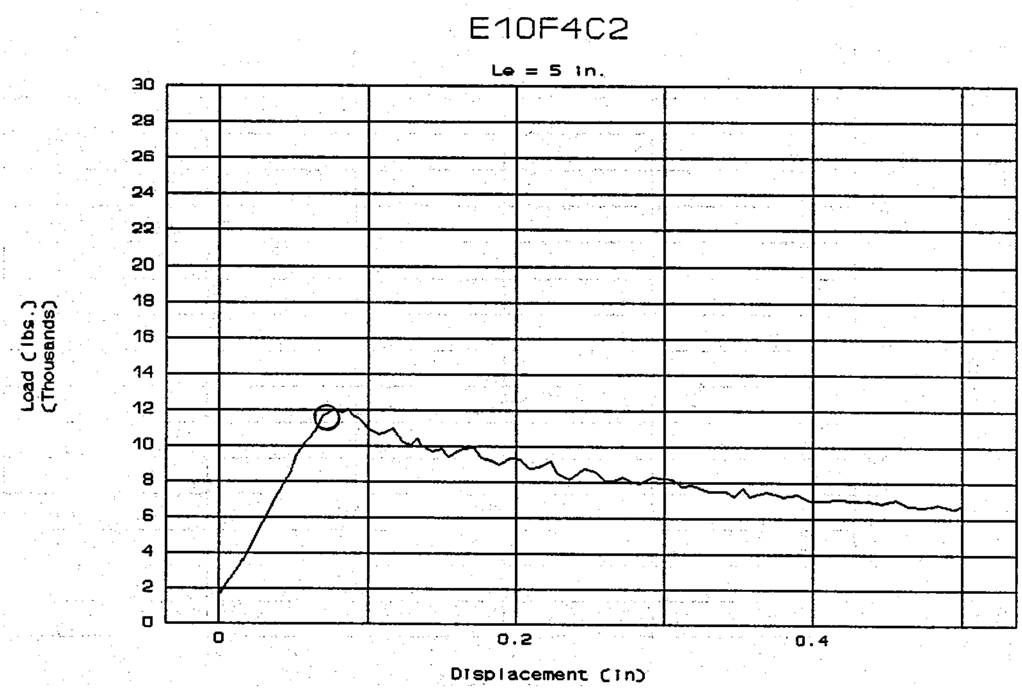


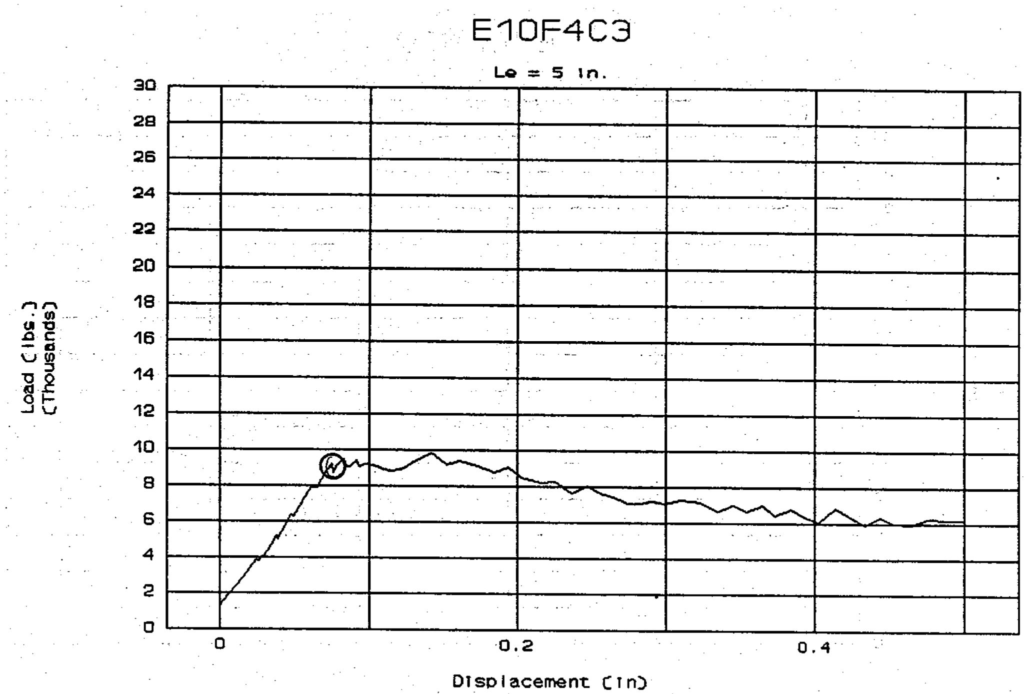

E9F6C1
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

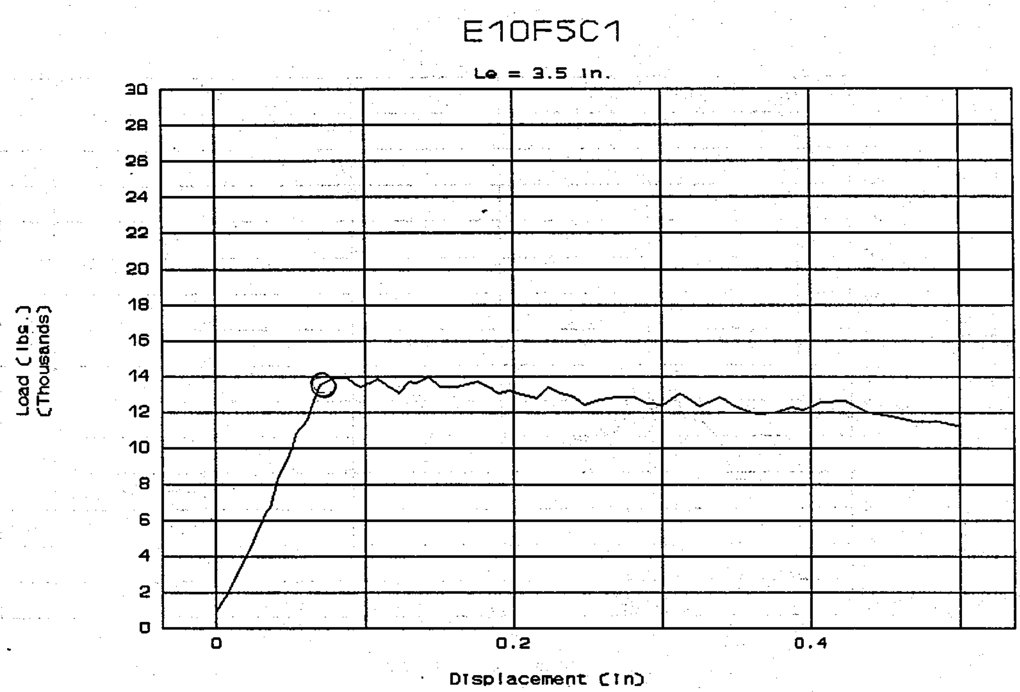

E9F6C2
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

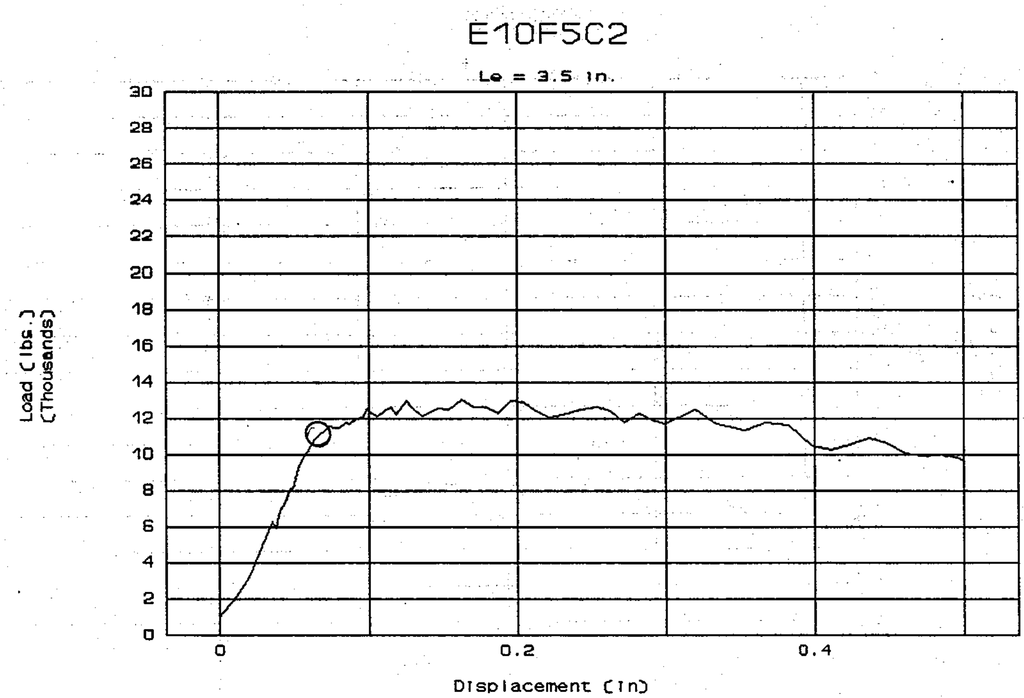

E9F6C3
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

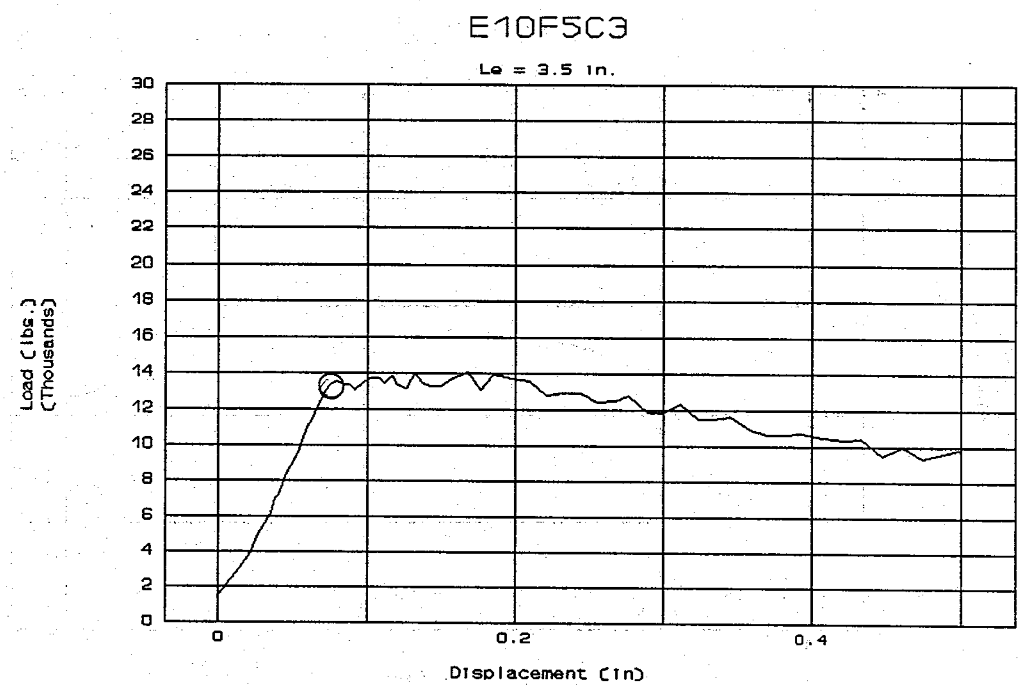

E10F4C1
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

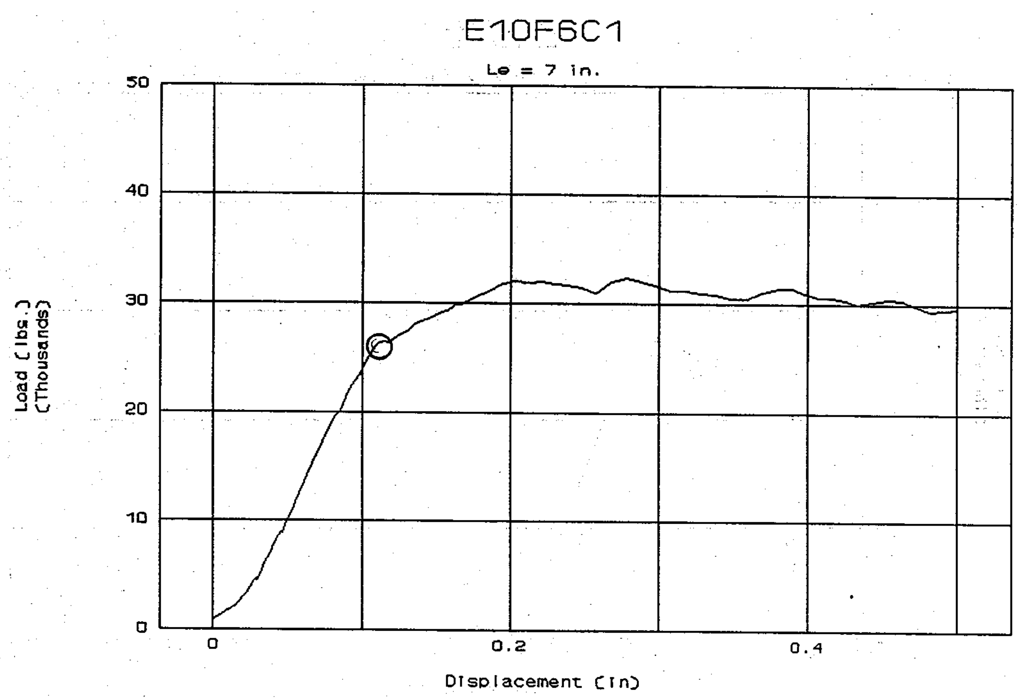

E10F4C2
Le = 5 in.
Load (lbs.) (Thousands)
Displacement (in)
0
0.2
0.4
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0

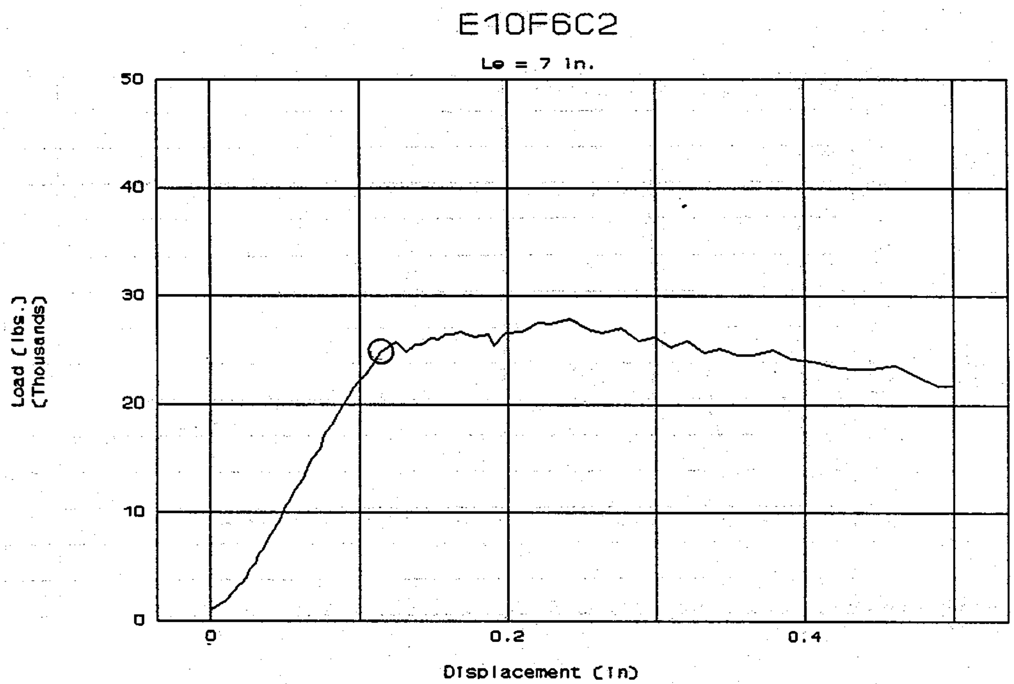

E10F4C3
Le = 5 in.
Load (lbs.) (Thousands)
Displacement (in)
0
0.2
0.4
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0

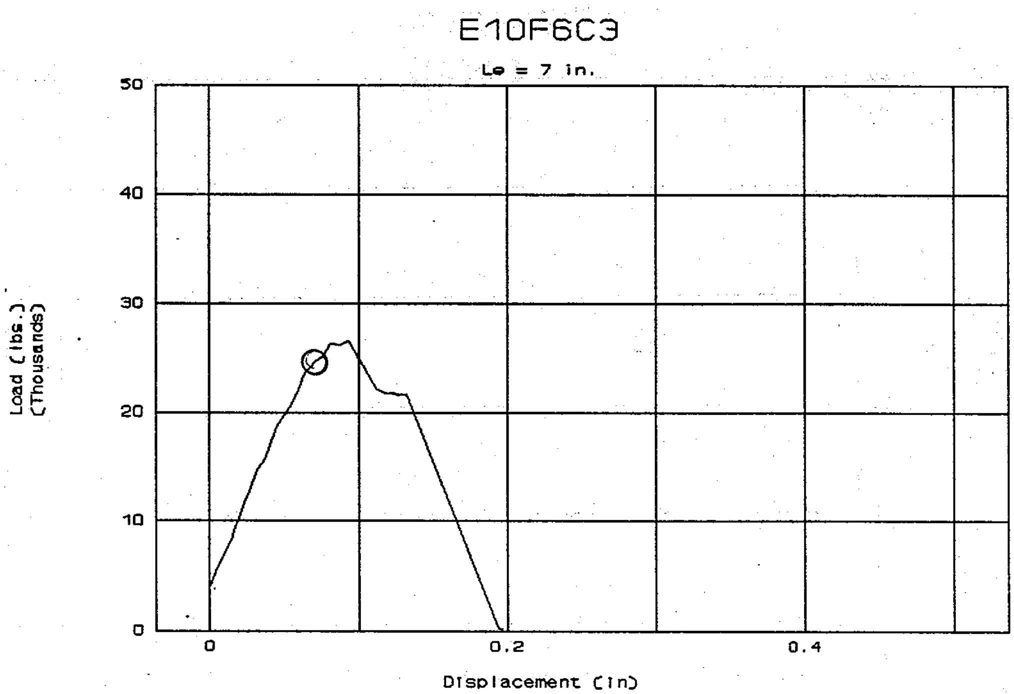

E10F5C1
Le = 3.5 in.
Load (lbs.) (Thousands)
Displacement (in)
0
0.2
0.4
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

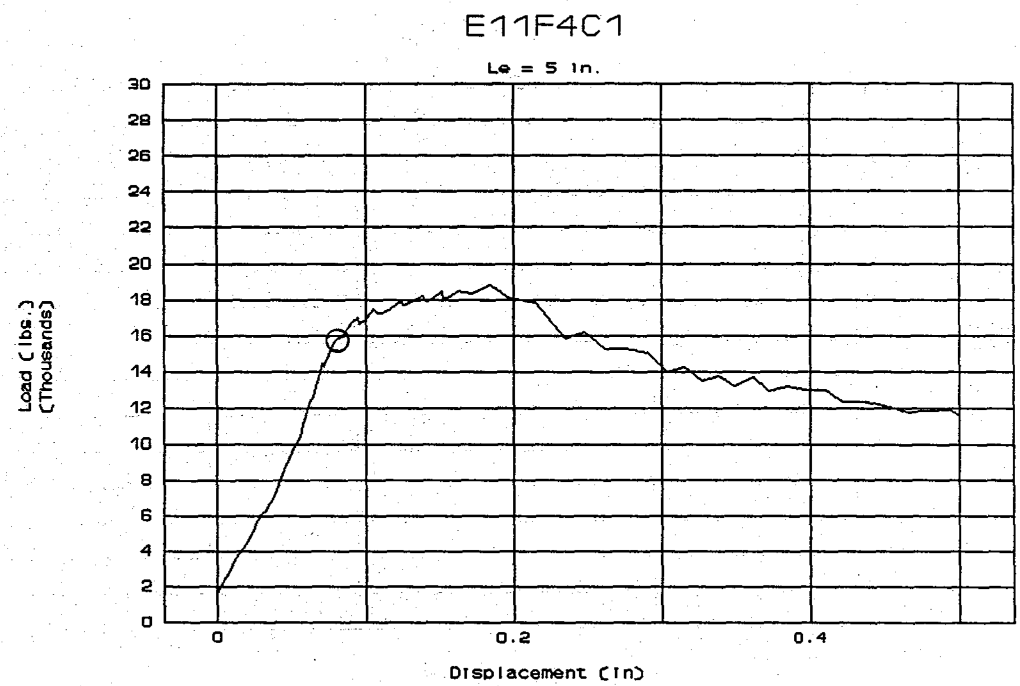

E10F5C2
Le = 3.5 in.
Load (lbs.) (Thousands)
Displacement (in)
0
0.2
0.4
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

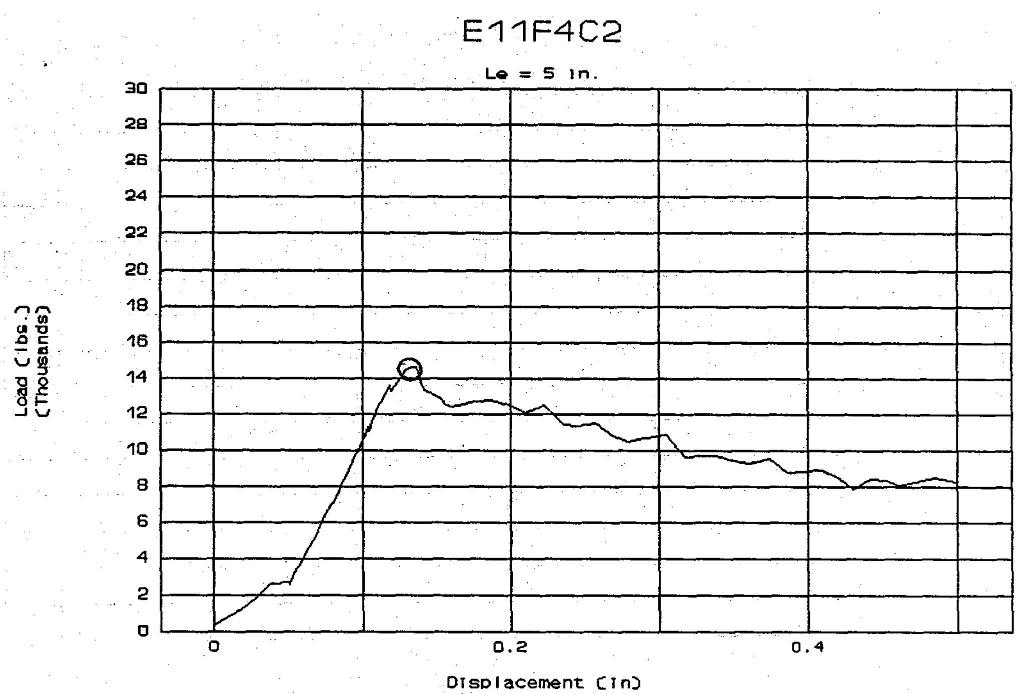

E10F5C3
Le = 3.5 in.
Load (lbs.) (Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

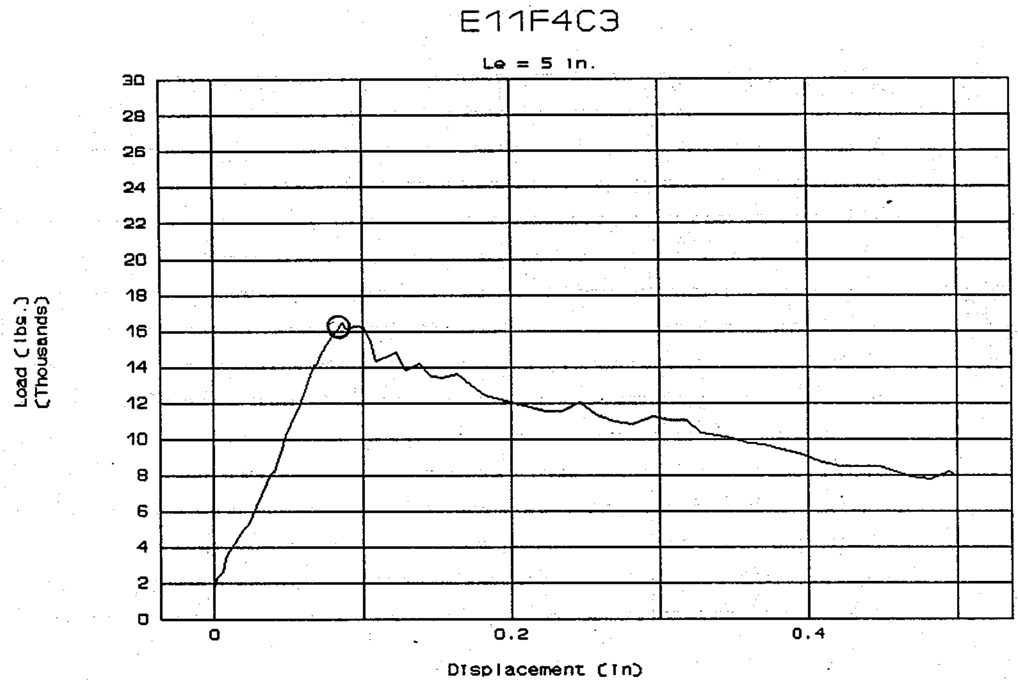

E10F6C1
Le = 7 in.
Load (lbs.) (Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)


E10F6C2
Le = 7 in.
Load (lbs.)
(Thousands)
0
10
20
30
40
50
0
0.2
0.4
Displacement (in)


E10F6C3
Le = 7 in.
Load (lbs.)
(Thousands)
0
10
20
30
40
50
0
0.2
0.4
Displacement (in)


E11F4C1
Le = 5 in.
Load (lbs.) (Thousands)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
0 0.2 0.4
Displacement (in)


E11F4C2
Le = 5 in.
Load (lbs.) (Thousands)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
0 0.2 0.4
Displacement (in)


E11F4C3
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
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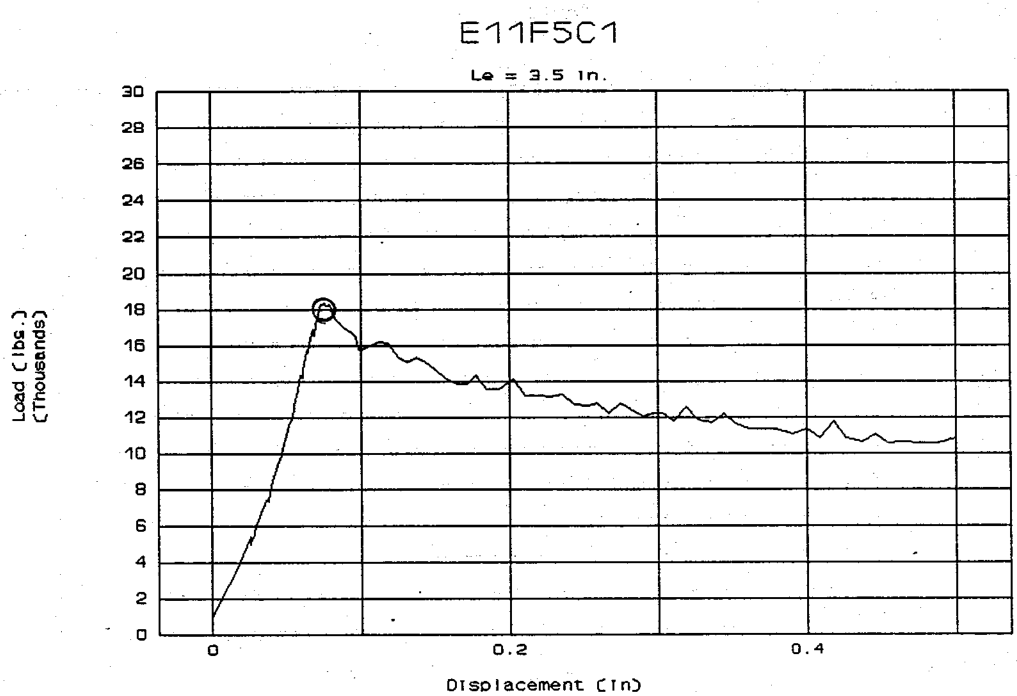
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E11F5C1
Le = 3.5 in.
Load (lbs.)
(Thousands)
30
28
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24
22
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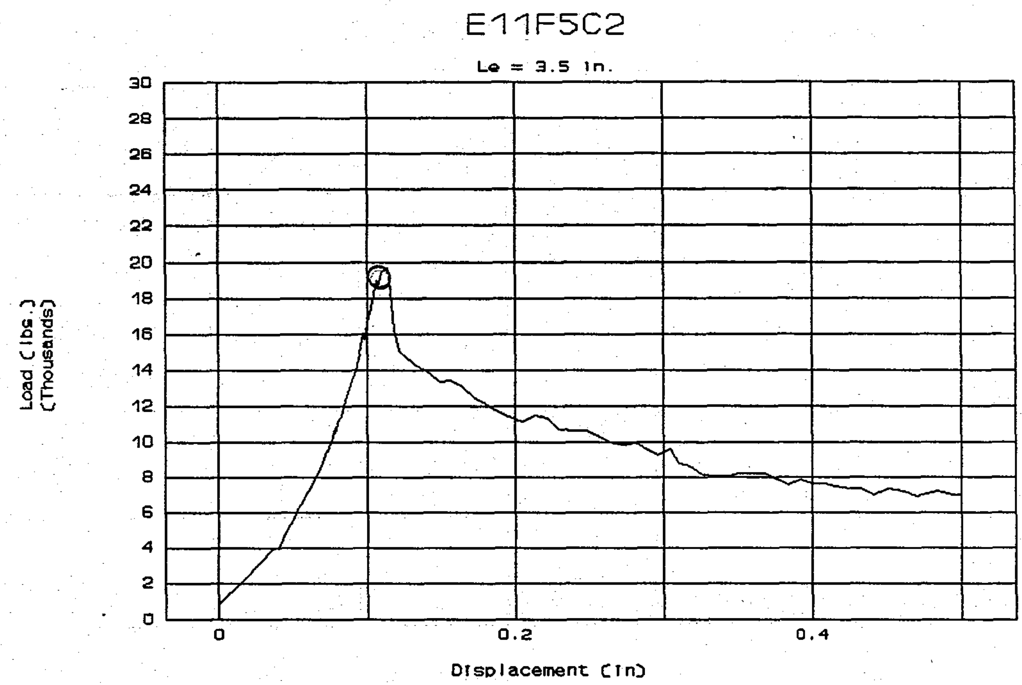
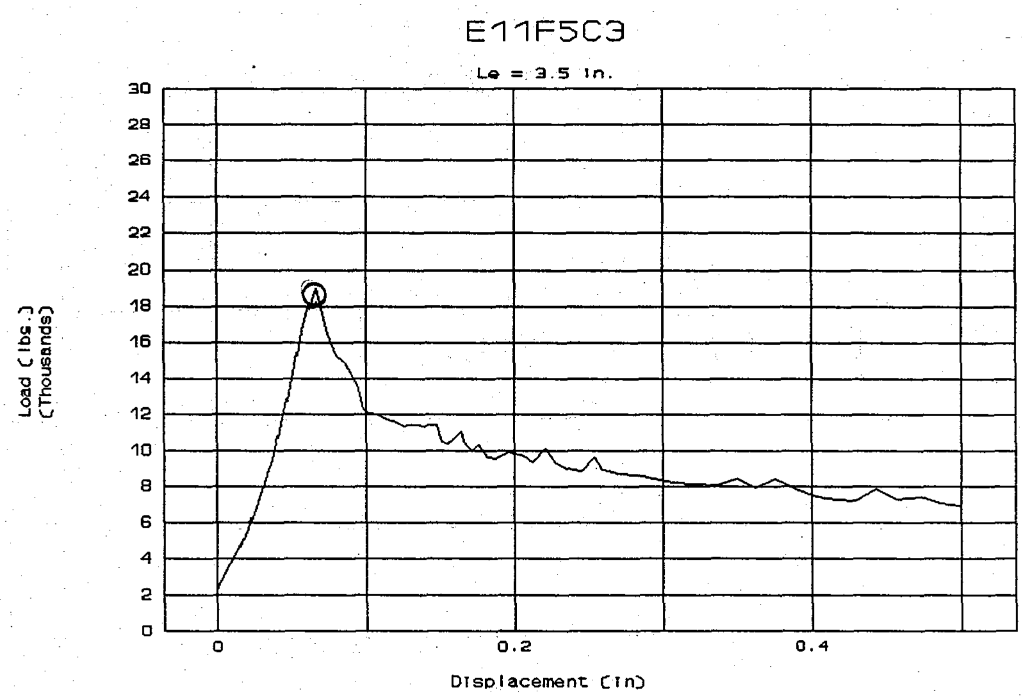
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E11F5C2
Le = 3.5 in.
Load (lbs.) (Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E11F5C3
Le = 3.5 in.
Load (lbs.) (Thousands)
30
28
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24
22
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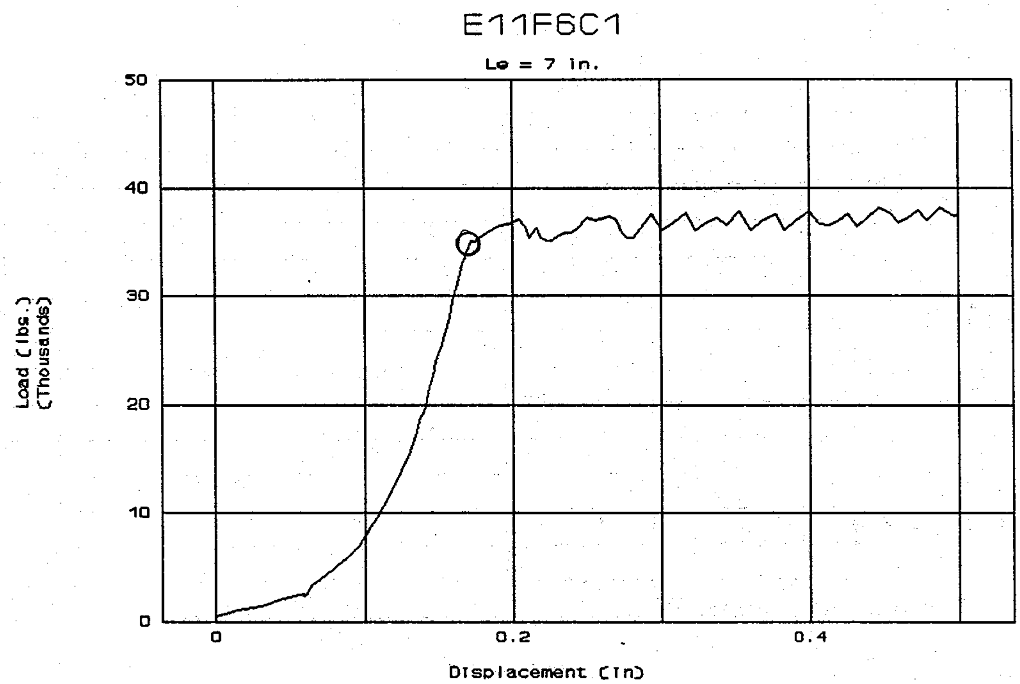
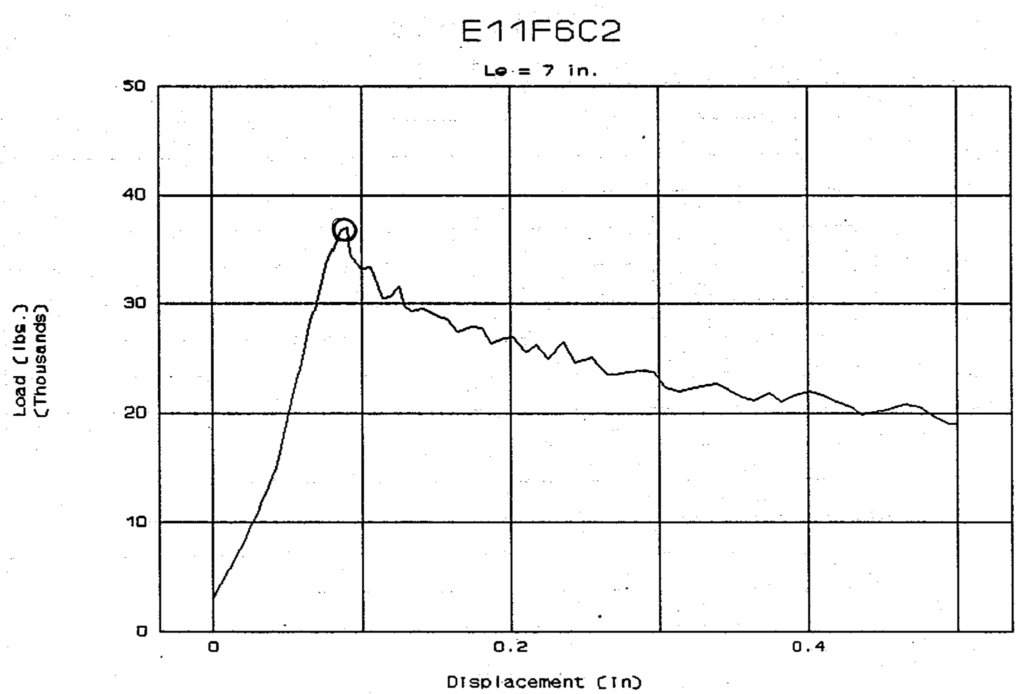
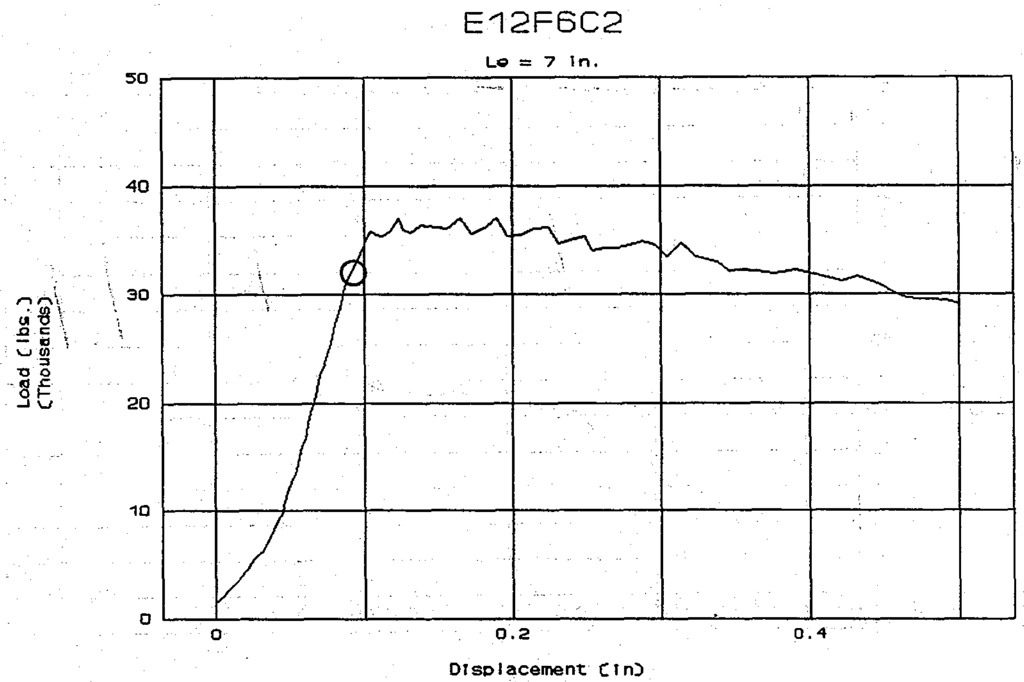
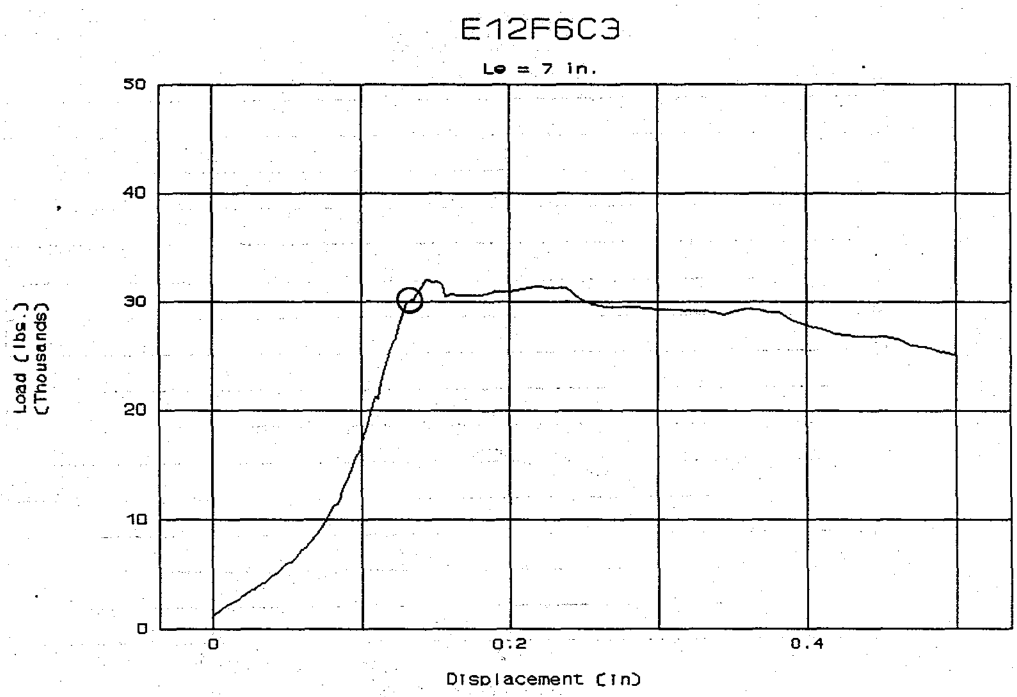
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E11F6C1
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (In)


E11F6C2
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (In)


E12F6C2
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)


E12F6C3
Le = 7 in.
Load (lbs.)
(Thousands)
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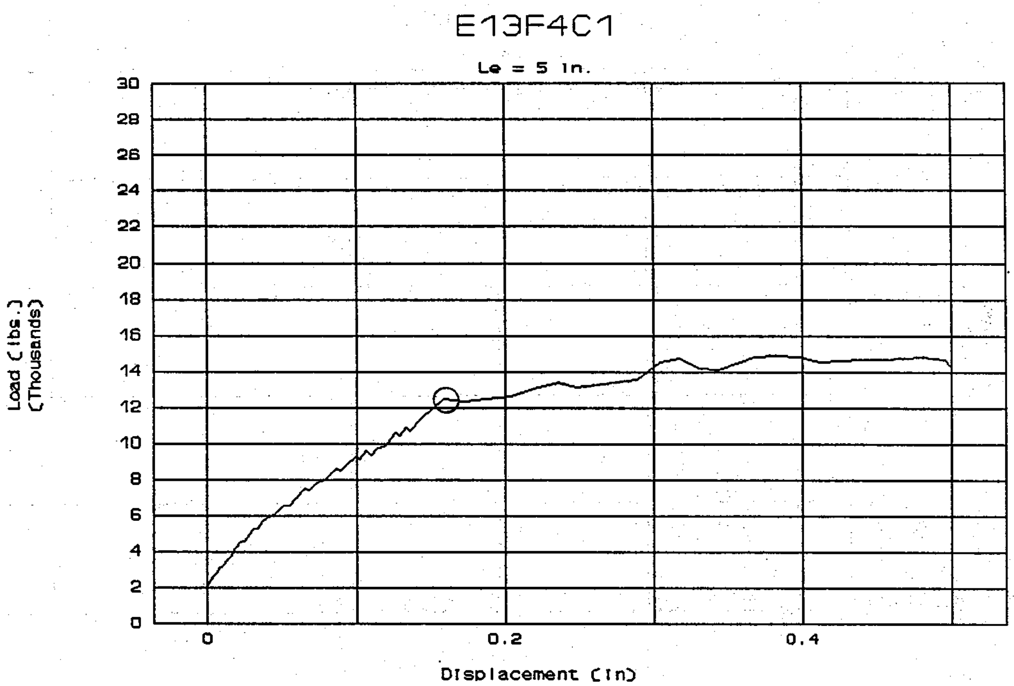
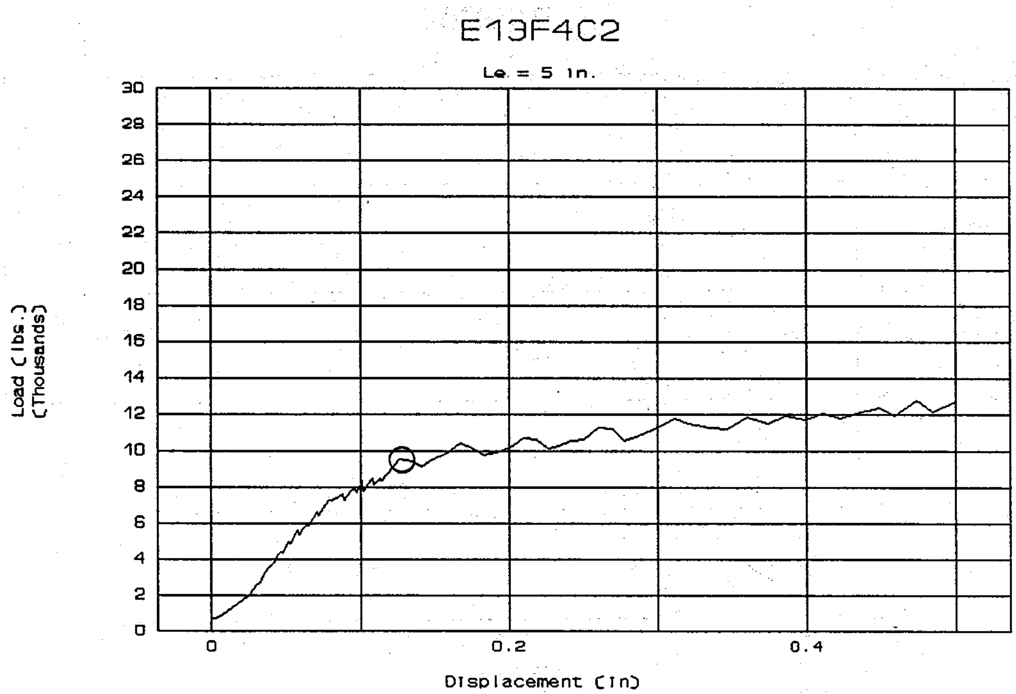
40
30
20
10
0
0
0.2
0.4
Displacement (in)


E13F4C1
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E13F4C2
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
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22
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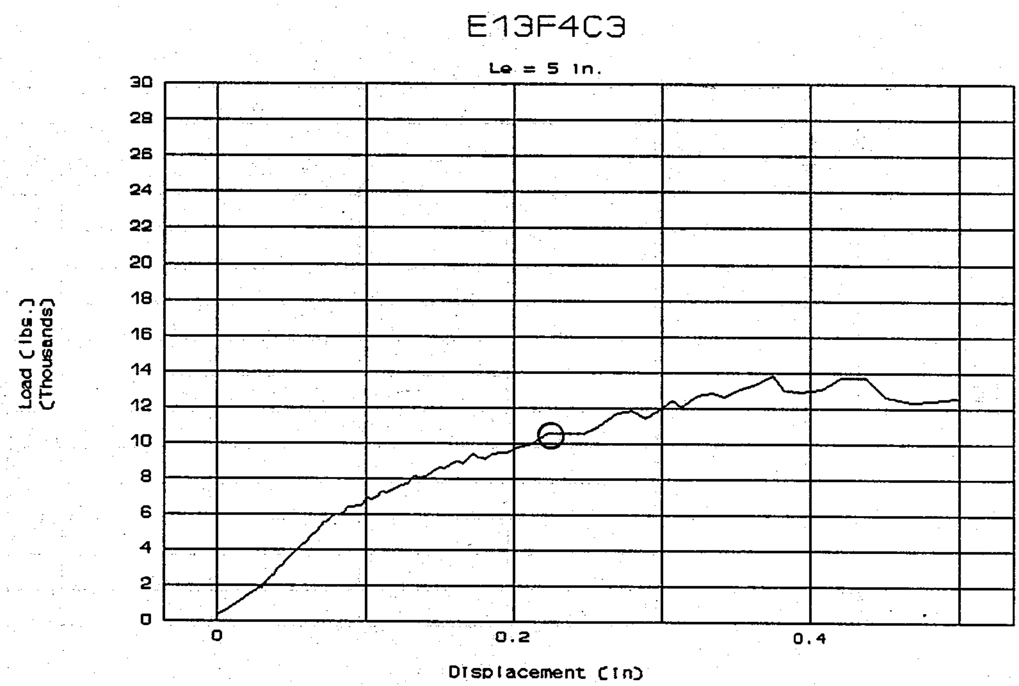
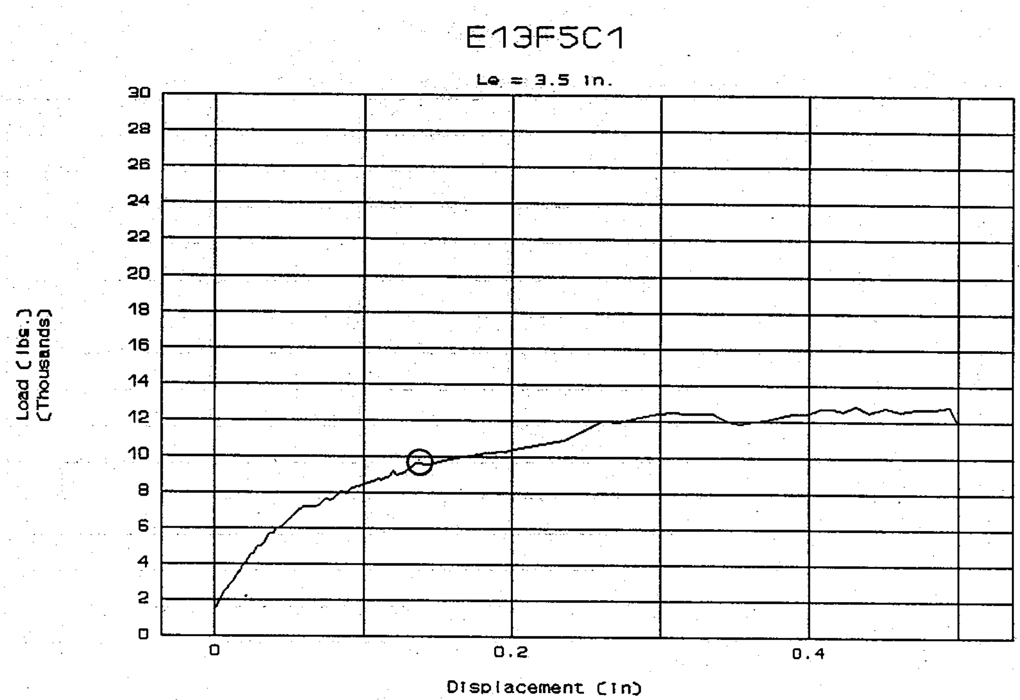
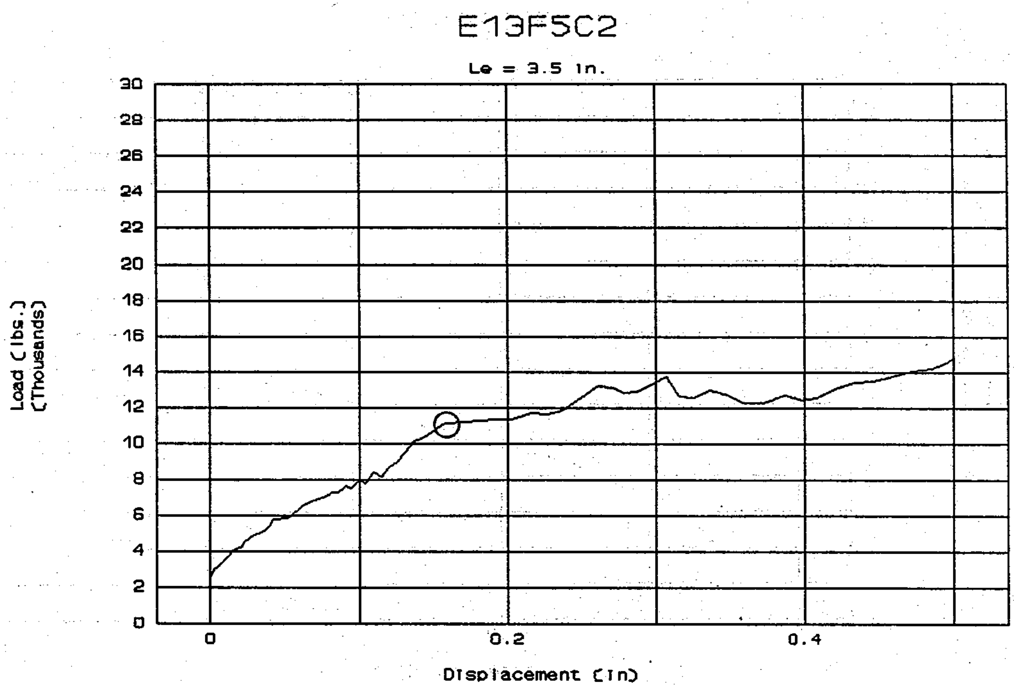
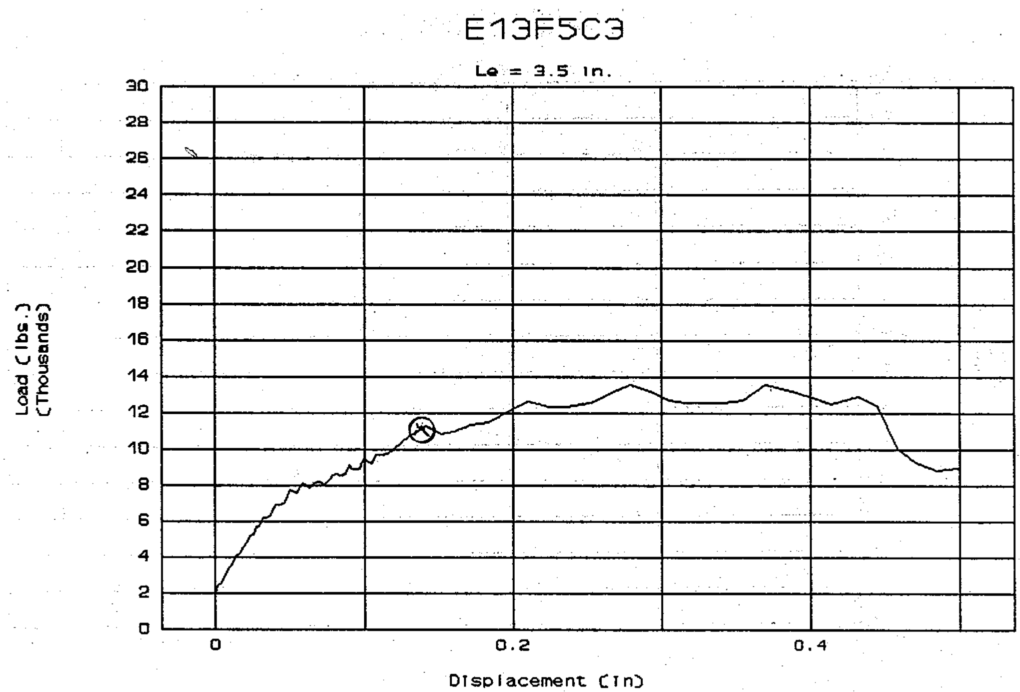
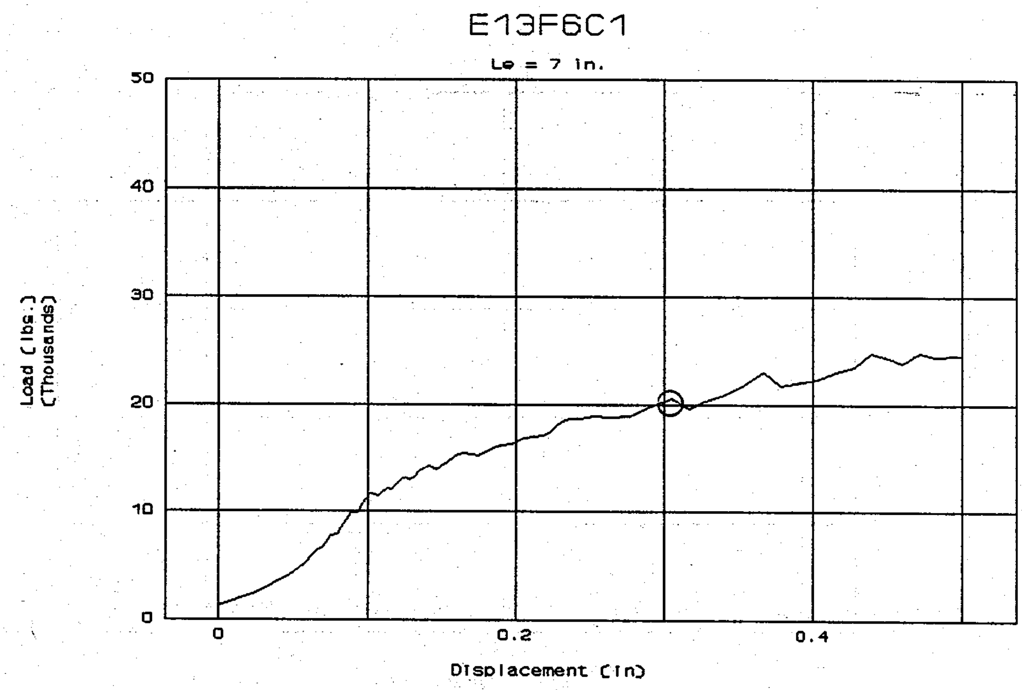
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

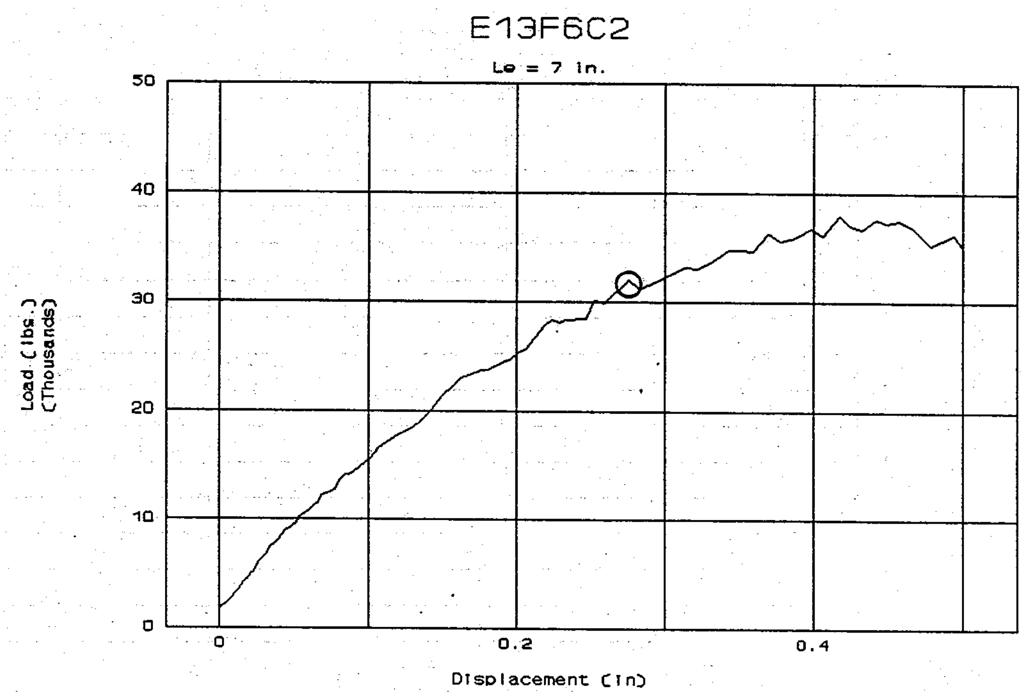

E13F4C3
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

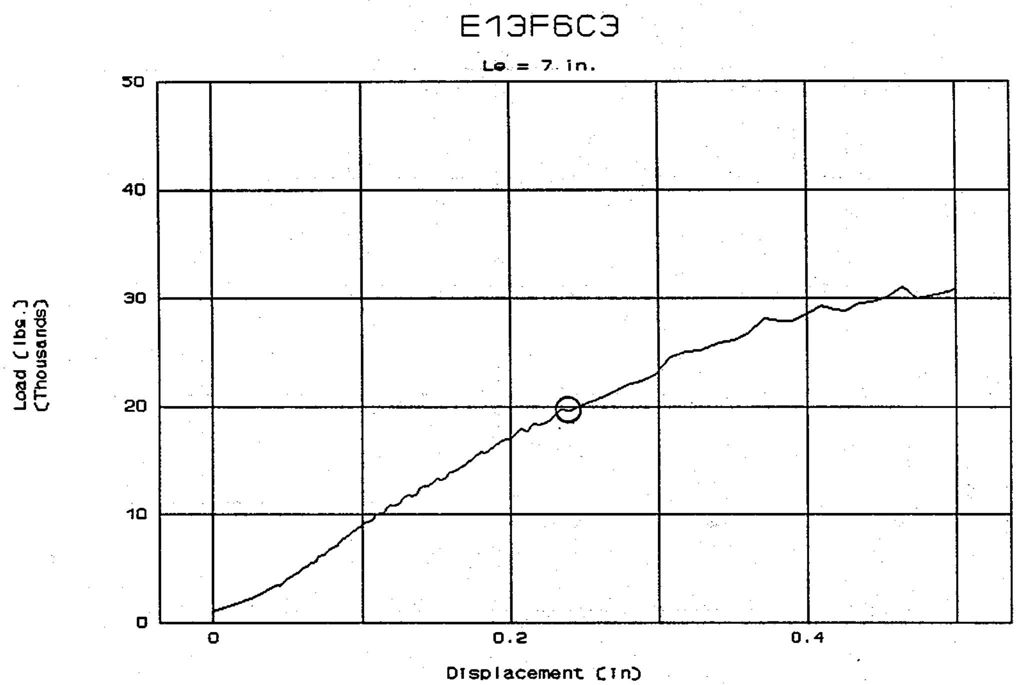

E13F5C1
Le = 3.5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

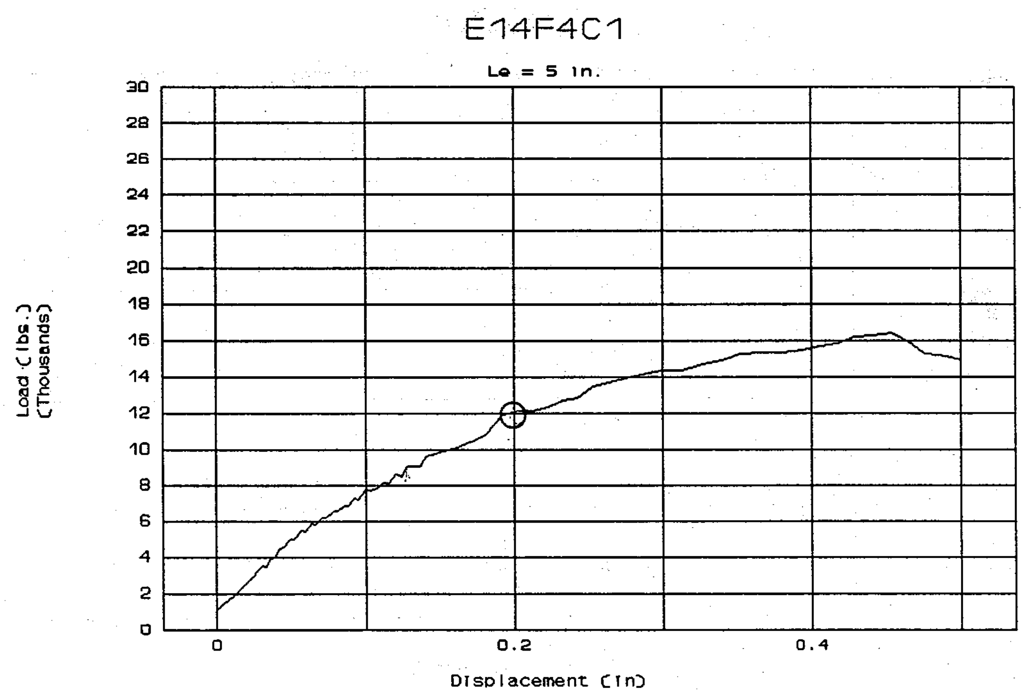

E13F5C2
Le = 3.5 in.
Load (lbs.) (Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

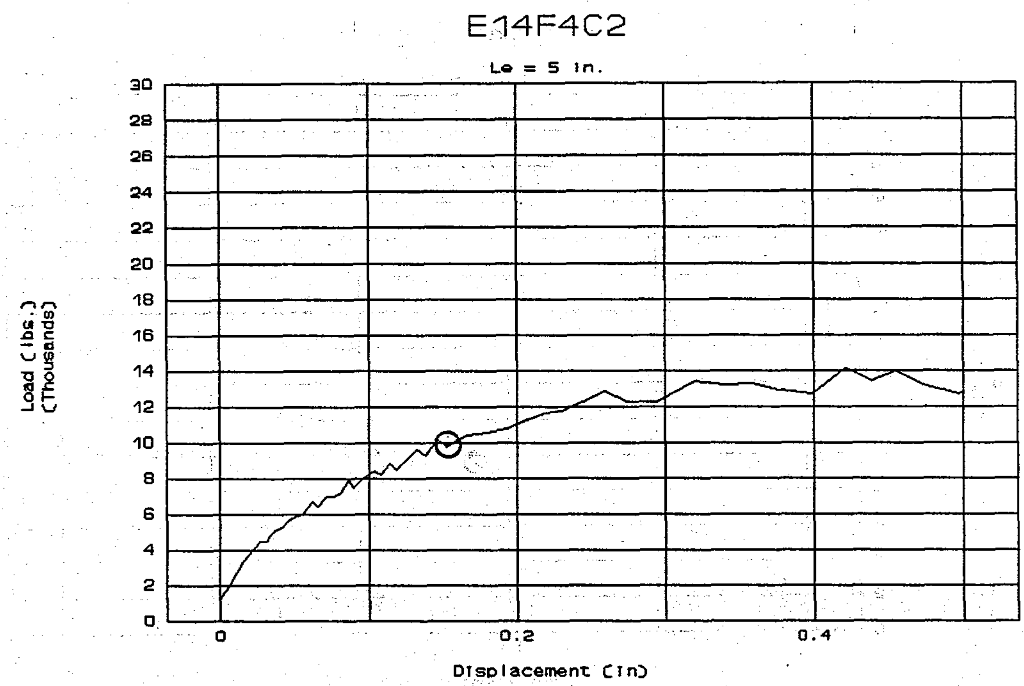

E13F5C3
Le = 3.5 in.
Load (lbs.) (Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

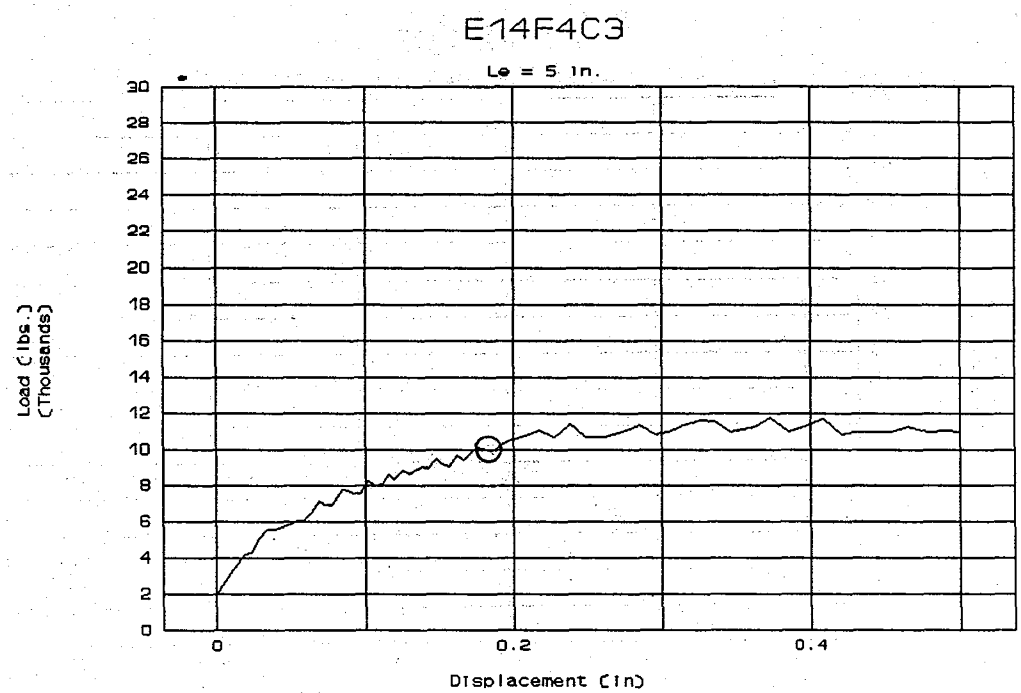

E13F6C1
Le = 7 in.
Load (lbs.) (Thousands)
Displacement (in)
0
10
20
30
40
50
0
0.2
0.4


E13F6C2
Le = 7 in.
Load (lbs.) (Thousands)
Displacement (in)
0
10
20
30
40
50
0
0.2
0.4

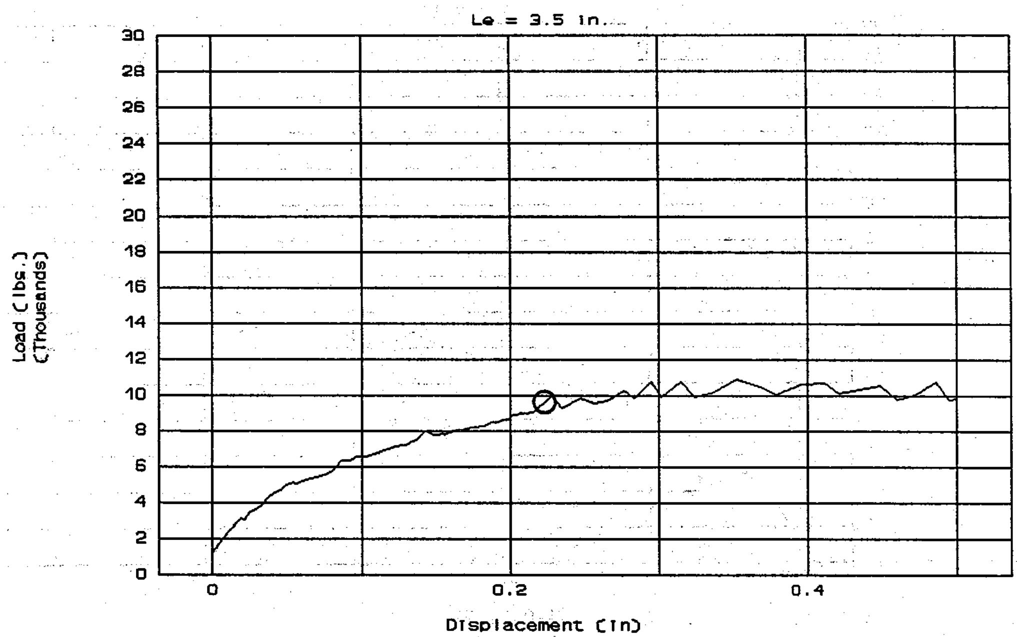

E13F6C3
Le = 7 in.
Load (lbs.) (Thousands)
Displacement (in)
0
10
20
30
40
50
0
0.2
0.4


E14F4C1
Le = 5 in.
Load (lbs.) (Thousands)
Displacement (in)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
0
0.2
0.4

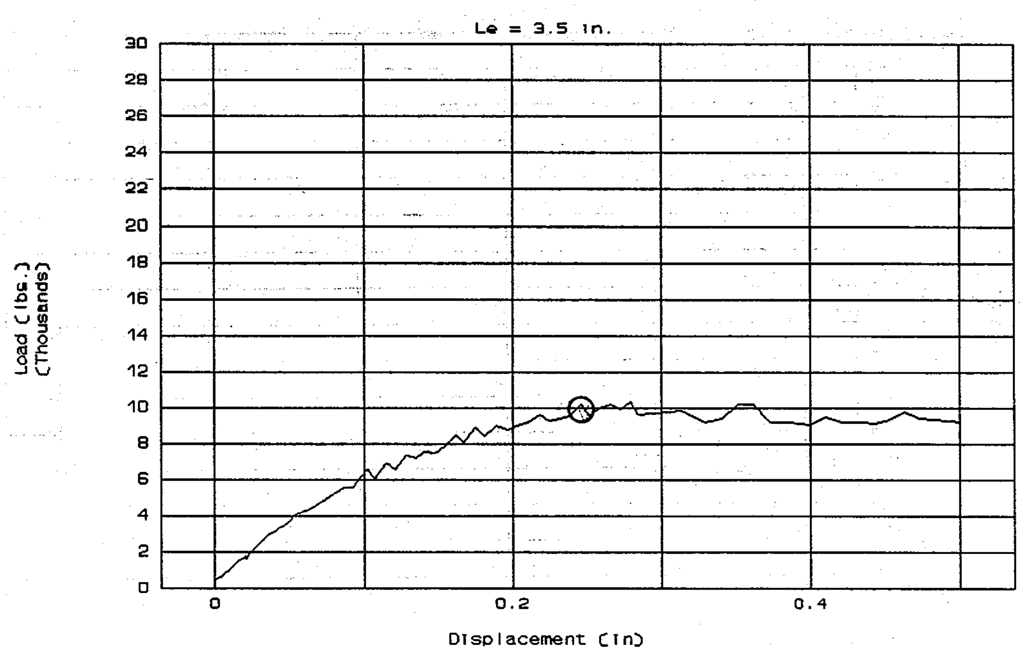

E14F4C2
Le = 5 in.
Load (lbs.) (Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

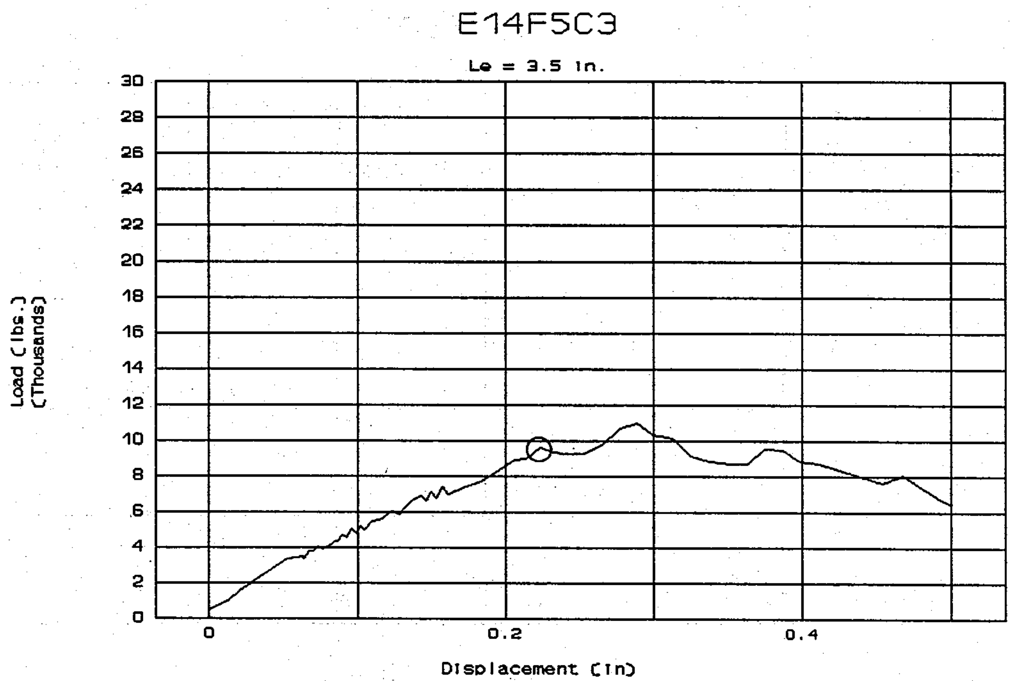

E14F4C3
Le = 5 in.
Load (lbs.) (Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

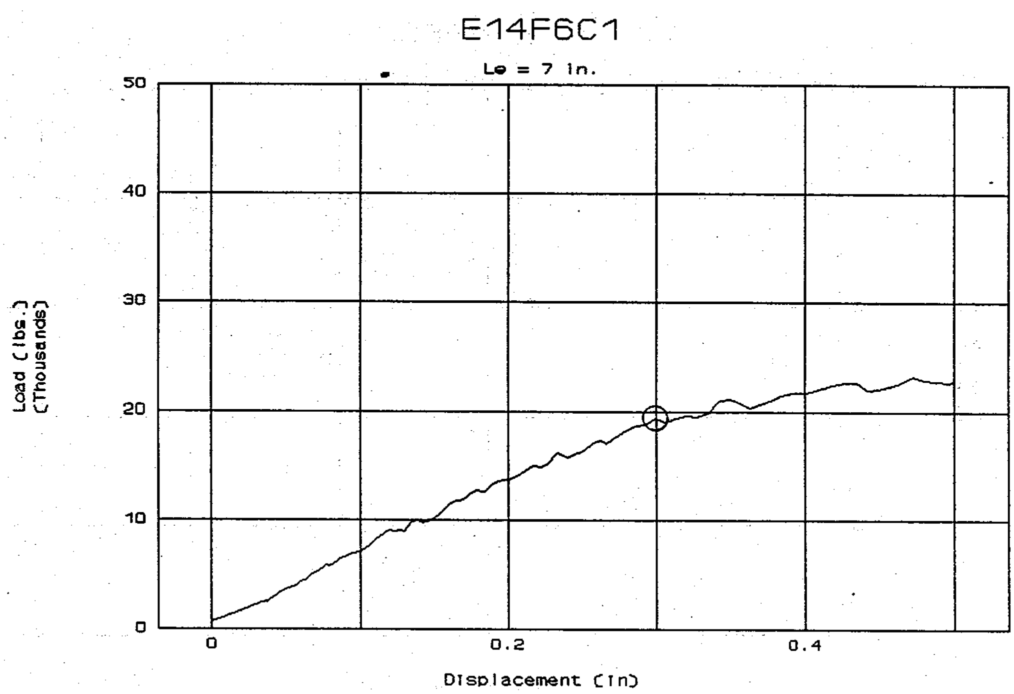
E14F5C1

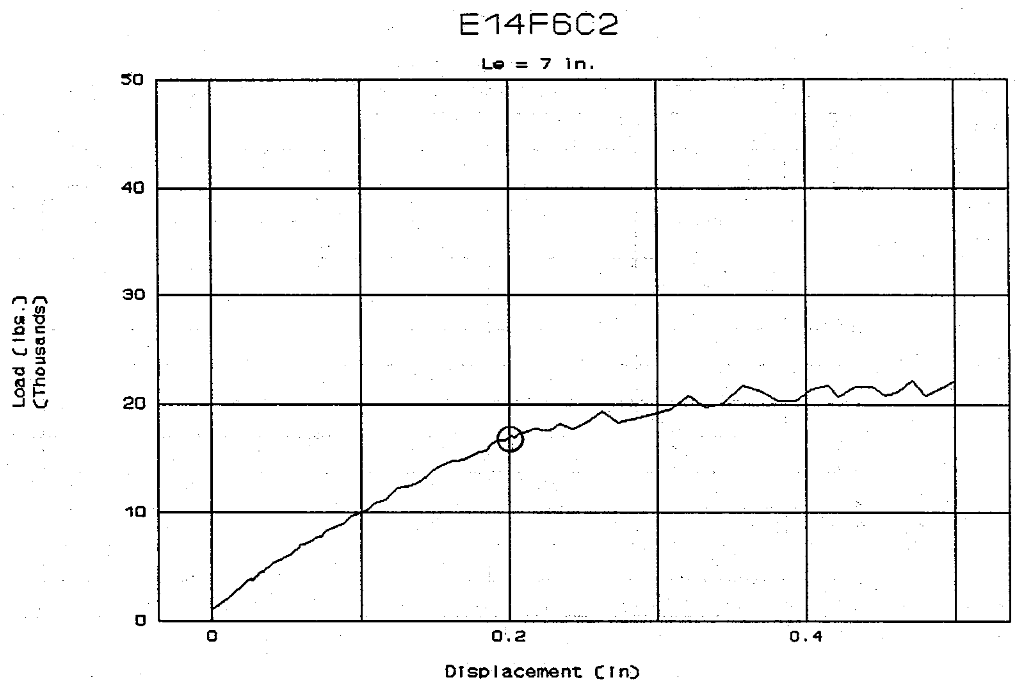


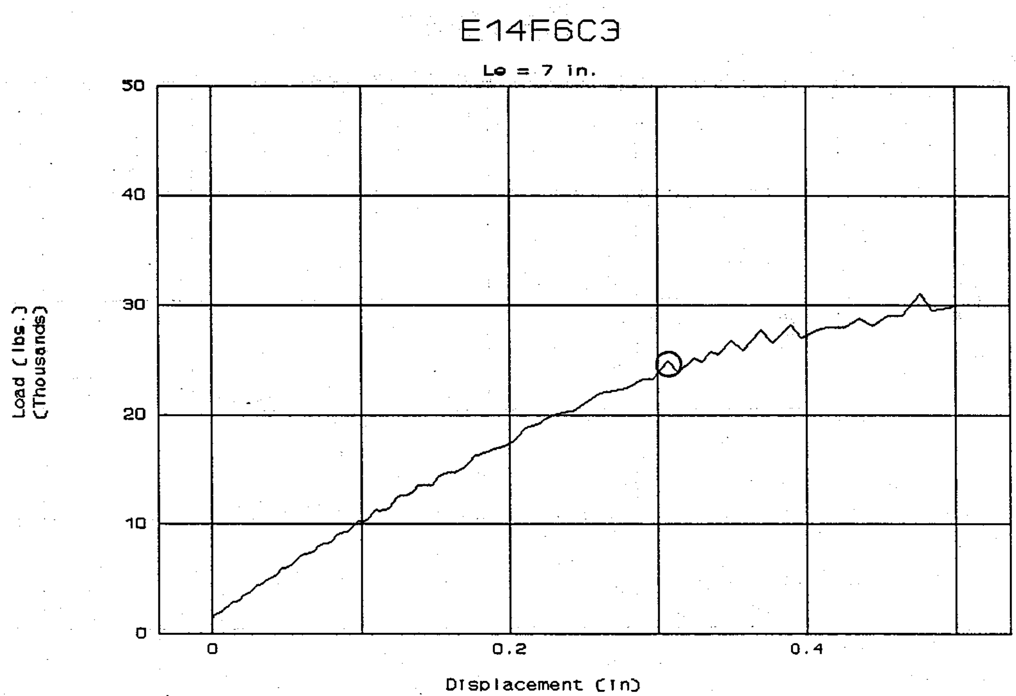
E14F5C2

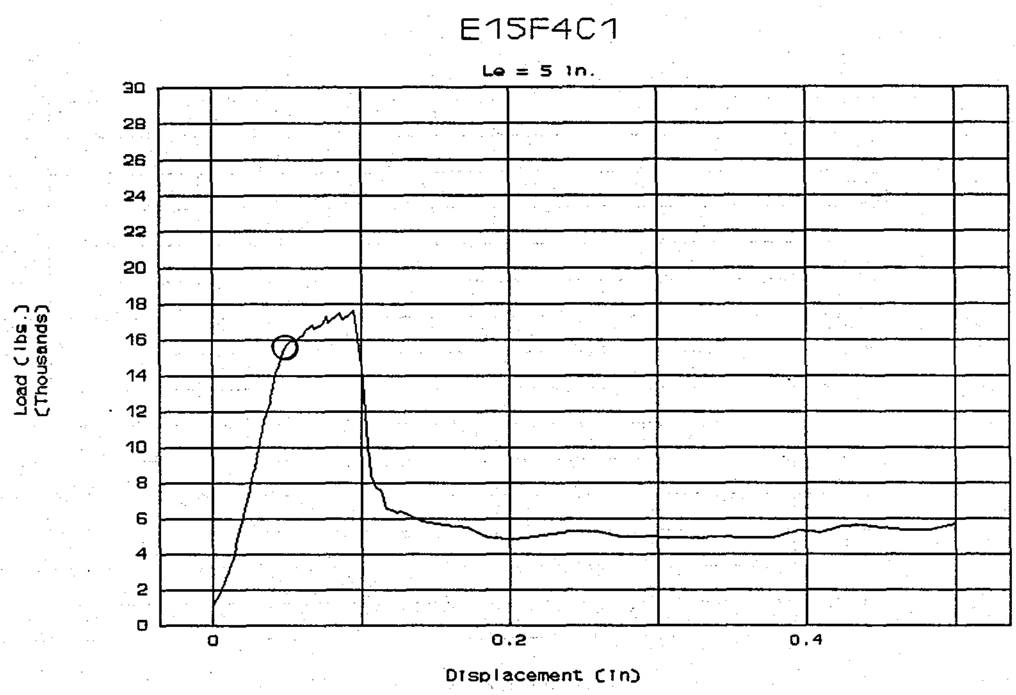


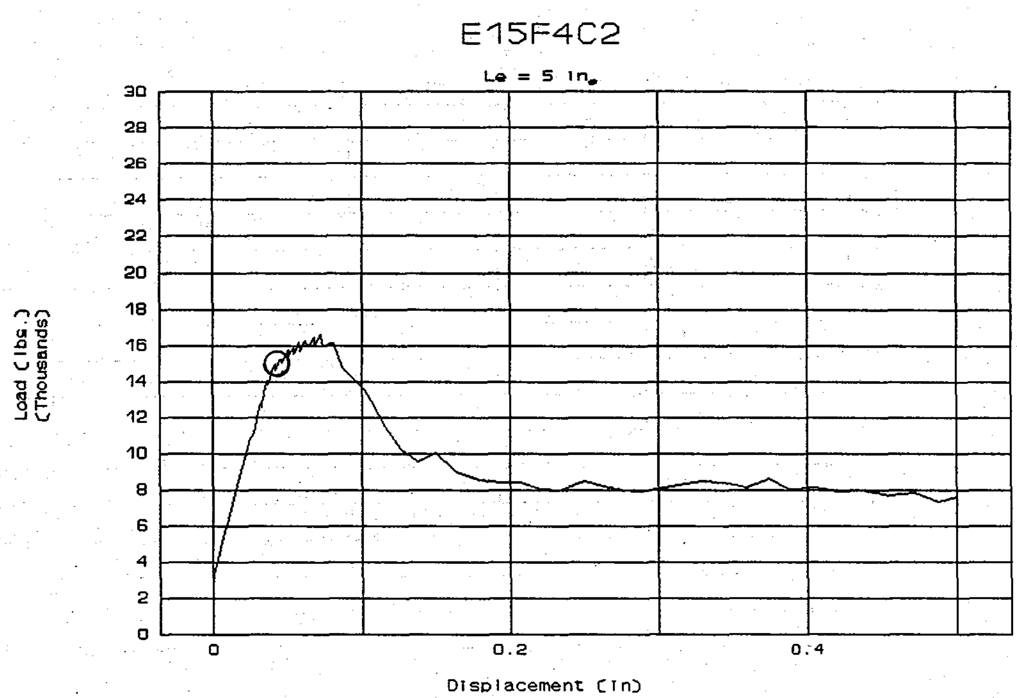

E14F5C3
Le = 3.5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

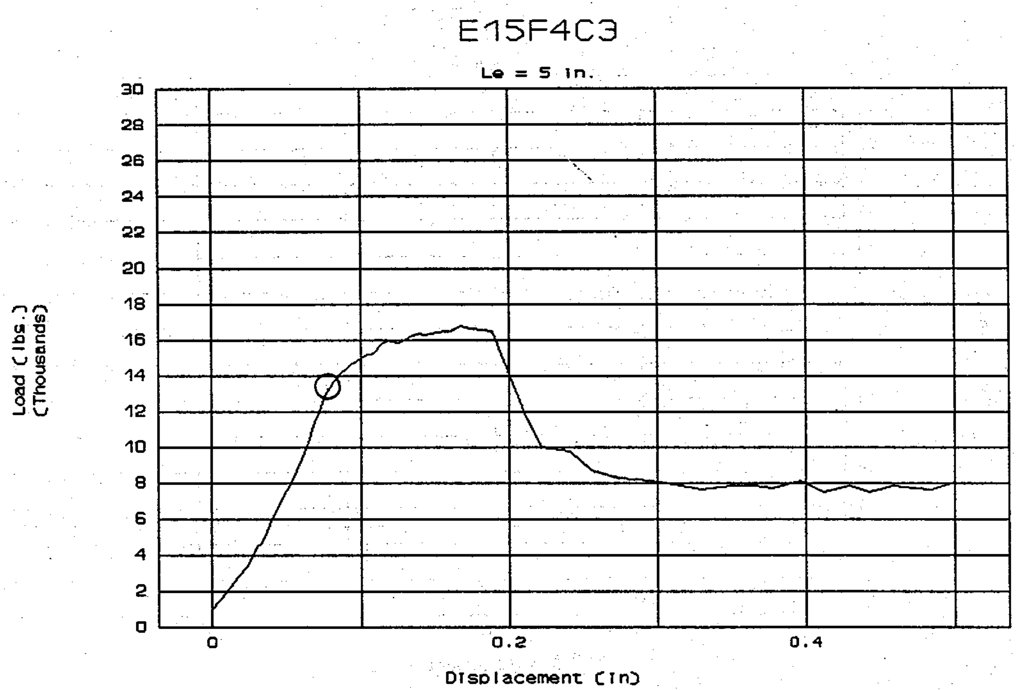

E14F6C1
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

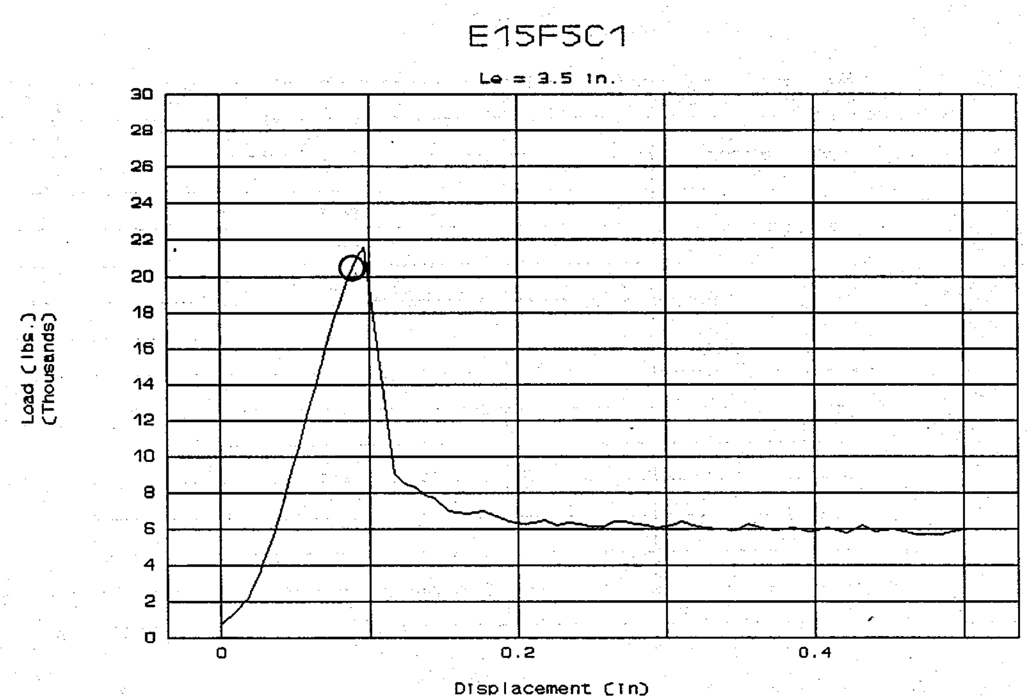

E14F6C2
Le = 7 in.
Load (lbs.)
(Thousands)
0
10
20
30
40
50
0
0.2
0.4
Displacement (in)

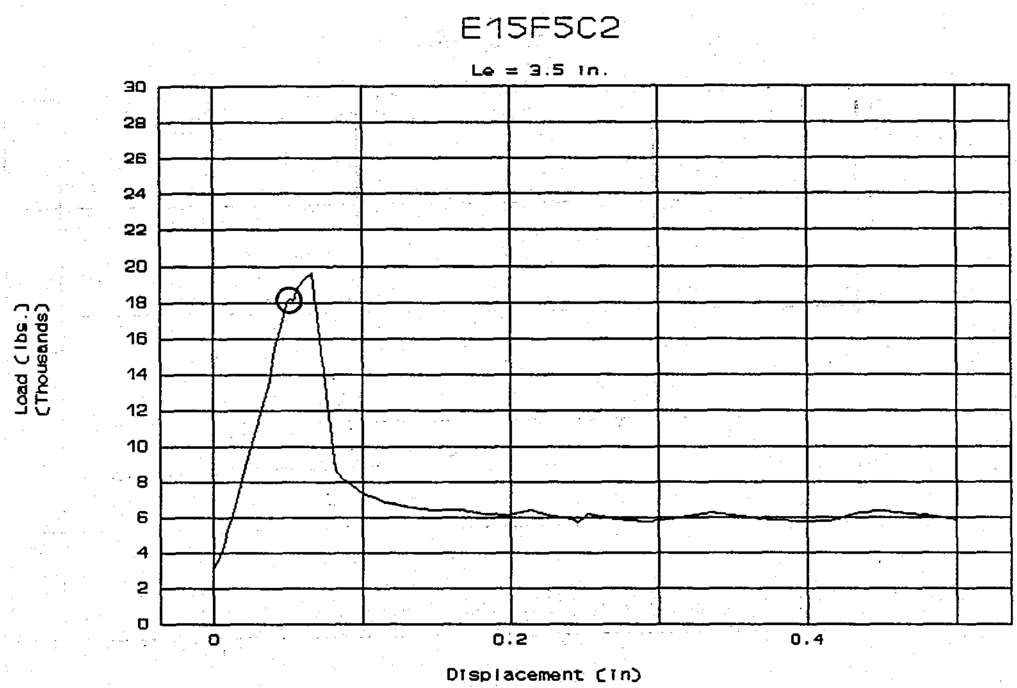

E14F6C3
Le = 7 in.
Load (lbs.)
(Thousands)
0
10
20
30
40
50
0
0.2
0.4
Displacement (in)

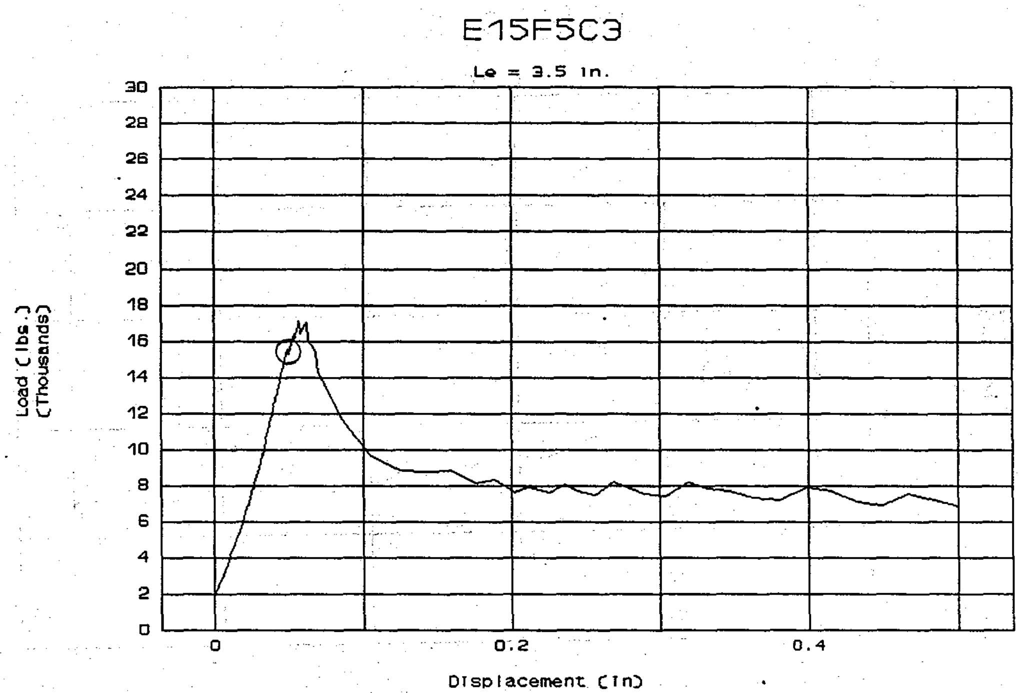

E15F4C1
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

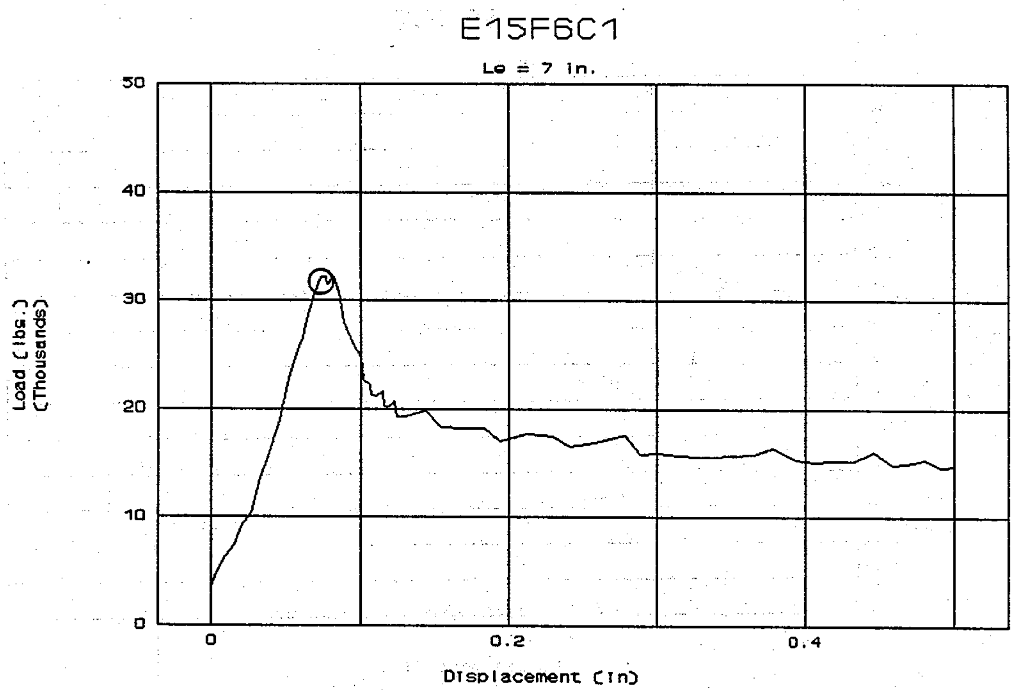

E15F4C2
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

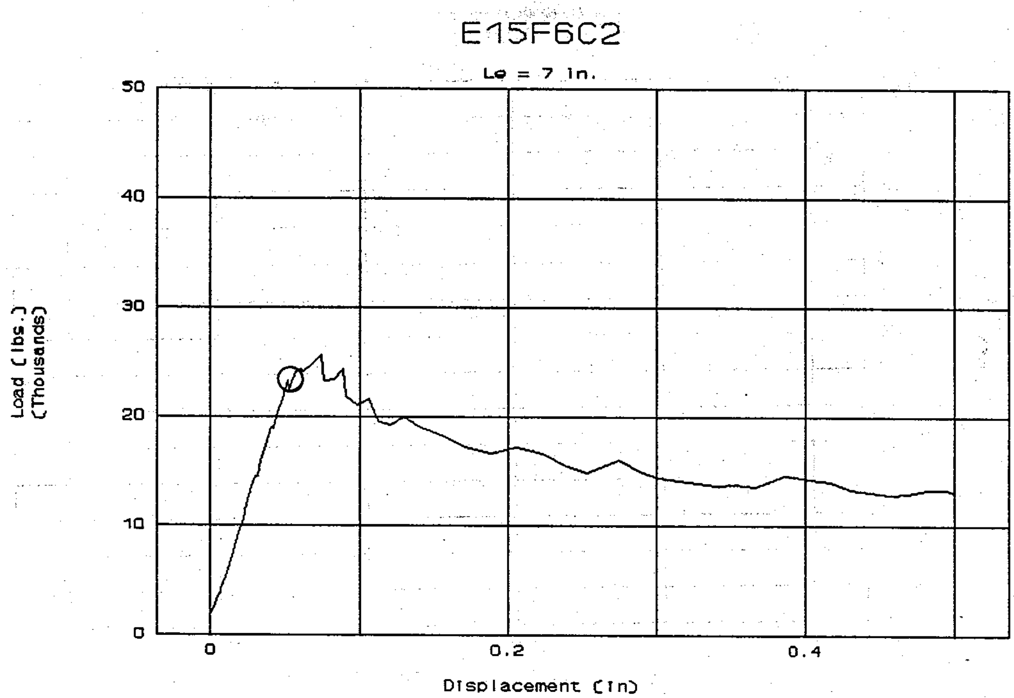

E15F4C3
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

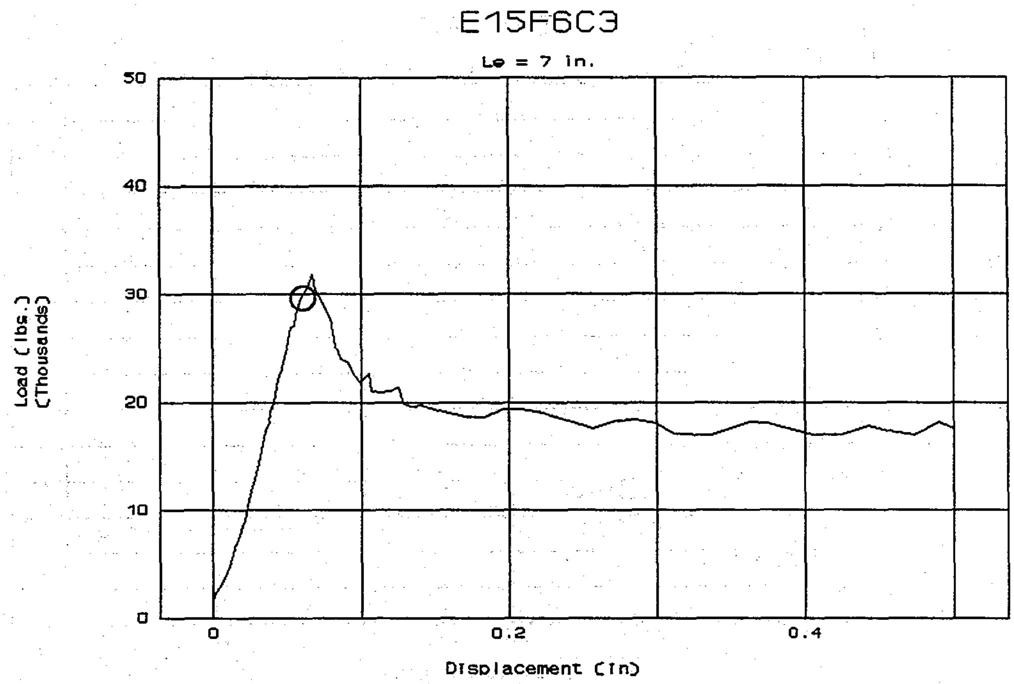

E15F5C1
Le = 3.5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

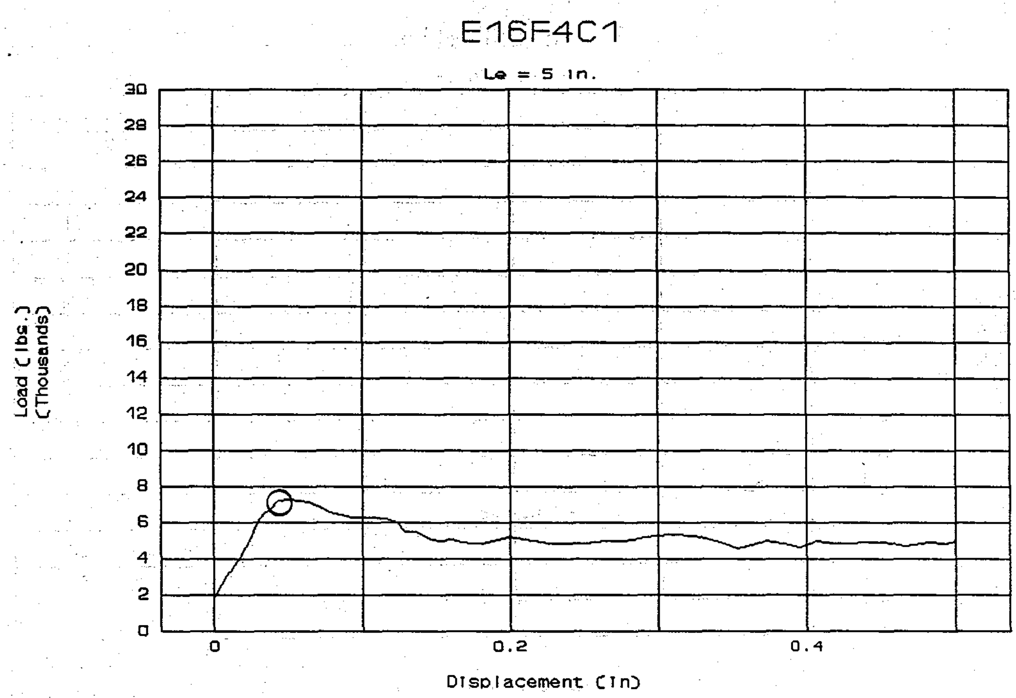

E15F5C2
Le = 3.5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

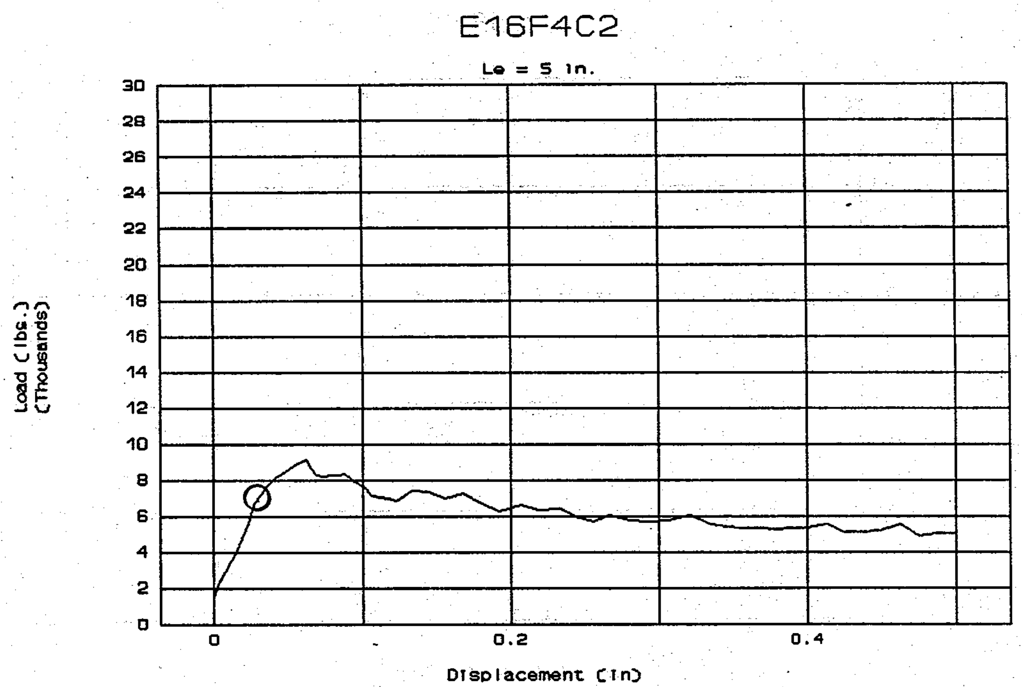

E15F5C3
Le = 3.5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

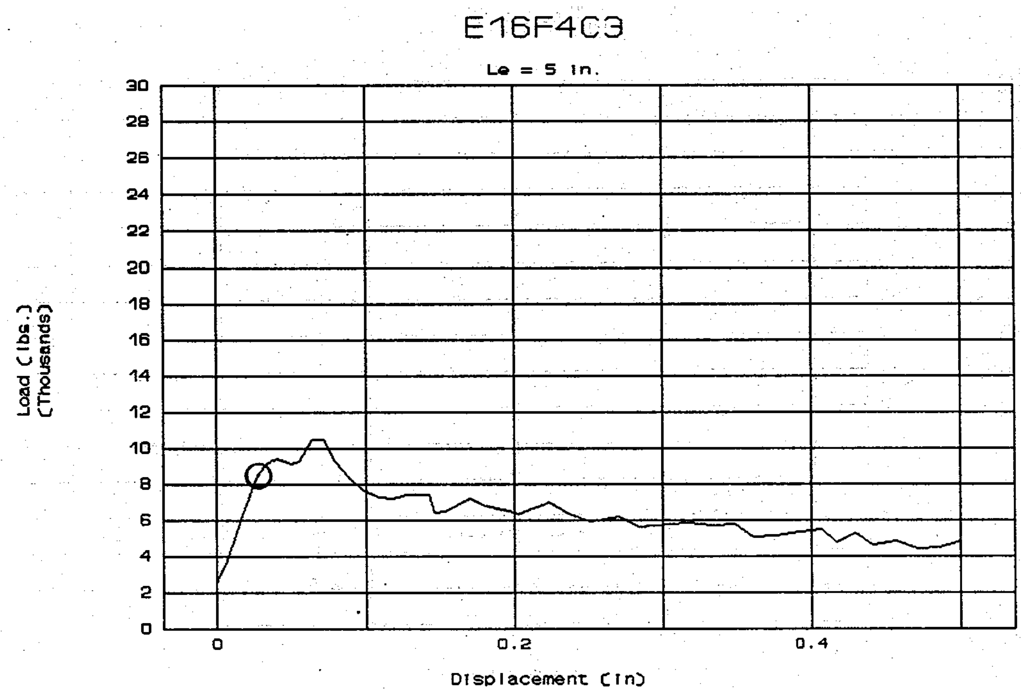

E15F6C1
Le = 7 in.
Load (lbs.) (Thousands)
Displacement (in)
0
10
20
30
40
50
0
0.2
0.4

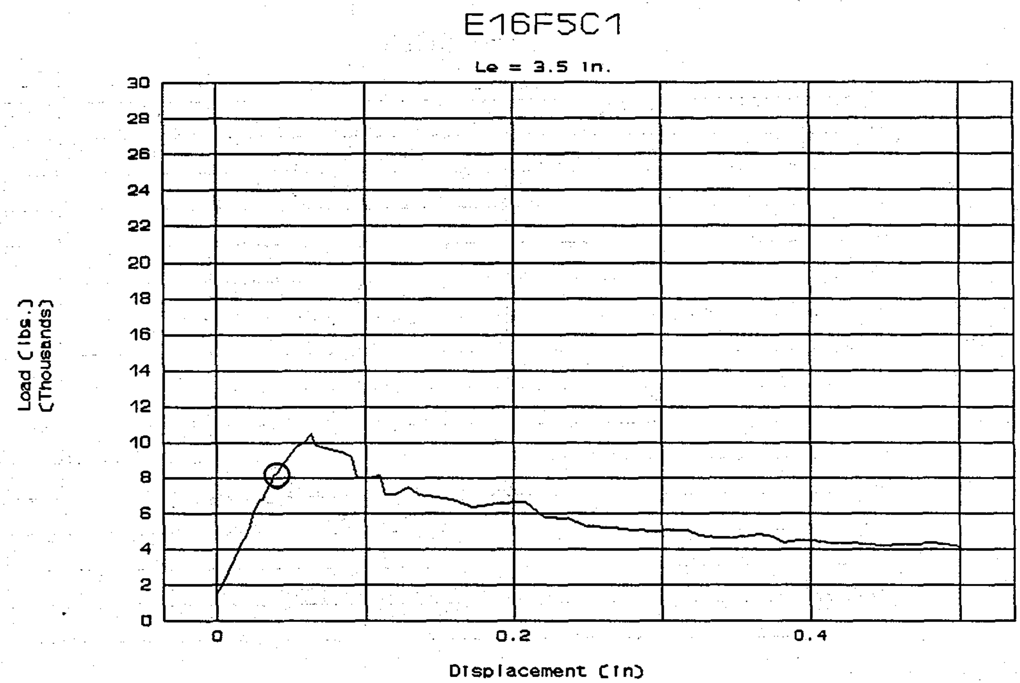

E15F6C2
Le = 7 in.
Load (lbs.) (Thousands)
Displacement (in)
0
10
20
30
40
50
0
0.2
0.4

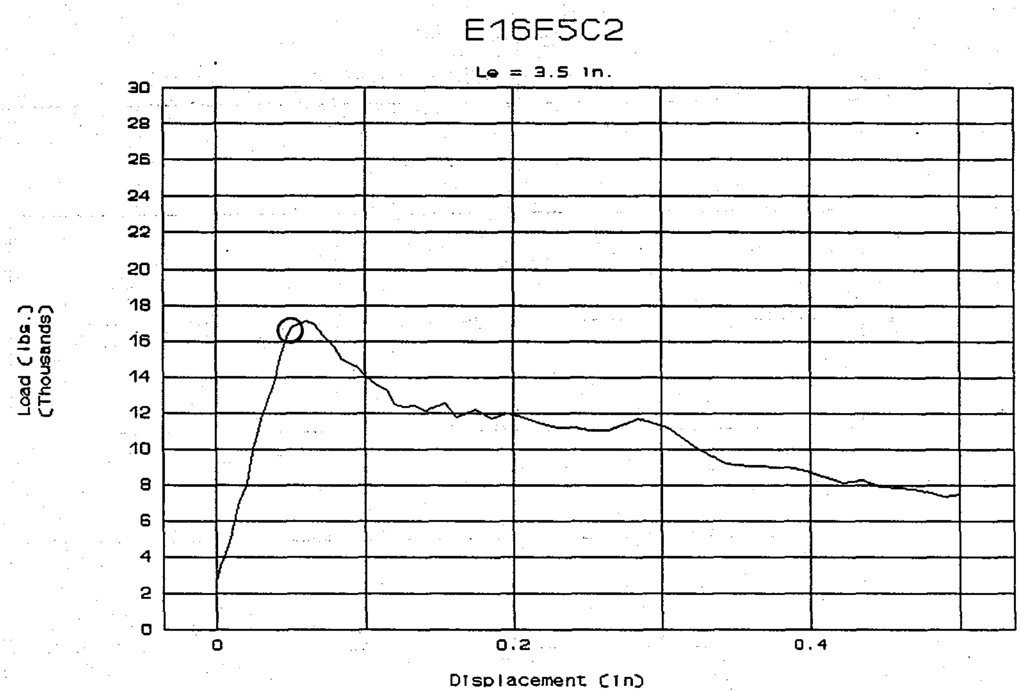

E15F6C3
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

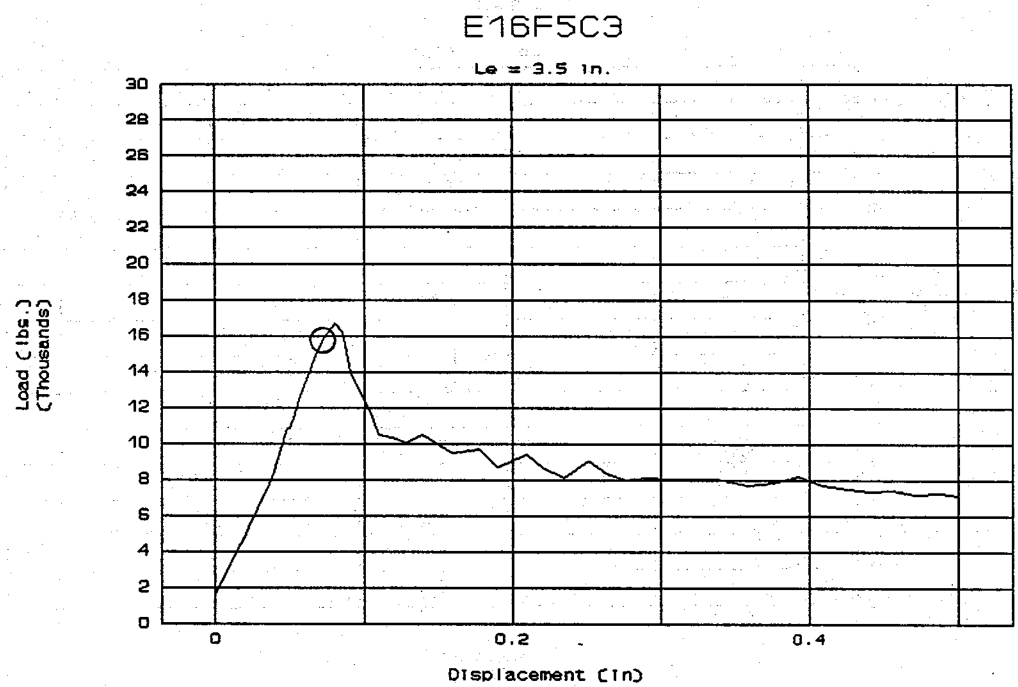

E16F4C1
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

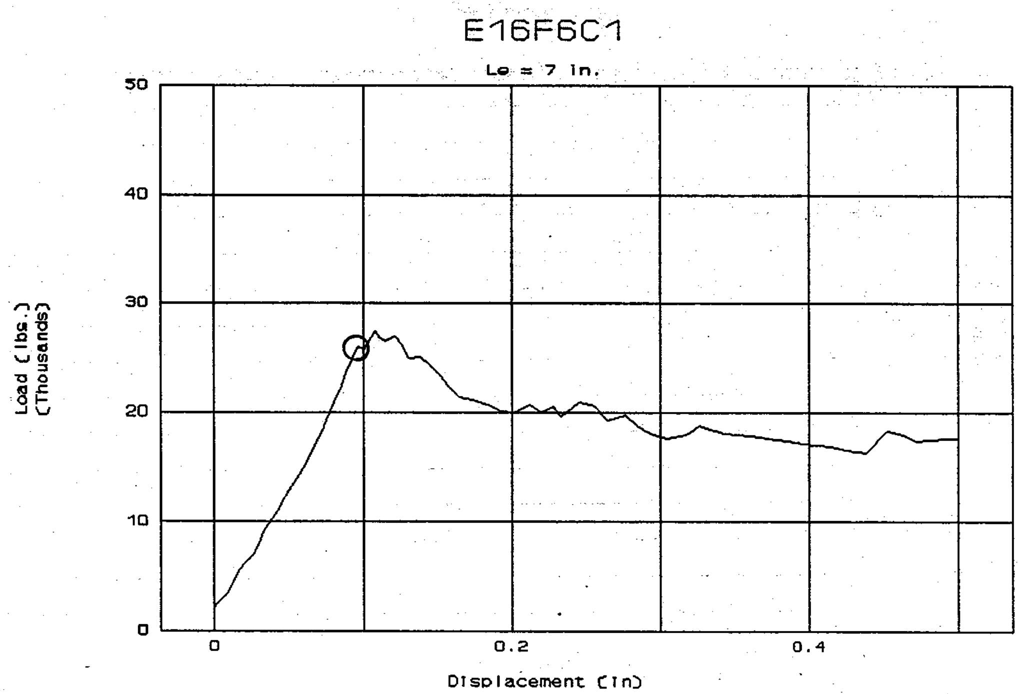

E16F4C2
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

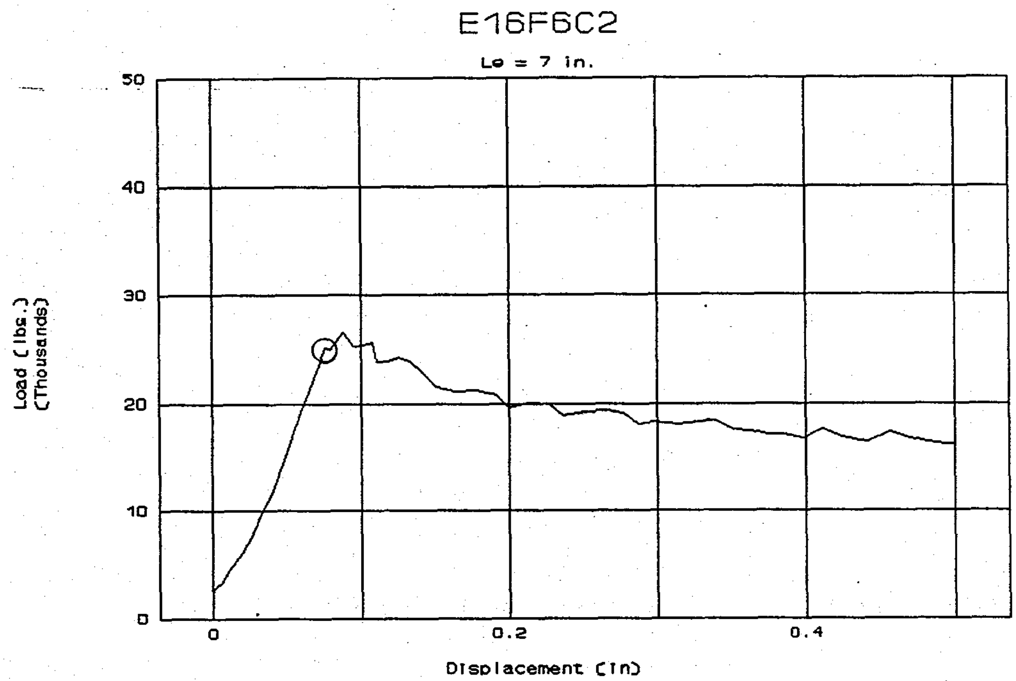

E16F4C3
Le = 5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

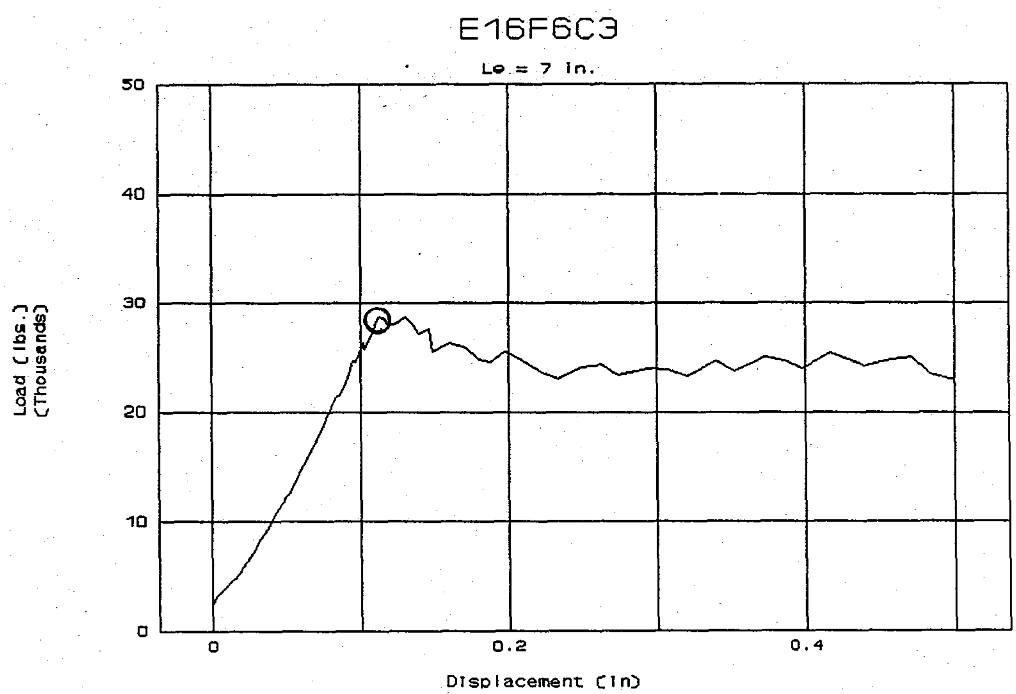

E16F5C1
Le = 3.5 in.
Load (lbs.) (Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E16F5C2
Le = 3.5 in.
Load (lbs.) (Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E16F5C3
Le = 3.5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E16F6C1
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)


E16F6C2
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)


E16F6C3
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

APPENDIX C

TABULATION AND GRAPHS FOR NONBASELINE TEST DATA

The nonbaseline tests employed methods that: were not used in the baseline tests. These methods are (in the order that they are presented): unconfined testing with fully-bonded anchors, unconfined testing with partially-bonded anchors, confined testing with partially-bonded anchors, and confined testing with fully-bonded anchors using embedment lengths different than those, used for the baseline tests.

The tests are designated as described in Chapter 4.

Table C-1 Data for unconfined testing with fully-bonded anchors

Adhes. Desig.	Anchor Dia. (in)	Embed. Length (in)	P_{exp} (kips) Trial 1	2	3
E1	3/4	7	22.23	22.63	
E2	3/4	7	17.45	17.98	20.10

Table C-2 Data for unconfined testing with partially-bonded anchors (2 in. bond-breaker)

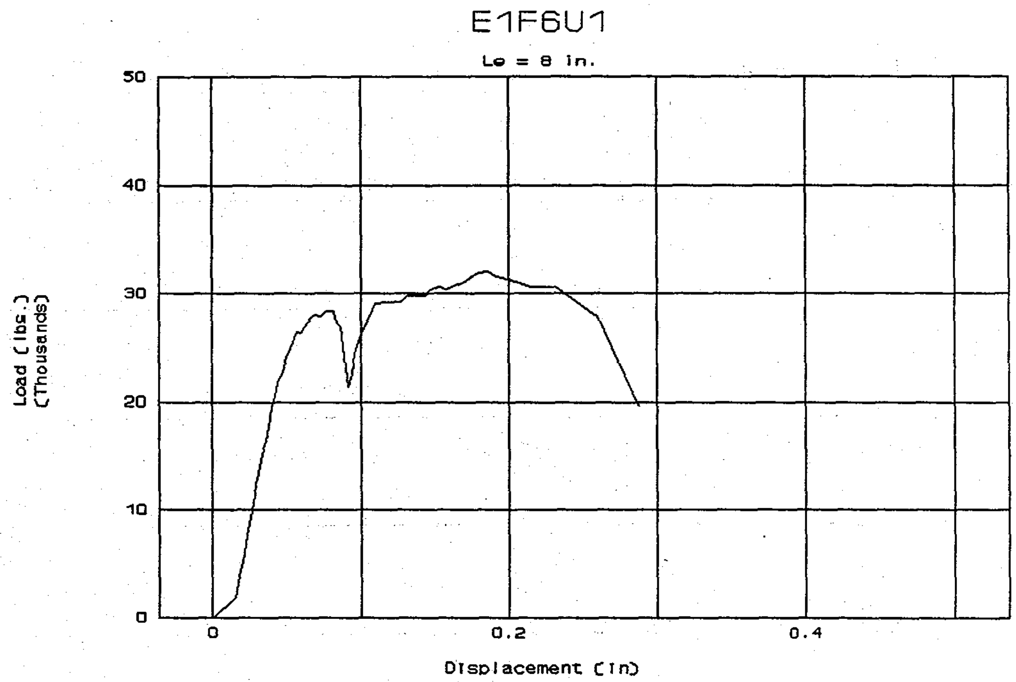
Adhes. Desig.	Anchor Dia. (in)	Embed. Length (in)	P_{exp} (kips) Trial 1	2	3
E2	3/4	5	19.83	19.64	19.34

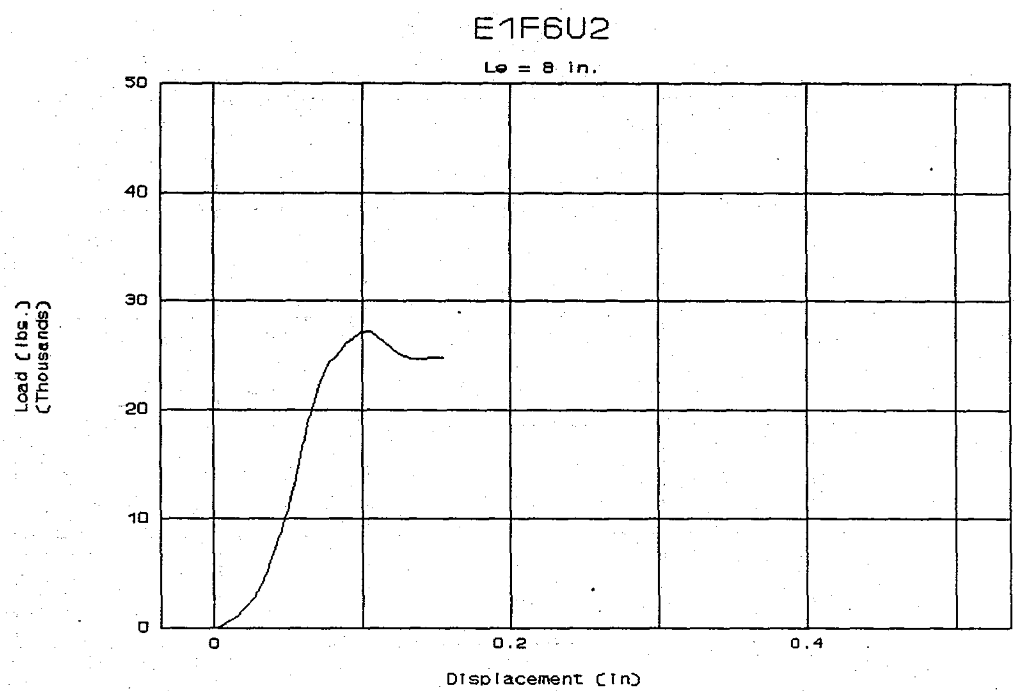
Table C-3 Data for confined testing with partially-bonded anchors (2 in. bond-breaker)

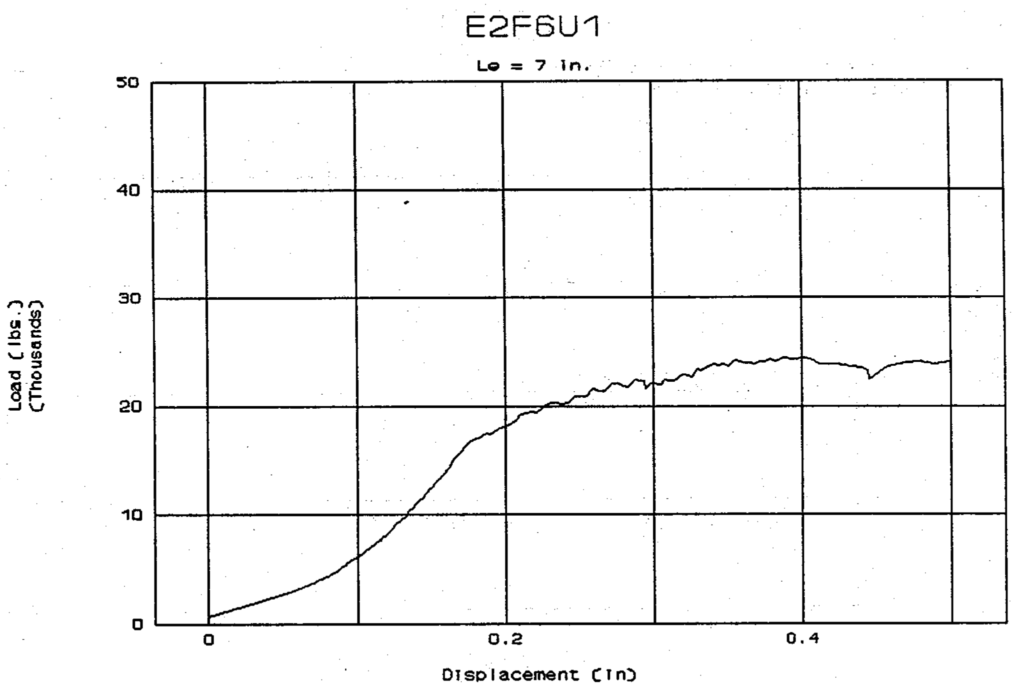
Adhes. Desig.	Anchor Dia. (in)	Embed. Length (in)	P_{exp} (kips) Trial 1	2	3
E2	1/2	5	10.18	11.22	9.17
E2	5/8	6	15.10	12.53	13.38
E2	3/4	7	18.74	16.63	19.02

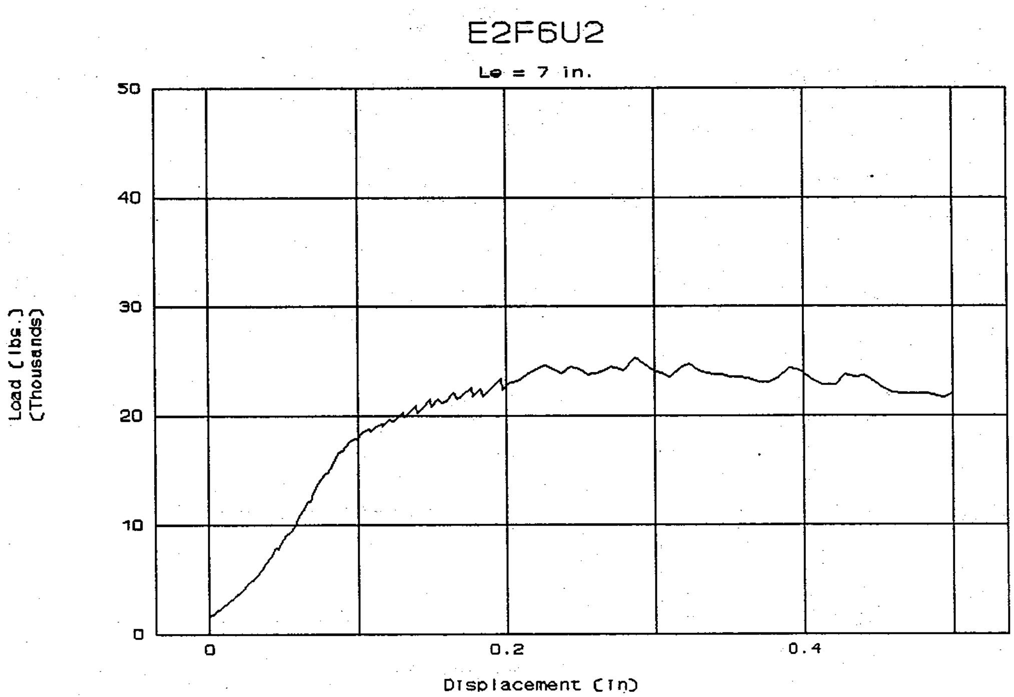
Table C-4 Data for confined testing with fully-bonded anchors (not included in baseline tests)

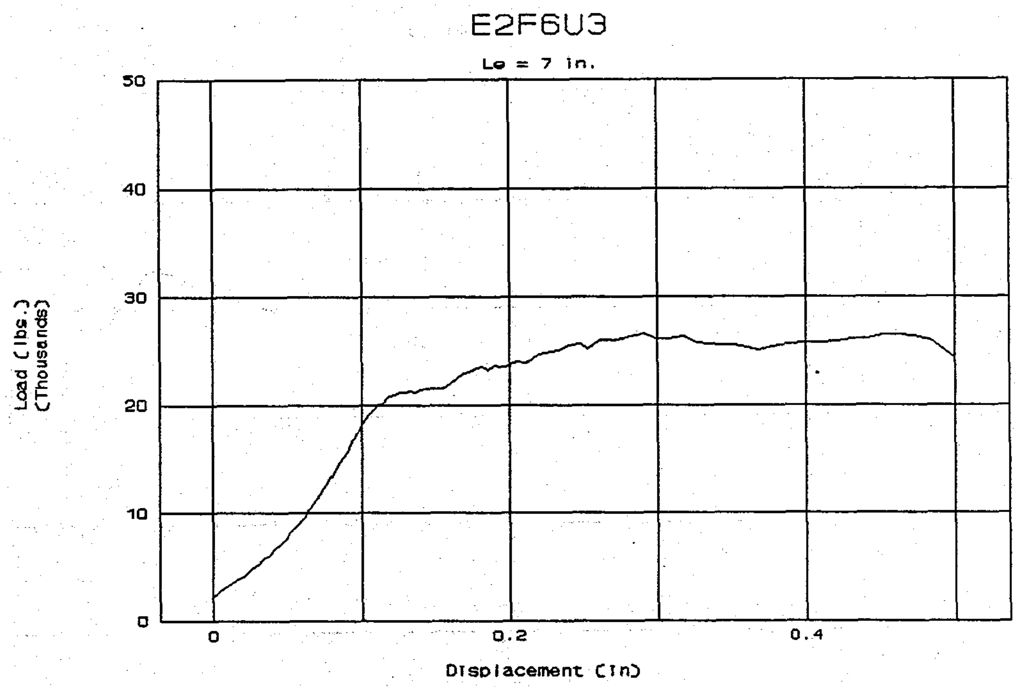
Adhes. Desig.	Anchor Dia. (in)	Embed. Length (in)	P_{exp} (kips) Trial 1	2	3
E2	5/8	6	16.25	20.00	16.49
E3	5/8	6	15.10	12.37	17.50

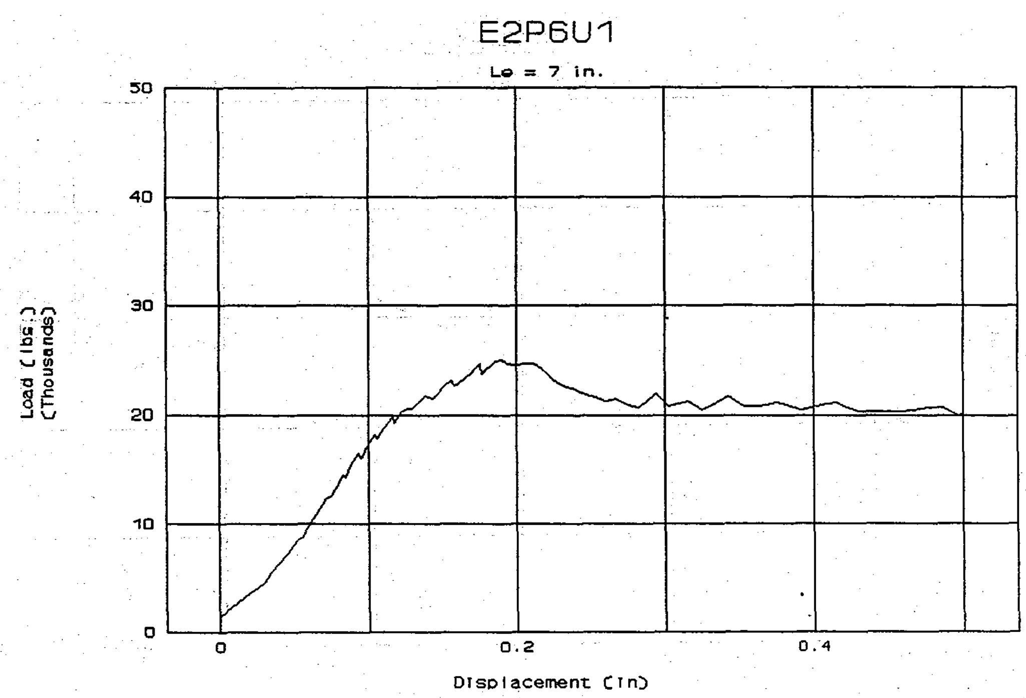

E1F6U1
Le = 8 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

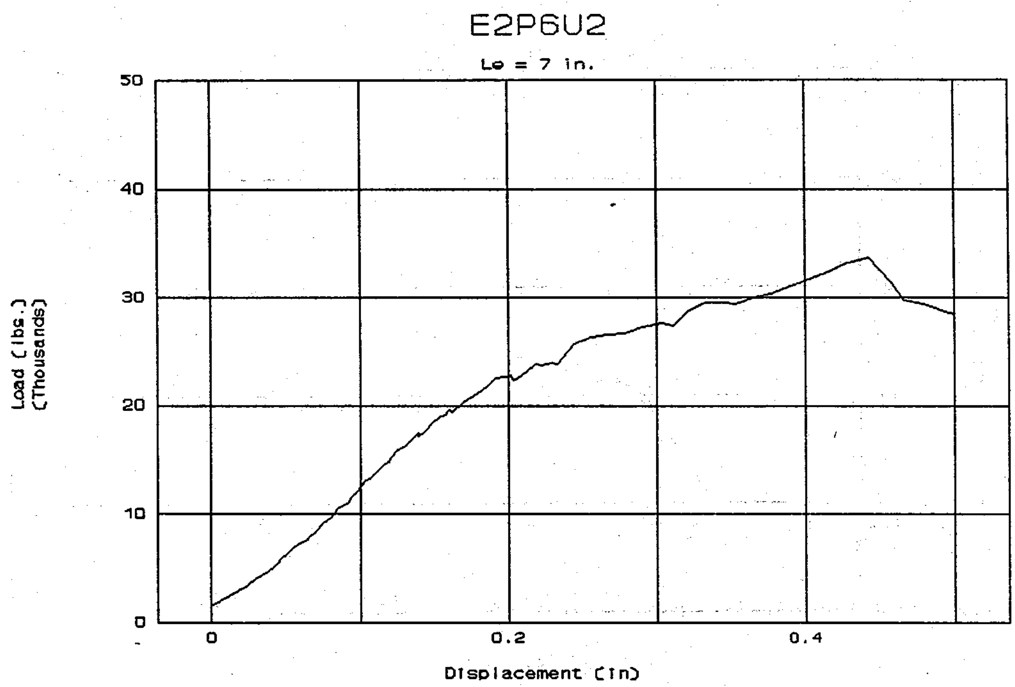

E1F6U2
Le = 8 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

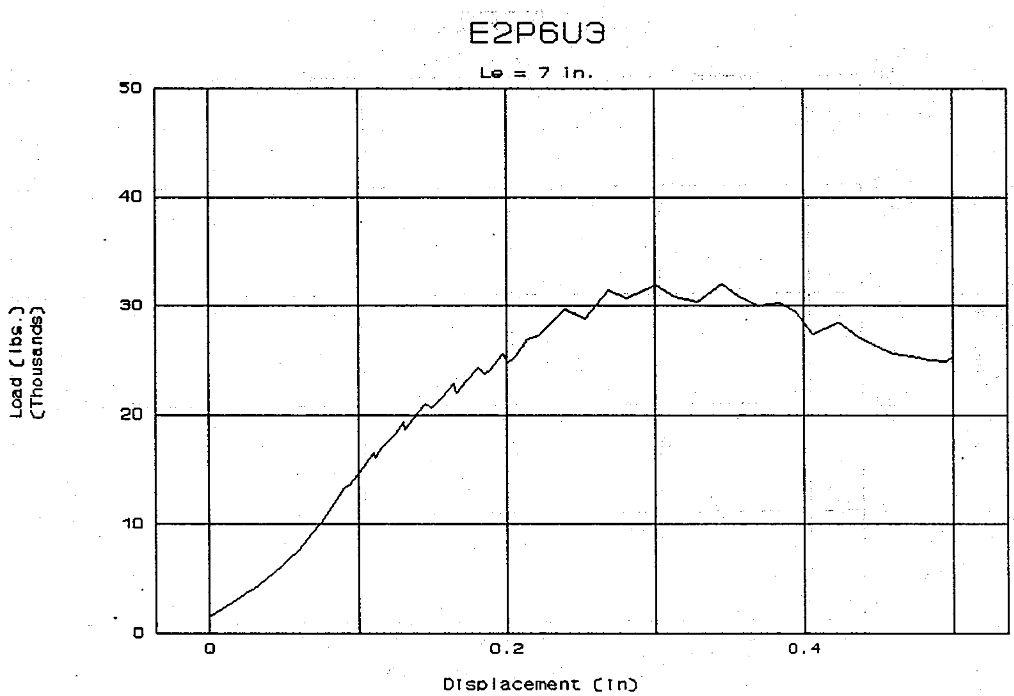

E2F6U1
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

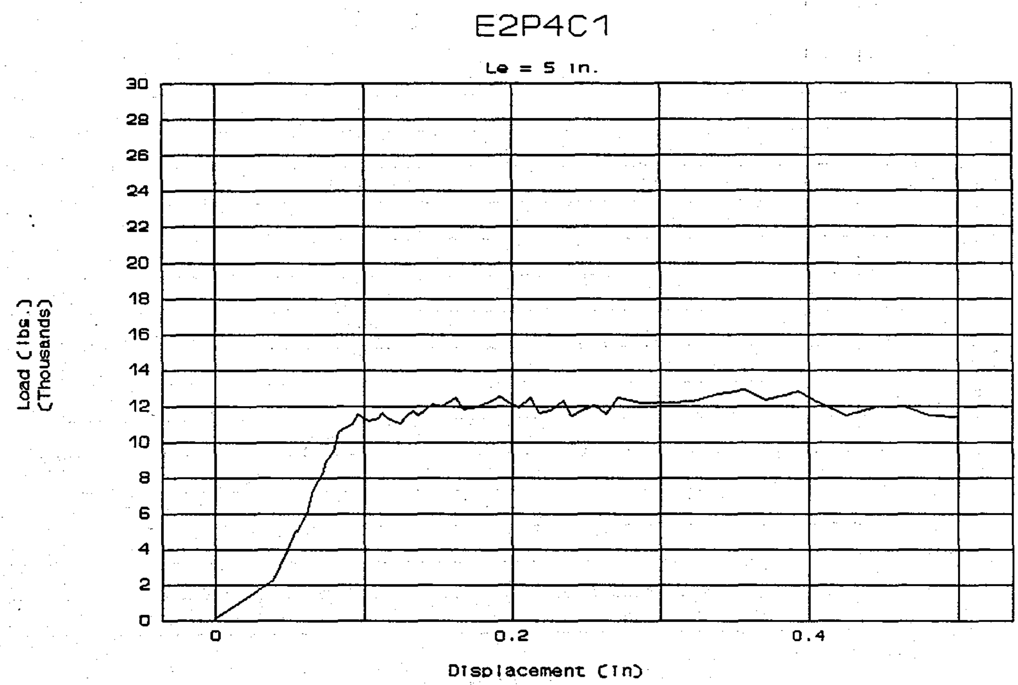

E2F6U2
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

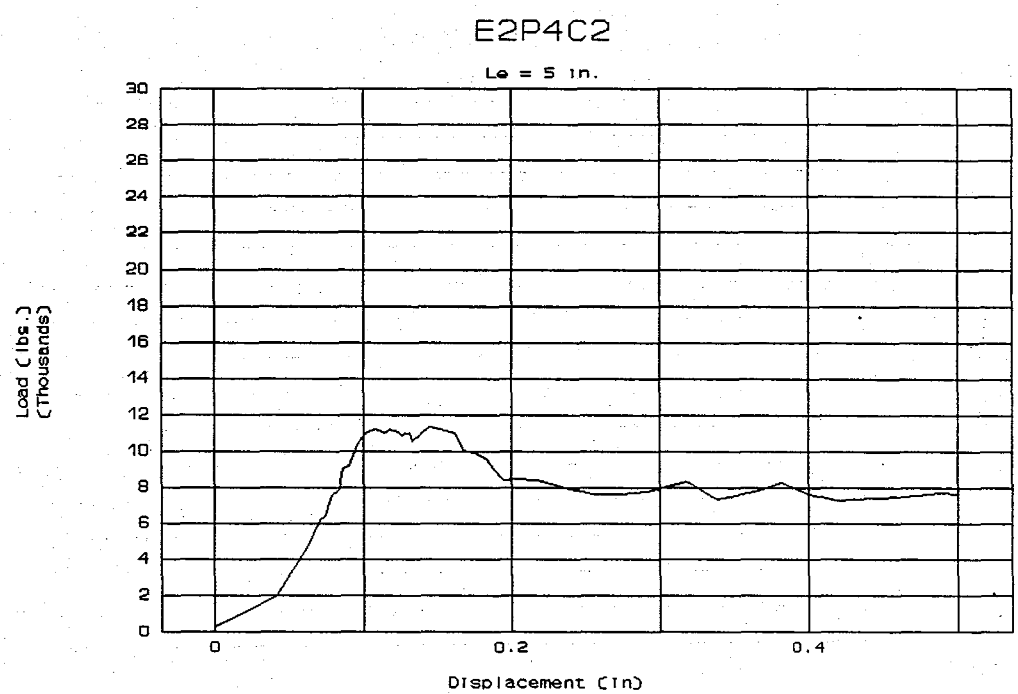

E2F6U3
Le = 7 in.
50
40
30
20
10
0
Load (lbs.)
(Thousands)
0
0.2
0.4
Displacement (in)

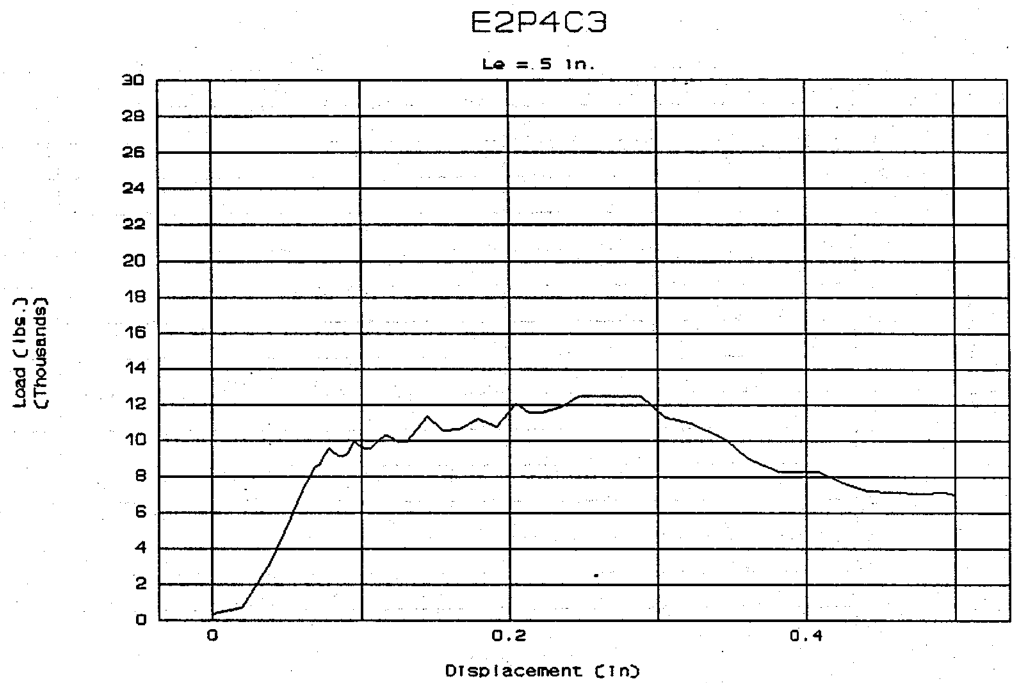

E2P6U1
Le = 7 in.
50
40
30
20
10
0
Load (lbs.)
(Thousands)
0
0.2
0.4
Displacement (in)

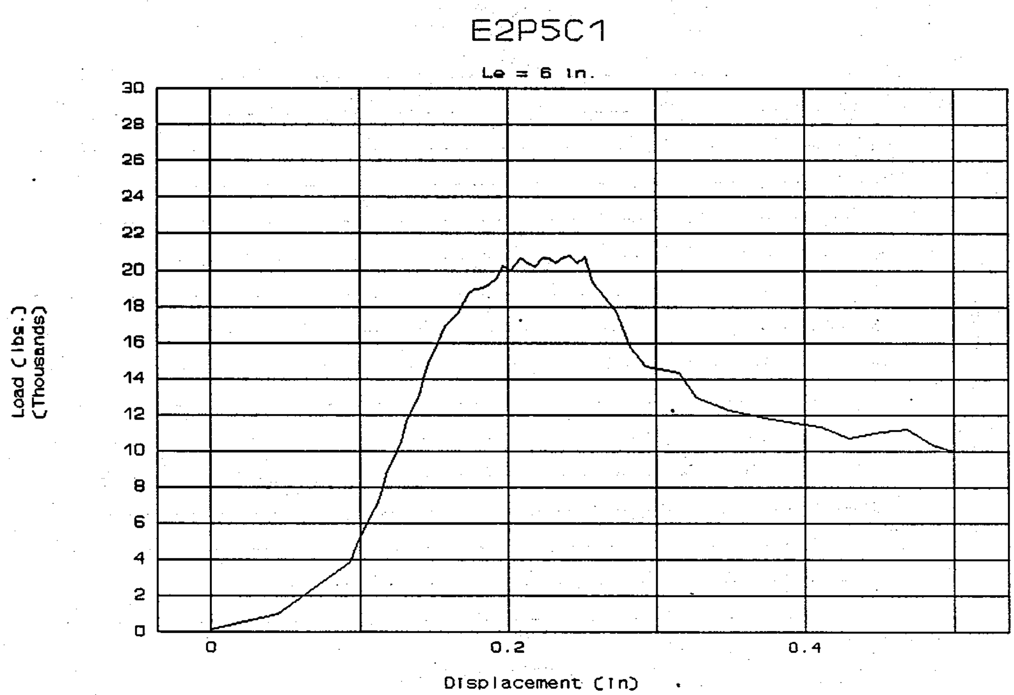

E2P6U2
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

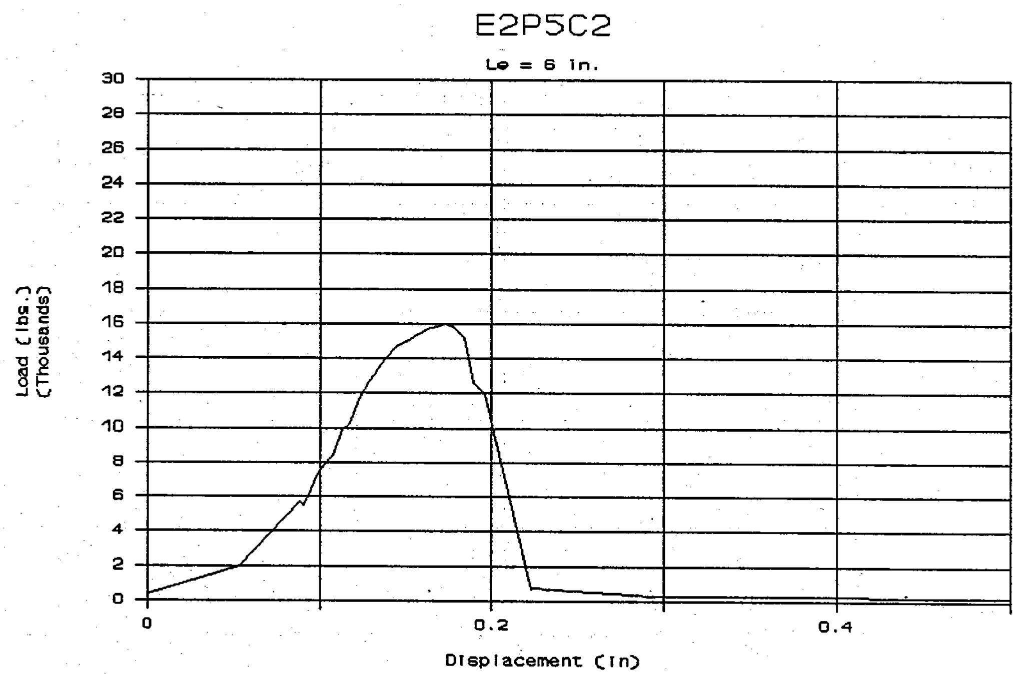

E2P6U3
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)


E2P4C1
Le = 5 in.
Load (lbs.) (Thousands)
Displacement (In)
0
0.2
0.4
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0

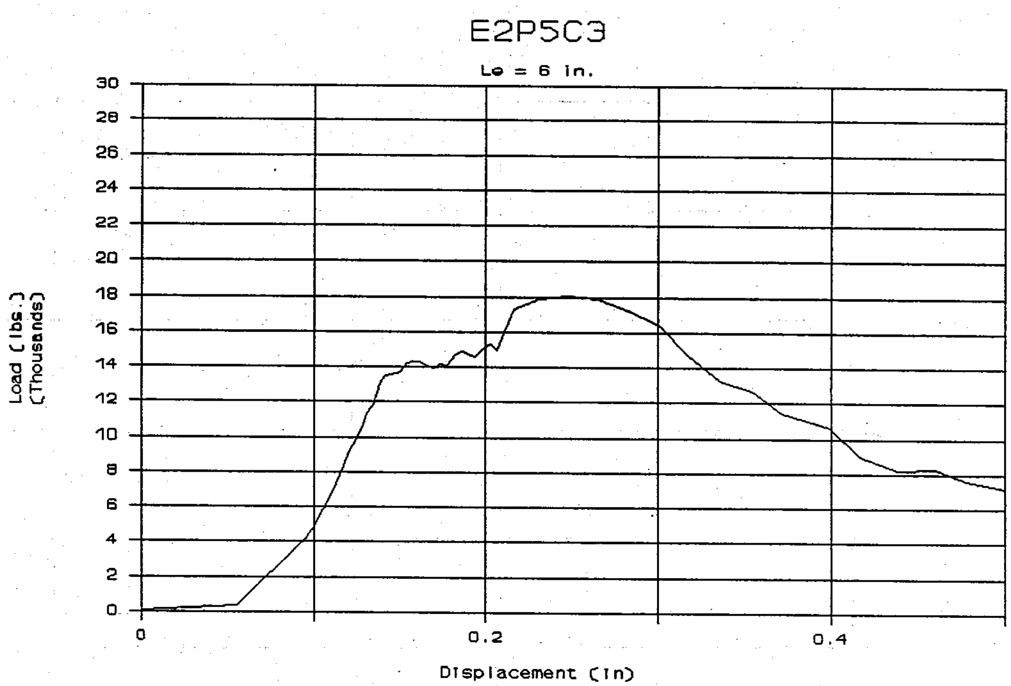

E2P4C2
Le = 5 in.
Load (lbs.) (Thousands)
Displacement (In)
0
0.2
0.4
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0


E2P4C3
Le =.5 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (In)

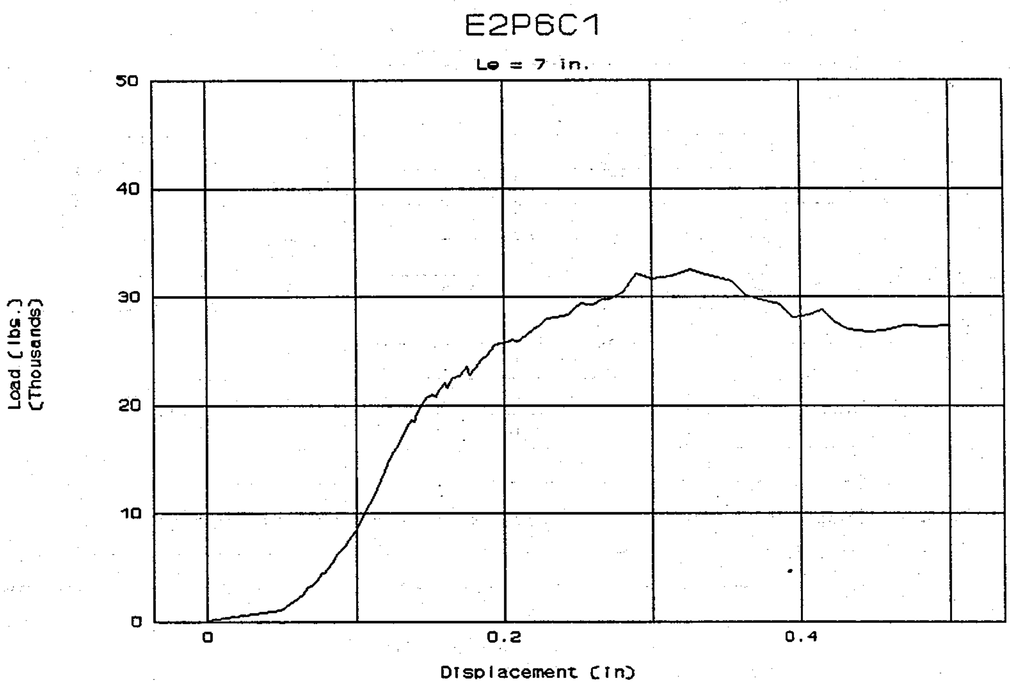

E2P5C1
Le = 6 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (In)

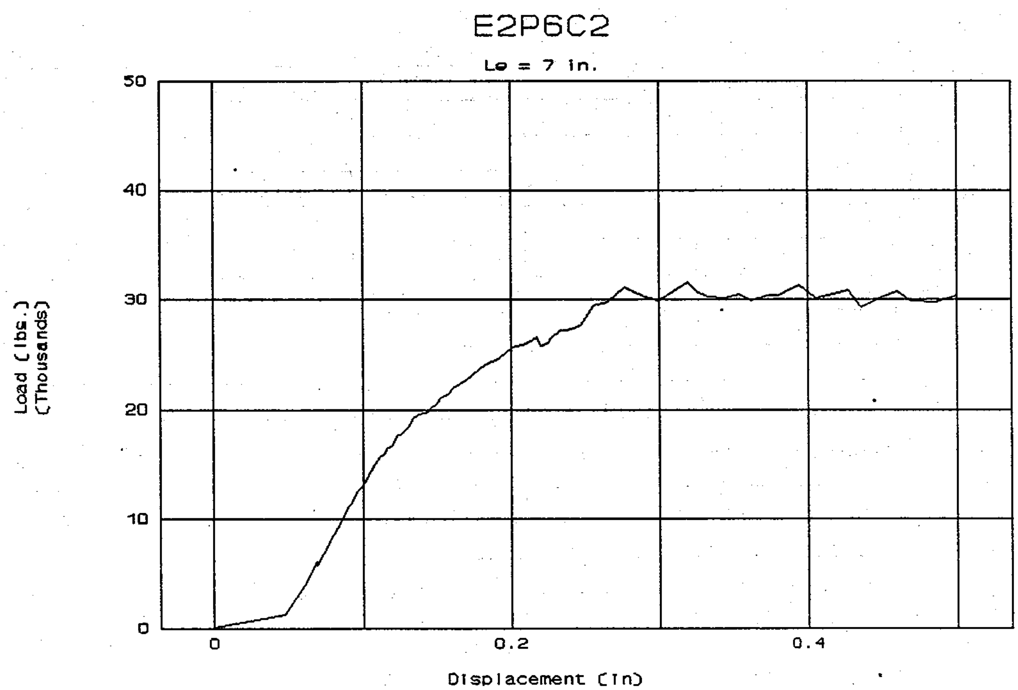


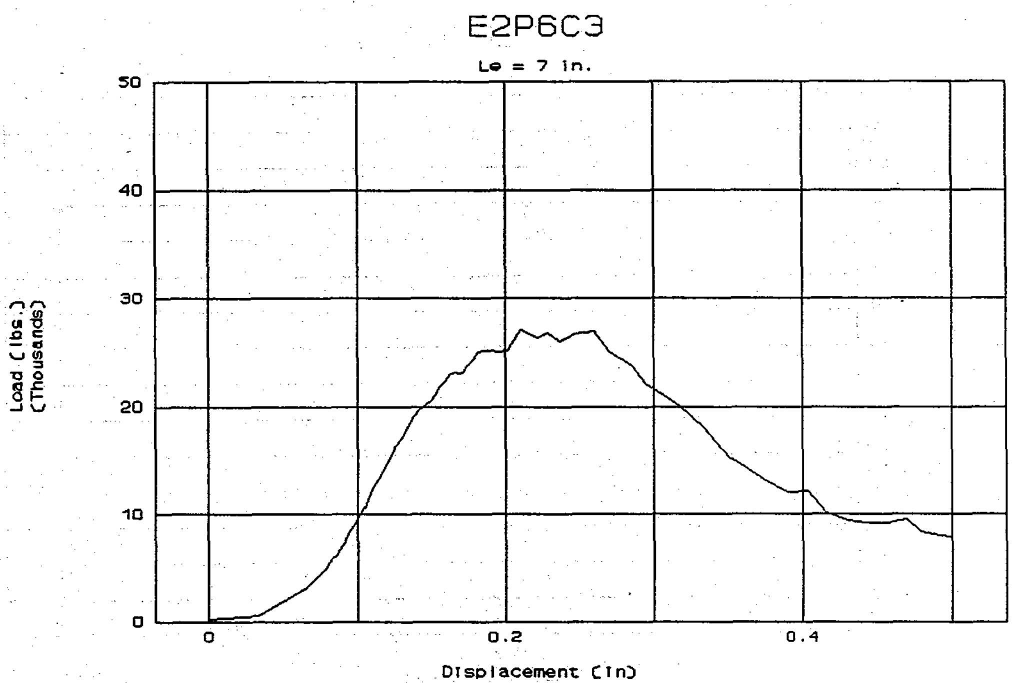
E2P5C2
Le = 6 in.
Load (lbs.) (Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (In)

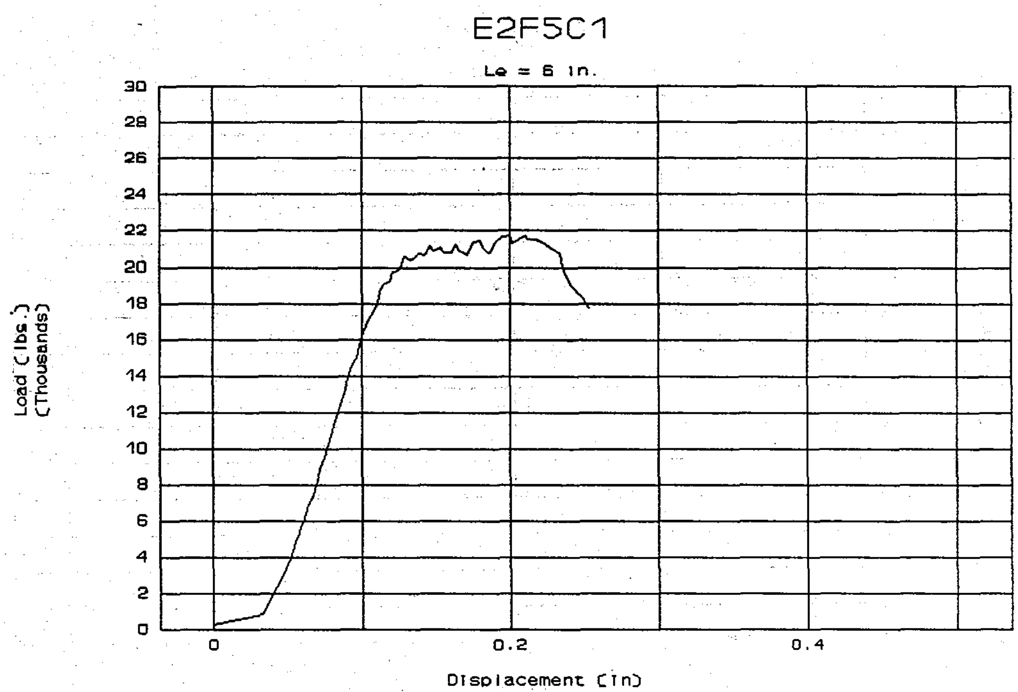


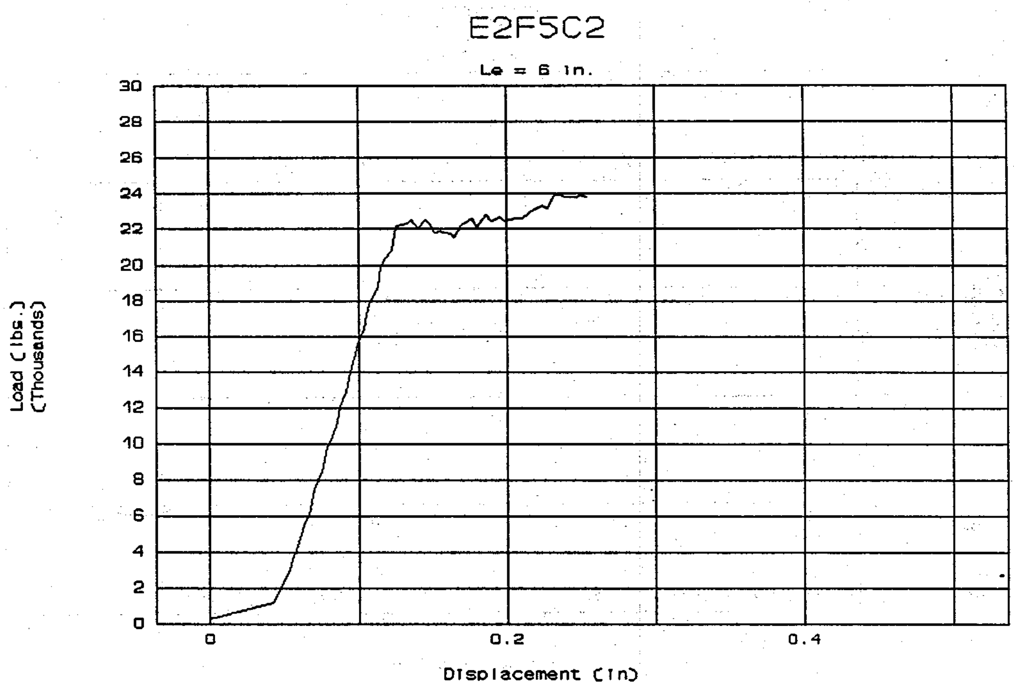
E2P5C3
Le = 6 in.
Load (lbs.) (Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (In)

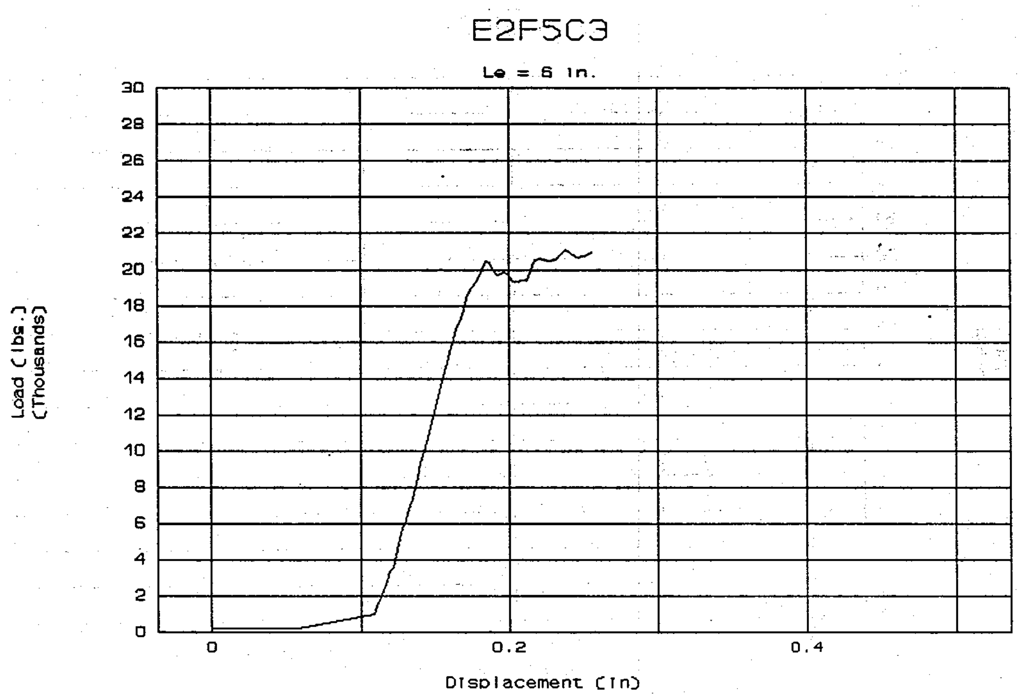

E2P6C1
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

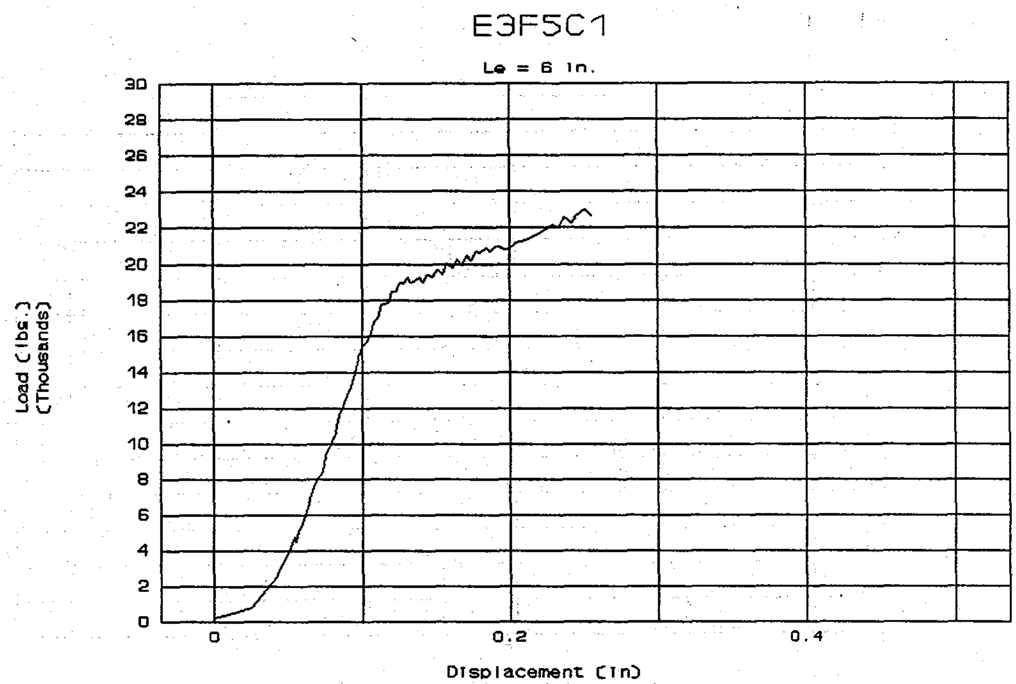

E2P6C2
Le = 7 in.
Load (lbs.)
(Thousands)
50
40
30
20
10
0
0
0.2
0.4
Displacement (in)

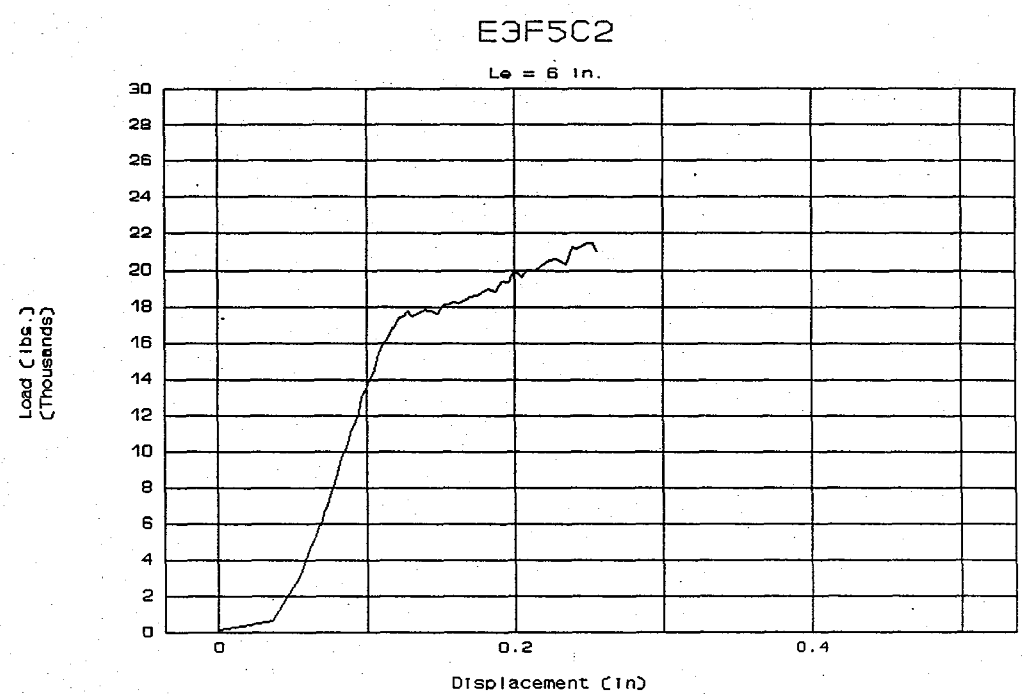

E2P6C3
Le = 7 in.
50
40
30
20
10
0
Load (lbs.)
(Thousands)
0
0.2
0.4
Displacement (in)

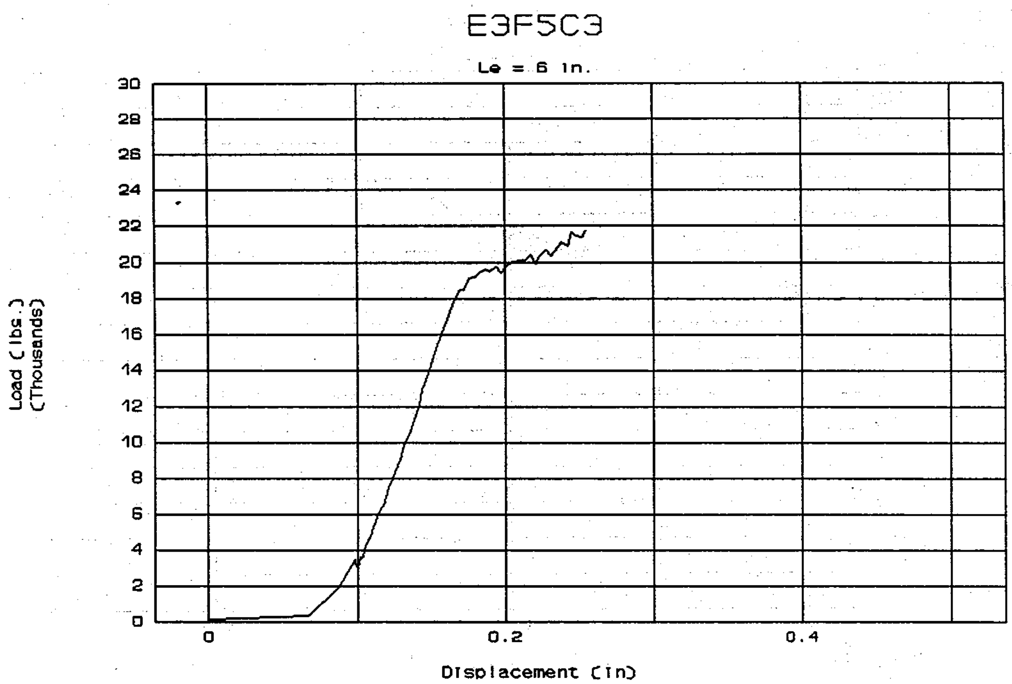

E2F5C1
Le = 6 in.
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
Load (lbs.)
(Thousands)
0
0.2
0.4
Displacement (in)


E2F5C2
Le = 6 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E2F5C3
Le = 6 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E3F5C1
Le = 6 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E3F5C2
Le = 6 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)


E3F5C3
Le = 6 in.
Load (lbs.)
(Thousands)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.2
0.4
Displacement (in)

APPENDIX D

TABULATION OF EXPERIMENTALLY DETERMINED CONSTANTS

Table D-1 Experimentally determined constants u_{max} and λ'

Adhes. Desig.	Anchor Diam. (in)	Bond Stress (ksi) u_0	u_{max}	λ'
E1	1/2	1.077	1.140	0.0601
	5/8	1.253	1.280	0.0734
	3/4	1.225	1.314	0.0552
E2	1/2	1.677	1.808	0.0736
	5/8	1.437	1.478	0.0806
	3/4	1.238	1.359	0.0648
E3	1/2	0.813	0.860	0.0666
	5/8	1.143	1.168	0.0644
	3/4	0.829	0.890	0.0592
E4	1/2	1.736	1.862	0.0786
	5/8	1.139	1.170	0.0714
	3/4	1.195	1.304	0.0615
E5	1/2	1.855	2.046	0.0766
	5/8	2.519	2.615	0.1061
	3/4	1.996	2.254	0.0698
E6	1/2	1.968	2.170	0.0826
	5/8	1.962	2.037	0.1013
	3/4	1.334	1.505	0.0681
E7	1/2	1.629	1.764	0.0800
	5/8	1.743	1.797	0.0829
	3/4	1.886	2.082	0.0634
E8	1/2	1.059	1.124	0.0628
	5/8	1.012	1.035	0.0774
	3/4	0.651	0.702	0.0548

Table D-1--continued

Adhes. Desig.	Anchor Diam. (in)	Bond Stress (ksi) u_0	u_{max}	λ'
E9	1/2	1.170	1.274	0.0680
	5/8	1.528	1.578	0.0915
	3/4	1.182	1.313	0.0745
E10	1/2	1.174	1.257	0.0636
	5/8	1.522	1.561	0.0817
	3/4	1.322	1.438	0.0626
E11	1/2	1.762	1.960	0.0747
	5/8	2.291	2.387	0.1038
	3/4	1.863	2.125	0.0857
E12	1/2	1.785	2.008	0.0854
	5/8	2.289	2.395	0.1098
	3/4	1.642	1.899	0.0838
E13	1/2	1.230	1.252	0.0351
	5/8	1.275	1.284	0.0386
	3/4	1.254	1.283	0.0309
E14	1/2	1.225	1.243	0.0330
	5/8	1.168	1.174	0.0317
	3/4	1.068	1.088	0.0298
E15	1/2	1.661	1.877	0.0930
	5/8	2.252	2.362	0.1065
	3/4	1.473	1.713	0.0851
E16	1/2	0.852	0.926	0.0753
	5/8	1.625	1.677	0.0929
	3/4	1.384	1.535	0.0634

Table D-2 Experimentally determined stiffness for steel anchors and pulling bars

Rod Diameter (in.)	AE (kips)	k (kip/in)
1/2	3922.4	1961.2
5/8	5946.5	2973.2
3/4	9577.7	4788.8
7/8	13519.2	6759.6
1-3/8	33762.7	16881.3

APPENDIX E

QUALIFICATION OF STRUCTURAL ADHESIVES

E.1 General

This specification describes the test procedure for the qualification of structural adhesives. The values determined by this qualification procedure are strictly valid only for adhesive anchors placed in dry, vertical holes drilled in FDOT Class II concrete, cured for at least 24 hours before loading, and subjected to short term tensile loads. Conditions not covered by this specification include horizontal or overhead hole orientation, elevated temperatures, wet installation, variations in concrete strength, variations in aggregate, variations in cure time, and long term loading. If any of these conditions are present, additional testing may be required.

E.2 Mixing and Application

Structural adhesives for bonding steel anchors to hardened concrete shall be mixed, applied and cured in accordance with the manufacturer's directions, or as might be directed otherwise by the Engineer.

E.3 Performance Test Preparation

E.3.1 Concrete Test Specimens

The concrete test specimens shall be constructed of FDOT Class II concrete unless directed otherwise by the Engineer. The concrete shall be cured for at least 28 days. The dimensions of the concrete test specimens shall be sufficient so that drilling and testing do not cause spalling of the concrete or splitting of the test specimen.

E.3.2 Anchor Steel

The steel used for adhesive anchors shall be ASTM A193-B7 rod. The steel shall be cleaned in mineral spirits or other solvents to remove any oily residue. The anchor diameters shall be 1/2", 5/8", and 3/4" with the embedment lengths of 5", 3.5", and 7" respectively. Three tests shall be performed per anchor diameter for a total of 9 tests per adhesive product.

E.3.3 Anchor Installation

Drill holes vertically in the hardened concrete test specimen with a rotary hammer drill, unless directed otherwise by the Engineer. Hole diameters shall be 9/16" for the 1/2" anchor, 3/4" for the 5/8" anchor, and 7/8" for the 3/4" anchor. Holes shall be cleaned out with compressed air until the dust leaving the hole is no longer noticeable. A stiff bottle brush connected to an electric drill shall then be used to loosen dust along the sides of the hole. Holes shall again be cleaned out with compressed air until residual dust is no longer visible.

The adhesive shall be allowed to cure for 24 hours plus or minus 2 hours unless specified otherwise by the Engineer. Remove excess adhesive after curing.

E.4 Performance Test Procedure

E.4.1 Data Acquisition

The adhesive anchor shall be pulled from the concrete using a center hole hydraulic ram. During the test, the concrete around the anchor shall be confined using a steel plate, mounted between the surface of the concrete and the hydraulic ram. The plate shall have a hole with a diameter 1/2" greater than that of the anchor. Load-displacement data shall be recorded (at least one reading every 3 sec.) until a displacement of 1/2" or greater has been recorded. The data shall be recorded in the form of a load-displacement graph. Displacement shall be measured from the top of the anchor relative to the surface of the concrete. The anchor shall be pulled from the concrete at a rate such that the test duration is no less than 2 minutes.

E.4.2 Data Interpretation

The slope of the initial straight line portion of the load-displacement graph represents the stiffness k of the adhesive anchor system. The failure load P is where the slope of the graph begins to deviate from the straight line portion of the graph. Note that this value is not necessarily the maximum load value obtained during the test.

E.5 Adhesive Properties

E.5.1 General

The values of u_o, λ’, and u_{max} shall be determined for each product as described in the following sections.

E.5.2 Bond Stress u_o

The following equation shall be used to calculate the bond stress u_o:

$$u_0 = \frac{P}{\pi d \ell}$$

where P is the failure load, d is the hole diameter, and ℓ is the embedment length.

E.5.3 Stiffness Parameter λ'

A sample of anchor steel for each diameter (3 samples) shall be subject to tensile testing. The steel shall be axially loaded past yield. Load-displacement data shall be recorded in the form of a load-displacement graph for each sample. The slope of the initial straight line portion of the load-displacement graph represents the stiffness k_s of the anchor steel. A value for k_s shall be recorded for each anchor size.

For each anchor size, the term AE shall be determined by the following equation:

$$AE = k_s \ell_g$$

where ℓ_g is the gage length of the specimen.

For each anchor size, the adhesive stiffness parameter λ' shall be determined by the following equation:

$$k = \frac{AE\lambda'}{\sqrt{d}} \tanh\left(\frac{\lambda' \ell}{\sqrt{d}}\right)$$

where k is the average stiffness of the adhesive for the specific anchor size, d is the diameter of the hole for the specific anchor size, and ℓ is the anchor embedment length for the specific anchor size.

An average of the three values of λ' (one for each anchor size) may be used to calculate the bond stress u_{max} of the adhesive.

E.5.4 Bond Stress u_{max}:

The following equation shall be used to calculate u_{max}:

$$u_{max} = \frac{P\lambda'}{\pi d^{\frac{3}{2}}} \frac{1}{\tanh\left(\frac{\lambda' \ell}{\sqrt{d}}\right)}$$

where *P* is the average failure load for a specific anchor size, *d* is the hole diameter for a specific anchor size, and ℓ is the embedment length for a specific anchor size.

E.6 Classification of Structural Adhesives

Based on the value of u_o, the adhesive shall fall into one of four classes. The classes shall be arranged as follows: Class I for $u_o \geq 1700$ psi, Class II for $u_o \geq 1450$ psi, Class III $u_o \geq 1200$ psi, and Class IV for $u_o \geq 900$ psi. An adhesive shall be rejected if $u_o < 900$ psi. Calculated values of u_o may be rounded to the nearest 50 psi.

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- Covert Operations
- Gunnebo (U.S.E. Diamond)
- Hilti
- ITW Ramset/Red Head
- Molly
- Sika-Bawl

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