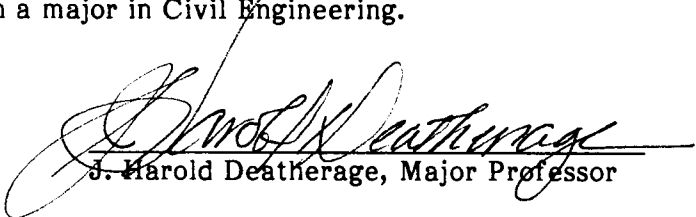


To the Graduate Council:

I am submitting herewith a thesis written by Ken L. Griffin entitled "An Investigation of the Variables Affecting Pullout of Seven-Wire Prestressing Strand." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.


J. Harold Deatherage, Major Professor

We have read this thesis
and recommend its acceptance:

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Accepted for the Council:


Vice Provost
and Dean of The Graduate School

AN INVESTIGATION OF THE VARIABLES AFFECTING
PULLOUT OF SEVEN-WIRE PRESTRESSING STRAND

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Ken L. Griffin

May 1989

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I would also like to thank Ross Prestressed Concrete, Florida Wire and Cable, and H. Kent Preston for generously providing technical assistance and materials to help support this research.

ABSTRACT

The pullout strength of untensioned prestressing strand is a function of several variables. This study is an attempt to identify and isolate these variables. Reviews of the existing studies of pretensioned and untensioned strand as well as the pullout testing of larger size untensioned strands are included.

The influence of strand diameter, concrete strength, length of embedment, and surface condition of the seven-wire strand was investigated. Relationships were developed between steel stress at the time of slippage and embedment length of strand for a given surface condition. These relationships were compared with recommended equations from previous work. The data was normalized by bond stress and some dependence of concrete compressive strength is suggested.

The major contributing factors affecting the pullout capacity of seven-wire prestressing strand were found to be the length of embedment and the surface condition of the strand.

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LIST OF SYMBOLS

Notation	Description
d_b	diameter of strand (in.)
f_b	nominal interfacial bond stress (ksi)
f'_c	concrete compressive strength (psi)
f_{ps}	stress in prestressed reinforcement at nominal strength (ksi)
f_s	maximum stress in strand (ksi)
f_{se}	effective stress in prestressed reinforcement (after allowances for all prestress losses) (ksi)
F	force in strand (kips)
F_I	force at initiation of pullout (kips)
F_Y	force at which steel yields (kips)
K	bond pullout factor
l_a	the portion of the embedment length actively involved in pullout (in.)
l_d	strand development length (in.)
l_e	strand embedment length (in.)
l_t	strand transfer length (in.)
M_n	nominal moment capacity (in.)
P_b	nominal perimeter of prestressing strand (in.)
P	axial force in strand (kips)

CHAPTER I

INTRODUCTION

Prestressed concrete products are widespread in the United States. Some major applications for prestressed elements are within highway bridge construction. Keeping the desired stress level in the prestressing reinforcement is an extremely vital function for the performance of these elements during the lifetime of the structure. In order to reach and maintain the stress level in the steel and concrete there must be sufficient transfer and development lengths for the strand. Prestress transfer length is defined as the distance over which the stress in a pretensioned tendon is transferred by bond to the concrete. Development length is the length at each end of a member that is required to develop nominal moment capacity, M_n . This relationship is shown in Figure 1.

The current AASHTO (1983) and ACI (1983) code provisions for development length are based largely upon research by Hanson and Kaar (1959). Their results were incorporated into the 1963 ACI 318 Code and were also adopted by AASHTO. The provisions are the same in the most updated versions of these codes. Some studies of the bond of strands have been made since 1959, and not all of them agree with the provisions of the current codes. The most recent study by Cousins, Johnston, and Zia (1986), concluded that development lengths may be longer than specified by the provisions of the ACI and AASHTO codes. This research created concern for the Federal Highway Administration which led to an imposition of restrictions on bond development length beyond

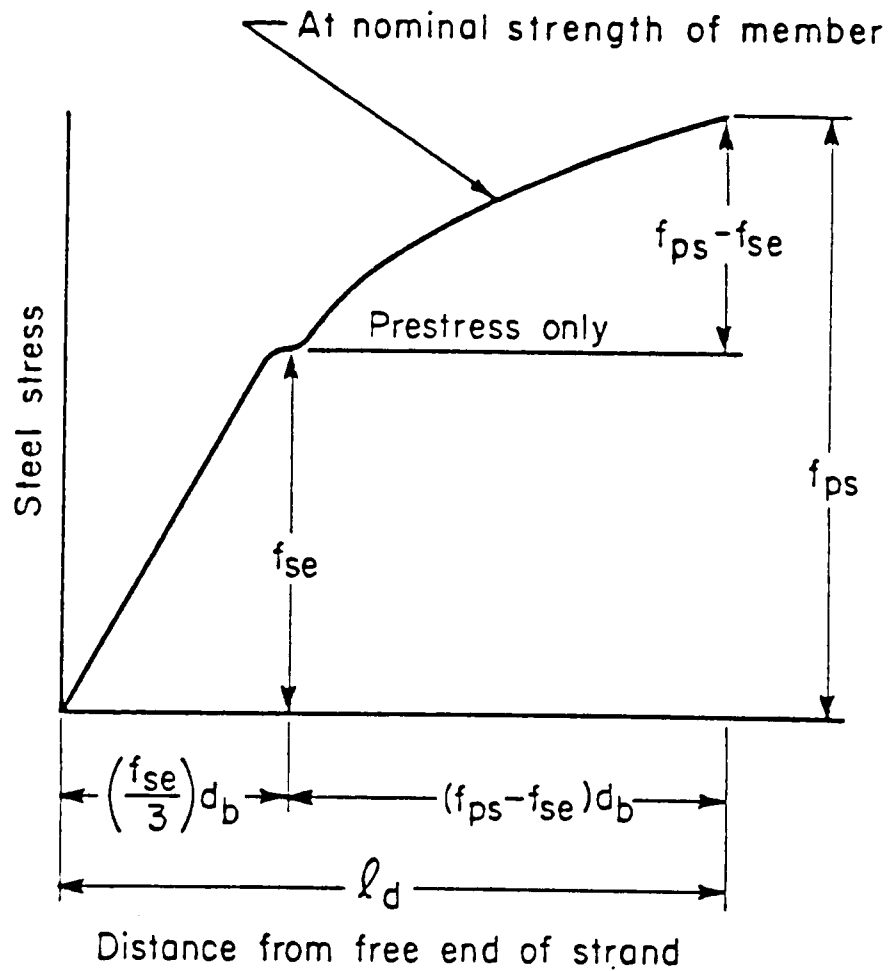


Figure 1. Variation of steel stress with distance from free end of strand (from ACI 318R-83).

that supplied by the codes, banned the use of large size strand (0.6" diameter), and established specific requirements for strand spacing.

Some producers of prestress components desire to use large diameter strand in order to extend allowable spans and moment capacities of bridge beams. These extensions allow the prestress industry to compete with certain steel framing systems thus affording an increased market share. Also, the increased development and spacing requirements are important for short spanning and/or thin prestressed members.

In order for manufacturers of prestressing components to provide a product which is economically competitive, they have developed a production cycle of approximately twenty four hours. During a typical production cycle the following operations take place:

1. The casting beds are cleaned and prepared for concrete placement.
2. Prestressing strands and component bulkheads are placed in the casting beds.
3. Concrete is placed in the bed.
4. The concrete curing process is accelerated by the use of steam curing and admixtures to provide the highest possible early strength.

5. After performing standard compressive strength tests on six inch diameter test cylinders, as a method of acceptability, the prestressing strands are individually released.
6. The components are then removed from the beds and stored on the plant yard until time for actual shipment to the job site.
7. The production cycle is then repeated.

Because of limited curing time before the strands are released, the early age bond strength is a vital concern to the prestressing industry.

With the restrictions which are presently imposed, it is no longer possible to develop nominal design strength in some short span members. Also, some thin members previously used are not allowed because there is not enough concrete coverage of the strands.

Most bridge components use pretensioned strands. However, there are wide spread uses of untensioned strand. A small number of studies have been made, but guidelines for the pullout capacities of untensioned strand and correlation of pullout capacities with development length and transfer length are essentially non-existent.

The objective of this study is to investigate the bond behavior of prestressing strand. Reviews of the existing studies of pretensioned and untensioned stands as well as the pullout testing of larger size untensioned strands are included. Variables considered are embedment length of strand, diameter of strand, concrete strength, the stress level in strand, and surface

condition of the strand. The significance of each of these variables was studied, and the data received from the pullout testing are also compared to existing values for transfer and development lengths.

CHAPTER II

LITERATURE REVIEW

The expressions for development length which exist in the current ACI code (1983) are based on three different studies (Hanson and Kaar, 1959; Kaar et al., 1963; Kaar and Magura, 1965). Each of these studies tested prestressed members reinforced with "clean" 1/4, 3/8, and 1/2 in. diameter strands. The nominal strength of the strands, in the early studies, was 250 ksi.

Prior to 1963 the ACI code contained no guidance for transfer and development lengths. The Hanson and Kaar work (1959) became the basis of the prediction equations for transfer and development lengths and were incorporated in the ACI 318-63 code. These provisions have remained unchanged since 1963. The research by Hanson and Kaar involved 47 beam tests divided into four series. All beams were tested to failure in a hydraulic loading machine. Beams in two of the series of testing were loaded at midspan with either a ball or roller arrangement. The other tests were conducted on beams loaded at two points through rollers spaced twice the beam width on either side of midspan. Strand tension was released at a concrete strength of 4500 psi except for one series, which were released at 3500 psi. Strain gages were cemented along individual helical wires of the twisted strand. Strand strain measured by the gages was converted into stress using applicable stress-strain curves. Dial indicators were used to measure beam deflections, and they were also mounted on each end of the beams to detect end slip. It was found that

strand size and embedment length have significant influence on when general bond slip occurs.

In the study done by Kaar, LaFraugh, and Mass (1963) an investigation was made of the influence of concrete strength on the strand transfer length. From this research it was concluded that concrete strength has little influence on transfer length for strands up to 1/2 in. in diameter. It was thought that lower concrete strengths would result in long transfer lengths. Rectangular, concentrically prestressed members with five different concrete strengths were used. Wittemore mechanical strain gages inserted in brass discs were attached on 2-inch centers along lines of two opposing sides of each specimen. Strand tension was measured before and after cutting the strand by SR4 gage load cells under strand grips.

Concrete strength was found to have little influence on the transfer lengths for concrete cylinder strengths of 1500 to 5500 psi and clean strand up to and including 1/2 inch. For a period of one year following prestress transfer, the average increase in transfer length was 6 percent for all sizes of strand. A 19 percent increase was the maximum value reported for the one year period.

In a report by Kaar and Magura (1965), the effect of debonded strand was studied. It was pointed out that the performance of debonded pretensioned girders with embedment lengths twice those required by ACI closely matched performance of similar girders with fully bonded strands. This resulted in a double development length requirement for strand not bonded through to the end of a member in the 1971 edition of the ACI code.

Current Code Provisions

Hanson and Kaar (1959) developed the following empirical relationship:

$$(f_{ps} - f_{se}) \text{ in ksi} = \frac{l_d - l_t}{d_b} \quad 2.1$$

where f_{ps} = stress in strand at nominal strength, (ksi)
 f_{se} = effective stress in strand (after allowance for prestress losses), (ksi)
 l_d = development length, (in)
 l_t = transfer length, (in)
 d_b = diameter of strand, (in)

$$l_t \approx \frac{1}{3} f_{se} d_b \quad 2.2$$

substituting Equation 2.2 into Equation 2.1 gives:

$$(f_{ps} - f_{se}) = \frac{l_d - 1/3 f_{se} d_b}{d_b}$$

Solving this equation for l_d , we get:

$$l_d = (f_{ps} - 2/3 f_{se}) d_b$$

which is the current equation given in ACI - 12.9.1. The expression $(f_{ps} - 2/3 f_{se})$ is treated as a dimensionless constant.

Some of the most recent work done by Cousins, Johnston, and Zia (1986) was a study of bond of epoxy coated strand as well as uncoated strand development. Their experimental program involved the testing of 60 prestressed concrete beams. The three strand sizes tested were 3/8", 1/2", and 0.6."

Three types of pretensioned, prestressed specimens were made: transfer length, development length, and bond fatigue. The transfer length specimens were used to determine the transfer lengths for various sizes and types of coated and uncoated prestressing strand. The development length specimens were tested under static load to determine the development length of coated and uncoated prestressing strand. The bond fatigue specimens were tested to determine if repeated loadings caused a degradation in the transfer or development length of coated and uncoated prestressing strands (Cousins, Johnston, and Zia, 1986, p. 29).

Some of the conclusions made were as follows:

1. For grit impregnated epoxy coated strand, the transfer and development lengths were shorter than that of uncoated strand. Epoxy coated strand without grit has almost no bond.
2. For the uncoated strand, the transfer and development lengths were found to be longer than those calculated by the ACI and AASHTO code provisions. The resulting values found for grit impregnated epoxy coated strand were shorter than those calculated.
3. Sudden release of the prestressing force increases the transfer length about 6% as compared to gradual release.

This work spawned much concern as to whether the current code provisions for transfer and development lengths are adequate. The Federal Highway Administration imposed certain restrictions on the use of prestressing strand. These restrictions include:

1. No 0.6 inch diameter strand is to be used in pretensioned concrete.
2. Strands must be spaced four times the nominal strand diameter.
3. Bond development length shall be determined on the basis of 2.5 times the current AASHTO equation (9-32). It should be noted that in January, 1989 this requirement was reduced to a factor of 1.6.

These actions have established a need for this research and additional evaluations of transfer and development lengths.

Some investigations have been performed to investigate the bond strength of untensioned prestressing tendons. These experimental studies have been conducted to determine design criteria for the following applications in the precast concrete industry:

1. Lifting handles for precast components
2. Reinforcing for crack control
3. Connection reinforcing between precast elements
4. Longitudinal ties in hollow-core floor slabs
5. Comparison of transfer-lengths of pretensioned strands.

Salmons and McCrate (1977) performed some of the initial studies related to the behavior of untensioned strands. The three different types of strand configurations studied were straight unfrayed, straight frayed, and unfrayed

strands bent 90 degrees over a reinforcing bar. Design equations were developed which relate the necessary embedment length to prevent slippage. Equations based on both working stress and ultimate strength were presented. The following equation was proposed to evaluate the necessary embedment of a straight strand based on ultimate capacity considerations:

$$L_e = 0.337 f_s + 8.00 \text{ in}$$

Relationships based on working stress considerations were derived by modifying the steel stresses at general slip by a factor of 0.71 (1/1.4). This resulted in the following equation:

$$L_e = 0.472 f_s + 8.00 \text{ in.}$$

where L_e = Embedment length of strand, in.
 f_s = Maximum stress in strand, ksi

Research on initially untensioned strands by Burnett and Anis (1981) was primarily to determine the embedment length needed to maximize pullout capacity. Results based on 3/8 in. diameter, 270 ksi strand have been presented. Tests of other size strands indicated that their behavior is comparable. Three expressions were suggested for design according to the range of the load applied. For $F < F_I < F_y$ the pullout resistance could be expressed as follows:

$$F = f_b l_a p_b$$

where F = Force in strand
 F_I = Force at the initiation of pullout
 F_y = Force at which the steel yields
 f_b = Nominal interfacial bond stress

l_a = The portion of the embedment length activity involved
where $l_a \leq l_e$

l_e = Embedment length of the strand

p_b = Nominal perimeter of the strand

At the initiation of overall slip or $F = F_I \leq F_y$

$$F_I = f_b l_e p_b$$

In order to incorporate their experimental results, two assumptions were made. As the untensioned strand is loaded, there is a radial decrease in size which in turn reduces the adhesive and frictional contribution to bond. Therefore, as F approaches F_I , pullout is mostly due to the shear strength of the spiral protrusions of the concrete. The nominal bond stress was assumed to be linearly proportional to the square root of the compressive strength. Also the interfacial area, $l_a p_b$, is assumed to be linearly proportional to $l_a d_b$. The nominal surface perimeter, p_b is approximately equal to $(4/3) \pi d_b$. Using these assumptions the pullout resistance may be taken as:

$$F_I = K l_e d_b \sqrt{f'_c}$$

where K is a bond pullout factor which is obtained experimentally and takes into account size-related considerations of the strand and the quality of the material surrounding the strand. All of the experimental work was carried out on rotationally restrained seven wire strand embedded in uncracked concrete. Because of this it was concluded that more extensive testing should be performed, and caution should be exercised when applying the results.

An experimental study of bond characteristics of strand reinforcement was conducted by R.W. Keuning (1961) at the University of Illinois. The objective of this study was to provide information on anchorage zone stresses in pretensioned beams.

Concrete specimens with the same configurations and strand embedment lengths were tested under two different loading conditions. One set of tests involved the pullout of untensioned strand, and others were tested by releasing pretensioned strand. The transfer of stress from strand to concrete was investigated for 1/4 inch diameter strand only. The bond versus slip relationship was presented, and also the tensioned and untensioned strand characteristics were compared. The pretensioned specimens resulted in better bond stresses than untensioned ones, but the difference was small. Kuening concluded that the transfer length for 1/4 inch strand would be less than 10 in. for the working load and 20 in. under short time loading conditions.

CHAPTER III

FABRICATION OF SPECIMENS

A series of tests were conducted by pulling untensioned seven-wire strand from concrete specimens. The pullout specimens were 6 in. x 6 in. in cross-section with the lengths varying according to desired embedment of strand. The prestressing strands were placed concentrically in the specimen.

Materials

- (a) Prestressing strand: all prestressing steel used was seven-wire, 270 ksi ultimate tensile strength, low-relaxation strand supplied by Florida Wire and Cable Company. The four sizes used were 1/2", 1/2" special, 9/16", and 0.6" nominal diameters.
- (b) Concrete: A Tennessee Department of Transportation concrete mix design for a compressive strength of 5000 psi was used. The mix design is shown in Table 1.

Three 6 x 12 inch concrete cylinders were cast with each pour and the concrete compressive strengths were determined at the time the specimens were tested. The concrete was mixed in the concrete laboratory at The University of Tennessee. The specimens were moist cured, and varying concrete strengths were obtained by testing at different ages.

TABLE 1
CONCRETE MIX DESIGN

Quantity	Description
752 lb.	Type I Cement (Signal Mountain)
1920 lb.	No. 67 Course Aggregate (American Limestone Company)
1326 lb.	Fine Aggregate (Manufactured Sand, American Limestone Co.)
21.2 oz.	Low Range Pozzolin 300
35 gal.	Water

CHAPTER IV

INSTRUMENTATION AND TEST PROCEDURE

The pullout characteristics of the seven-wire prestressing strand were investigated using the test set-up shown in Figure 2. The prestressing strands were loaded with the aid of a hydraulic jack. A steel plate with a 2 in. diameter hole was placed on the face of the concrete. A flat doughnut compression load cell was placed on the steel plate and directly connected to a Vishay/Ellis - 20 digital strain indicator which read the amount of load being applied to the strand. The hydraulic jack was then located on the top of the load cell, and load was transferred to the strand with the use of a conventional prestressing strand chuck. Deflection of strand was monitored with a dial gage indicator.

Care was taken to avoid any eccentric load being applied to the strand. Before the dial gage was zeroed a small load was applied and then backed off to attempt to seat the chuck. The load was applied in increments of 0.2 to 2 kips, depending on the length of embedment, and deflection was recorded at each load increment. The specimens were loaded up to major slippage of the strand, and in most cases data was recorded beyond this point. Load-deflection curves for each strand are shown in Appendix Figures A-1 thru A-32. It should be noted that there is a certain amount of strand elongation included in these curves. Table A-1 shows the deformation due to axial load for each strand. These values are based on an axial load of 10 kips. The length used was 10 in., which was the distance from the face of the concrete to the point where the strand chuck was attached. Also, the shape of the initial part of the load-deflection

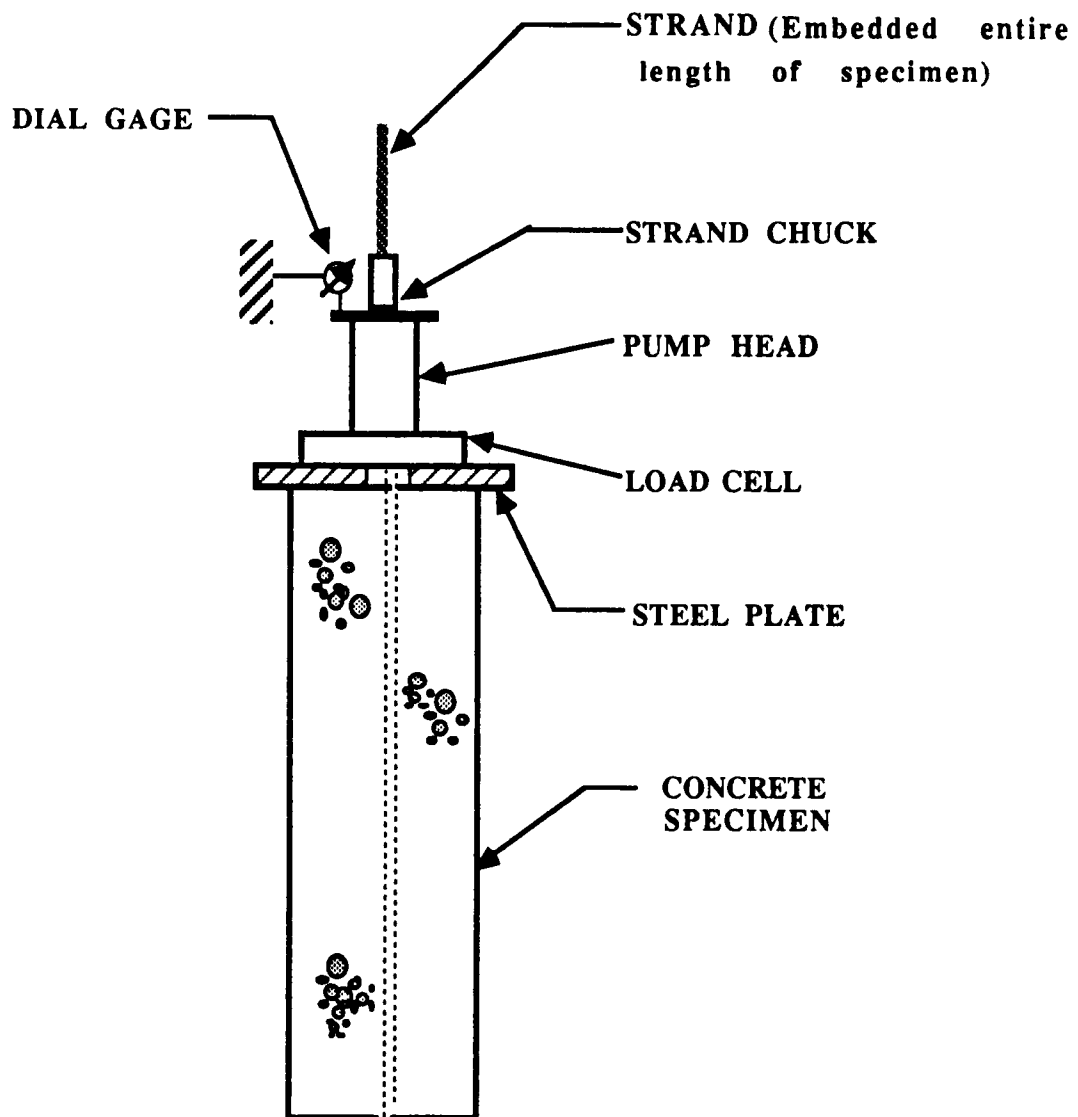


Figure 2. Test Setup.

curves was affected by some further chuck seating. The load at failure was taken from these curves as the point where there is a change in the slope and major slipping occurs.

CHAPTER V

DISCUSSION OF TEST RESULTS

Thirty-three pullout tests were performed with various diameters of seven wire strand, various compressive concrete strengths, various lengths of embedment, and various surface conditions of the wire. The magnitude of the pullout strength of untensioned seven wire strand depends on a combination of mechanical and adhesive bond. Adhesive bond is the adherence of the concrete to the surface of the outside wires. As such, it is primarily influenced by the surface condition of the strand. Mechanical bond is provided by the concrete in valleys between the individual wires of the strand. After the adhesive bond is lost, all load is transferred by mechanical bond. If the strand could be pulled straight out, the concrete in the valleys would provide retention until a shear failure occurred. The test results indicated that once the adhesive bond is broken, the strand may tend to unscrew. After the adhesive bond failed, the strand began to unscrew and then bunch up or the individual strands overlapped resulting in a temporary increase in load capacity. These loads are time dependent, and significant reductions in load capacity can be expected under a sustained load condition.

The results of the tests are summarized in Tables 2 thru 5. The embedment length of strand had a very predictable effect on the pullout strength. For a given strand diameter, longer lengths of embedment resulted in greater pullout capacities. A typical plot of the load at failure versus the embedment length is given in Figure 3 for 1/2" diameter strand. It is also shown

TABLE 2
TEST RESULTS FOR 1/2" DIAMETER STRAND

Specimen No.	l_e (in)	f'_c (psi)	Paxial @ Failure (kips)
1	6	3080	3.0
2	12	3080	6.8
3	16	3080	9.5
4	19.5	4775	14.0
5	23.5	4775	19.0
6	36	4775	25.0
8	12	5240	6.0
9	12	6790	9.4
11	18	5240	12.0
12	24	5240	17.0
13	23.5	6790	17.0
14	36	6790	24.5

TABLE 3
TEST RESULTS FOR 1/2" SPECIAL STRAND

Specimen No.	l_e (in)	f'_c (psi)	P_{axial} @ Failure (kips)
16	12	1440	1.6
17	17.5	1440	4.4
18	18	1440	3.7
20	24	1440	4.0
22	42	1440	13.1
24	12	5530	6.3
25	24	5530	8.2
26	30	5530	9.3
27	36	5530	8.7
28	42	5530	10
29	48	5530	11.3

TABLE 4

TEST RESULTS FOR 9/16" SPECIAL STRAND

Specimen No.	l_e (in)	f'_c (psi)	Paxial @ Failure (kips)
30	12	4650	4.4
31	24	4650	8.7
32	36	4650	14.0
33	48	4650	19.0
34	60	4650	21.0

TABLE 5

TEST RESULTS FOR 0.6" DIAMETER STRAND

Specimen No.	l_e (in)	f'_c (psi)	P_{axial} @ Failure (kips)
35	12	6750	4.4
36	24	6750	10.0
37	36	6750	12.0
38	48	6750	16.0
39	60	6750	22.0

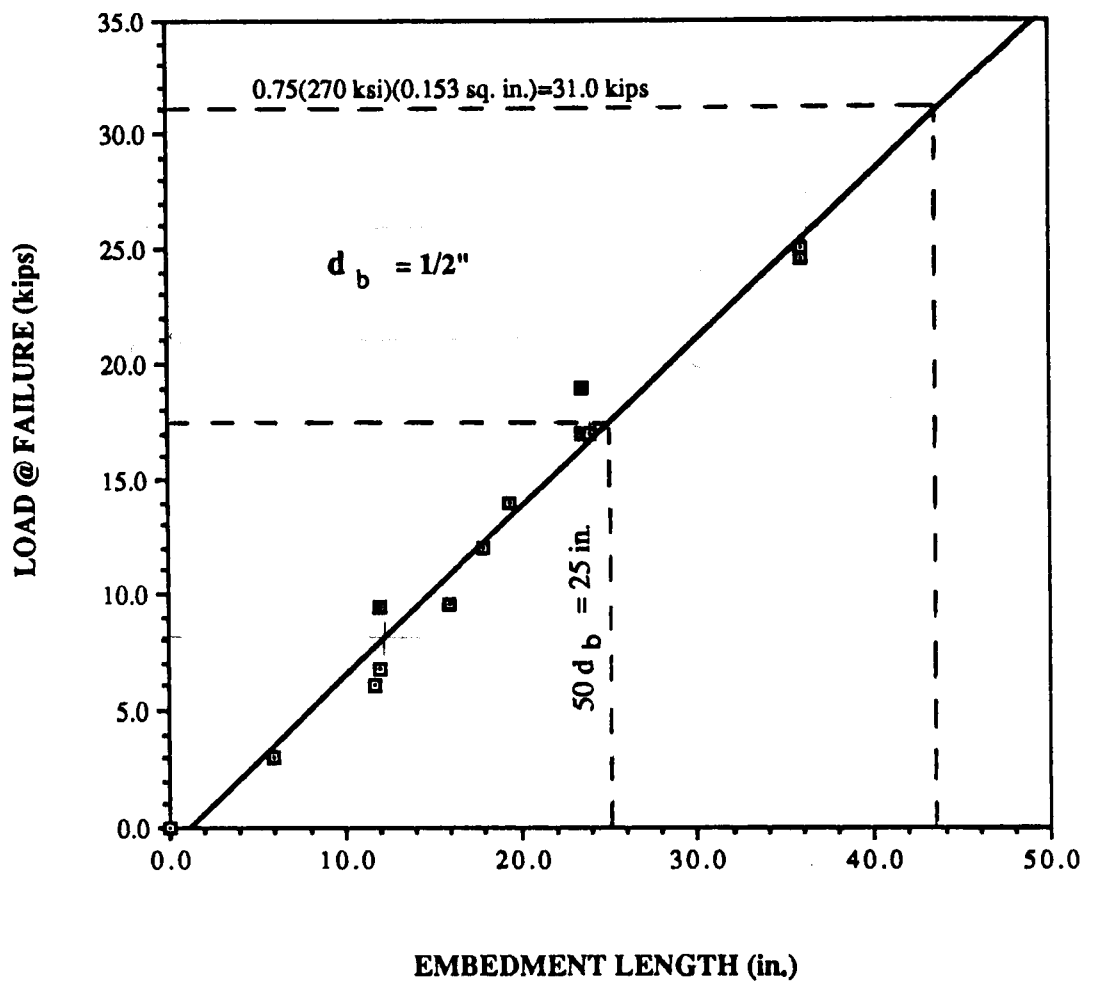


Figure 3. Load Versus Embedment Length Curve for 1/2" Diameter Strand.

on this plot what embedment length would be required for 75 percent of the ultimate strength of the tendon, and the load which would be obtained from the suggested ACI transfer length of 50 diameters. Similar plots for the other diameters are shown in Appendix B. All of the lengths tested show a linear increase in pullout capacity. Once the ultimate tensile strength of strand is reached, the curve is expected to become nonlinear.

Increasing the diameter should have a positive effect on the load capacity. A larger diameter would increase the strand surface area and therefore the pullout load per unit of length of embedment would be increased. The data support this for a given lot or mill run of strand. Variations between different lots are believed to be influenced by the surface conditions of the strands. All of the 1/2" strand tested were drops or scrap pieces of strand obtained from a local precast producer. This steel had been weathered and was slightly rusted. All of the remaining diameters were obtained directly from a wire manufacturer and care was taken to protect them from exposure until the concrete was cast. The 1/2" specimens obtained from a local producer had pullout strengths greater than any of the other diameters. It has been concluded that the light amount of rust improved the adhesive bond. The strands which were protected from exposure had significantly lower adhesive bond strengths. As Preston (1988) pointed out, "The wires of all stress-relieved and low-relaxation strands have a degree of shininess resulting from residuals of the lubricants used during the wire drawing process. This is typical of the strand that has been used since 1950 and of the strand used in tests that established the transfer length formulas in the specifications."

In this study, the surface condition of the strands was not rated in any form other than, as stated previously, the 1/2" strands were slightly rusted, and the others were shiny and had a slight film of residual lubricants from the milling process.

All of the data obtained were plotted in the form of embedment length versus steel stress. It is obvious there are two different sets of results from this plot. For each of the strand surface conditions there is a linear relationship. These relationships are shown in Figure 4. Salmons and McCrate's (1977) equation for the recommended embedment length is also plotted in this figure and falls between these two curves. As no mention of strand surface condition was made in their report, it was believed to be at some intermediate point of the two conditions studied here. In the work done by Burnett and Anis (1981), they pointed out that no attempt was made to assess the effects of surface conditions. Figure 4 shows that the surface condition plays a significant role in the pullout capacity of untensioned seven-wire prestressing strand.

It has been determined that adhesive bond is influenced by the concrete properties and placement. In cases where there is dry or no slump concrete the spaces in between and around the wires are not filled as well. This is important because it decreases the amount of strand surface area in contact with cement paste and thus decreases the amount of adhesive bond. In order to properly fill these spaces, a concrete with good workability is needed, and it should also be properly vibrated.

Upper and lower bound relationships have been developed, from Figure 4,

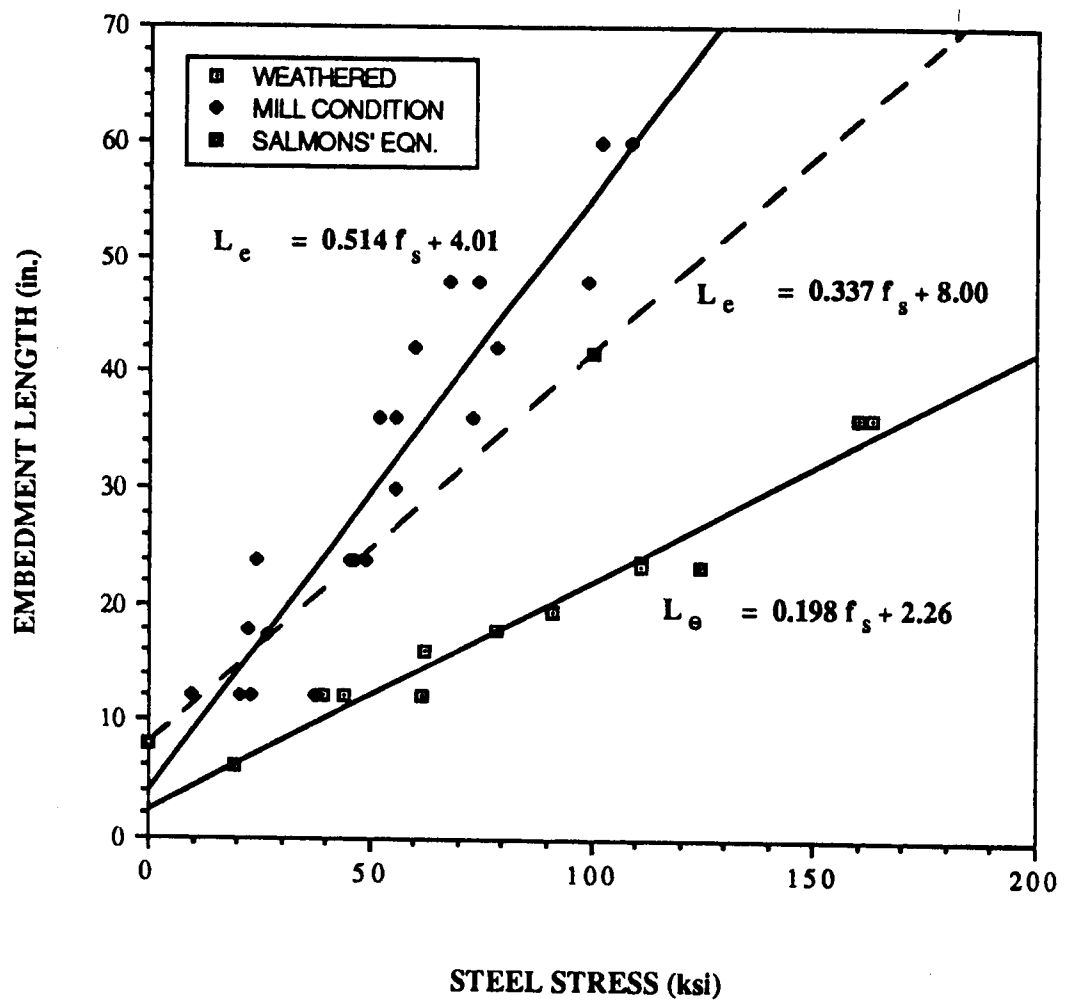


Figure 4. Embedment Length Versus Steel Stress.

which predict the required embedment length for a particular strand stress level. The lower bound equation for required embedment, which corresponds to the "mill condition" strand is as follows:

$$L_e = 0.514 f_s + 4.01 \quad (5.1)$$

The upper bound relationship for required embedment, which corresponds to the "weathered" strand is shown below.

$$L_e = 0.198 f_s + 2.26 \quad (5.2)$$

It should be noted that these prediction equations represent empirical relationships developed the test data and as such contain no factor of safety.

In previous work many people have concluded that bond strength of prestressing strand is independent of the compressive strength of concrete. Initially the results of this study seemed to indicate this also, but it seems illogical. There is shearing of concrete involved in the pullout of strand, and it is generally accepted that the shear strength of concrete is as a function of the square root of the compressive strength. Close inspection of the data indicates a dependence of bond strength to concrete compressive strength. An attempt has been made to normalize the data by bond stress at failure. This bond stress was taken as the load at failure divided by the nominal surface area of the embedded strand. The nominal perimeter of strand was taken as $(4/3) \pi d_b$, which results in a surface area of $(4/3) \pi d_b l_e$. Plots of bond stress versus concrete compressive strength are shown in Figures 5 and 6. These figures are

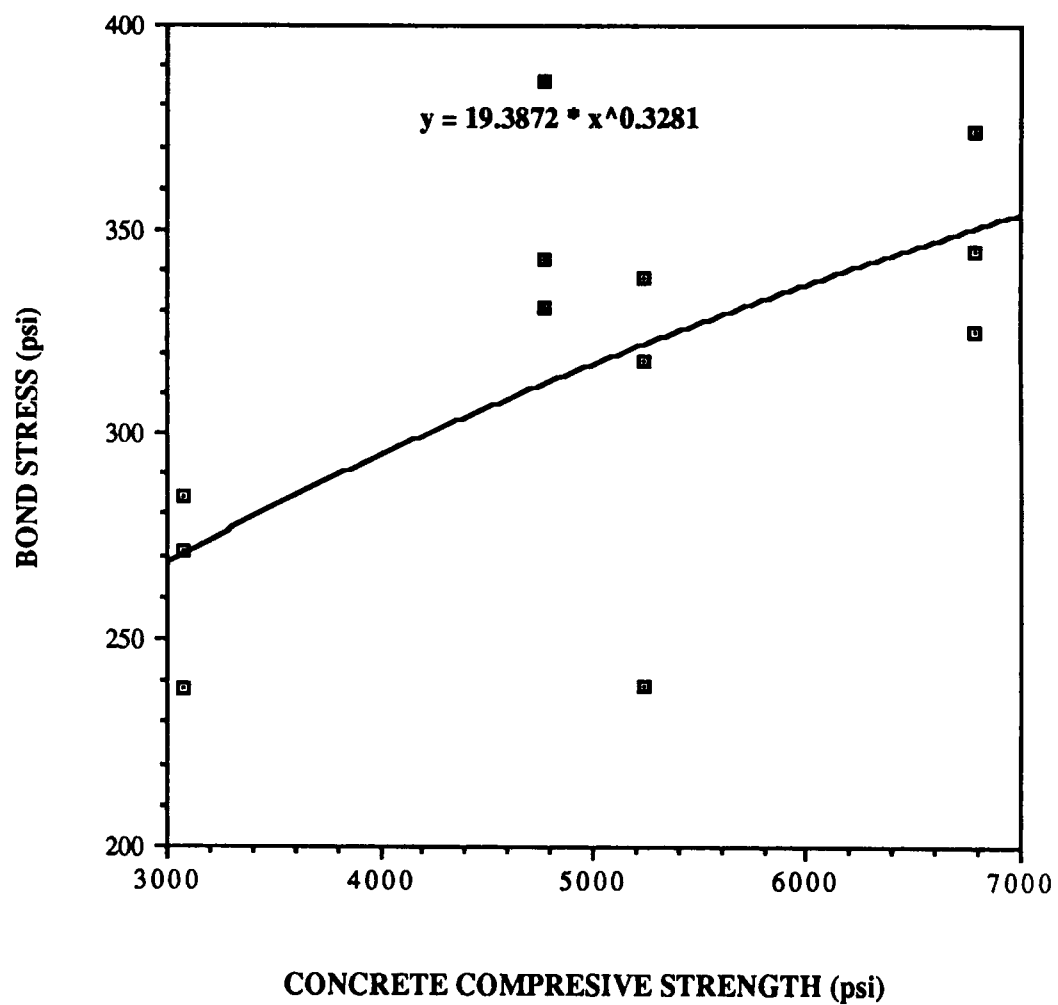


Figure 5. Bond Stress Versus Concrete Compressive Strength for Weathered Strand.

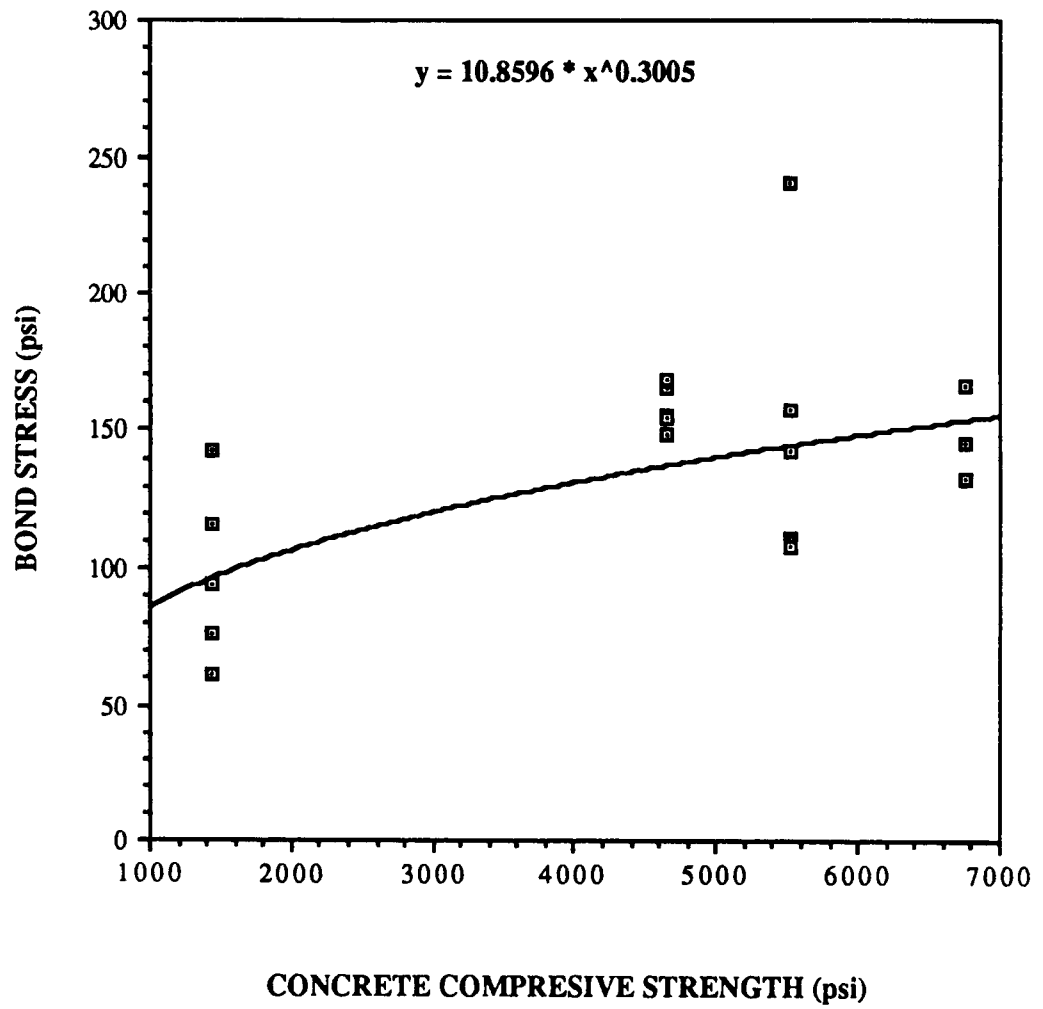


Figure 6. Bond Stress Versus Concrete Compressive Strength for Mill Condition Strand.

representative of each surface condition of strand. There is a considerable scatter of data, and linear, logarithmic, and exponential curve fits were all attempted. The logarithmic curve is the best fit as previous theory would lead one to expect. Both curves show the bond stress as a function of $(f'_c)^{0.3}$.

Empirical relationships have been developed to predict bond stress as a function of f'_c . Again the surface condition of strand is a major factor in the development of bond stress. The equations best representing bond stress as a function of f'_c are as follows:

$$f_b = 19.39 (f'_c)^{0.33} \quad (\text{Weathered})$$

$$f_b = 10.86 (f'_c)^{0.30} \quad (\text{Mill Condition})$$

These data represent a limited number of tests, but the trend shows some definite correlation between concrete strengths and the pullout capacities of untensioned strand. While there may be significant dependence on compressive strength for the transfer and development lengths of pretensioned strand, much of the previous work in this area suggests that there is little influence.

CHAPTER VI

CONCLUSIONS

Extensive testing of the pullout characteristics of prestressing strand has been undertaken, and the variables investigated were strand diameter, concrete compressive strength, strand surface condition, and length of embedment. These results were compared with existing studies and relationships of considered variables were formed. The following conclusions were made:

1. The surface condition of strand is of vital importance to the pullout strength. There is a need to establish some means of quality control for the surface condition, or some type of roughened strand may be a possibility. The relationship found for the mill condition strand is an acceptable lower bound solution for the requirements of embedment length. It is not readily apparent by visual observation if a particular strand has been weathered. Significant increases in adhesive bond strength can be expected long before oxidation is apparent.
2. The pullout capacities are related to the concrete compressive strength, and more testing is needed to pursue this further. Investigations indicate that pullout is approximately proportional to $(f'_c)^{0.3}$.

3. The larger size strand diameters seem to follow the same basic trends as studies done on small sizes. The relationship between embedment length and stress in the strand is linear. Upper and lower bound prediction equations have been developed which incorporate diameter of strand, length of embedment, and surface condition of strand.

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APPENDICES

APPENDIX A
LOAD-DEFLECTION CURVES

TABLE A-1
ELONGATION OF STRAND

Diameter (in.)	Area (in ²)	$\frac{*Pl}{AE}$ (in)
1/2	0.153	0.023
1/2 Spec.	0.167	0.021
9/16	0.192	0.019
0.6	0.215	0.017

* P = 10 kips

l = 10 in.

E = 28,000 ksi

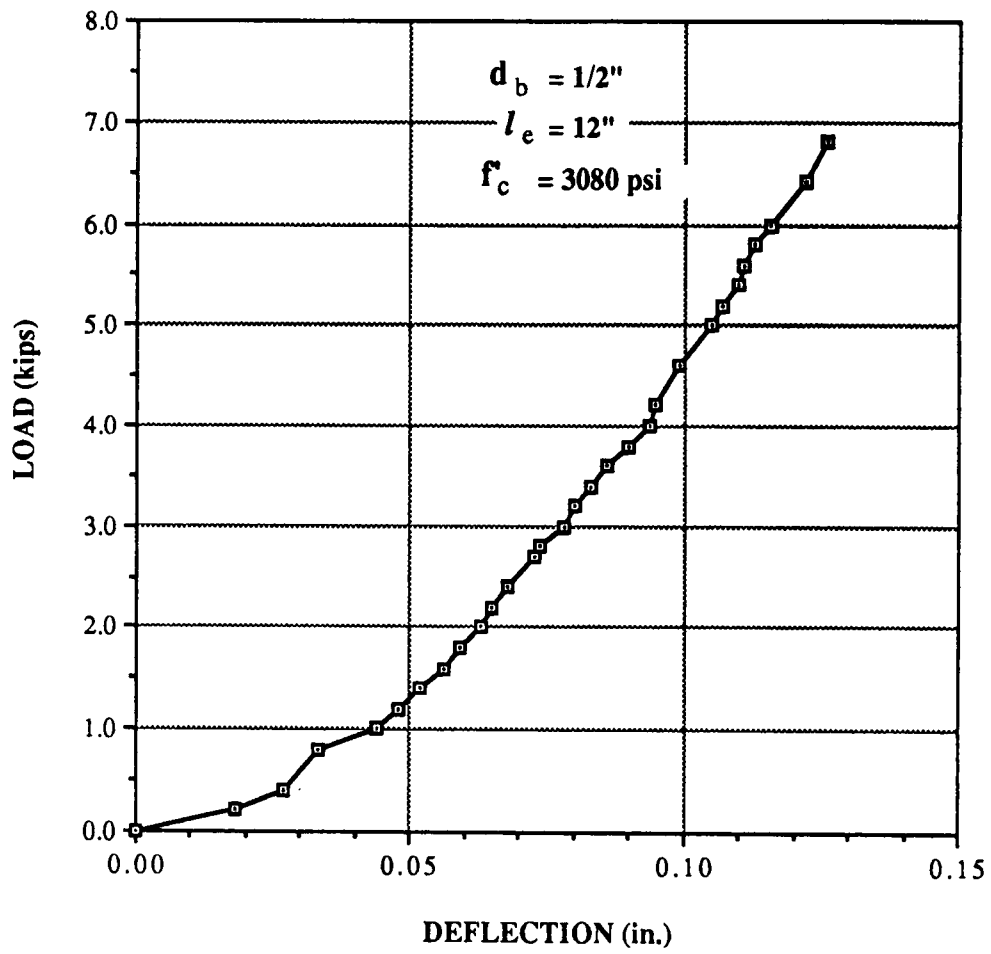


Figure A-1. Load-Deflection Curve for Specimen #2.

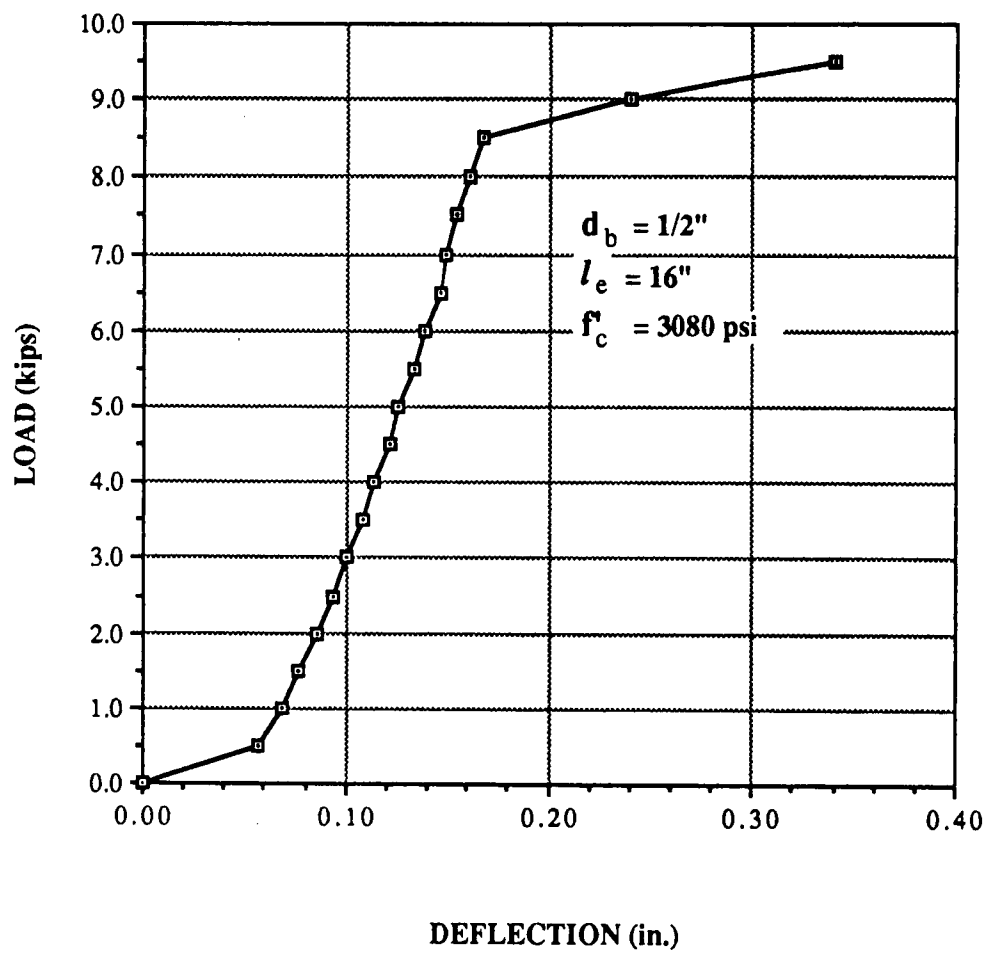


Figure A-2. Load-Deflection Curve for Specimen #3.

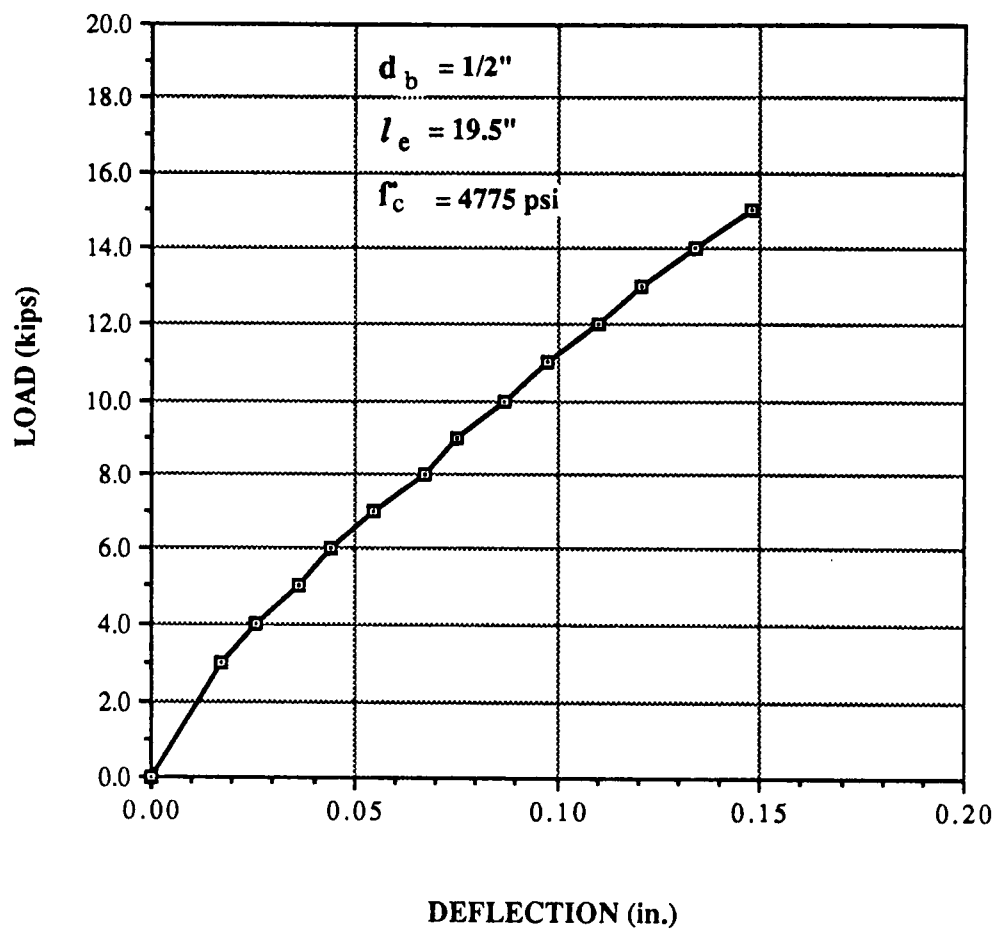


Figure A-3. Load-Deflection Curve for Specimen #4.

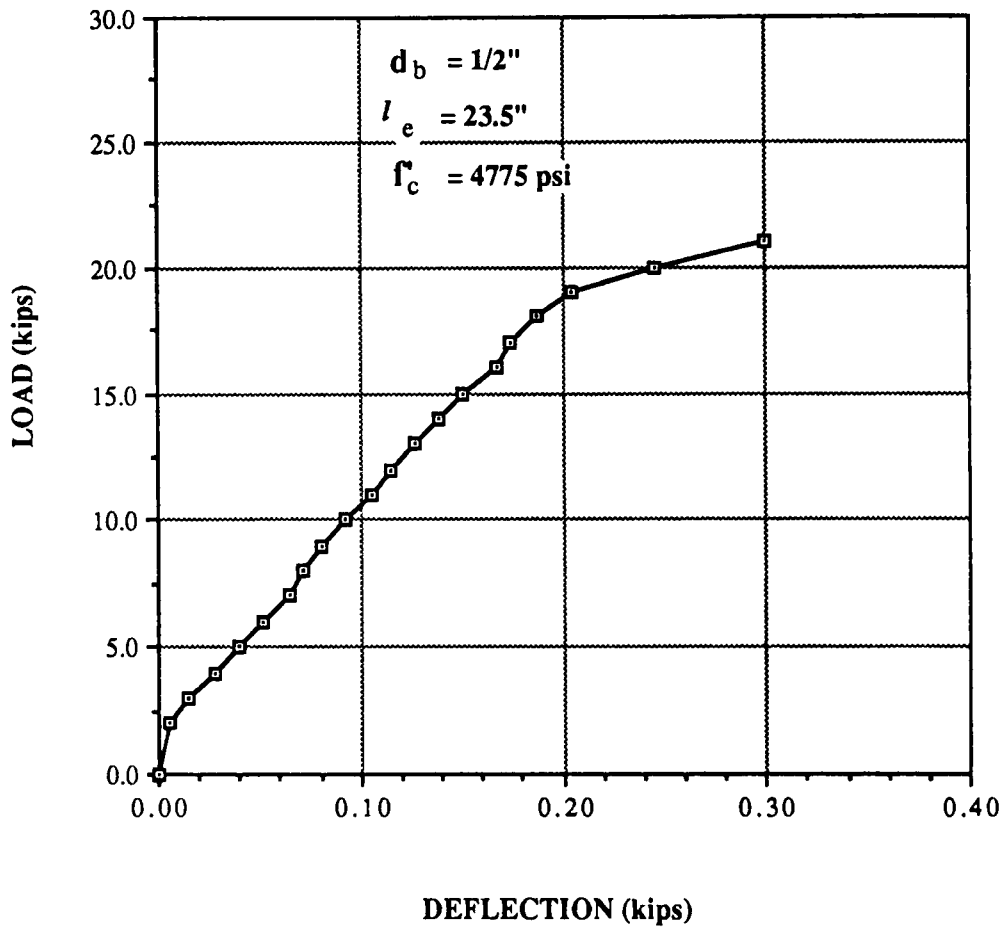


Figure A-4. Load-Deflection Curve for Specimen #5.

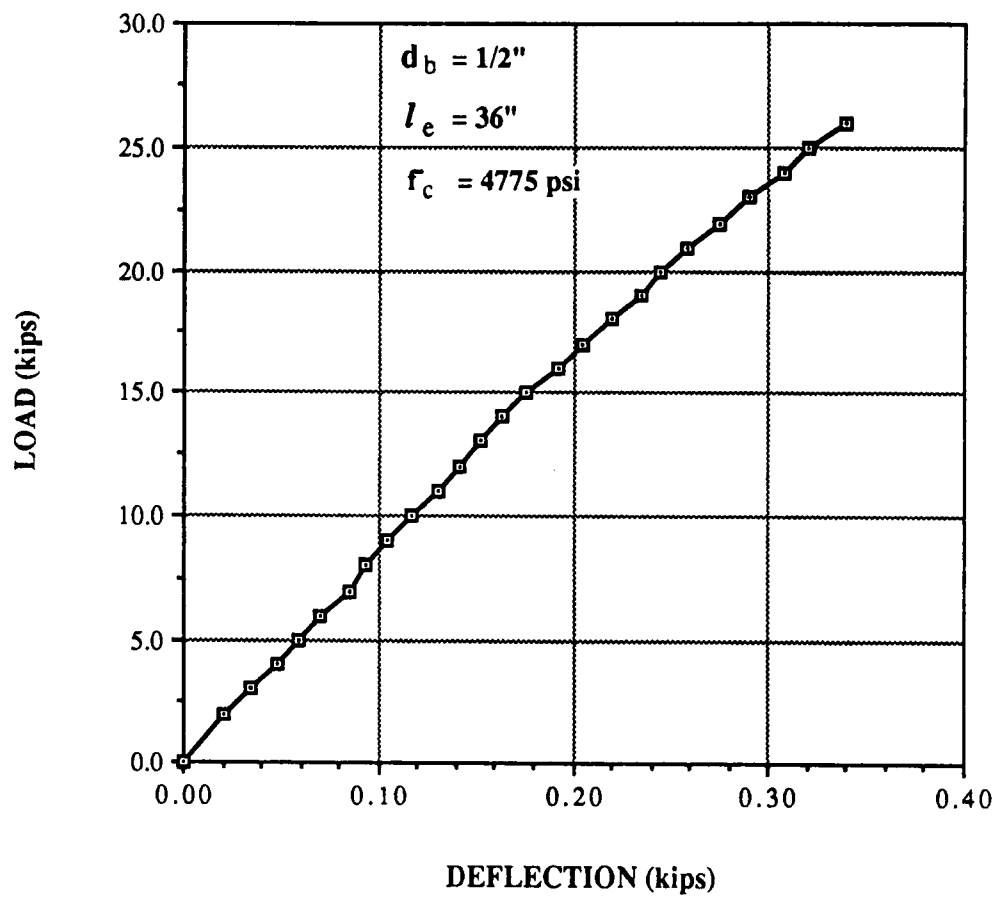


Figure A-5. Load-Deflection Curve for Specimen #6.

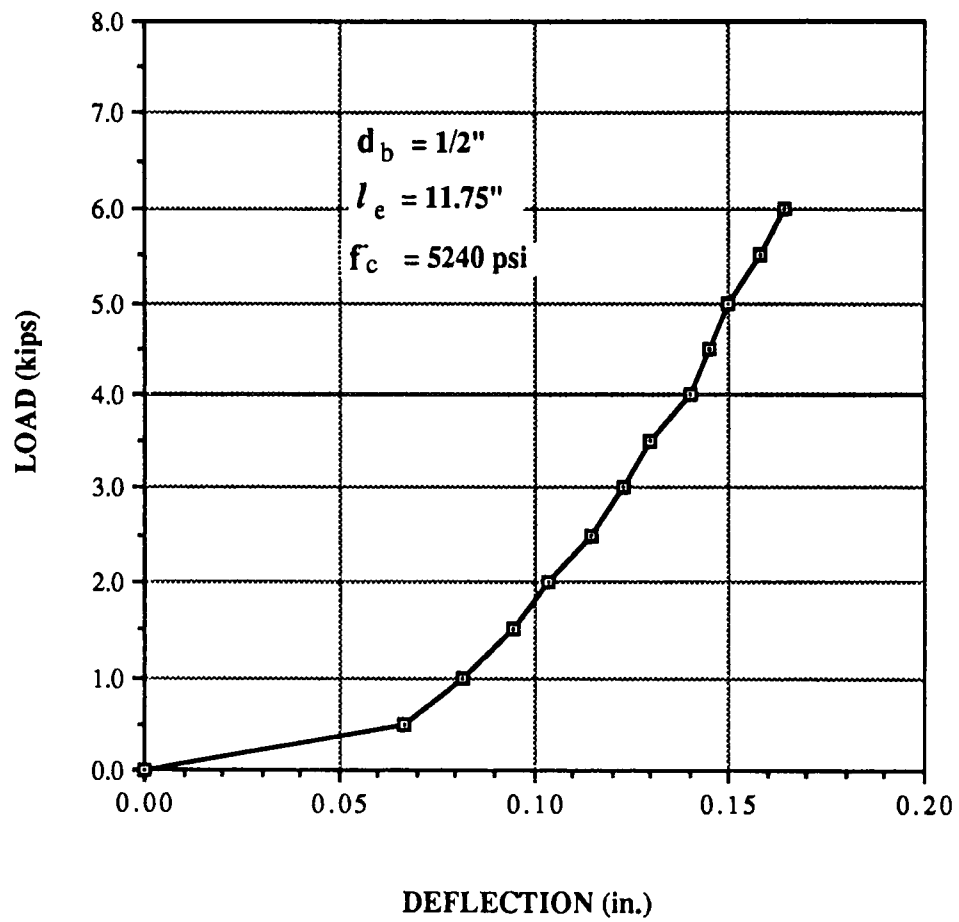


Figure A-6. Load-Deflection Curve for Specimen #8.

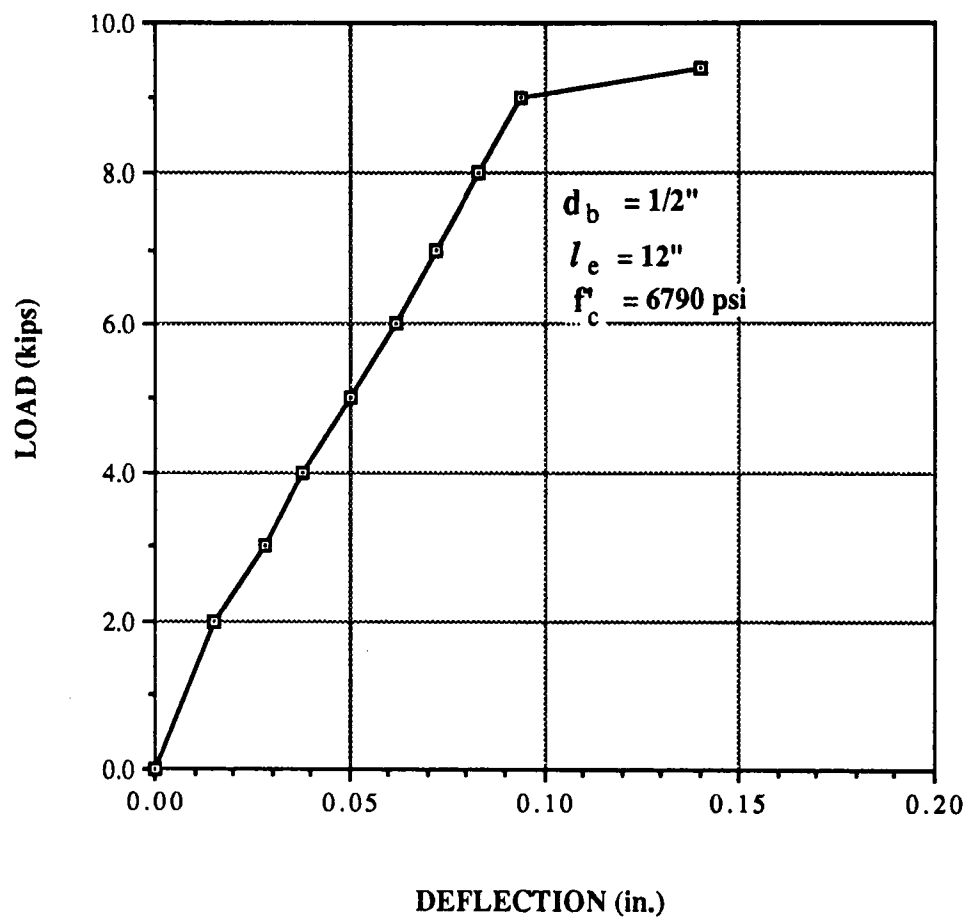


Figure A-7. Load-Deflection Curve for Specimen #9.

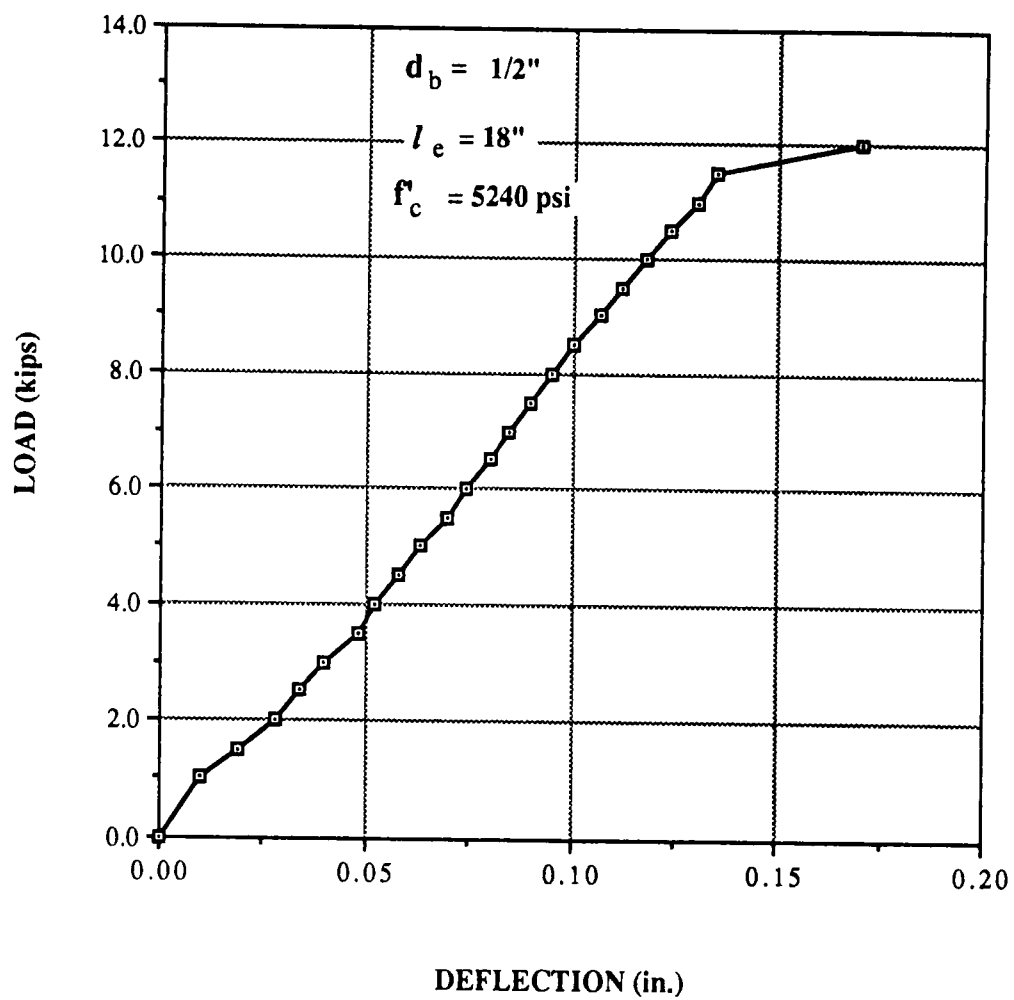


Figure A-8. Load-Deflection Curve for Specimen #11.

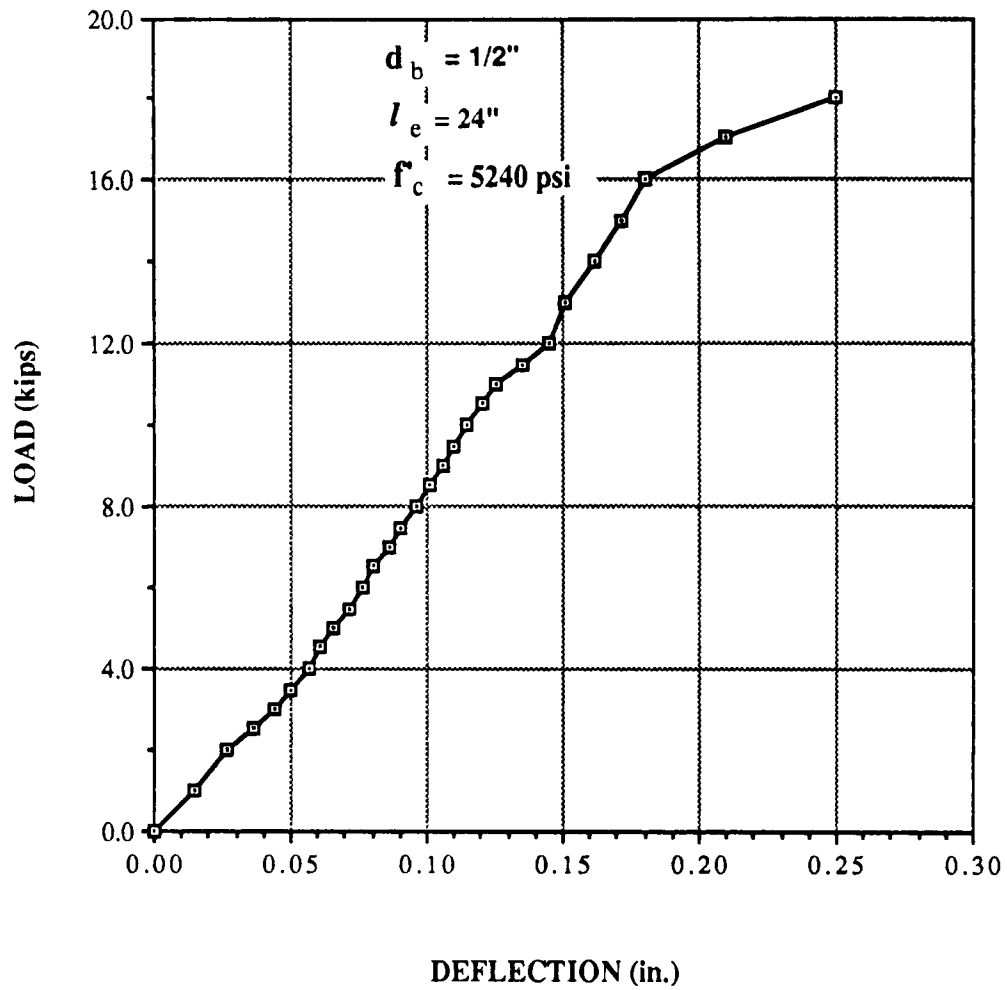


Figure A-9. Load-Deflection Curve for Specimen #12.

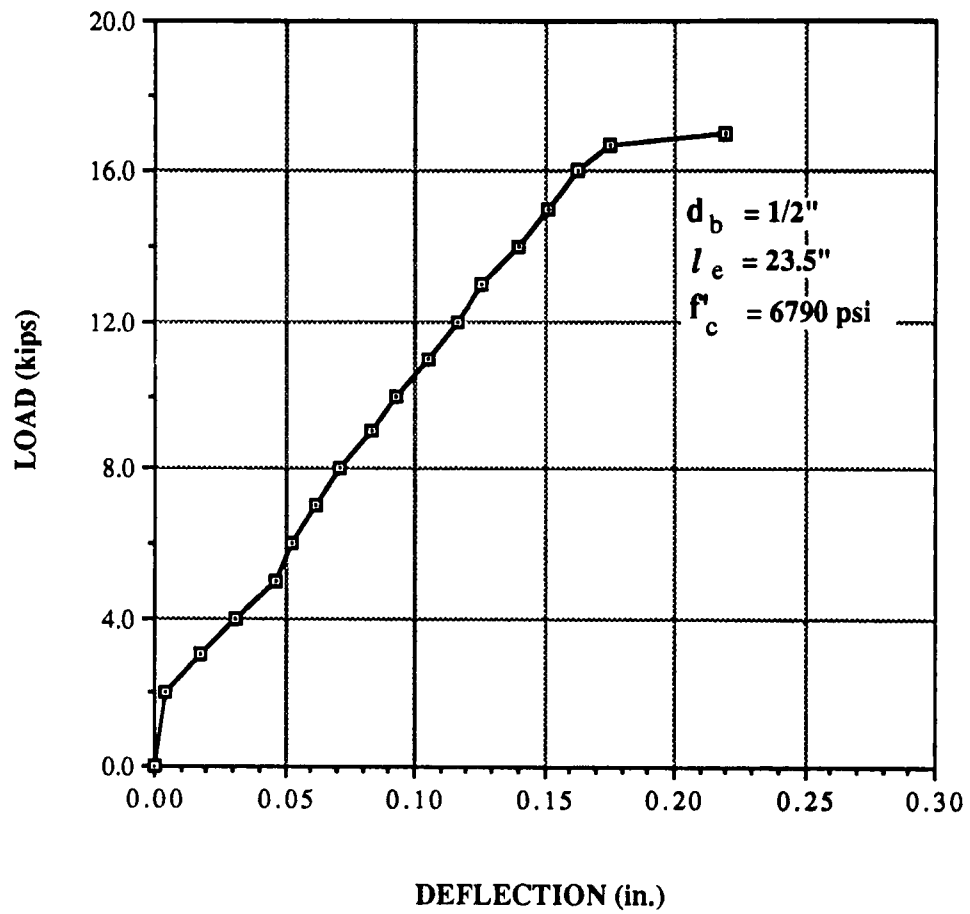


Figure A-10. Load-Deflection Curve for Specimen #13.

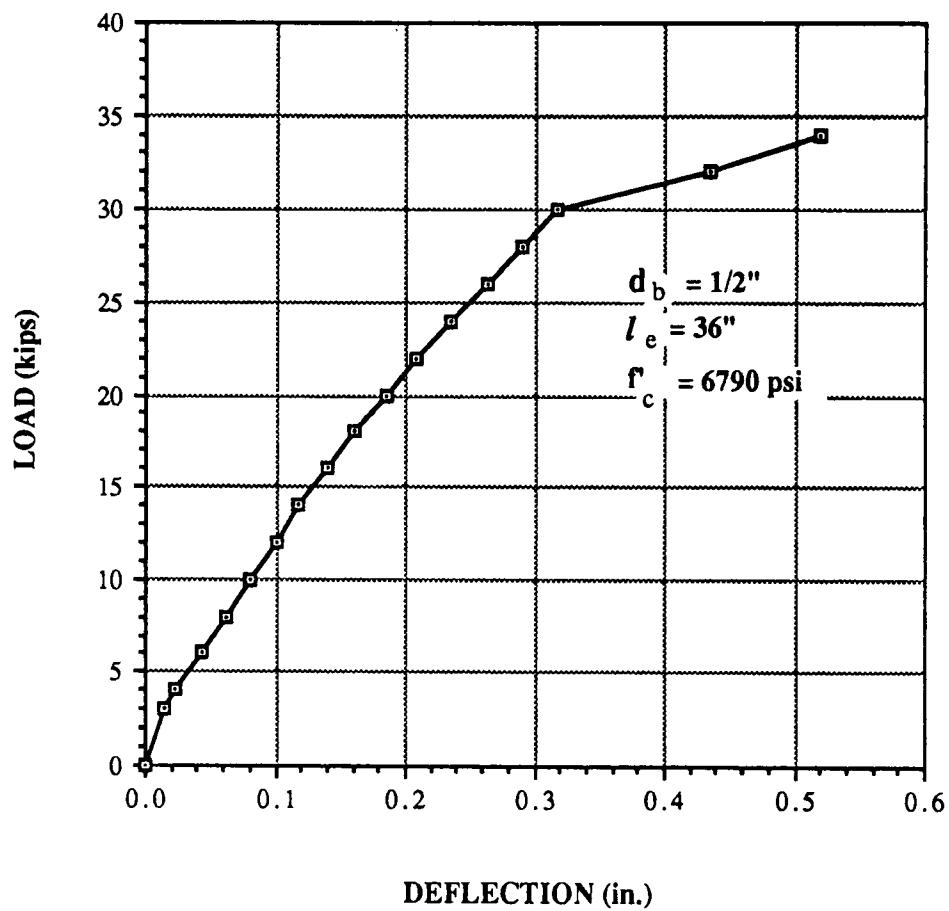


Figure A-11. Load-Deflection Curve for Specimen #14.

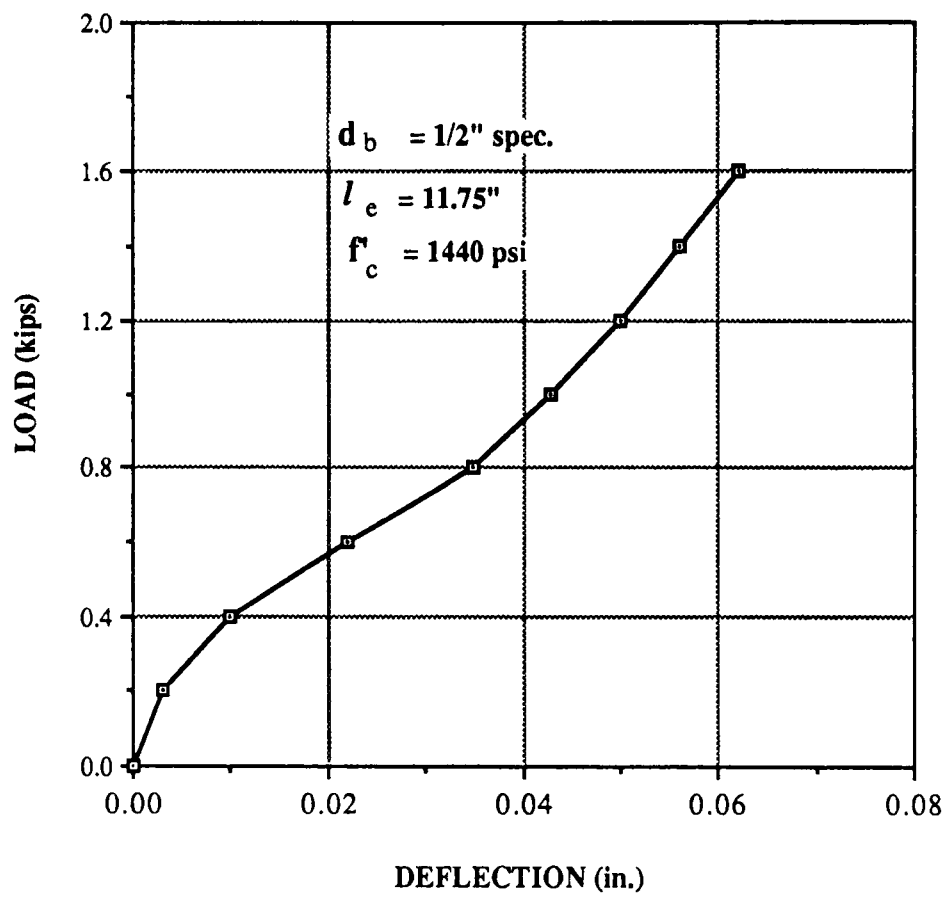


Figure A-12. Load-Deflection Curve for Specimen #16.

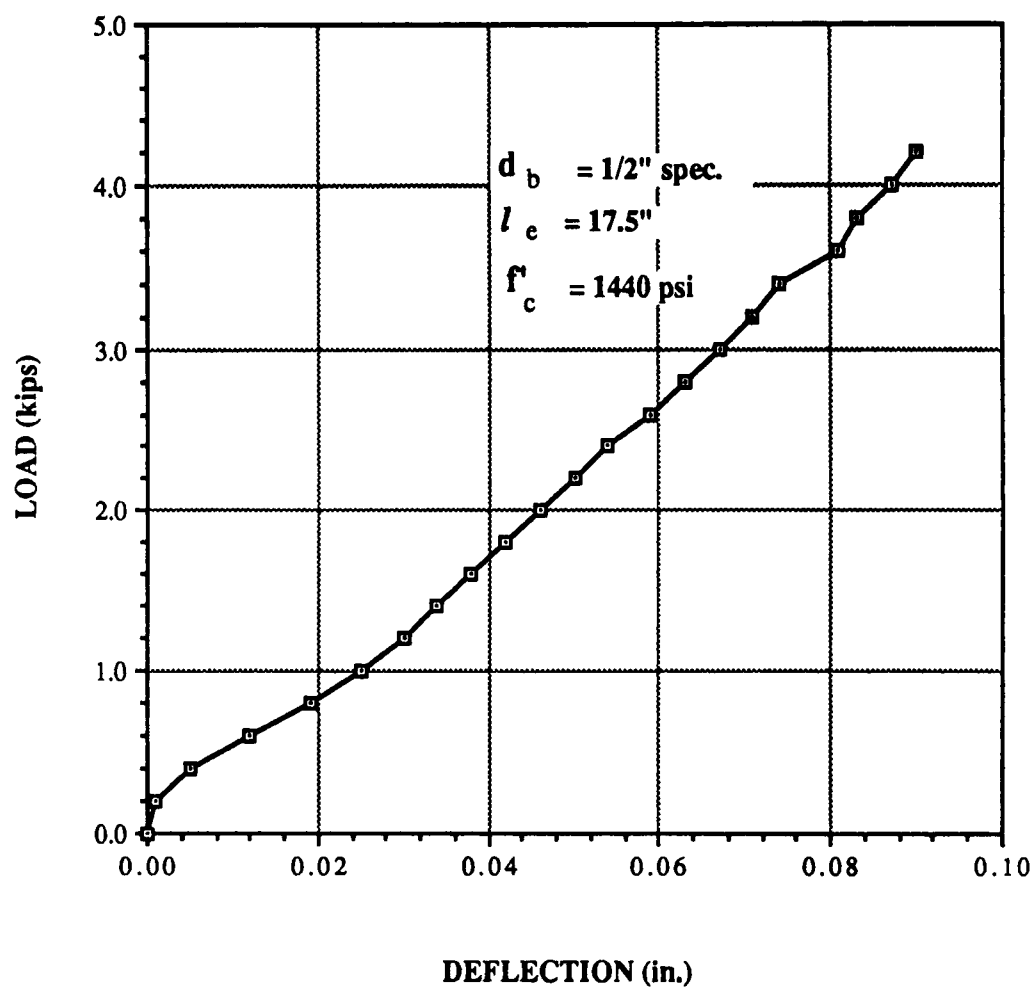


Figure A-13. Load-Deflection Curve for Specimen #17.

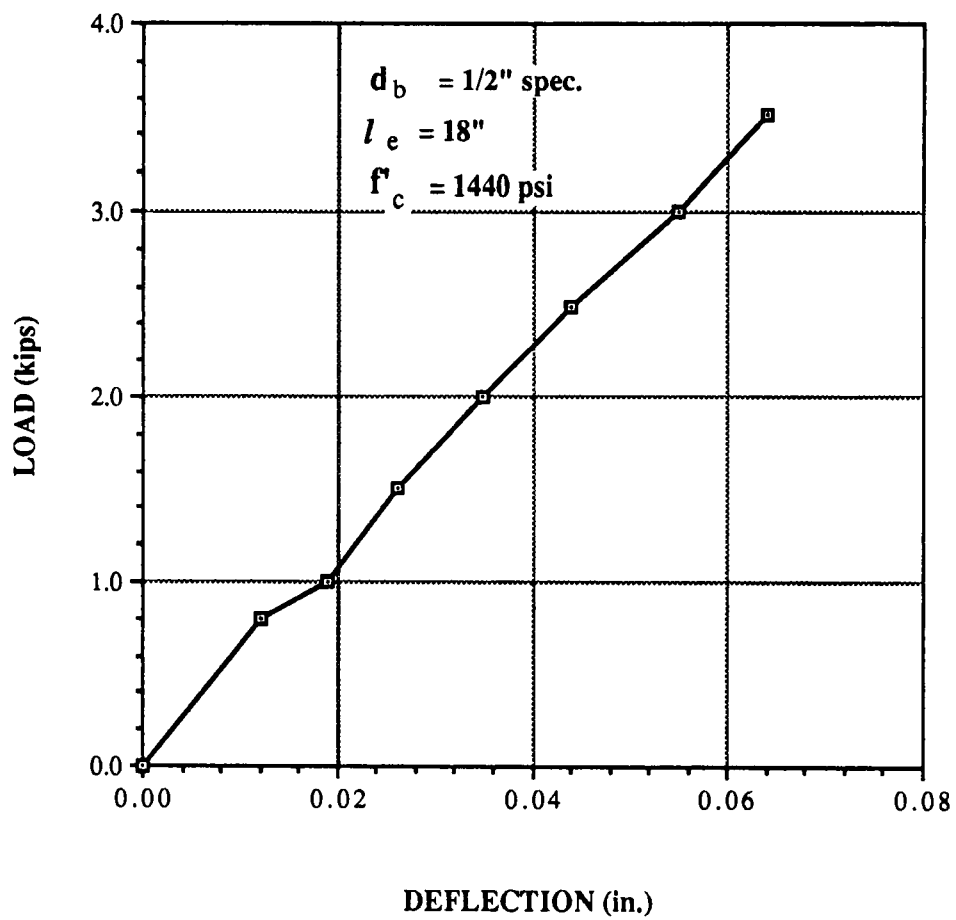


Figure A-14. Load-Deflection Curve for Specimen #18.

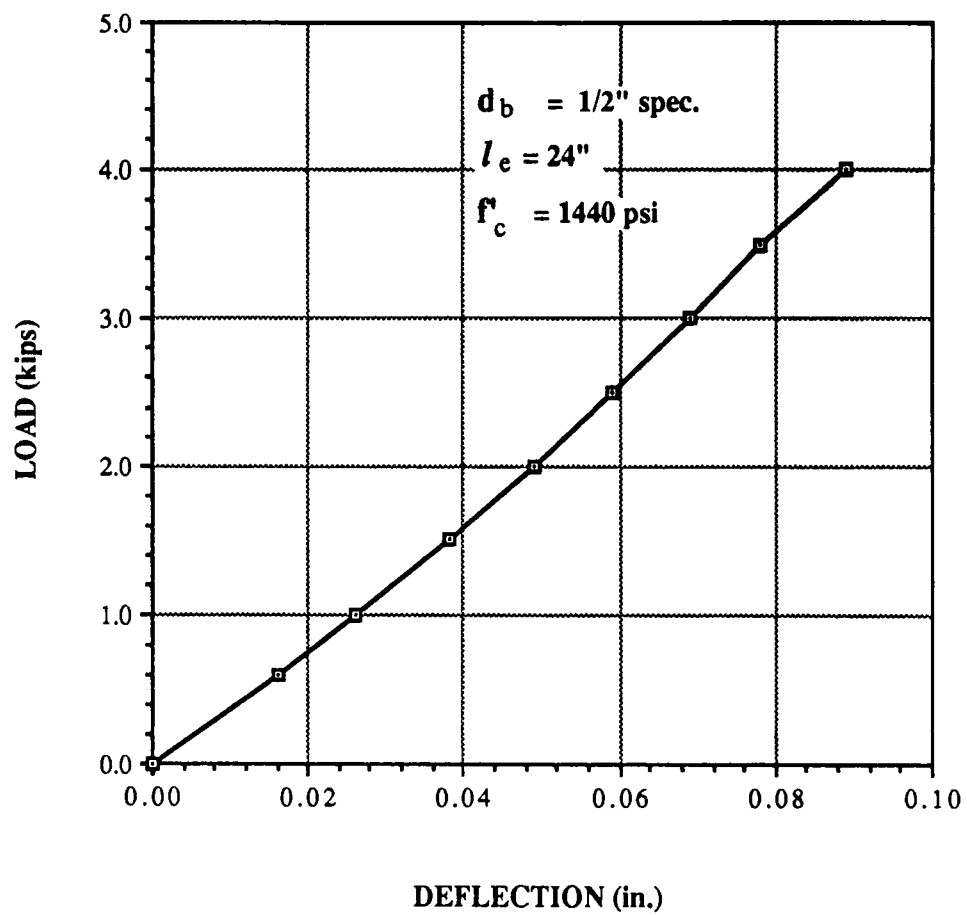


Figure A-15. Load-Deflection Curve for Specimen #20.

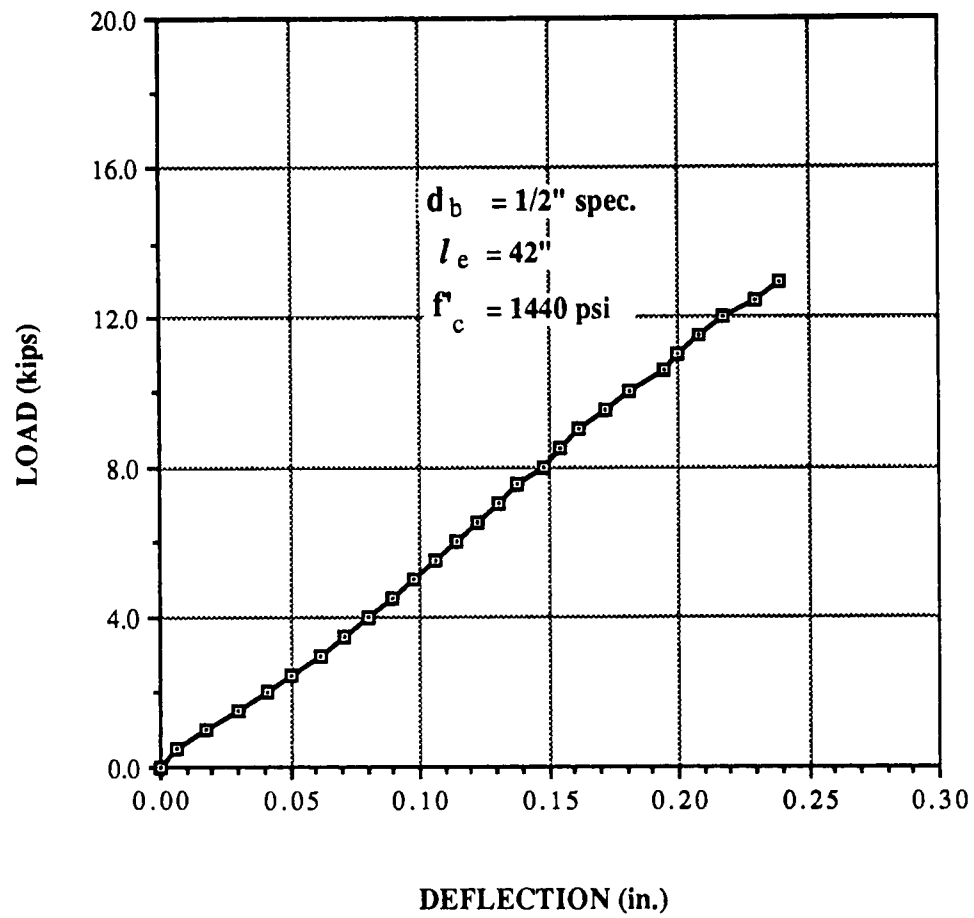


Figure A-16. Load-Deflection Curve for Specimen #22.

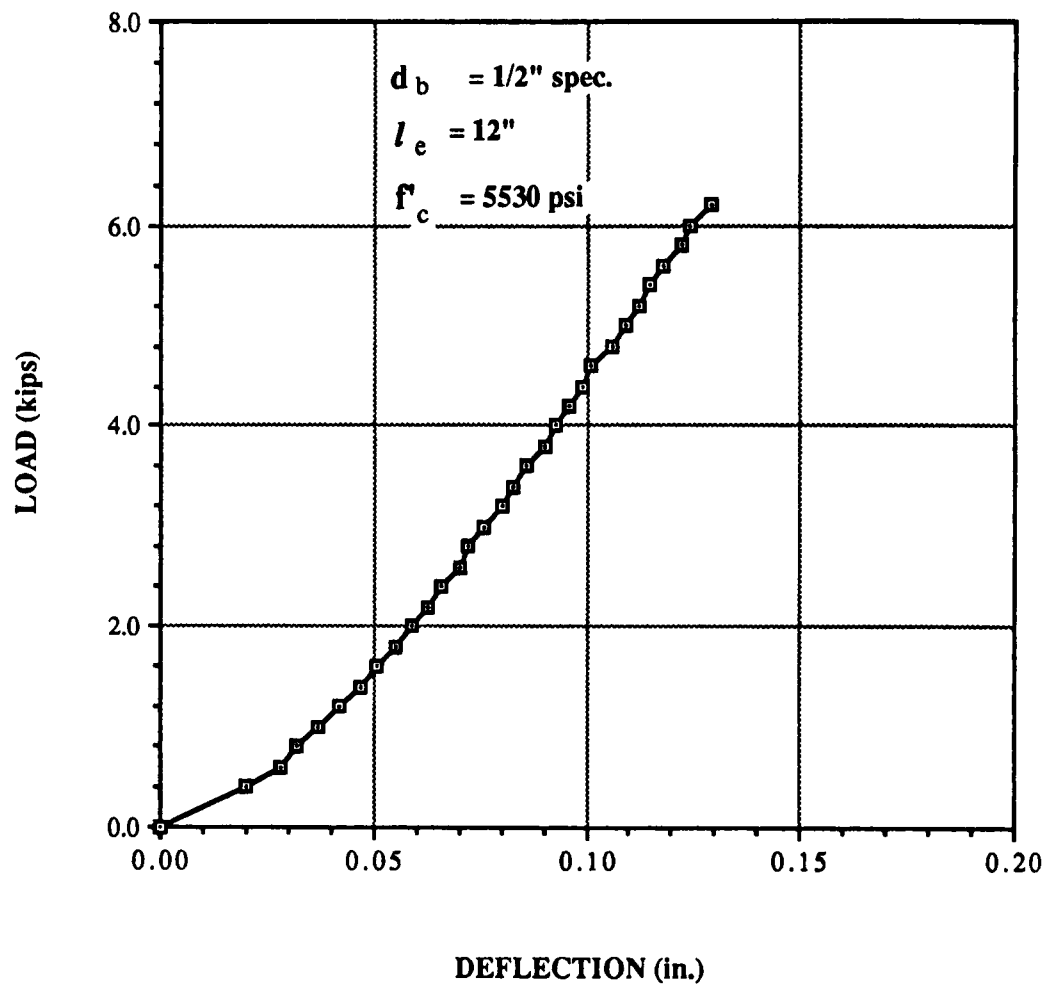


Figure A-17. Load-Deflection Curve for Specimen #24.

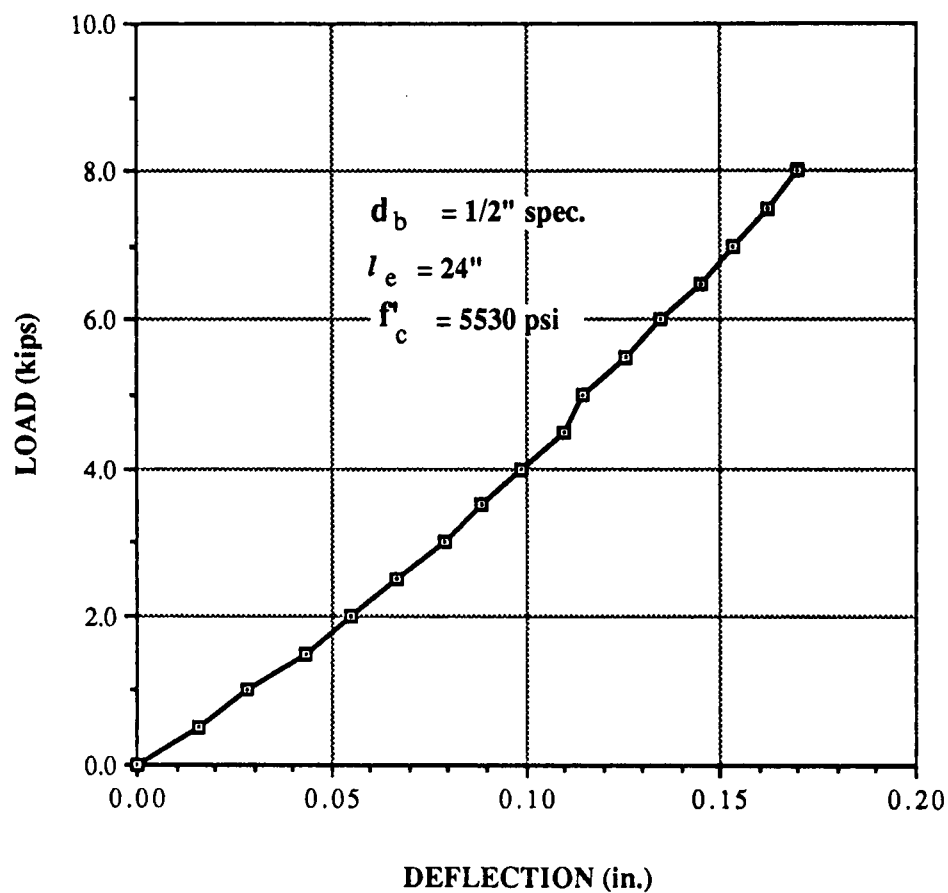


Figure A-18. Load-Deflection Curve for Specimen #25.

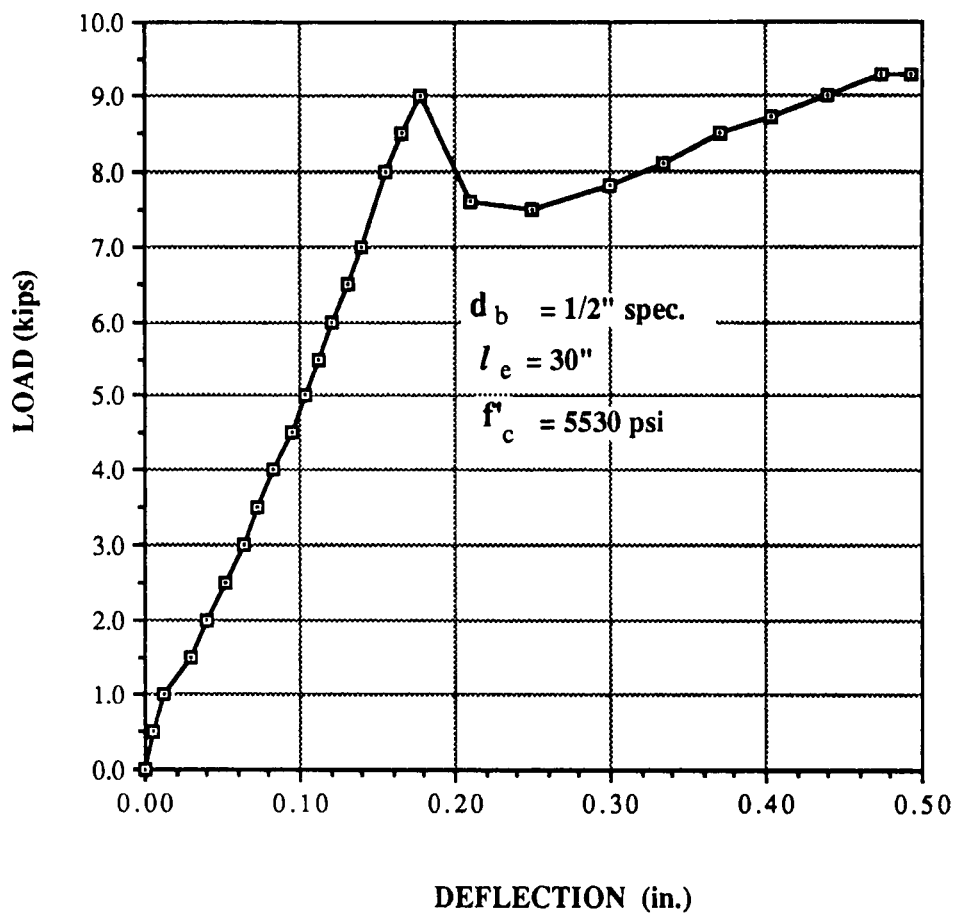


Figure A-19. Load-Deflection Curve for Specimen #26.

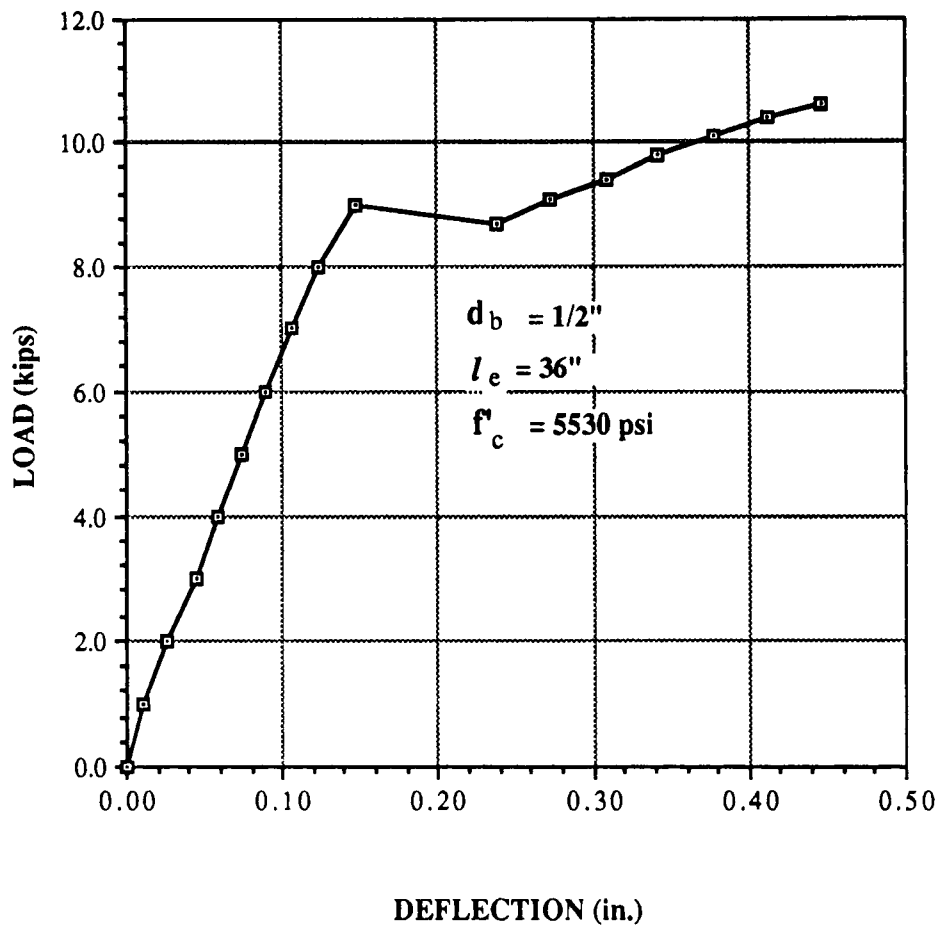


Figure A-20. Load-Deflection Curve for Specimen #27.

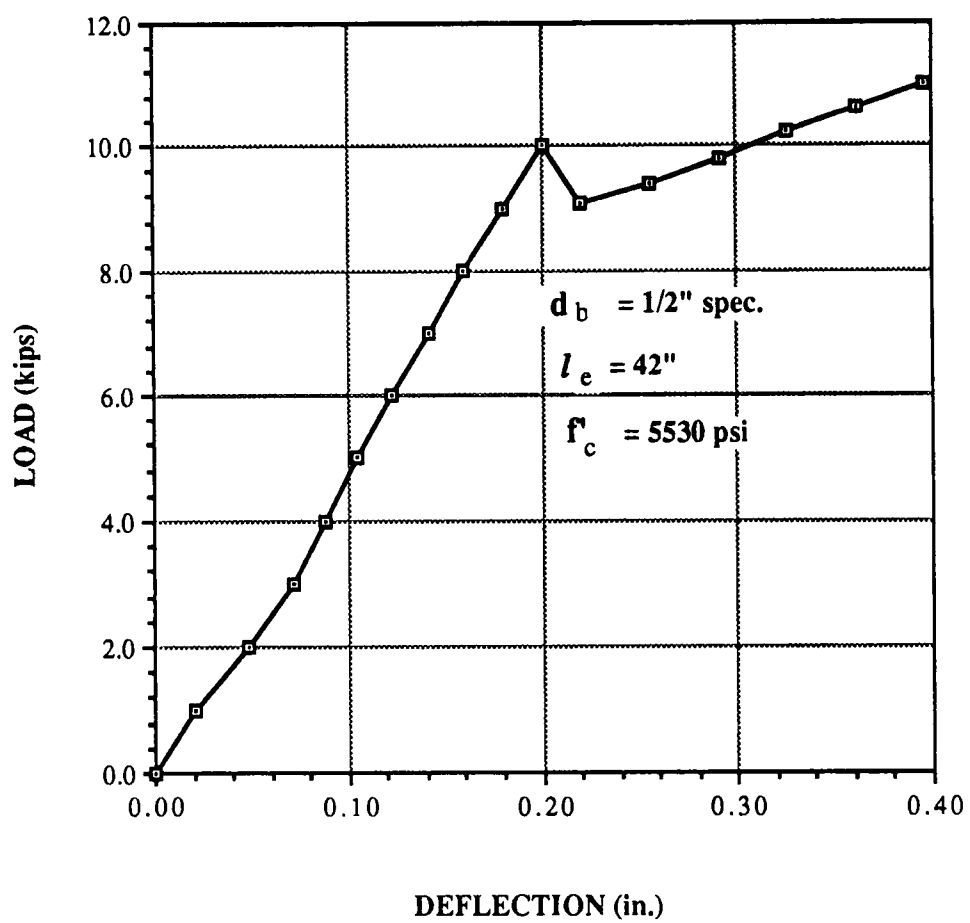


Figure A-21. Load-Deflection Curve for Specimen #28.

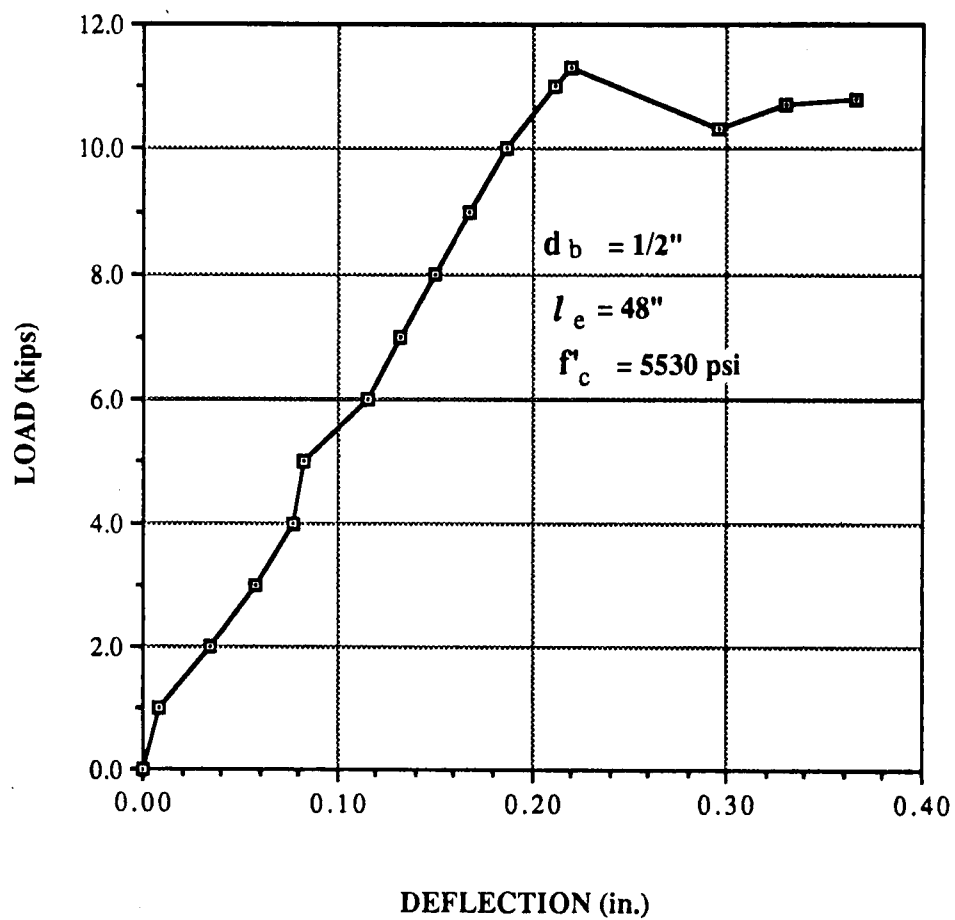


Figure A-22. Load-Deflection Curve for Specimen #29.

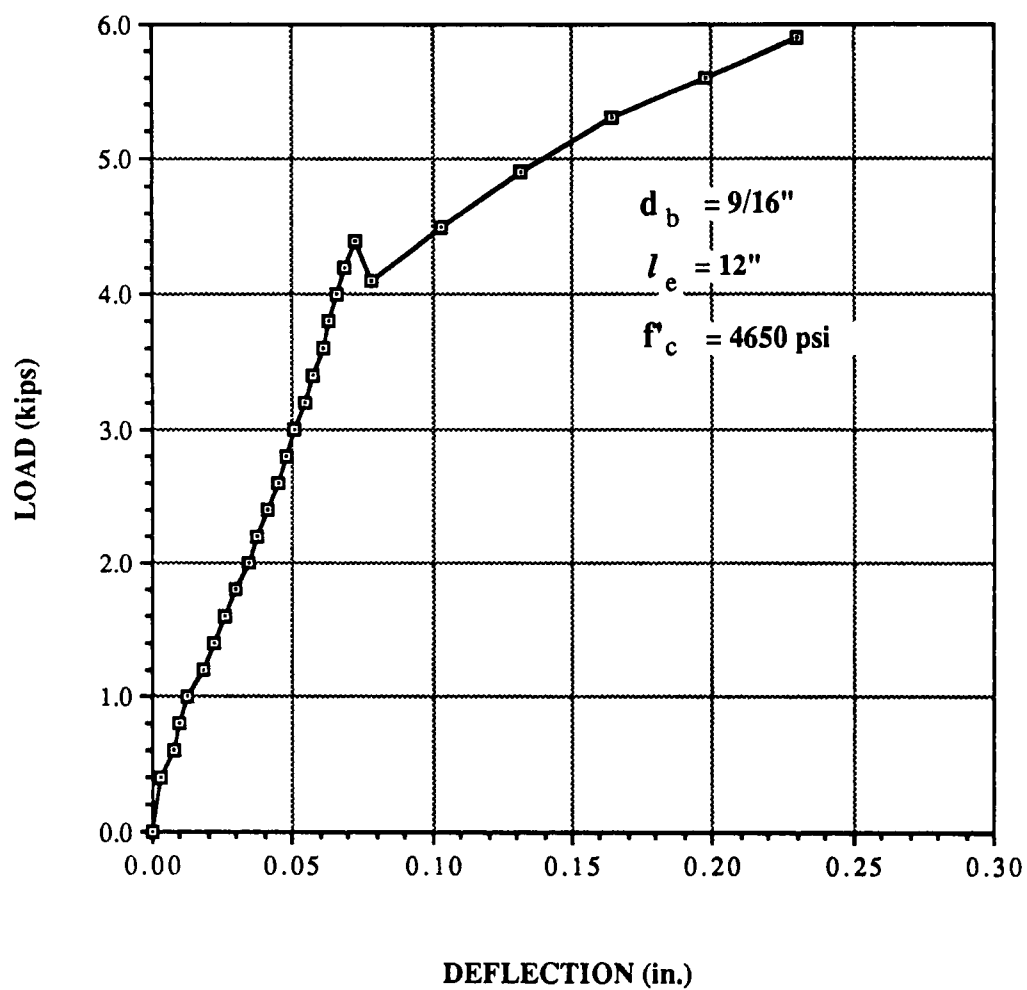


Figure A-23. Load-Deflection Curve for Specimen #30.

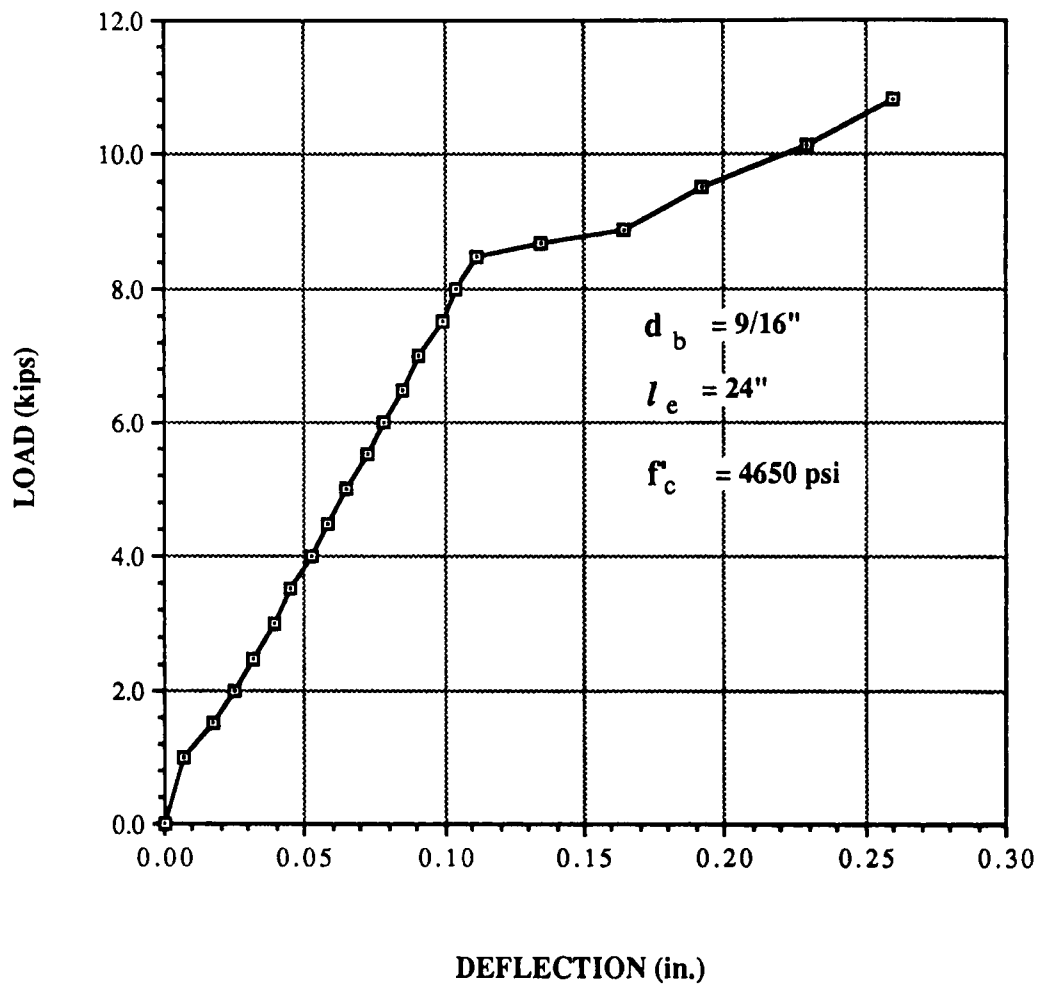


Figure A-24. Load-Deflection Curve for Specimen #31.

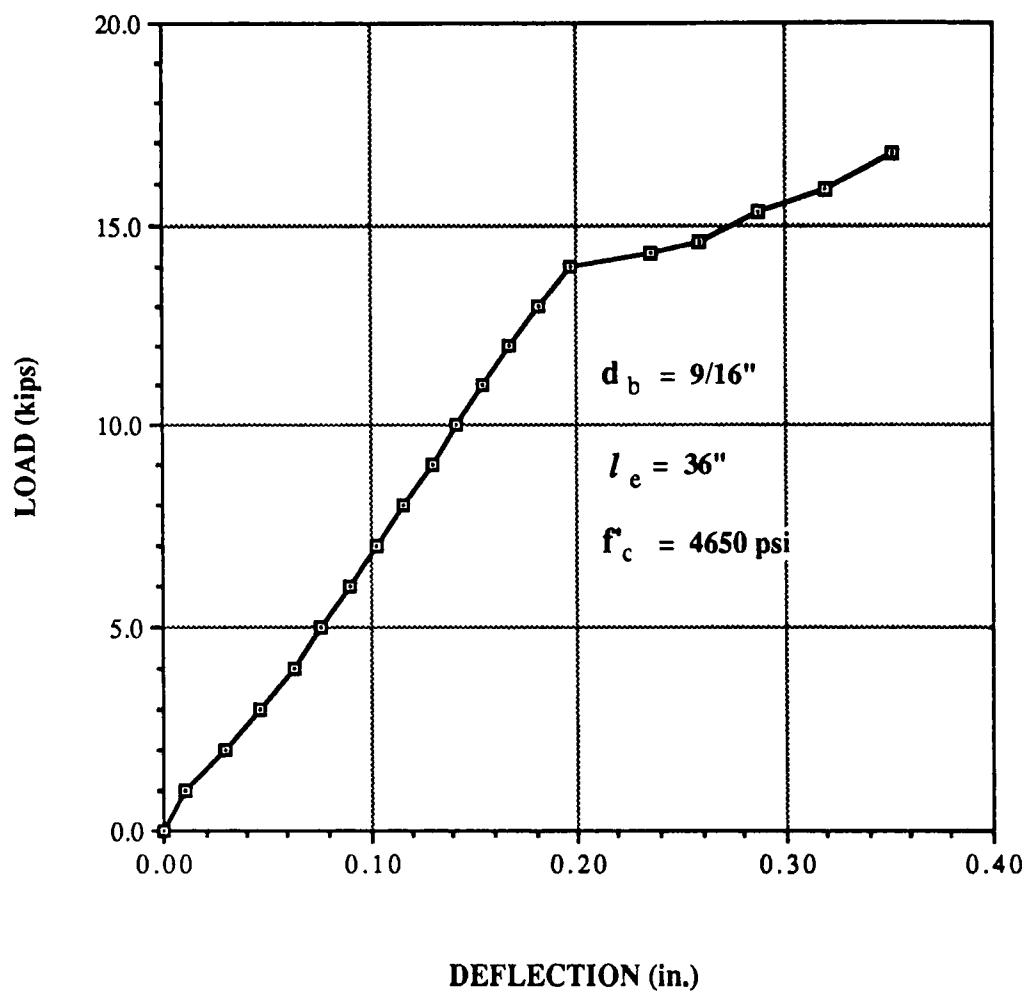


Figure A-25. Load-Deflection Curve for Specimen #32.

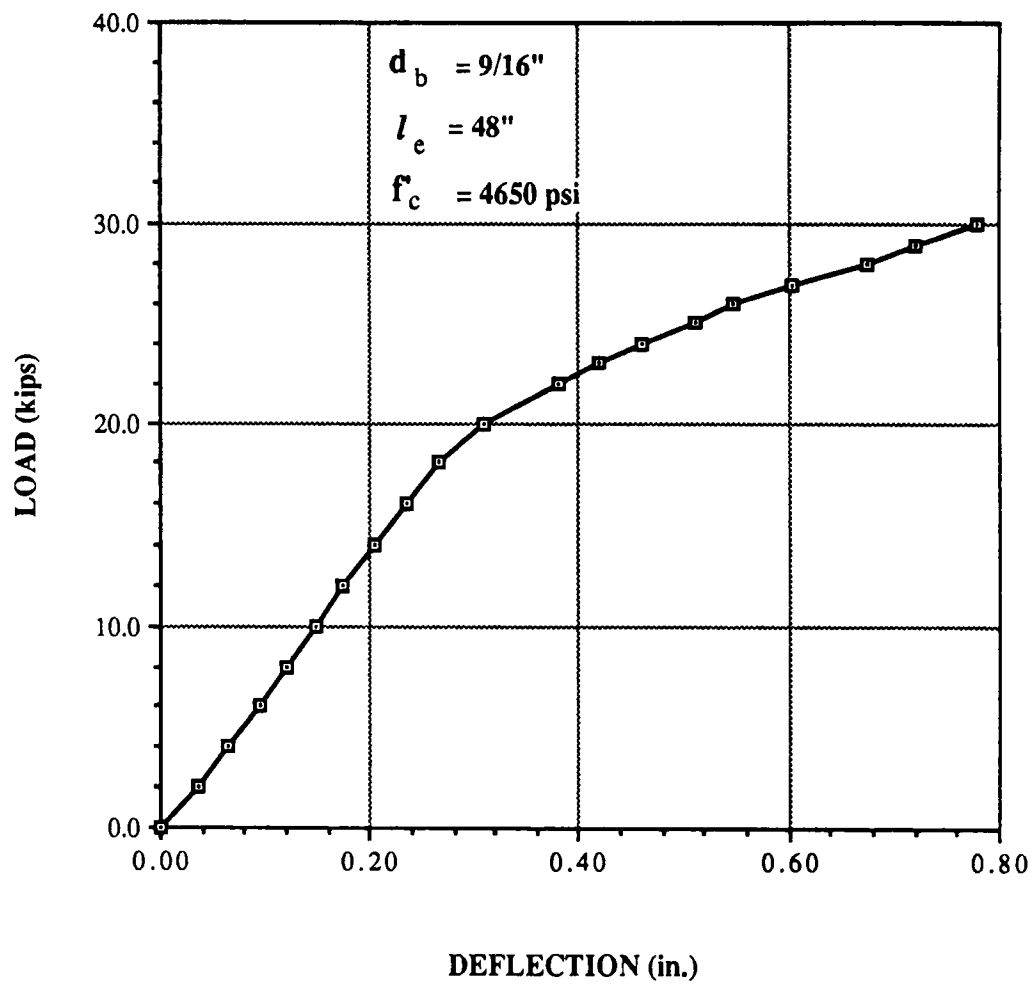


Figure A-26. Load-Deflection Curve for Specimen #33.

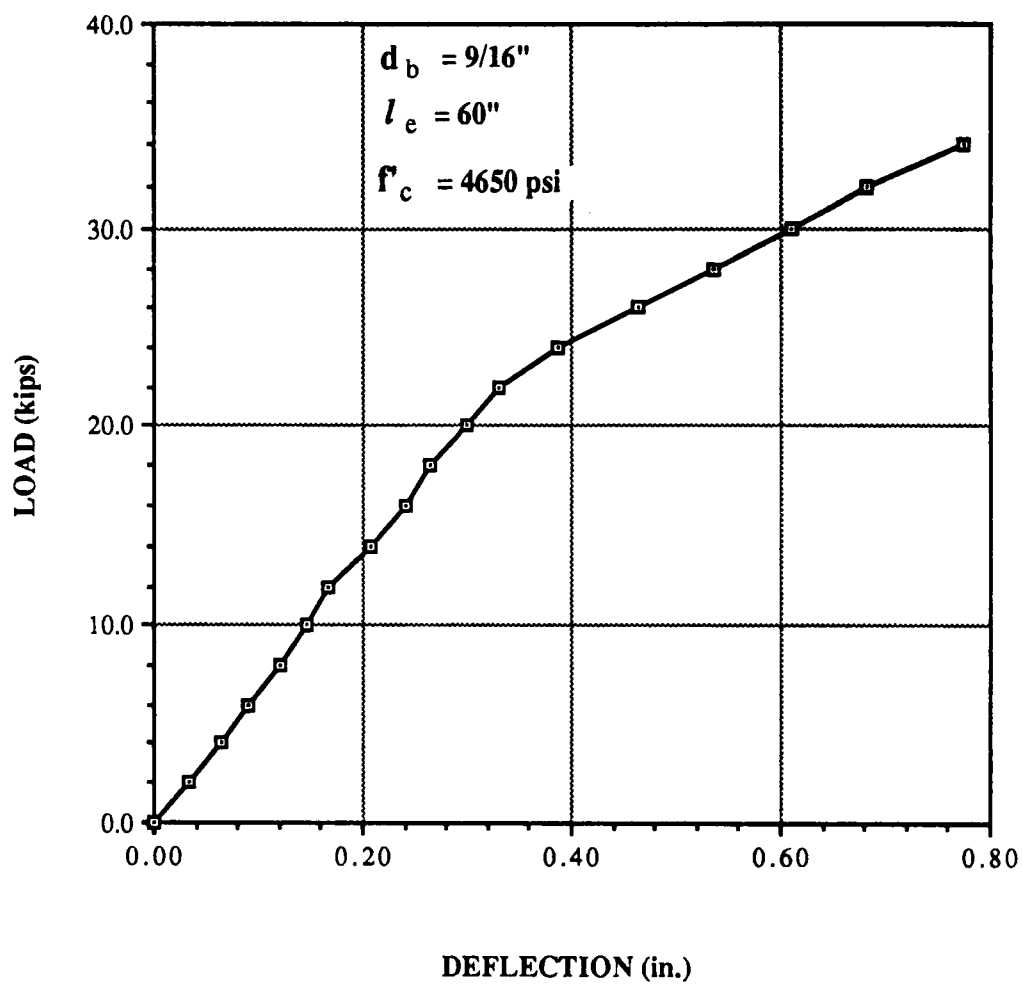


Figure A-27. Load-Deflection Curve for Specimen #34.

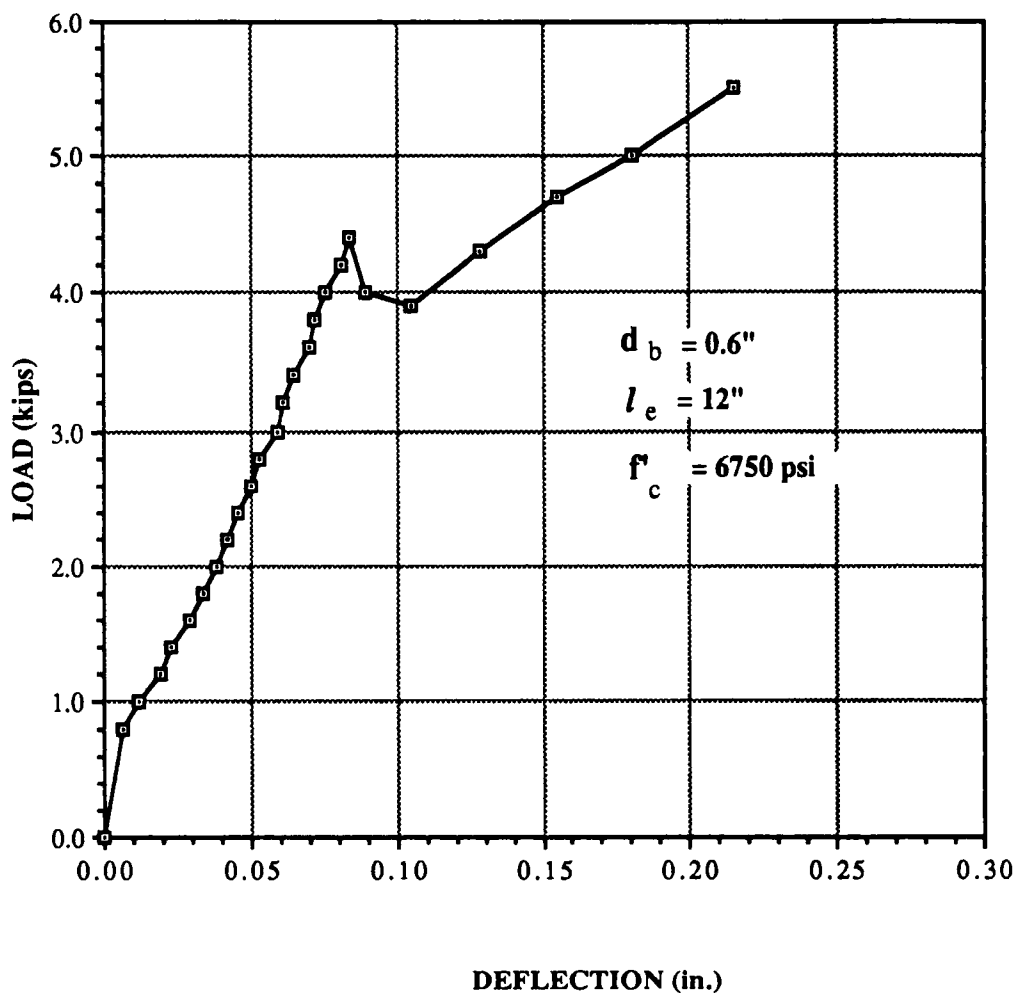


Figure A-28. Load-Deflection Curve for Specimen #35.

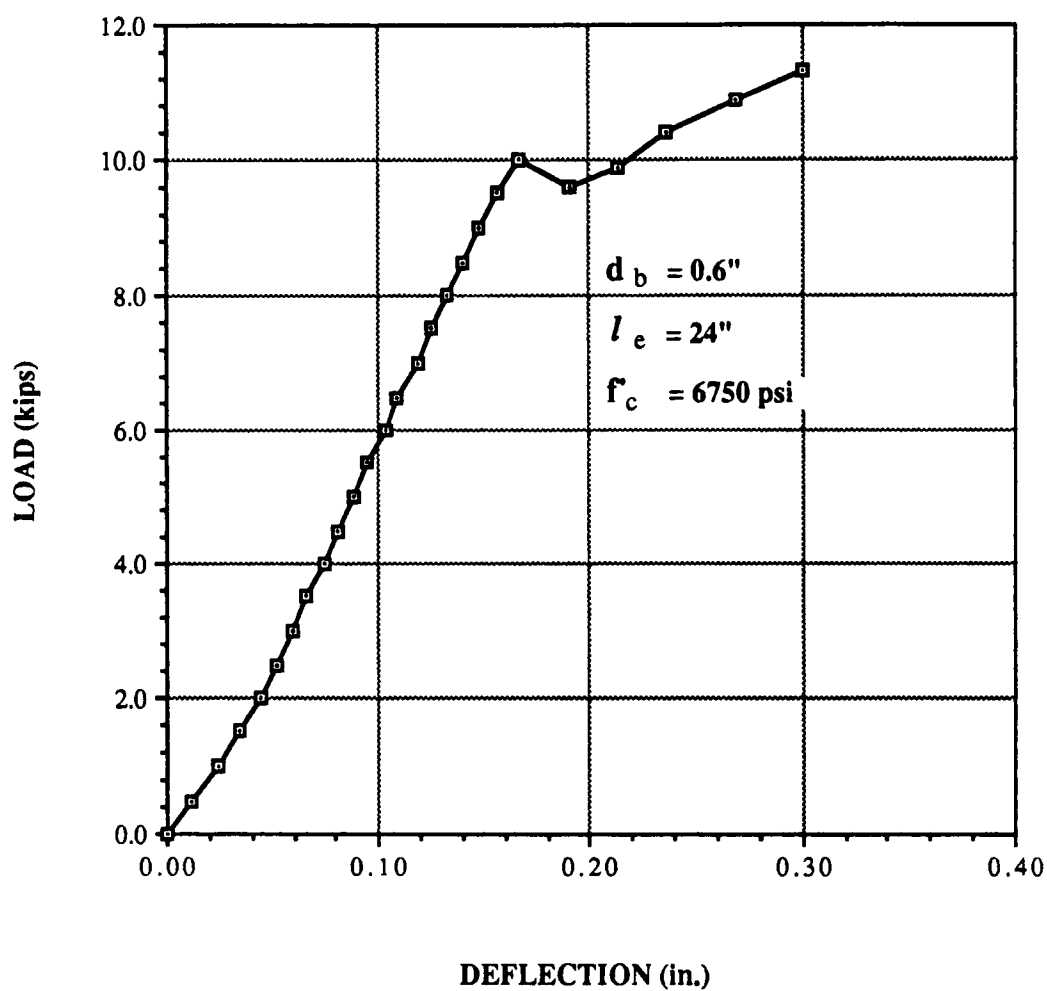


Figure A-29. Load-Deflection Curve for Specimen #36.

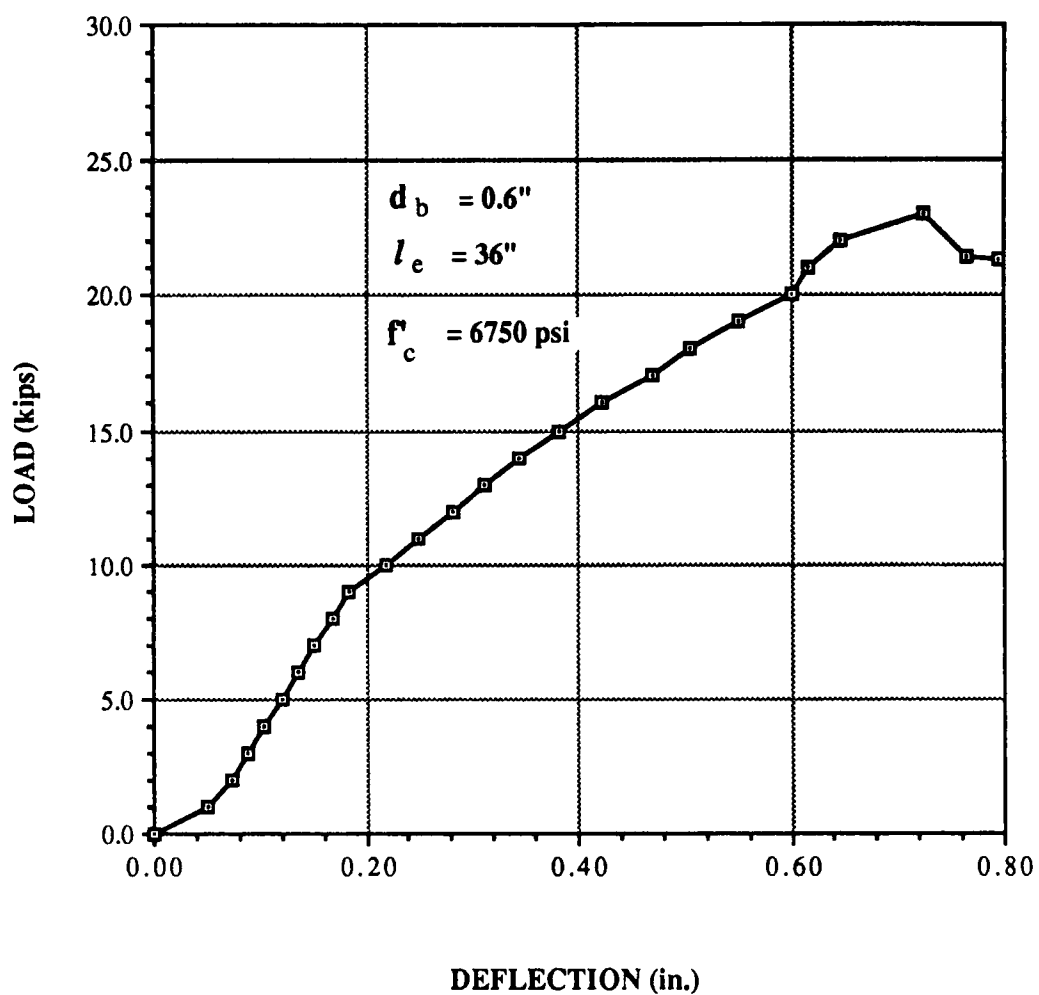


Figure A-30. Load-Deflection Curve for Specimen #37.

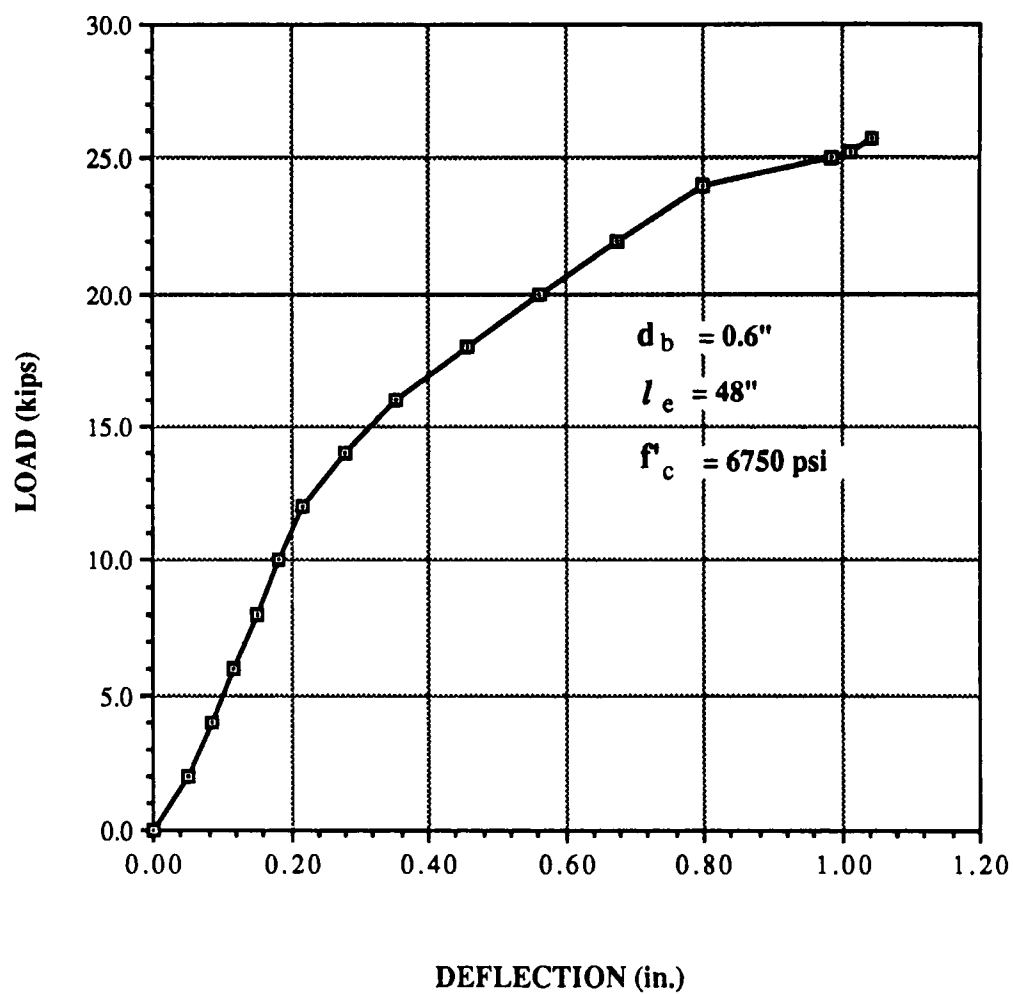


Figure A-31. Load-Deflection Curve for Specimen #38.

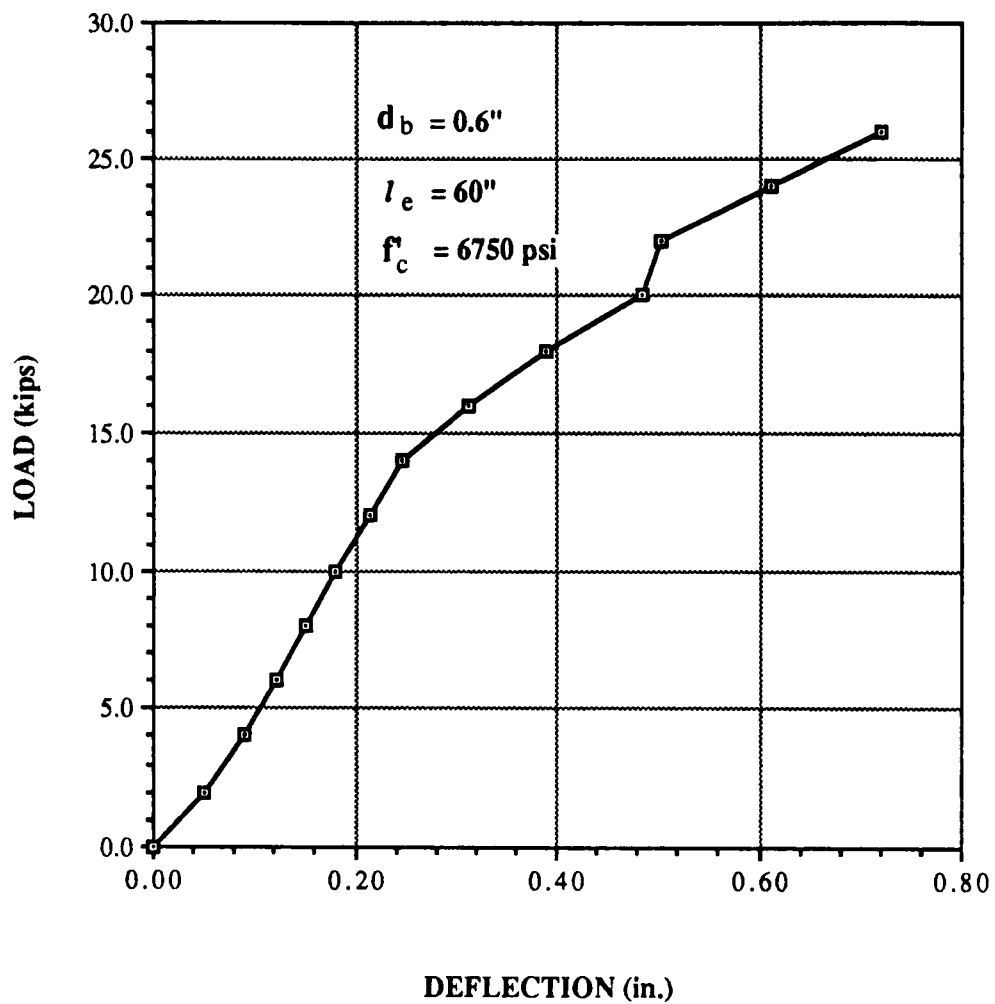


Figure A-32. Load-Deflection Curve for Specimen #39.

APPENDIX B

LOAD VERSUS EMBEDMENT LENGTH CURVES

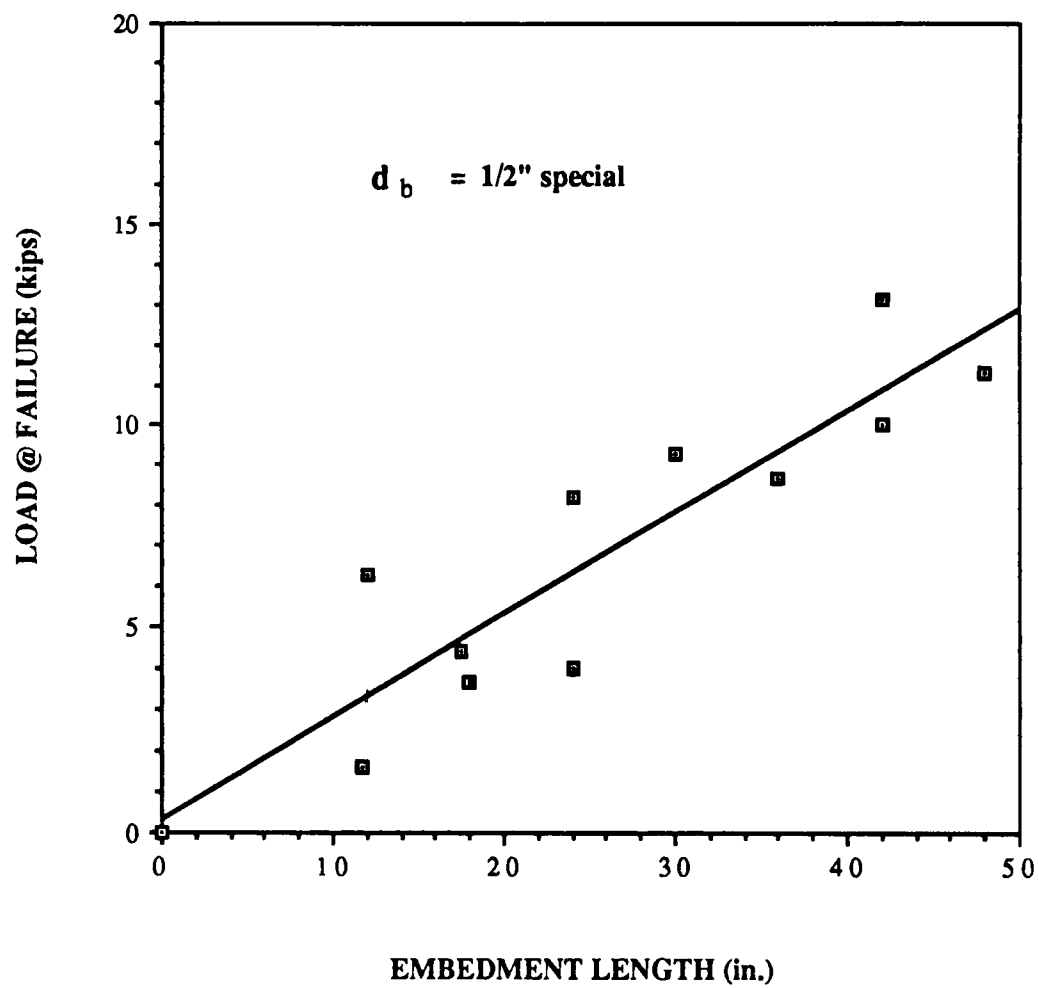


Figure B-1. Load Versus Embedment Length Curve for 1/2" Special Strand.

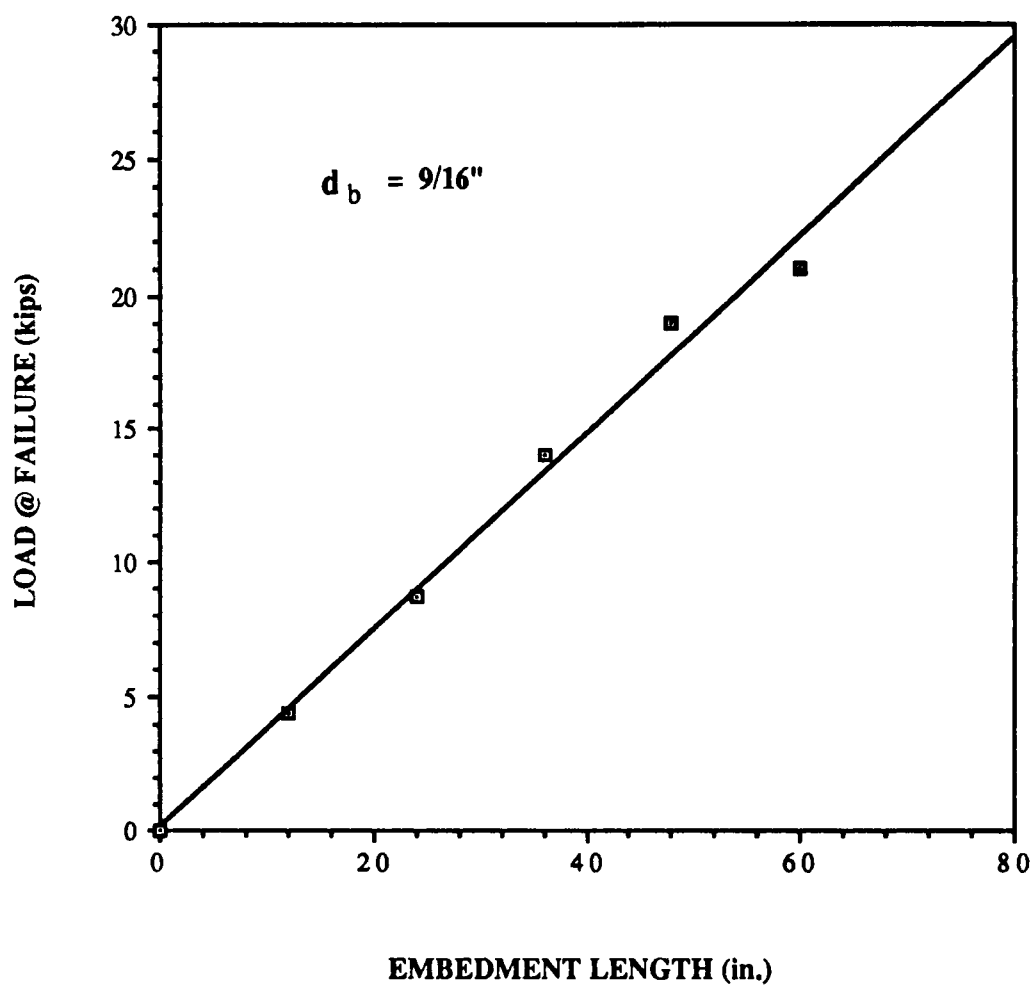


Figure B-2. Load Versus Embedment Length Curve for 9/16" Diameter Strand.

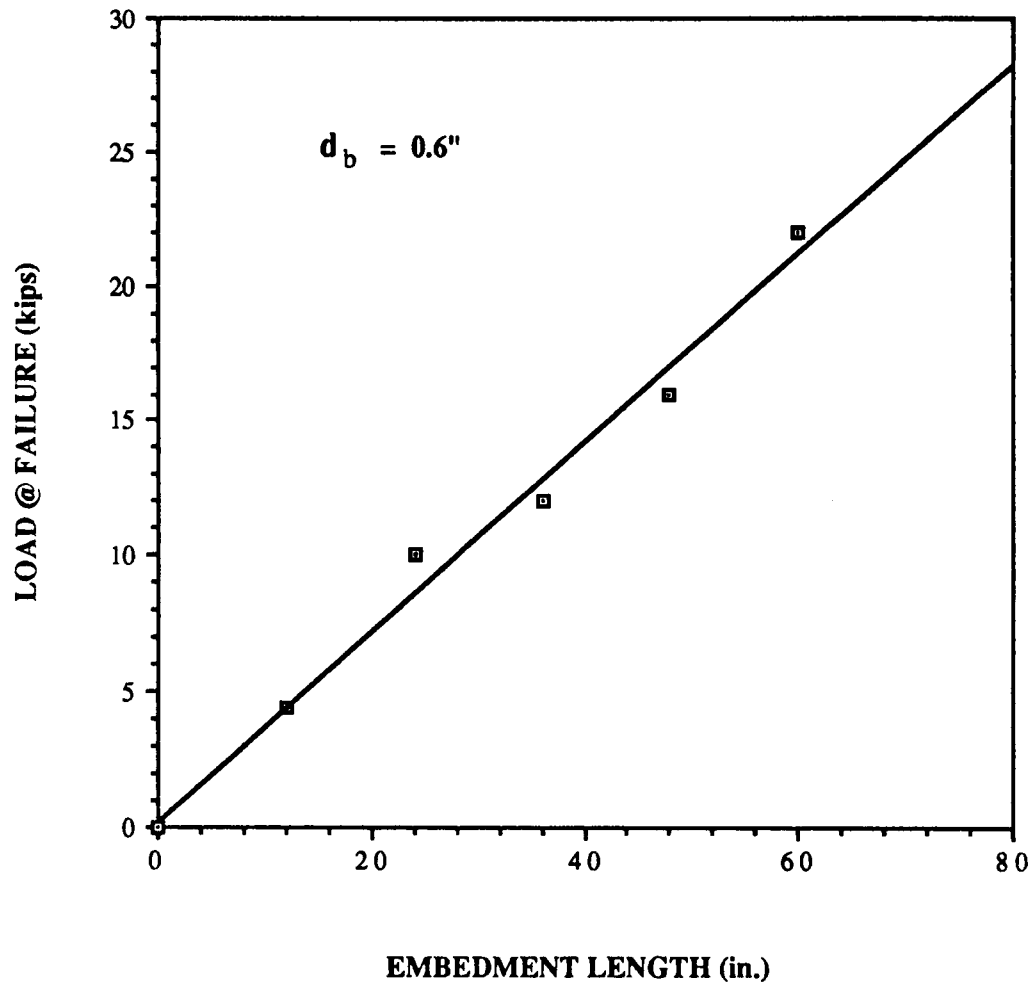


Figure B-3. Load Versus Embedment Length Curve for 0.6" Diameter Strand.

VITA

Ken Louis Griffin was born in Cleveland, Tennessee on February 22, 1965. He attended elementary school in that city and was graduated from Bradley Central High School in May 1983. The following September he entered The University of Tennessee where he received a Bachelor of Science Degree in Civil Engineering in December 1987. He continued his education at The University of Tennessee, and in May 1989, he was granted a Master of Science Degree in Civil Engineering.

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