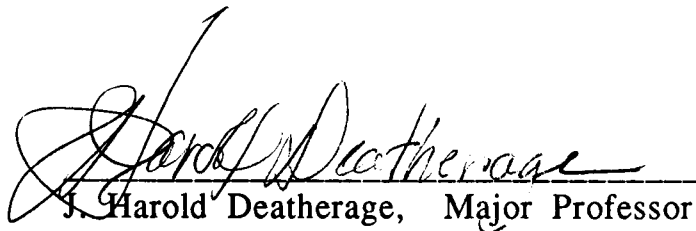
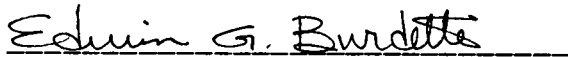


To the Graduate Council:

I am submitting herewith a thesis written by Brian R. Smith entitled "An Investigation of the Variables Affecting the Transfer Length of Prestressed Concrete Members." 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 major in Civil Engineering.


J. Harold Deatherage, Major Professor

We have read this thesis
and recommend its acceptance:


Edwin G. Burdette


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Vice Provost
and Dean of the Graduate School

**AN INVESTIGATION
OF THE
VARIABLES AFFECTING
THE TRANSFER LENGTH OF
PRESTRESSED CONCRETE MEMBERS**

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

Brian R. Smith

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ABSTRACT

The transfer length of pretensioned/prestressed concrete members is a function of several variables. This study is an attempt to establish relationships between these variables and the transfer length. Reviews of the existing studies on transfer and development length are also included.

The influence of strand diameter, strand stress, surface condition of the strand, initial end slip of the strand, concrete strength, and concrete consolidation around the strand was investigated. Relationships were then developed and compared with prediction equations from previous research.

The major contributing factors affecting transfer length were found to be strand diameter, strand stress, and surface condition of the strand.

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LIST OF SYMBOLS

SYMBOL	DESCRIPTION
A_s	Area of tensile steel (in^2)
B	Bond modulus (psi/in)
C_b	Distance from bottom of member to neutral axis (in)
d_b	Diameter of strand (in)
E	Modulus of elasticity of the strand (psi)
f'_c	Compressive strength of concrete (psi)
f'_{ci}	Compressive strength of concrete at transfer (psi)
f_{ps}	Stress in the strand at nominal strength (ksi)
f_{sb}	Stress in the strand at general bond slip (ksi)
f_{se}	Effective stress in the strand after losses (ksi)
f_{si}	Initial jacking stress (ksi)
f_{su}	Ultimate stress in the strand (ksi)
f_u	Ultimate stress in the strand (ksi)
I	Moment of inertia (in^4)
L_b	Flexural bond length (in)
L_d	Development length (in)
L_p	Distance from maximum stress to free end (in)

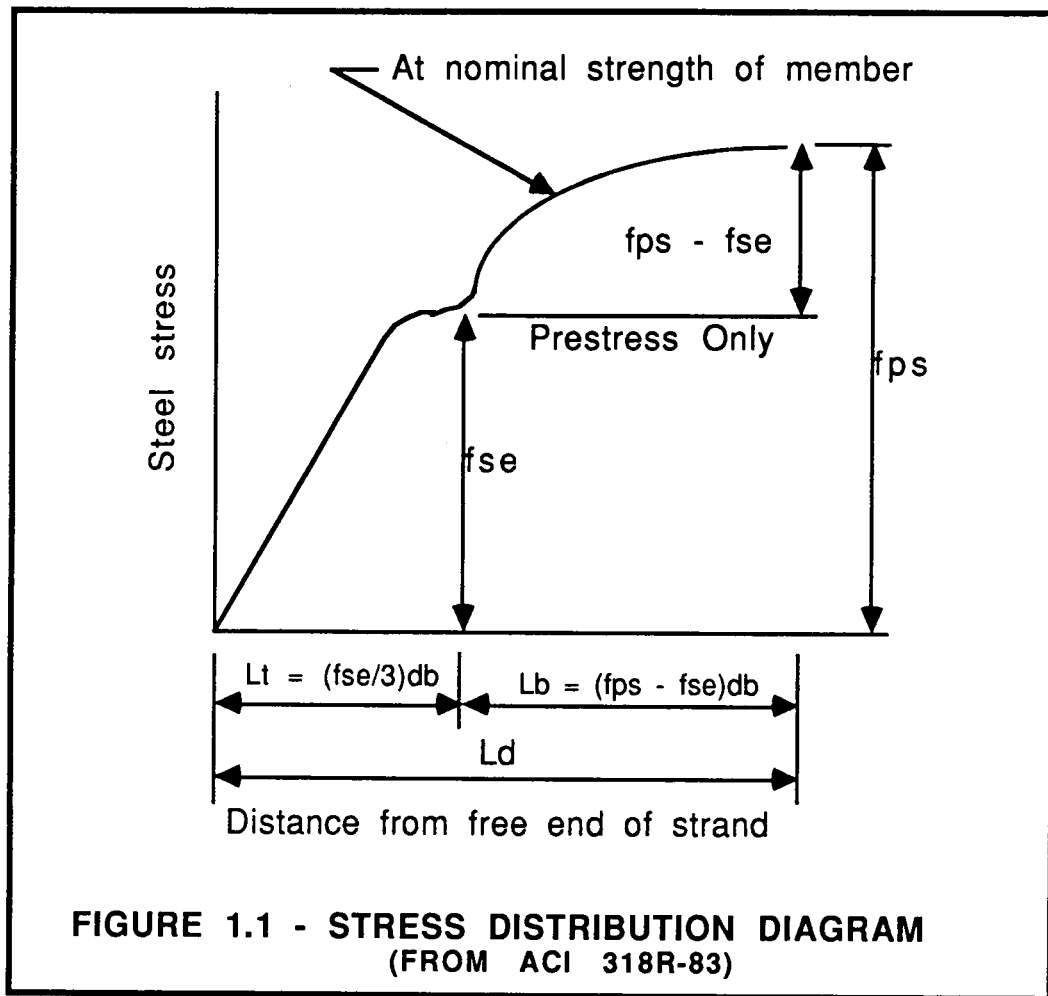
L_t	Transfer length (in)
L_x	Distance from end of beam to point of consideration (in)
M_n	Nominal moment capacity (kft)
U_a	Average bond stress over embedment length (ksi)
U'_d	Average bond stress over the flexural bond length (psi)
U'_t	Plastic transfer bond stress (psi)
Δ	measured initial strand slip (in)
Δ_{ct}	proposed limiting measured amount of slip (in)
Σ_p	Total circumferential area per inch of length of beam (in ²)

Chapter I

Introduction

Prestressed concrete products have been in use in this country for over 40 years. Most commonly these prestressed members are used for highway bridge construction. Maintaining a desired stress level in the prestressing steel is vital to the performance of a member during its lifetime. In order to achieve and maintain the desired stress level in the steel and concrete there must be sufficient transfer and development lengths for the strand. Transfer length is defined as the distance over which the stress in a pretensioned tendon is transferred to the concrete. Development length is the distance from each end of a member that is required to develop nominal moment capacity (M_n). Figure 1.1 illustrates this relationship.

The current ACI and AASHTO code provisions for transfer and development lengths are based on the research of Hanson and Kaar (9) in 1959. Since its inclusion in the 1963 ACI code, several studies of bond between prestressing strand and concrete have not agreed with the current code. The most recent study by Cousins, Johnston, and Zia (5) concluded that the current ACI and AASHTO provisions for development length may be unconservative. This led the Federal Highway Administration to impose restrictions on development length, banning .6" diameter strand and imposing



more stringent strand spacing requirements.

These limitations hurt the prestressing industry because producers and designers of prestressed members desire to use large diameter strand to extend the allowable spans and moment capacities to compete with steel framing systems, and subsequently obtain a larger portion of the market. In order for prestressed manufacturers to provide a product which is economical, they have developed a production cycle of approximately twenty four hours. A typical production cycle is as follows:

- 1) The casting bed is cleaned and oiled;
- 2) Prestressing strands are pulled and bulkheads are placed;
- 3) Forms and shear reinforcement are placed;
- 4) Concrete is placed;
- 5) The concrete is steam cured;
- 6) Prestressing strands are cut and forms are removed;
- 7) The member is removed from the bed and stored until shipment to the job site.

The objective of this study is to investigate the effects of certain variables on transfer length. These variables include strand diameter, strand stress, surface condition of the strand, initial end slip of the strand, concrete strength, and consolidation of the concrete around the strand. Also included is a review of related research, a development of a theoretical stress distribution model, and a comparison of measured results to code and prediction equations.

Chapter II

Literature Review

Considerable research on the bond between pretensioned steel and concrete in prestressed concrete products has been reported since 1950. Jack R. Janney (11) was one of the earliest pioneers to research physical characteristics of bond between pretensioned steel and concrete and its relationship to the transfer and development lengths of prestressed products. In 1963 the American Concrete Institute (ACI) first provided an equation for minimum development length based on the research of Hanson and Kaar in 1959. This equation although controversial, is still used today by the ACI and the American Association of State Highway Transportation Officials (AASHTO).

Subsequent investigators have performed many tests on pretensioned concrete products and have formulated theories for transfer length based on different concepts of bond between concrete and steel. With a wide diversification of theories and results, the current provisions for transfer and development length have been a source of great controversy since its adoption into the 1963 ACI code. This review will summarize the major theories developed by the investigators, their test programs, results, and conclusions.

In his research during the early 1950's, J.R. Janney concluded that there are three factors that may effect bond between the prestressing steel and the surrounding concrete:

- 1) Adhesion between the concrete and steel;
- 2) Friction between the concrete and steel; and
- 3) Mechanical resistance, ie. deformations in the prestressing tendons.

Since adhesion between the concrete and steel can only be present if the prestressing steel does not slip, Janney explained that friction and mechanical interlock must be responsible for the transfer of the stress to the concrete because of a finite amount of slip at the ends of the beam.

Janney also concluded that friction is probably most responsible for transfer due to the normal forces created by the swelling of the the wire in the end regions of the beam at transfer of the prestress. This swelling is caused by Poisson's effect due to the loss in stress in the wire and is known as the "Hoyer Effect". He concluded that the normal forces in the concrete due to swelling of the wire were well beyond the elastic tensile range of the concrete, and therefore, an elastic analysis was not applicable. After comparing observed stress distributions with theoretical stress distributions, Janney concluded that the two were very similar in distribution but not magnitude. This led him to believe his assumptions on frictional bond seemed reasonable.

Janney used two types of tests to investigate bond characteristics between concrete and pretensioned steel. First, tests were performed to determine the distribution of prestress on prisms 2" x 2" in cross section and between 72" and 96" long. Each prism contained a single prestressing wire or strand. Table 2.1 summarizes the tendon sizes and surface conditions tested.

Table 2.1 - Test Specimens: Janney; 1959			
Wire	Surface Condition		
Diameter	Clean	Lubricated	Rusted
(in)			
0.1	X	X	X
0.162	X	X	
0.197	X	X	
0.276	X	X	
5/16" Strand	X	X	

In the second test, short beams were loaded at midspan to obtain stresses. The strain in the steel and concrete were monitored along the length of the beam. Several variables were also considered including different strand sizes, surface conditions, and pretensioned force. From these tests Janney made the following conclusions:

- 1) Larger prestressing diameter will slightly increase the transfer length (in);
- 2) Quality of the concrete mixture influences the ability of the concrete to tolerate the radial pressure exerted on it by the swelling of the wire;
- 3) Rusted wire develops the full prestress transfer at a more rapid rate and in a shorter distance; and
- 4) A bond failure was threatened if the flexural bond stress reaches the transfer zone.

In 1962, Janney (12) also conducted tests on transfer characteristics of 270 ksi seven wire prestressing strands. Tests were performed to determine the stress transfer relationship of the 270 ksi strand and compare the results to the stress transfer relationship obtained for the more conventional 250 ksi strand. The test specimens consisted of concrete prisms 3 1/2" in height, 4 1/4" in width, and 18' 10" in length. Six specimens were cast and tested. Two were prestressed with 1/2" diameter 250 ksi clean and bright strand. Two were prestressed with 1/2" diameter 270 ksi clean and bright strand, and two were prestressed with 1/2" diameter 270 ksi strand which had a medium coat of rust over the surface. The prestress was transferred when the concrete compressive strength reached 4000 psi for all cases. Table 2.2 contains the resulting transfer lengths for the three conditions. From these tests the author concluded that the transfer length is slightly greater for high

Table 2.2 - Transfer Length of Uncoated 1/2" Strand: Janney; 1959				
Ultimate Strength (ksi)	Surface Condition	f _{se} (ksi)	f' _c (psi)	Transfer Length Measured (in)
270	Clean	175.8	4115	33
270	Rusted	175.8	4090	24
250	Clean	150.0	4200	28

strength strand because of the higher initial pretension force. As a result of the satisfactory performance from these tests, Janney also stated that small diameter 270 ksi strand will be satisfactory with respect to stress transfer for all normal applications.

Hanson and Kaar's (9) investigation of development length in 1959 consisted of 47 beams of varying strand diameters and concrete cross sections. Strands of 1/4", 3/8", and 1/2" diameter with an ultimate strength of 250 ksi were stressed to between $.45f_u$ and $.59f_u$ before release. Strand stress was transferred with gradual release to the concrete when the concrete compressive strength reached 4500 psi, except for a few specimens in which stress was transferred when the concrete strength reached 3500 psi. All specimens were loaded to failure in a hydraulic testing machine with beams loaded at either midspan or two point loads located symmetrically about midspan. The strands were gaged to measure the change in stress in the strand along the length of the beam

during loading. Dial gages were also used to measure deflection of the beam and strand slip at the ends of the beam.

Two modes of failure were observed. Thirteen beams failed in flexure with no strand slip at the end of the beam. Thirty four beams failed in flexure after general bond slip of the strand was observed. The researchers observed a change of stress in the strand of the beams that failed in bond. Prior to cracking, the strand stress increased only slightly. After cracking, the strand stress increased dramatically in the vicinity of the crack. With a further increase in the load, the stress increase moved as a wave toward the transfer region. When the stress wave reached the transfer region, a general bond slip occurred and the strand stress decreased. Despite general bond slip, mechanical interlock and friction in the development length were enough to maintain a substantial stress in the strand to enable the load to increase further, until a flexural failure occurred. From these tests the development lengths were found to be 60" and 80" for 3/8" and 1/2" diameter strands respectively. The author made the following conclusions:

- 1) A high percentage of steel reduces the chance of bond failure because the steel stress at failure is lower for a higher percentage of steel;
- 2) Reducing the concrete strength reduces the the steel stress at failure, subsequently reducing the bond stress over the development length;

- 3) Lower concrete strength increases the chance of a flexural failure;
- 4) General bond slip occurs when the stress wave reaches the transfer region; and
- 5) Mechanical interlock and friction between seven wire strand and concrete are sufficient to develop additional beam strength after general bond slip.

From these tests, Hanson and Kaar developed an empirical relationship which was adopted into the ACI code in 1963 and the AASHTO code in 1983. The equation appears in section 12.9.1 of the current ACI code in the following form:

$$L_d = (f_{ps} - 2/3 f_{se})d_b \quad (2.1)$$

where: L_d = development length (in)

f_{ps} = stress in prestressed reinforcement at nominal strength (ksi)

f_{se} = effective stress in the prestressed reinforcement (ksi)

d_b = nominal diameter of prestressed reinforcement (in)

Rewriting equation (2.1) we obtain the following:

$$L_d = (f_{se}/3)d_b + (f_{ps} - f_{se})d_b \quad (2.2)$$

In this form the first term, $(f_{se}/3)d_b$, is the transfer length and the second term, $(f_{ps} - f_{se})d_b$, is the flexural bond length.

The authors also derive an equation to account for the the average bond stress from the free end of the beam to a section of maximum stress ($u_a L_p \Sigma_p$). By equating the tensile force in the steel at general bond slip ($f_{sb} A_s$) to the resisting bond force at a section of maximum stress results in the average bond stress along the embedded length of the strand.

$$u_a = f_{sb} A_s / (L_p \Sigma_p) \quad (2.3)$$

where: u_a = average bond stress over the
embedment length

f_{sb} = stress in reinforcement at general bond
slip

A_s = area of tensile reinforcement

L_p = distance from section of maximum steel
stress to free end

Σ_p = total circumferential area per inch of
length of beam

In 1963, Kaar, LaFraugh, and Mass (13) studied the effects of concrete strength at transfer. The main purpose of this investigation was to determine the minimum allowable concrete strength at transfer. It is of economic importance to the fabricator of prestressed concrete products to be able to transfer the prestress as quickly as possible and free his prestressing beds to continue production. The test program included strand diameters of 1/4", 3/8", 1/2", and .6" in members of varying cross section. Five concrete

strengths at transfer were evaluated: 1600, 2500, 3330, 4170, and 5000 psi. The strands ultimate strength ranged from 253 ksi to 275 ksi, while the stress immediately after transfer varied from $.58f_u$ to $.72f_u$. The transfer lengths were determined by plotting the change in the strain in the concrete. Readings were taken at intervals of 1, 3, 7, 14, 28, 56, 90, 180, and 365 days after transfer. Table 2.3 is a partial summary of the results for 3/8", 1/2", and .6" diameter strands with concrete strengths of 4170 and 5000 psi at transfer. All transfer lengths reported were adjusted to reflect a strand tension after transfer of 175 ksi ($.7f_{pu}$). The authors concluded that:

- 1) Concrete strength has little influence on transfer length for strands up to 1/2" diameter;
- 2) Transfer length was reduced with an increase in concrete strength for .6" diameter strand at the cut end, but no relationship could be determined for the dead end;
- 3) The average increase in transfer length over one year was 6%; and
- 4) Transfer length at the cut ends were approximately 20% higher than at the dead ends for 1/2" diameter strand and 30% higher for .6" diameter strand.

**Table 2.3 - Transfer Length of Uncoated Strand:
Kaar, LaFraugh, and Mass; 1963**

Strand Diameter (in)	Concrete Strength (psi)	Type of Release	Transfer Length (in)		
			1 Day	28 Days	365 Days
3/8	4170	Sudden	---	---	---
		Gradual	---	---	---
	5000	Sudden	25.5	26	27.5
		Gradual	20	23	25.5
1/2	4170	Sudden	37	35.5	37.5
		Gradual	34	34	38
	5000	Sudden	41	42	44
		Gradual	34	36.5	37.5
0.6	4170	Sudden	39	38.5	40.5
		Gradual	31.5	32.5	33.5
	5000	Sudden	39.5	40.5	39
		Gradual	28.5	30	32

During 1965, Kaar and Magura (14) studied the effects of strand blanketing on transfer and development lengths. Plastic tubing was placed over the strand in the end regions of the beam to prevent bonding. This results in a longer development length. If the embedment length is inadequate, the ultimate strength will be governed by bond instead of flexure. The authors suggest that the bond slippage occurs in three stages: 1) Slip transfers through cracks due to flexure, 2) General bond slip occurs along the entire embedment length, 3) Mechanical interlock is destroyed. They also confirmed Janney's conclusion that as general bond slip occurs

mechanical interlock between the strand and concrete is enough to maintain some of the stress in the strand. Therefore, the stress in the strand drops only to the level of prestress and not to zero.

That same year Over and Au (17) compared the effects of friction and mechanical interlock of smooth wire and seven wire strand used in pretensioned concrete products. The strand diameters, size of concrete prisms, average maximum prestress, effective prestress, and transfer lengths for each specimen are outlined in Table 2.4. From these results the authors concluded that:

- 1) Transfer length for larger diameter strand is greater than that of smaller strand;
- 2) Multiwire strands will develop additional stresses through mechanical interlock after general slip; and
- 3) Multiwire strand requires less transfer length than single wires of equal stress.

Table 2.4 - Transfer Length of Uncoated 1/2" Diameter Strand: Over and Au (1965)				
Strand Diameter (in)	Concrete Strength (psi)	Size of Prism (in)	fse (ksi)	Transfer Length (in)
1/2	5500	3x3x80	170	35
3/8	4180	3x3x60	160	30
1/4	4900	3x3x60	164	20

In 1975, Kaar, Hanson, Corley, and Hognestad (10) studied the effects of surface condition of 3/8", 270 ksi prestressing strand. Three surface conditions were used: sandblasted, lightly rusted, and smooth. The stress was transferred to the concrete when its compressive strength reached 4000 psi. Both sudden and gradual releases were studied. In their report the authors define transfer length as the distance required for the strain in the concrete to reach 95% of the concrete strain plateau. Table 2.5 summarizes their results. Although there is a large scatter in the results, it appears that the type of release and surface condition significantly affect the transfer length. Sudden release of the smooth strand increased the transfer length by approximately 20%, while the slightly rusted and sandblasted strand decreased the the transfer length by 51% and 36% respectively in comparison with the smooth strand.

Table 2.5 - Transfer Length of 3/8" Uncoated Strand: Kaar, Hanson, Corley, and Hognestad; 1975					
Surface Condition	Type of Release	Number of Tests	Transfer Length (in)		
			Low	Avg.	High
Smooth	Gradual	39	12	23.9	39
Smooth	Sudden	37	17	29.2	54
Slightly Rusted	Sudden	12	9	14.2	23
Sand Blasted	Sudden	15	11	18.6	28

In 1976, A. R. Anderson and R. G. Anderson (1) evaluated the flexural bond performance of 36 pretensioned hollow-core slabs. The test specimens were produced by five different manufacturers. Each slab was 8" in depth with 1/2" diameter 270 ksi strand pretensioned to $.7f_{pu}$. The concrete strength was approximately 5000 psi and the release was sudden by saw-cutting. The authors derived the following relationship between flexural bond performance and free end slip:

$$\Delta_{ct} = f_{si}d_b/950 \quad (2.4)$$

where: Δ_{ct} = proposed limiting measured amount of slip
(in)

f_{si} = initial jacking stress (ksi)

d_b = strand diameter (in)

From their tests the authors concluded that:

- 1) Flexural bond performance is directly related to the amount of free end slip. In twelve of fifteen tests that failed in flexural bond, the first strand to slip was the one with the largest amount of free end slip. Twenty four specimens met or exceeded the ACI code when the measured free end slip was less than that calculated in their prediction equation.
- 2) The primary cause of excessive free end slip and premature flexural bond failure was due to poor consolidation of the concrete around the strands.

In 1977, Zia and Mostafa (23) developed empirical equations for transfer length and flexural bond length, based on an extensive review of the literature and previous research involving development length of prestressed members. The authors used a linear regression analysis of all research completed before 1977 to derive the proposed equation for transfer length, L_t :

$$L_t = [1.5(f_{si}/f_{ci})d_b] - 4.6 \quad (2.5)$$

and flexural bond length, L_b :

$$L_b = 1.25(f_{su} - f_{se})d_b \quad (2.6)$$

where: f_{si} = initial stress in strand before losses (ksi)

f_{ci} = concrete strength at transfer (ksi)

d_b = diameter of prestressing strand (in)

f_{su} = ultimate stress of the prestressing strand (ksi)

f_{se} = effective stress of the strand after losses (ksi)

The equation for the transfer length differs from other equations because it allows for adjustment for different concrete strengths at release, different strand sizes, and different initial prestressing. This equation is comparable to the ACI code equation for small strands, but is more conservative for the larger strands. The flexural bond length equation is based on a reevaluation of Hanson and Kaar's test results from 1959. Zia and Mostafa concluded

that the flexural bond length specified in the ACI code needed to be increased 25%.

In 1979, Martin and Scott (16) proposed a code equation by fitting a bilinear curve to data obtained from Hanson and Kaar's research of 1959.

For $L_x \leq 80d_b$:

$$f_{ps} < L_x/80d_b[(135/d_b^{1/6}) + 31] \quad (2.7)$$

For $L_x \geq 80d_b$:

$$f_{ps} < (135/d_b^{1/6}) + (.39L_x/d_b) \quad (2.8)$$

where: L_x = distance from end of beam to point of consideration (in)

d_b = diameter of strand (in)

f_{ps} = stress in prestressed reinforcement at nominal strength (ksi)

In no case shall f_{ps} be greater than that of equation 18-3 of the ACI 318-83 code. The authors also concluded that the effects due to mechanical interlock should not be considered in design because of its low degree of reliability.

In 1988, Brook, Gerstle, and Logan (2) combined Anderson and Anderson's theory of bilinear transfer stresses with Robert F. Mast's theory of bilinear strand development diagrams to compose the concepts of what the authors refer to as the "Slip Theory". This

theory directly relates bond quality of the concrete to the initial end slip of the strand. Their tests involved 11 hollow-core prestressed slabs 8" deep, 48" wide, with varying lengths up to 27'. The prestressing reinforcement was a combination of 3/8" and 1/2" diameter 270 ksi strand, initially pretensioned to $.6f_u$ and $.7f_u$ respectively. Strand release was by saw-cutting when the concrete strength reached 4000 psi. From the equations of the other investigators, the authors derived the following equations:

For transfer length, L'_t :

$$L'_t = 2\Delta E / f_{si} \quad (2.9)$$

For flexural bond length, L'_b :

$$L'_b = (f_{ps} - f_{se})L'_t / f_{se} \quad (2.10)$$

where:

Δ = measured initial strand slip at ends (in)

E = modulus of elasticity of the strand (psi)

f_{si} = stress in the prestressing reinforcement at transfer (psi)

f_{ps} = stress in the prestressing reinforcement at nominal (psi)

f_{se} = effective stress in prestressing reinforcement after losses (psi)

During the early 1980's, it became evident that prestressing reinforcement needed to be protected from deterioration, especially

in bridge members exposed to salt and de-icers. This led to the development of epoxy coated prestressing strand by Florida Wire and Cable. At first the epoxy coating was smooth, which presented some problems with transfer and development bond. Later, crushed glass was impregnated into the epoxy coating to improve its bonding capabilities.

In 1984, Dorsten, Hunt, and Preston (7) reported their results of transfer lengths of seven pretensioned beams: four with smooth epoxy coating and three with bare strand. The specimens were 3 1/2" wide, 4 1/2" deep, and 8' long. The prestressing reinforcement was 1/2" diameter low relaxation 270 ksi strand tensioned to $.75f_u$. The prestress was transferred when the concrete strength reached 4000 psi. The test results are summarized in Table 2.6. The average transfer length, immediately after release, for uncoated strand was 26.9", while the average transfer length for coated strand was 31.3", an increase of 16%. After 14 months the transfer length for coated strand was 3% less than that of the uncoated strand.

In 1986, Cousins, Johnston, and Zia (5) researched the performance of epoxy coated strands in prestressed members. Their tests included the determination of transfer and development lengths of 60 beams with uncoated, smooth epoxy coated, and glass impregnated epoxy coated strand varying in size from 3/8" to .6"

Table 2.6 - Transfer Length of Coated and Uncoated 1/2" Strand: Dorsten, Hunt, and Preston; 1984				
Strand Type	Type of Release	Number of Tests	Transfer Length (in)	
			Initial	14 Months
Bare	Gradual	4	26.3	33
	Sudden	4	27.5	33.5
Coated	Gradual	3	33.3	35

diameter. The transfer length was determined by measuring the strain in the concrete before and after release, while the development length was determined by a series of static tests. From their results, the authors derived the following equations:

For transfer length, L_t :

$$L_t = (.5U'_t\sqrt{f'_c})/B + f_{se}A_s/(\pi d_b U'_t\sqrt{f'_c}) \quad (2.11)$$

For flexural bond length, L_b :

$$L_b = (f_{ps} - f_{se})(A_s/\pi d_b)/(U'_d\sqrt{f'_c}) \quad (2.12)$$

where:

U'_t = plastic transfer bond stress (psi)

f'_c = compressive strength of concrete (psi)

B = bond modulus (psi/in)

f_{se} = effective prestress in strand after losses (psi)

A_s = area of prestressing strand (in)

d_b = nominal diameter of prestressing strand (in)

U'_d = average bond stress over flexural bond length (psi)

Note that U'_t , B , f_{se} , and U'_d must be determined from experimental results which are given in their report for coated and uncoated 3/8", 1/2", and .6" diameter strands. The authors made the following conclusions:

- 1) Chuck slip for coated strand is considerably greater than that for uncoated strand and may continue to slip up to 24 hours after tensioning;
- 2) The transfer length and development length of glass impregnated epoxy strand were shorter than that of uncoated strand of the same diameter. Epoxy coated strand without glass has virtually no bond to the concrete;
- 3) The glass impregnated epoxy strand had shorter transfer and development lengths than required by the ACI and AASHTO, while the uncoated strands did not meet the code; and
- 4) Measured end slip of the strands could be used to confirm transfer lengths through concrete strain.

Chapter III

Test Program

Description of Specimen

Sixteen type I ASSHTO prestressed concrete I-beams were cast by a local prestress producer for researchers at the University of Tennessee, Knoxville. All beams were 31 feet in length. Figure 3.1 illustrates the cross-sectional properties and dimensions of the specimen. Each end of every beam is identified by its three part designation as illustrated by 5S-1-EXT. The first part refers to the strand diameter where:

5S = 1/2" Special strand, nominal diameter of 0.5224"

5 = 1/2" Regular strand, nominal diameter of 0.5000"

916 = 9/16" strand, nominal diameter of 0.5625"

6 = 6/10" strand, nominal diameter of 0.6000".

The second part refers to which number specimen that individual beam is, and the third part refers to a specific end of each beam. The interior/exterior end of a specimen will be defined later in this chapter under the subheading "Fabrication". The size and number of prestressing strands were varied from beam to beam. Figure 3.2 shows the different strand configurations used, while Table 3.1 summarizes the number of specimens tested for each strand configuration. In addition to the 16 beams, 6 concrete prisms were also cast. Each prism was 12' long and square in cross-section with a

single prestressing strand located concentrically through its cross-section. The cross-sections were varied to obtain a constant strain in the concrete for all specimens. Table 3.2 summarizes the cross-section, strand size, and prestressing force of each prism cast.

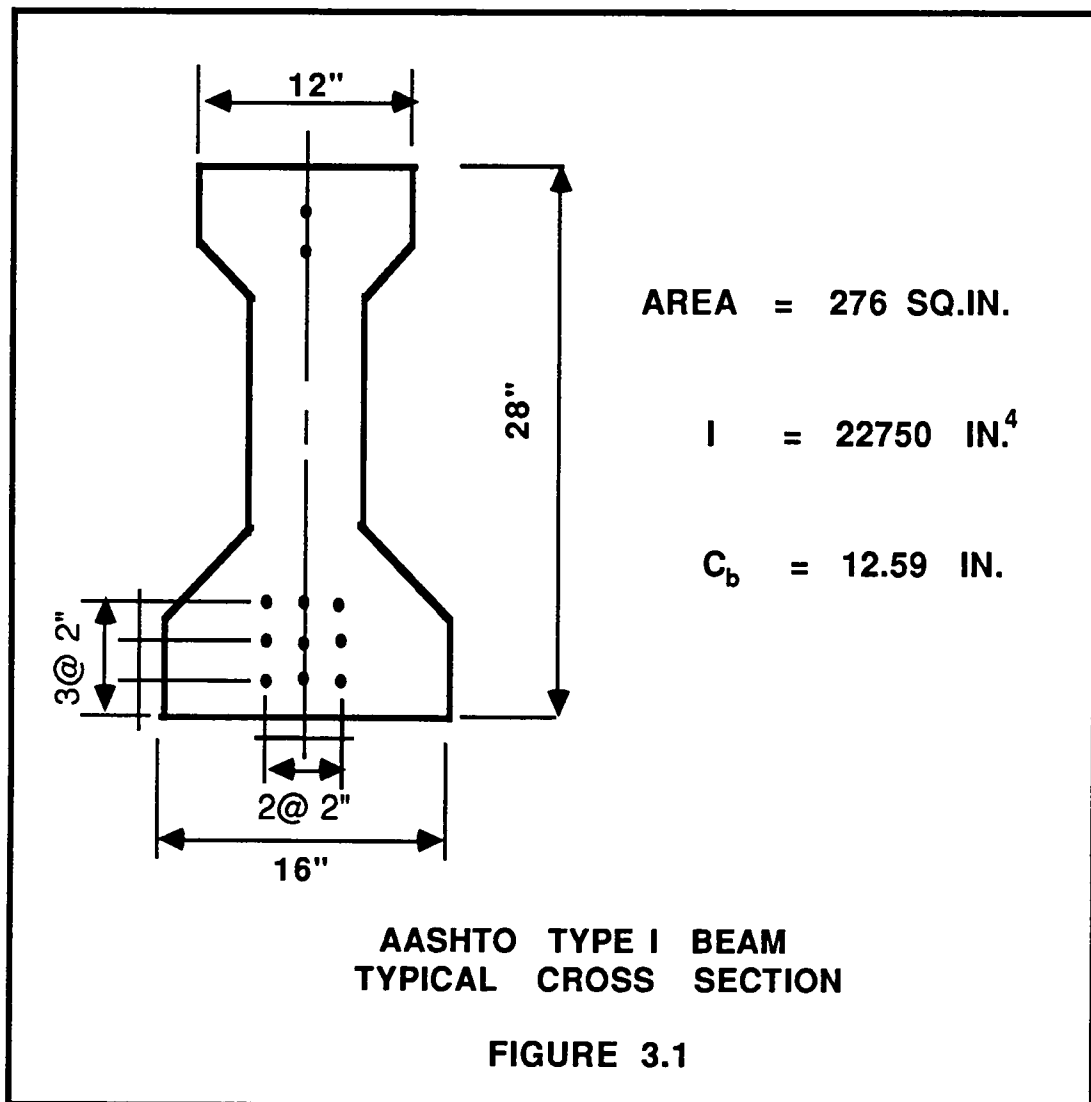


Table 3.1 - Test Specimen Data		
Strand Diameter	Strand Pattern	Number of Specimens
1/2" Reg.	B	8
1/2" Spec.	A	4
	B	4
9/16" FW	B	4
	C	4
6/10" FW	C	8

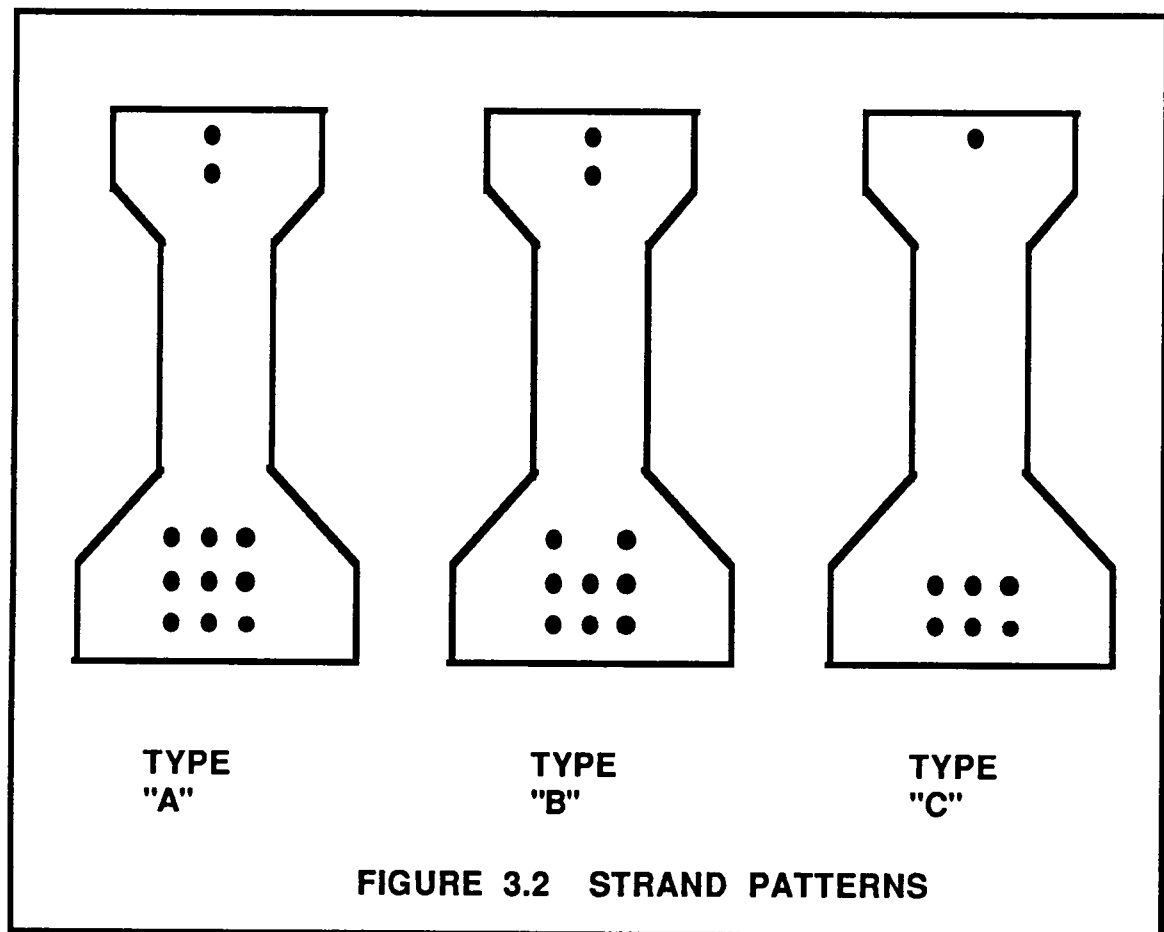


Table 3.2 - Transfer Prism Data		
Strand	f s i	Cross-Section
Diameter	(ksi)	(inches)
1/2" Reg.	175.00	3.5 x 3.5
1/2" Reg.	202.50	3.75 x 3.75
6/10" FW	202.50	4.5 x 4.5

Fabrication of Specimens

The test specimens were fabricated by a local producer for the study. Although minor modifications were made in the production process, an attempt was made to produce the beams in accordance with generally accepted production practices approved by the Precast/Prestress Concrete Institute. Two beams were cast simultaneously, end to end in a 123' long prestressing bed. Figure 3.3 illustrates a plan view of the casting bed and defines the exterior and interior faces of each beam. The fabrication process consists of three stages: stressing the strand, casting the beam, and transferring the prestress force.

Stressing was accomplished with an electronically controlled hydraulic jack at the live end of the bed. To obtain the correct

prestress, the strands were stressed to a predetermined force then checked by comparing the observed elongation to a calculated elongation for the desired prestress in the strand. The measured elongations accounted for losses due to chuck seating and expected relaxation.

After stressing the strands, the rest of the reinforcement was tied and the forms placed around it. The concrete was mixed on-site and was placed directly into the forms with a 3 cubic yard bucket. The concrete was then vibrated to provide good consolidation around the strands. Eight test cylinders were made for each beam and were used to monitor the concrete compressive strength at transfer and during the static testing of each specimen. After placement of the concrete, the casting bed was covered with polyethylene and steam cured for 8 to 14 hours.

The transfer of the prestress force was made when the concrete compressive strength reached a minimum of 4000 psi, except for two cases where the prestress was transferred when the compressive strengths were 3350 and 3750 psi. Transfer of the prestress force was achieved by simultaneously flame cutting the strands at both ends of the beam. Figure 3.3 also outlines the approximate locations of the flame cuts.

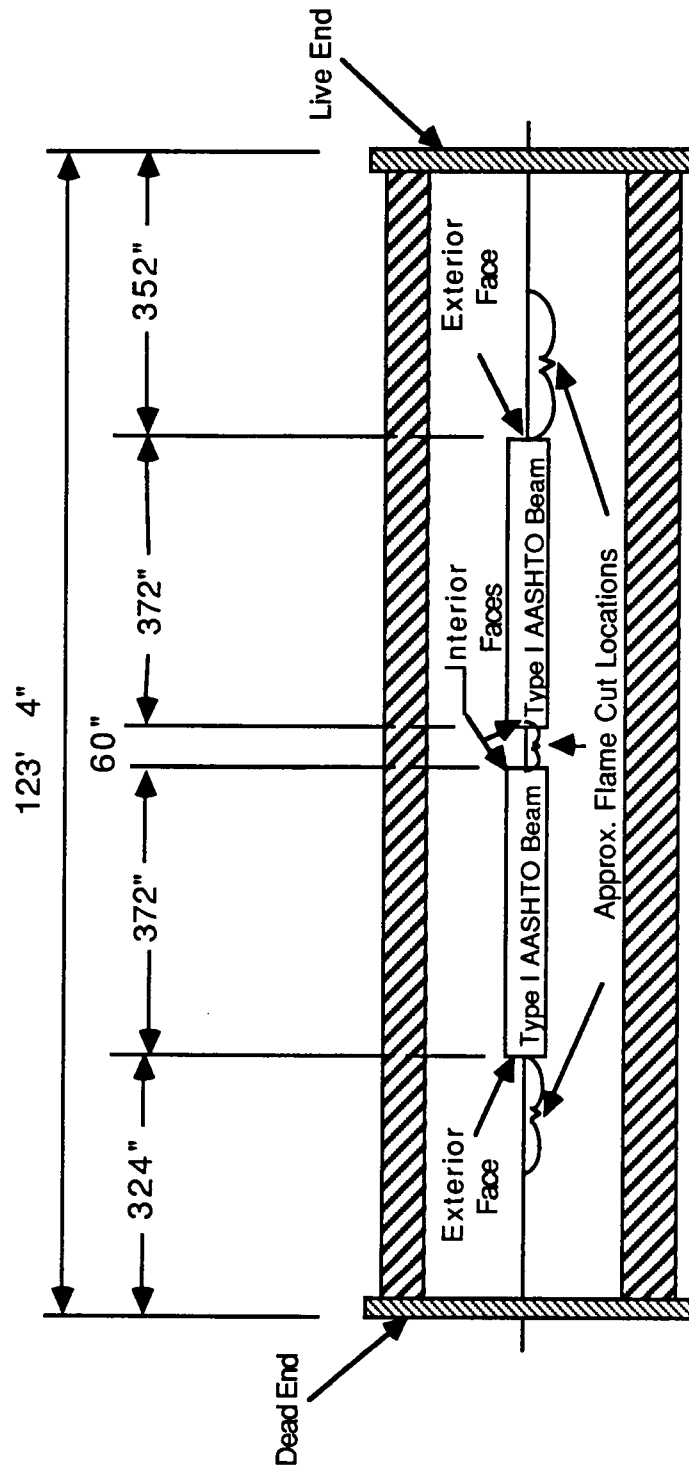


FIGURE 3.3 - PLAN VIEW OF CASTING BED

Materials

All prestressing steel used was seven-wire, low relaxation strand with an ultimate tensile strength of 270 ksi. The four sizes of wire used were 1/2", 1/2" special, 9/16", and .6" diameter strand supplied by Florida Wire and Cable Company.

A Tennessee Department of Transportation concrete mix design for 5000 psi was used. The mix design is shown in table 3.3.

Table 3.3 - Concrete Mix Design	
Quantity	Description
752 lbs.	Type I Cement (Signal Mountain)
1920 lbs.	No. 67 Course Aggregate (American Limestone Company)
1326 lbs.	Fine Aggregate - Manufactured Sand (American Limestone Co.)
21.2 oz.	Low Range Pozzolin 300 (Master Builders)
35 gal.	Water

Instrumentation and Test Procedure

Transfer length measurements were made on both ends of 16 prestressed concrete beams using the following method. After removing the forms, mechanical gage points were affixed to both sides of the beam. Starting from each end of the beam, 15 gage points were equally spaced at 125mm. The gages are located along the neutral axis and the center of gravity of the steel (see figure 3.4). Initial readings of the length between gage points were measured using a Mayes Mechanical Strain Indicator (accurate to .002mm). Immediately after detensioning of the strands, a second set of readings were taken. The change from precut to postcut length was calculated and averaged with corresponding points on the opposite side of the beam. This data is then converted to strain. The concrete strains were then plotted vs distance from the end of the beam. The transfer length is defined as the distance from the end of the beam at which the strain becomes essentially constant (see appendix).

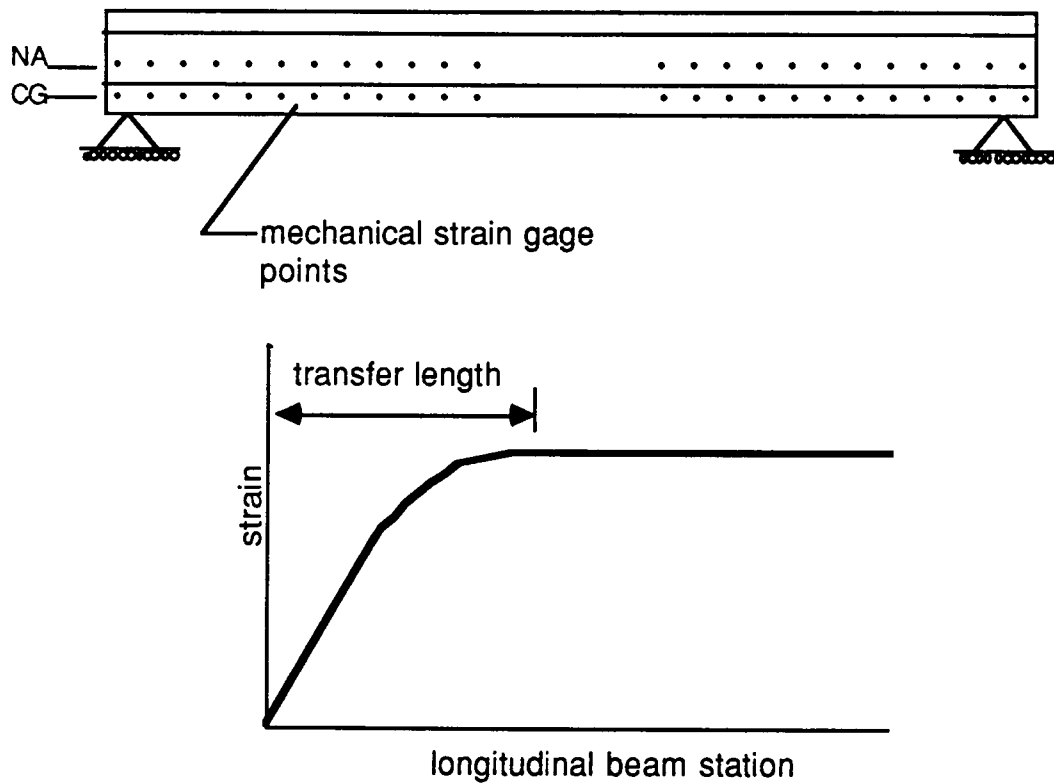


FIGURE 3.4 - TRANSFER LENGTH MEASUREMENT

Chapter IV

Discussion of Results

Results

The transfer lengths of both ends of 16 beams are listed in Table 4.1. The table also summarizes the strand size, strand condition, total area of tensile steel, and concrete strength at transfer associated with each specimen. A typical plot of concrete strain versus distance from the end of the beam is presented in Figure 4.1, while plots for all specimens can be found in the appendix. There are two curves plotted on each figure. Each curve represents the average of data determined from both sides of an end of a beam. The curve with the larger strains relates to data from the center of gravity of the tensile steel, while the curve with the smaller strains relates to data from the neutral axis. The variations between the curve and the actual data points is due primarily to the nonhomogeneous concrete and the inaccuracy of the measuring device. The transfer length is defined as the minimum distance from the end of the beam to the point where both curves respectively reach constant strains. The selection of the exact point where full transfer of the prestress has occurred is somewhat arbitrary. Thus, some variation in the measured transfer length may occur as a result of different interpretations of the data.

Table 4.1 - Transfer Data Summary

BEAM NUMBER	END	STRAND SIZE	STRAND CONDITION	db (IN.)	AREA OF STRAND	AREA OF STEEL	f'c (PSI)	MEASURED L1 (in)	MEASURED L1 (db)
5-1	EXT	1/2" R FW	MILLED	0.5	0.153	1.224	4000	44.00	88
5-1	INT	1/2" R FW	MILLED	0.5	0.153	1.224	4000	44.00	88
5-2	EXT	1/2" R FW	MILLED	0.5	0.153	1.224	4000	44.00	88
5-2	INT	1/2" R FW	MILLED	0.5	0.153	1.224	4000	39.00	78
5-3	EXT	1/2" R FW	W-1DAY	0.5	0.153	1.224	4775	34.00	68
5-3	INT	1/2" R FW	W-1DAY	0.5	0.153	1.224	4775	34.00	68
5-4	EXT	1/2" R FW	W-1DAY	0.5	0.153	1.224	5225	34.00	68
5-4	INT	1/2" R FW	W-1DAY	0.5	0.153	1.224	5225	39.00	78
5S-1	EXT	1/2" S FW	MILLED	0.5224	0.167	1.503	4350	49.11	94
5S-1	INT	1/2" S FW	MILLED	0.5224	0.167	1.503	4350	48.06	92
5S-2	EXT	1/2" S FW	MILLED	0.5224	0.167	1.503	4350	44.40	85
5S-2	INT	1/2" S FW	MILLED	0.5224	0.167	1.503	4350	39.18	75
5S-3	EXT	1/2" S FW	W-3 DAYS	0.5224	0.167	1.336	5400	40.22	77
5S-3	INT	1/2" S FW	W-3 DAYS	0.5224	0.167	1.336	5400	44.40	85
5S-4	EXT	1/2" S FW	W-3 DAYS	0.5224	0.167	1.336	5300	39.18	75
5S-4	INT	1/2" S FW	W-3 DAYS	0.5224	0.167	1.336	5300	30.30	58
916-1	EXT	9/16" FW	MILLED	0.5625	0.192	1.536	3350	52.31	93
916-1	INT	9/16" FW	MILLED	0.5625	0.192	1.536	3350	48.94	87
916-2	EXT	9/16" FW	MILLED	0.5625	0.192	1.536	3750	48.94	87
916-2	INT	9/16" FW	MILLED	0.5625	0.192	1.536	3750	47.25	84
916-3	EXT	9/16" FW	W-3 DAYS	0.5625	0.192	1.152	5060	48.94	87
916-3	INT	9/16" FW	W-3 DAYS	0.5625	0.192	1.152	5060	40.50	72
916-4	EXT	9/16" FW	W-3 DAYS	0.5625	0.192	1.152	5000	47.25	84
916-4	INT	9/16" FW	W-3 DAYS	0.5625	0.192	1.152	5000	46.69	83
6-1	EXT	6/10" FW	MILLED	0.6	0.215	1.29	4100	46.80	78
6-1	INT	6/10" FW	MILLED	0.6	0.215	1.29	4100	44.40	74
6-2	EXT	6/10" FW	MILLED	0.6	0.215	1.29	4280	40.20	67
6-2	INT	6/10" FW	MILLED	0.6	0.215	1.29	4280	39.60	66
6-3	EXT	6/10" FW	MILLED	0.6	0.215	1.29	5230	40.80	68
6-3	INT	6/10" FW	MILLED	0.6	0.215	1.29	5230	39.60	66
6-4	EXT	6/10" FW	MILLED	0.6	0.215	1.29	5450	43.80	73

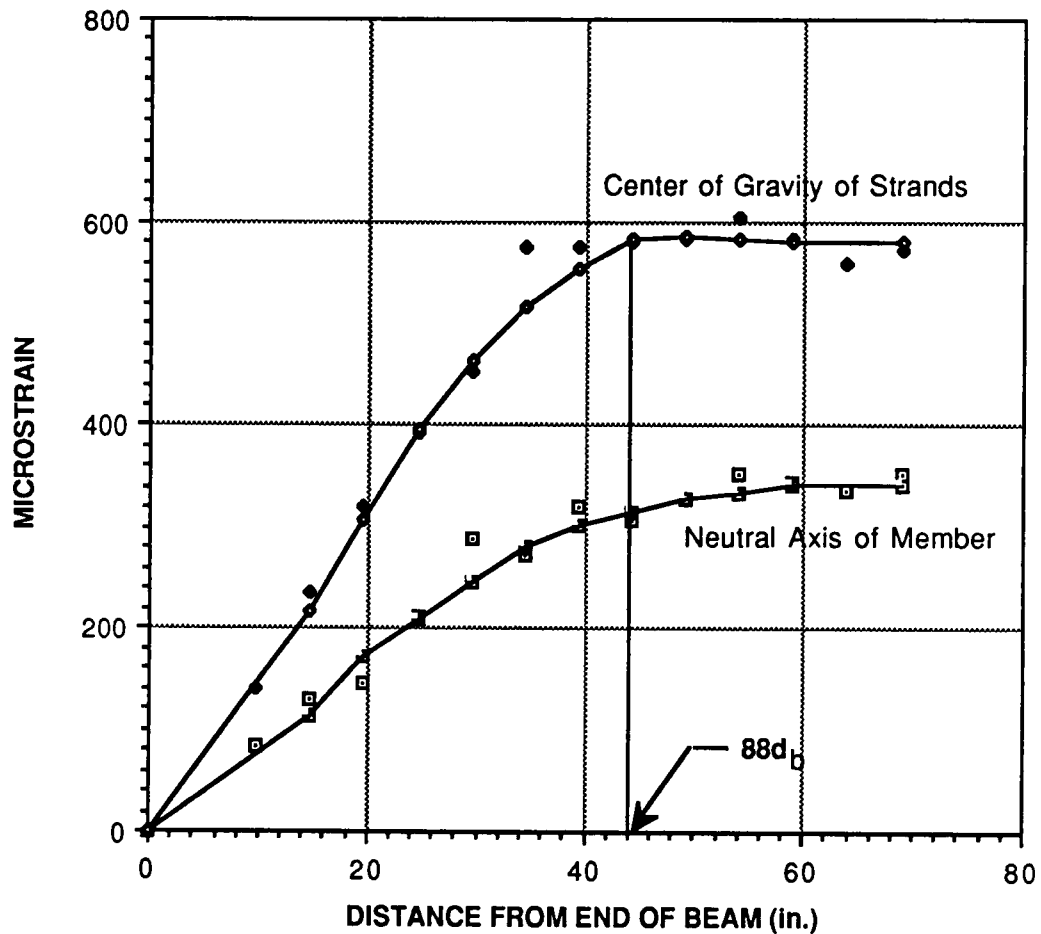


**FIGURE 4.1 - TYPICAL
MEASURED STRESS DISTRIBUTION**

Effects of Variables

The force in the prestressing strand is transferred to the concrete by bond in the end region of the beam. In 1954, Janney (11) concluded that there are three factors that may effect bond between the prestressing strand and the surrounding concrete:

- 1) Adhesion between the concrete and steel;
- 2) Friction between the concrete and steel; and
- 3) Mechanical resistance, ie. deformations in the prestressing tendons.

These three factors are independent of each other, but together compose the bonding action necessary to transfer the prestressing force from the steel to the concrete.

Previous researchers have determined that the transfer length is directly related to the following variables :

- 1) Diameter and stress of the strand;
- 2) Surface condition of the strand;
- 3) Initial end slip of the strand;
- 4) Concrete strength; and
- 5) Consolidation of the concrete around the strand.

In this section the relationships of these variables to each of the three factors affecting bond are examined.

Effects of strand diameter

In today's prestressing industry several different strand sizes (ranging from 3/8" to .6" diameter) are utilized in various products. Previous researchers have shown that the perimeter of seven-wire prestressing strand was approximately equal to $4/3\pi d_b$. Table 4.2 summarizes the cross-sectional area, surface area, and a ratio of the two for the four strand.

Table 4.2 - Properties of Prestressing Strand				
Name	Diameter (in)	As (in)	$4/3\pi d$ (in)	$(4/3\pi d)/A_s$
1/2" Reg.	0.5	0.153	2.094	13.68
1/2" Spec.	0.5224	0.162	2.188	13.51
9/16	0.5625	0.192	2.356	12.27
.6"	0.6	0.215	2.513	11.70

diameters used in this study. This shows that the ratio of surface area to cross-sectional area decreases with increasing strand diameter. Figure 4.2 is a plot of transfer length versus strand diameters for 1/2", 1/2" special, and 9/16" diameter strand. From these physical properties and relationships the following conclusions can be drawn:

- 1) Adhesion is directly proportional to strand diameter.
As the diameter increases so does the surface area. As the surface area increases, the capacity for adhesion between the concrete and the steel increases;
- 2) Friction is unaffected by strand diameter;
- 3) Mechanical resistance increases with increasing strand diameter. As the diameter increases, the grooves between individual wires gets larger, thus increasing the mechanical resistance capabilities;
- 4) The force in the strand increases with increasing diameter. Since the stress is held constant for all diameters, the force in each strand increases proportionally with increasing diameter;

- 5) Transfer length will increase with increasing diameter up to 9/16" diameter strand. Adhesion and mechanical bond are directly related to surface area, while force is directly related to cross-sectional area. Since the cross-sectional area increases more rapidly than the surface area, the effects of the greater force outweigh the effects of better adhesion and mechanical resistance, resulting in longer transfer lengths for larger diameter strand up to 9/16" in diameter; and
- 6) More research must be done with .6" diameter strand before any conclusions can be drawn.

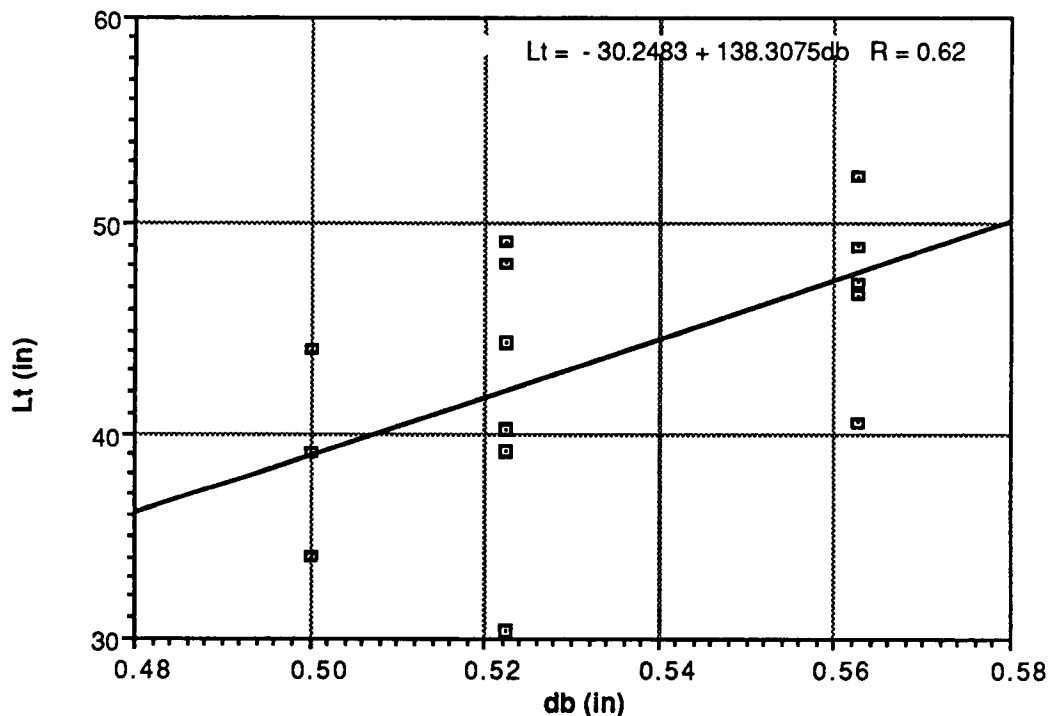


FIGURE 4.2
TRANSFER LENGTH VS. STRAND DIAMETER

Effects of strand surface condition

In 1988, Preston (19) reported that, "The wires of all stress relieved and low relaxation strands have a degree of shininess resulting from residuals of the lubricants used during the drawing process." These residuals make the strand smooth and slippery, drastically reducing its coefficient of friction and its ability to adhere to the concrete. If the strand is allowed to "weather" enough to wash away the residuals of the drawing process and form a light layer of rust over its surface, then the coefficient of friction will increase as well as the strand's ability to adhere to the concrete. Data shows that beams with slightly weathered strand had an average transfer length of 13% less than that of beams with milled condition strand. Figure 4.3 illustrates the relationship of measured transfer length versus $(f_{si}/f'_c)d_b$. It is obvious that there are two different sets of results from this plot. For each of the strand surface conditions there is a linear relationship. This relationship is compared to previous research results later in this chapter. Table 4.3 summarizes the average transfer lengths of weathered and milled strand for each strand diameter. From this it may be concluded that:

- 1) Weathering of the strand increases its ability to adhere to the concrete;
- 2) Weathering of the strand increases the coefficient of friction between the concrete and steel, subsequently increasing the frictional bond; and

3) Mechanical resistance is not affected by the surface condition of the strand.

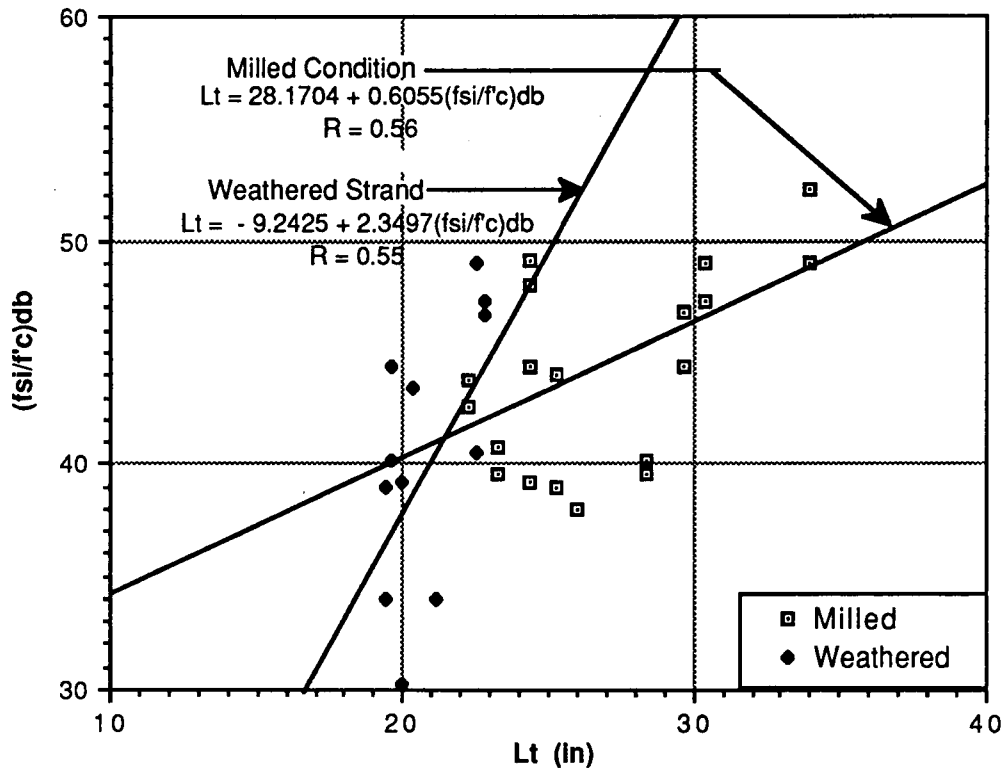


FIGURE 4.3
TRANSFER LENGTH VS. $(f_{si}/f_c)db$

Table 4.3 - Average Measured Transfer Lengths		
Diameted (in)	Average Transfer Lengths (in)	
	Milled	Weathered
1/2" Reg.	85.50	70.50
1/2" Spec.	86.50	73.75
9/16"	87.75	81.50
.6"	71.25	69.50

Effects of initial strand slip

Initially strands are prestressed to a predetermined stress and anchored to bulkheads at the ends of the casting bed. After the concrete has been placed and cured, the force must be transferred from the bulkhead to the concrete through the steel. This may be accomplished by gradual or sudden release of the prestress. A gradual release is done by slowly unjacking the strand from the bulkhead, which minimizes the initial strand slip. A sudden release is done by flame-cutting or saw-cutting the strand at some point beyond the end of the beam. This type of release causes a more severe bond stress concentration in the end region of the beam and a greater initial strand slip. After release the stress in the strand is zero at the end of the beam and increases through the transfer length to f_{se} . If the strand slips, it will break the adhesive bond between the concrete and steel in the slip region. Slip will then cause the stress in the strand to increase slower and at a greater distance from the end of the member. With lower stresses in the steel in the slip region the Hoyer Effect will increase the frictional component and somewhat compensate for the loss of adhesion. Therefore, the net effect will be a slight increase in transfer length with increasing initial strand slip. Figure 4.4 is a plot of transfer length versus initial strand slip. The following conclusions can be made on the effects of initial strand slip:

- 1) Adhesion is inversely related to initial strand slip. The greater the initial slip, the longer the slip

- region, over which the adhesive bond is broken;
- 2) Friction increases with increasing initial strand slip.
Greater slip means lower steel stresses in the slip region, which ultimately increases the normal forces produced by the Hoyer Effect;
 - 3) Mechanical resistance is reduced with increasing initial strand slip. As the strand draws in, it not only breaks the adhesive bond but also breaks some of the ridges of concrete which provide mechanical resistance; and
 - 4) The effects of reduced adhesion and mechanical bond outweigh the effects of increased friction.
- Consequently, the transfer length increases with increasing initial strand slip.

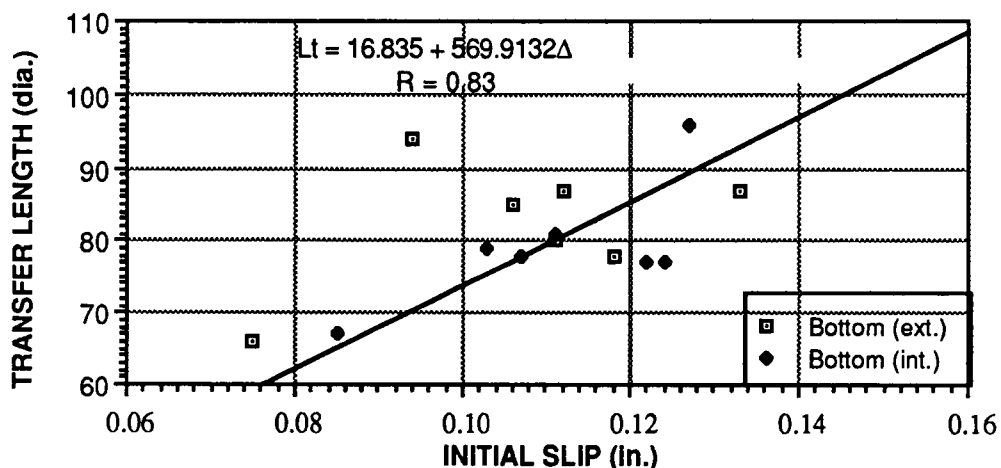


FIGURE 4.4
TRANSFER LENGTH VS. INITIAL SLIP

Effects of concrete strength

In 1963, Kaar, LaFraugh, and Mass (13) concluded that concrete strength has little influence on transfer length. When looking at the effects of concrete strength on the separate factors affecting transfer length, it can be seen that concrete strength does not affect the adhesive properties between the concrete and steel. Friction and mechanical resistance will only be affected if the concrete is unable to withstand the normal and shearing forces applied by the strand. Therefore, friction and mechanical resistance may be decreased in the end region of the of the beam if the concrete cannot withstand the applied forces. This study of limited data measured transfer lengths for concrete ranging in strength from 3500 psi to 5500 psi. Figure 4.5 is a plot of transfer length versus concrete strength. The plot shows some correlation between concrete strength and transfer length from which we can draw the following conclusions:

- 1) Adhesion is unaffected by concrete strength;
- 2) Friction and mechanical resistance increase with increasing concrete strength in the end region of the beam; and
- 3) The transfer length will decrease slightly with increasing concrete strength.

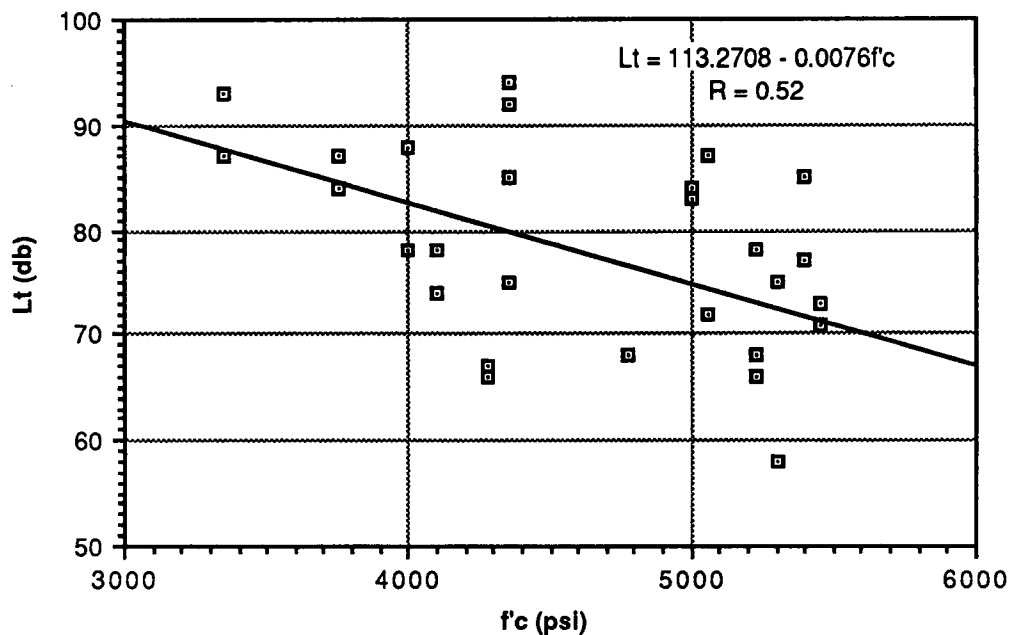


FIGURE 4.5
TRANSFER LENGTH VS. CONCRETE STRENGTH

Effects of concrete consolidation around strands

Concrete is consolidated around the prestressing strand by vibration immediately after pouring. This process aids the bonding capabilities by eliminating air pockets around the strands and enabling the concrete to work into the grooves of the strand. If the concrete is not consolidated around the strands it will reduce adhesive bond, frictional bond, and mechanical resistance. Therefore, poor consolidation of the concrete around the strands will result in increased transfer lengths.

Effects of Bond on Stress Distribution

Three types of bond are used to transfer the prestress force from the strand to the concrete. This section shows how each of these three types of bond independently affect the stress distribution throughout the transfer length. Finally, a theoretical stress distribution diagram will be developed from the three independent diagrams and compared to the actual stress distribution measured in the field.

Effects of adhesion

Adhesive bond can only be present in a region where no slip has occurred. Therefore, adhesive bond is nonexistent in the slip region of the transfer length. From the end of the slip region to the transfer length the adhesive bond is constant, increasing the stress linearly. Figure 4.6 shows the stress distribution due to adhesive bond.

Effects of friction

Frictional bond is a function of the normal stresses applied by the swelling of the strand in the end regions of the beam (previously defined as the Hoyer Effect). This effect is a function of the change in stress in the strand. At the end of the member the strand stress is zero, therefore, the change in the stress is greatest as well as the normal stresses caused by the Hoyer Effect. As the stress

increases, the Hoyer Effect decreases, providing a parabolic stress distribution over the entire transfer length. Figure 4.7 shows the stress distribution due to friction.

Effects of mechanical resistance

Mechanical resistance is a function of the strength of the grooves of concrete around the strand. At the ends of the member the slip is significant, shearing the grooves of concrete, ultimately providing little mechanical resistance. As the amount of slip decreases through the slip region less damage is done to the concrete grooves, which increases the mechanical resistance through the slip region. From the end of the slip region to the transfer length the mechanical resistance is constant

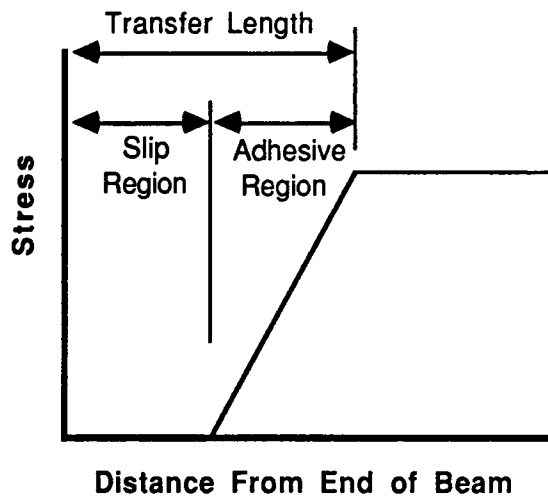


FIGURE 4.6
STRESS DISTRIBUTION
DUE TO ADHESION

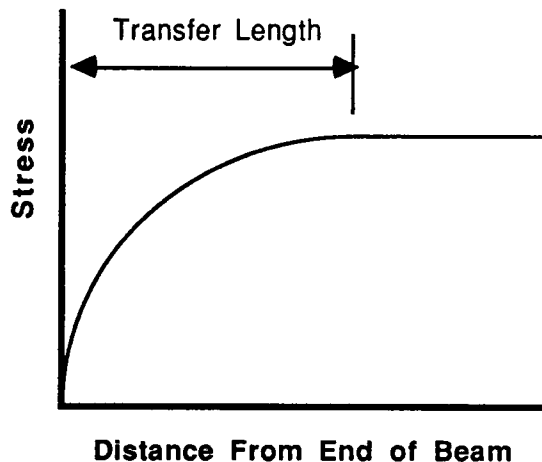


FIGURE 4.7
STRESS DISTRIBUTION
DUE TO FRICTION

due to the undamaged condition of the concrete around the strand. Figure 4.8 shows the stress distribution due to mechanical bond.

Total stress distribution

In order to develop a total stress distribution diagram (figure 4.9) it is necessary to look at two separate regions of the distribution; the slip region and the adhesive region. In the slip region there is no adhesive bond, while the frictional bond and the mechanical bond are represented by inversely parabolic curves which when added together have a linear resultant. In the adhesive region, adhesive bond and mechanical bond are constant, while the frictional bond decreases. This results in a parabolic distribution of stress

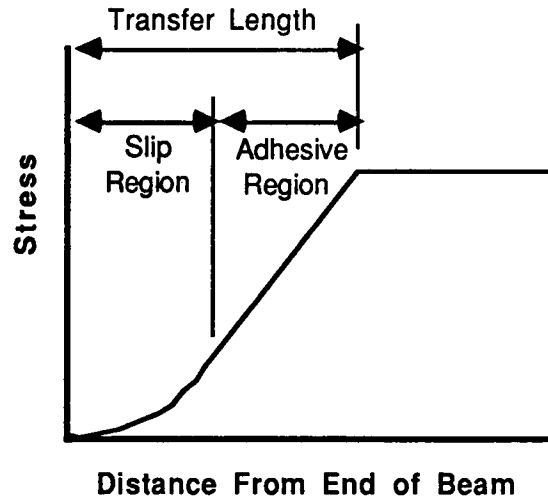


FIGURE 4.8
STRESS DISTRIBUTION DUE TO
MECHANICAL RESISTANCE

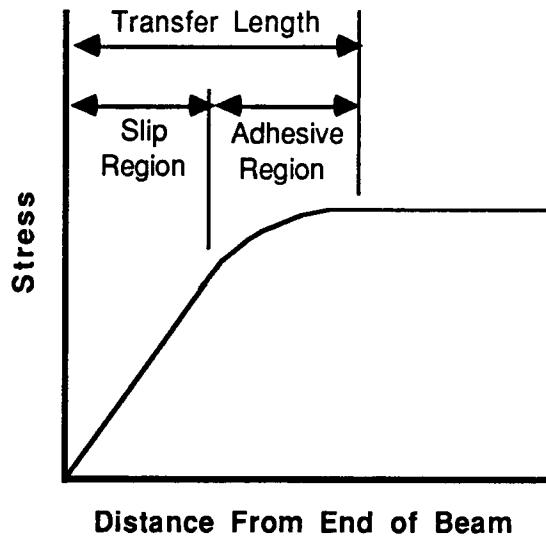


FIGURE 4.9
PREDICTED
STRESS DISTRIBUTION

over the adhesive region. Figure 4.9 represents the predicted stress distribution derived from the above discussion.

Comparison of Results

This section will compare measured transfer lengths with the current code provisions and several other prediction equations developed by previous researchers.

The current ACI and AASHTO code equation for development length is illustrated as equation (2.1) of this paper and rewritten in a different form in equation (2.2). In this form the first term, $(f_{se}/3)d_b$, is the transfer length. The "3" in the denominator is a conservative value for f'_c (in ksi). Using an average f_{se} of 180 ksi, the code equation simply defines the transfer length to be $60d_b$. Measured transfer lengths ranged from $58d_b$ to $94d_b$ with an average transfer length of $80d_b$ for milled condition strand.

In 1977, Zia and Mostafa (23) developed the following prediction equation using a linear regression analysis of transfer lengths plotted versus $(f_{si}/f'_c)d_b$ for milled condition strand:

$$L_t = [1.5(f_{si}/f'_c)d_b] - 4.6 \quad (4.1)$$

Earlier in this chapter figure 4.3 showed the same plot for measured data. A linear regression analysis provided the following equation for milled strand:

$$L_t = [.6(f_{si}/f'_c)d_b] + 28.2 \quad (4.2)$$

Figure 4.10 illustrates the relationship between these two equations. It is then clear that equation (4.2) is more conservative for values of $(f_{si}/f'_c)d_b$ less than 36.44. If the initial stress is equal to $.75f_u$ (or 202.5 ksi) and the strand diameter is held constant, then equation (4.2) is more conservative for concrete strengths greater than 2800 psi for 1/2" diameter strand and 3400 psi for .6" diameter strand.

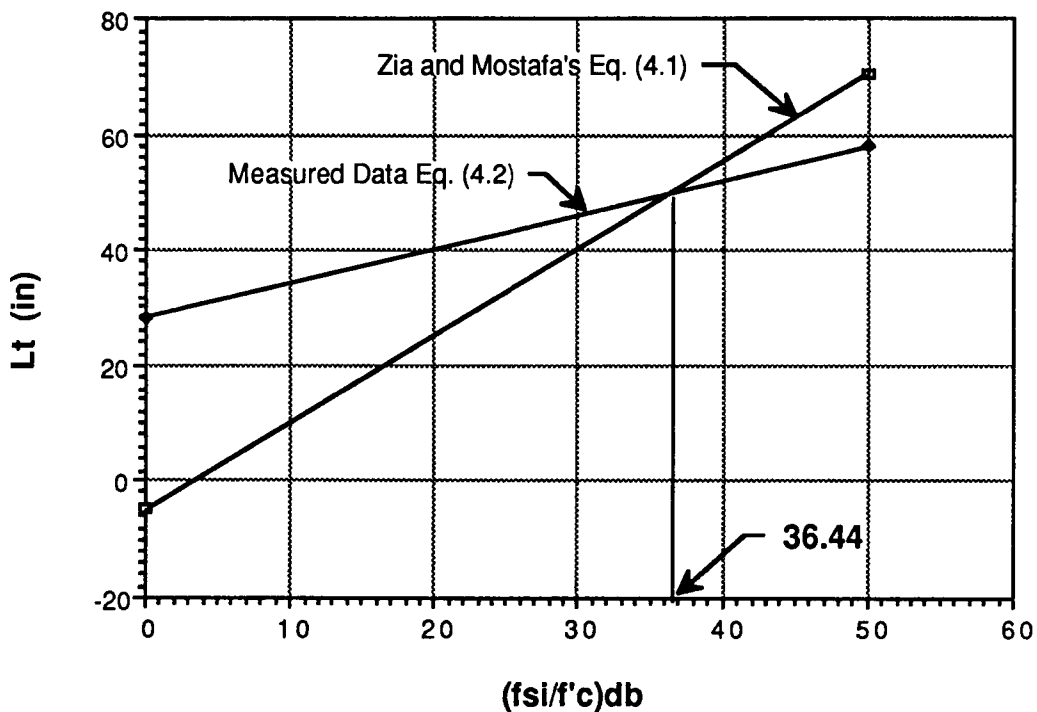


FIGURE 4.10 - EQUATION COMPARISON

In 1986, Cousins, Johnston, and Zia (5) developed a prediction equation for transfer length based on a two part stress distribution diagram as shown in figure 4.11. The plastic zone is said to be linear while the elastic zone is parabolic, which is similar to our theoretical and measured stress distribution diagrams. Their prediction equation

is as follows:

$$L_t = .5U'_t\sqrt{f'_c}/B + f_{se}A_b/(\pi d_b U'_t\sqrt{f'_c}) \quad (4.3)$$

where the first term $(.5U'_t\sqrt{f'_c}/B)$ is the elastic transfer length and the second term $(f_{se}A_b/(\pi d_b U'_t\sqrt{f'_c}))$ is the plastic transfer length. The authors recommend using values of 6.7 for U'_t and 300 psi/in for B which they derived from experimental data. Using these values leads to a very long plastic zone and very short elastic zone. From present data an average U'_t was calculated to be 9.1 and an average B to be 33 psi/in. This dramatic decrease in B increases the elastic zone considerably. With these constants the plastic zone covered approximately 75% of the transfer length. Although the transfer lengths calculated with this equation were very close to the measured transfer lengths the ratio of linear to nonlinear stress distribution was considerably different from theoretical and measured stress distributions. Our measured and calculated linear zones were approximately 50% of the transfer length.

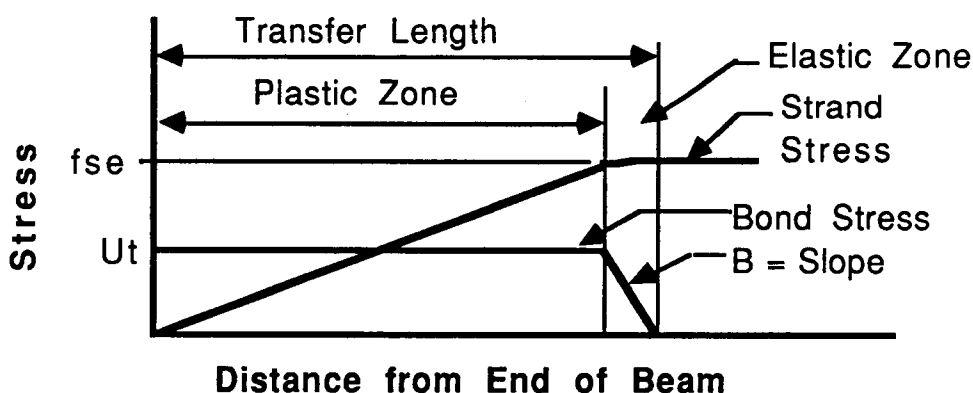


FIGURE 4.11 - COUSIN'S STRESS DISTRIBUTION

Chapter V

Conclusions

An experimental research program was conducted in order to determine the transfer length of four different size of prestressing strand in pretensioned, prestressed concrete beams. Also, a theoretical model was developed using the three factors of bond responsible for the transfer of stress. The effects of certain variables on these three factors were then analyzed. The variables studied included strand diameter, strand stress, surface condition of the strand, initial end slip of the strand, concrete strength, and consolidation of concrete around the strand. Based on the reviewed literature and the analysis of experimental results the following conclusions can be drawn:

- 1) The current ACI and AASHTO provisions for calculating transfer length are unconservative and need revision;
- 2) The surface condition of the strand is of vital importance to the transfer length. Therefore, some type of surface condition quality control needs to be implemented. The relationship found for milled condition strand is a conservative lower bound solution for the requirements of transfer length;

- 3) Transfer length is directly proportional to strand stress;
- 4) Transfer length is directly related to strand diameter for strand ranging from 1/2" to 9/16" in diameter. Larger diameter strand did not follow this relationship, therefore more testing is required to determine the effects of larger strand on transfer length;
- 5) The stress distribution through the transfer length has two distinct zones, a linear zone over the slip region and a nonlinear zone over the adhesive region.

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LIST OF REFERENCES

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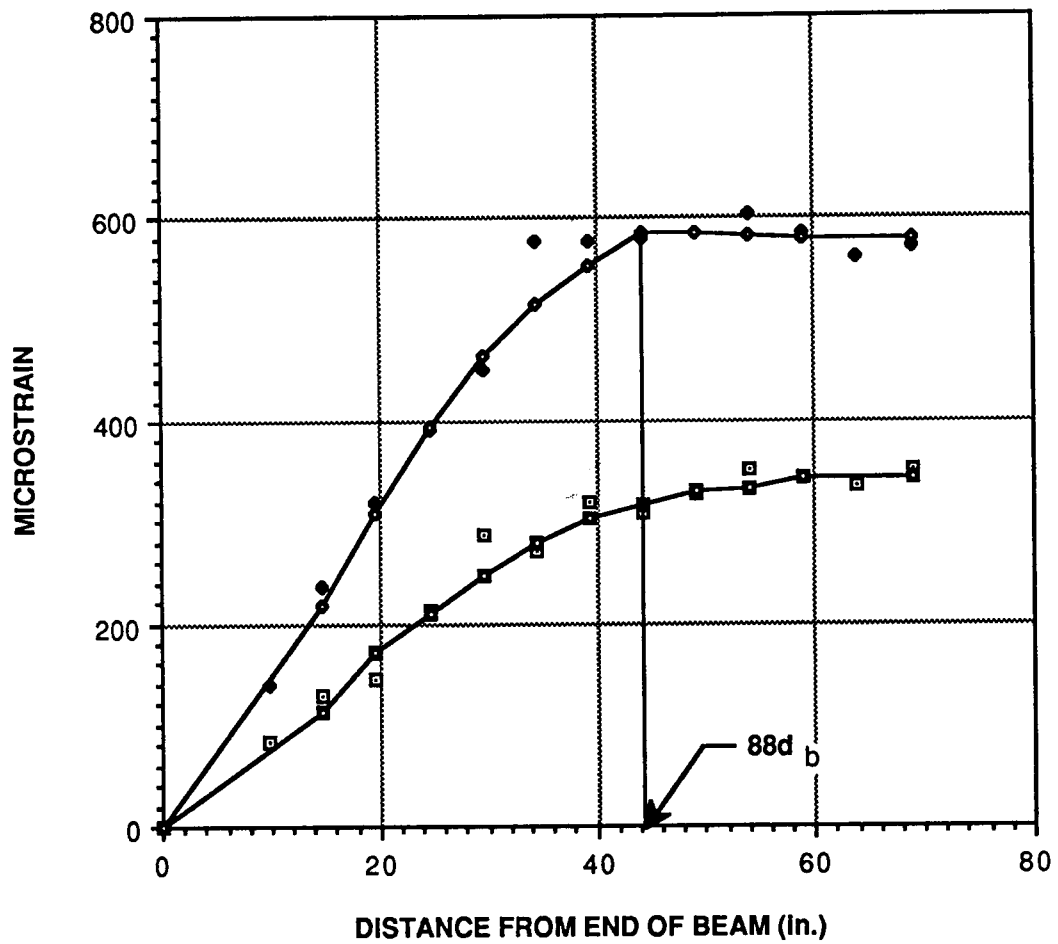
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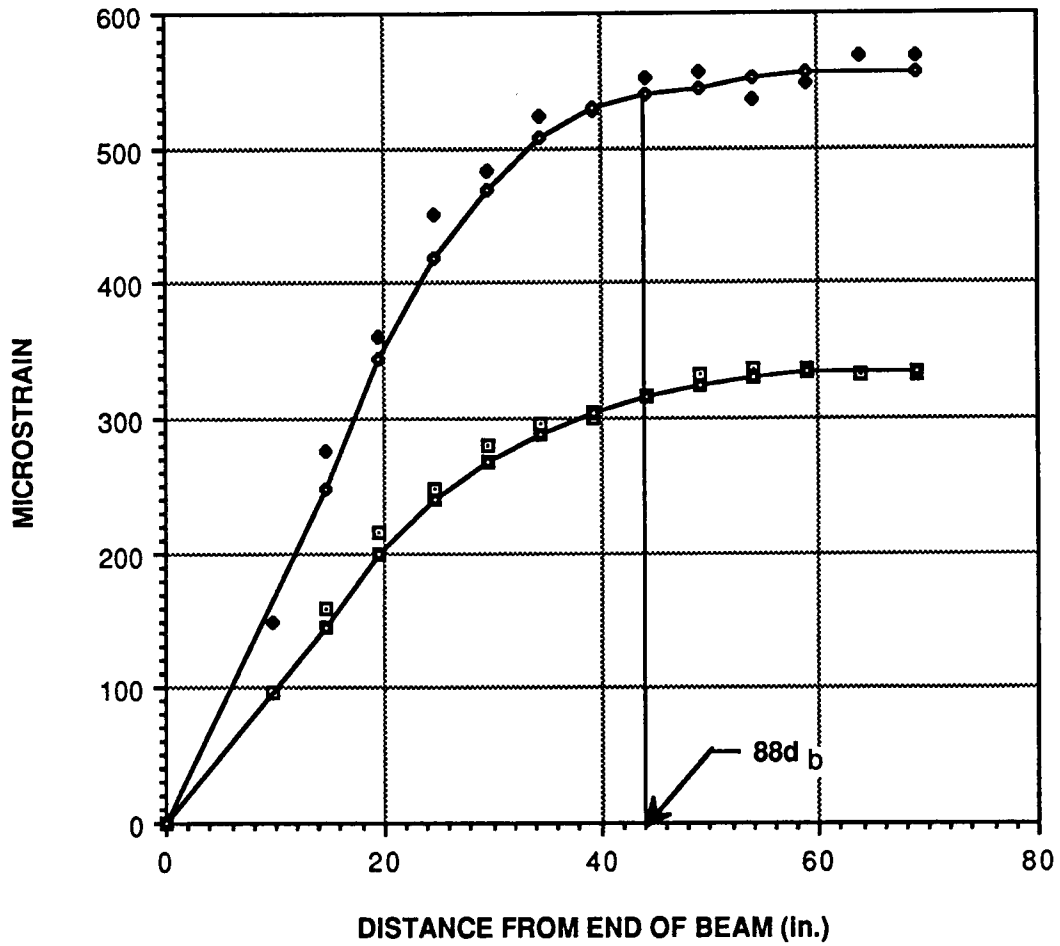
APPENDIX

MEASURED STRESS DISTRIBUTION DIAGRAMS

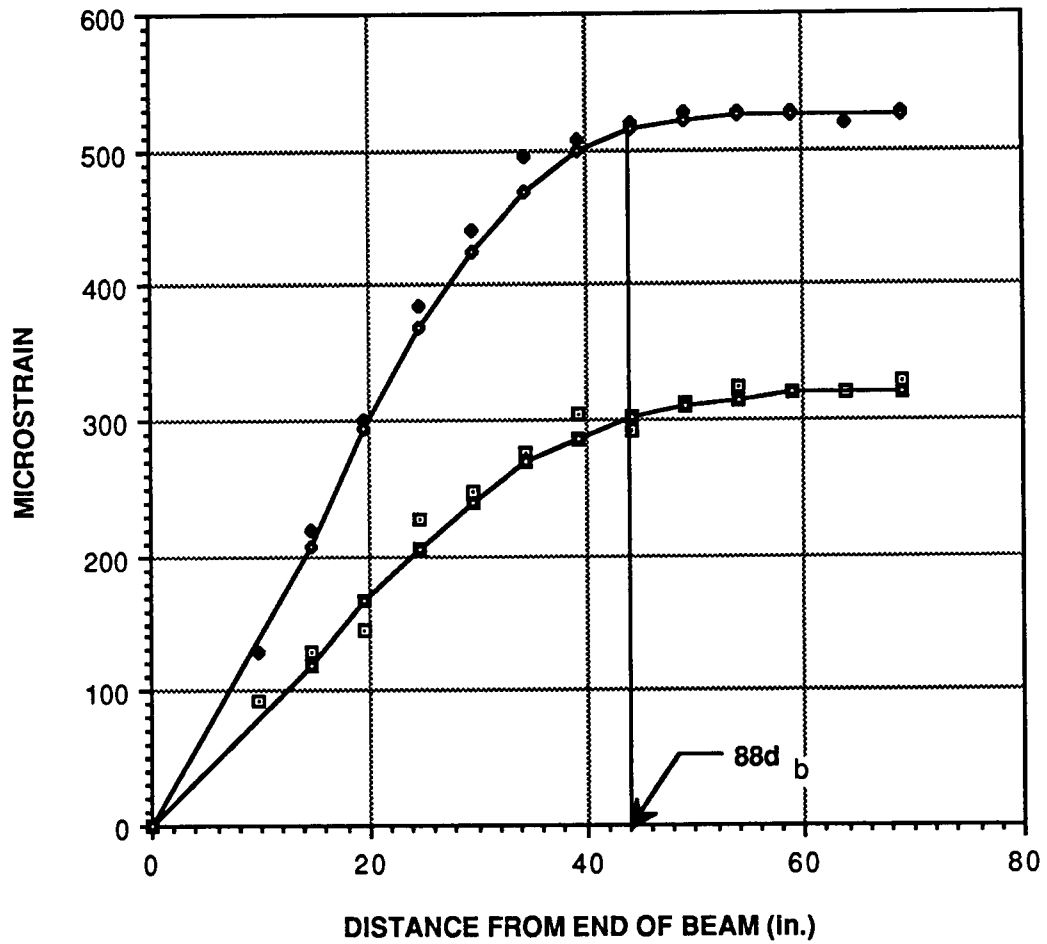
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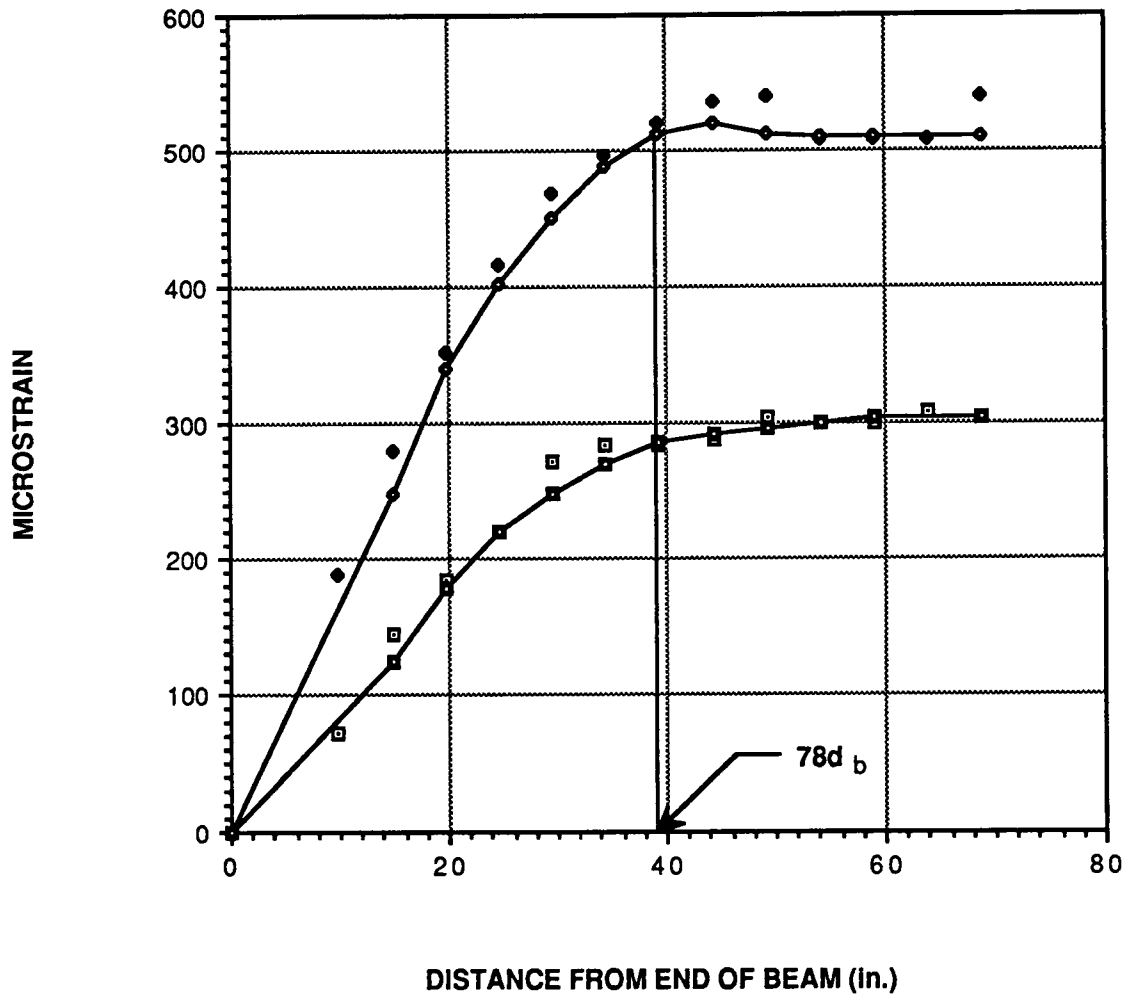
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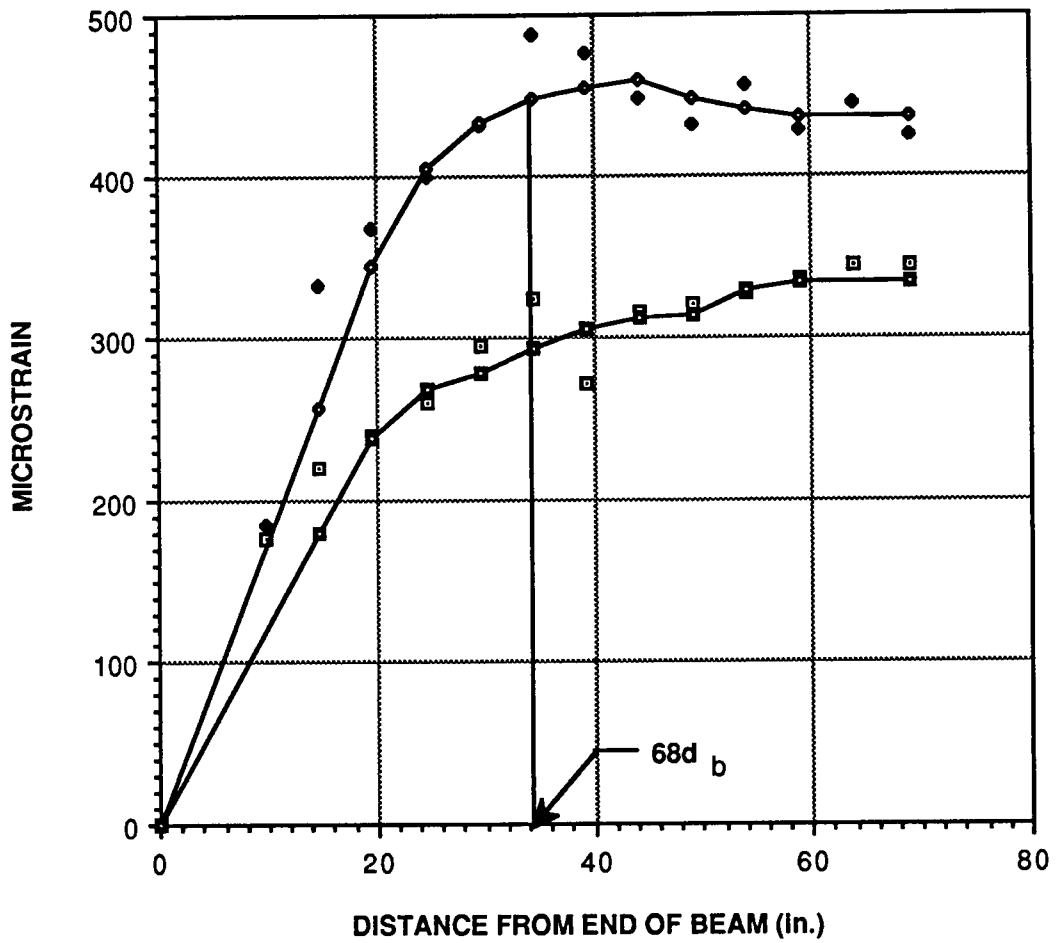
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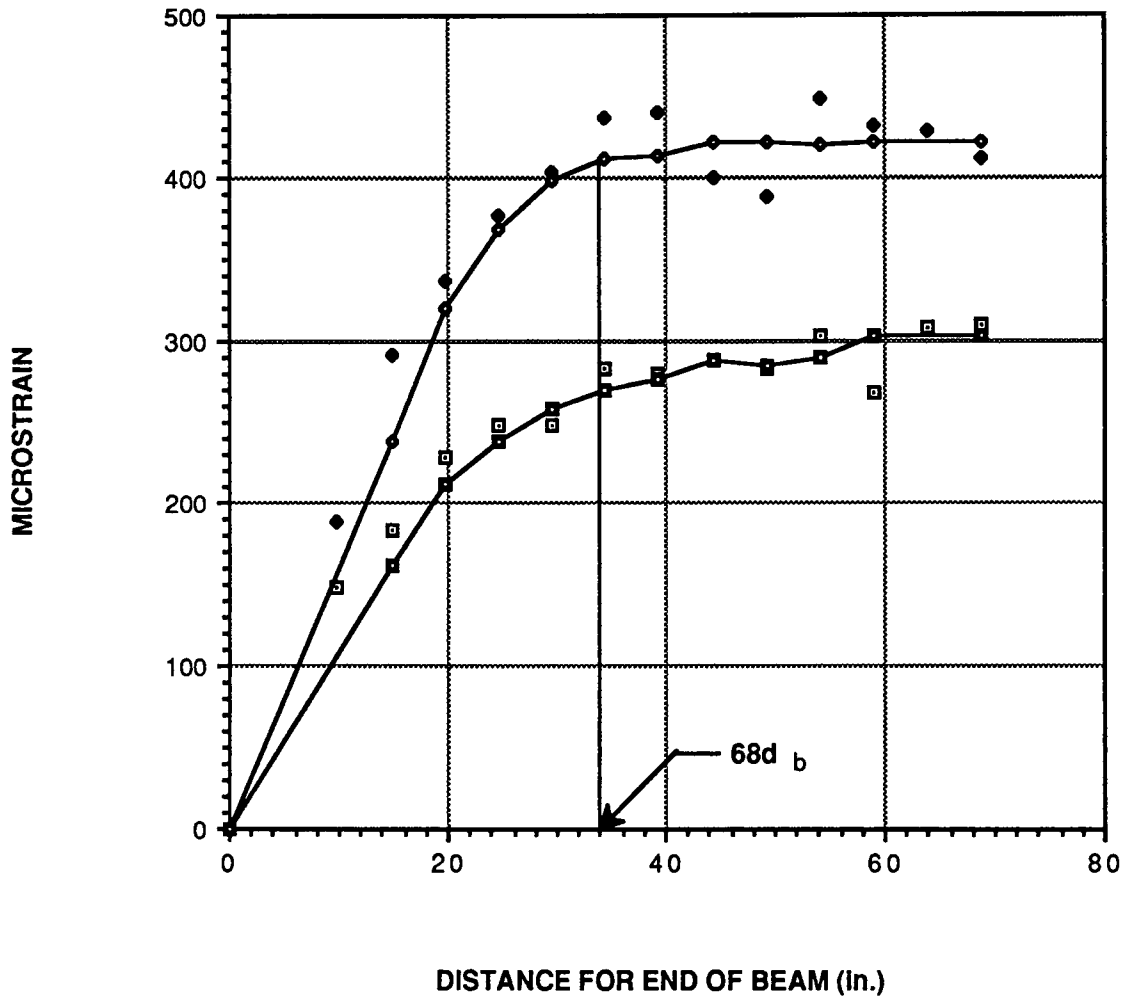
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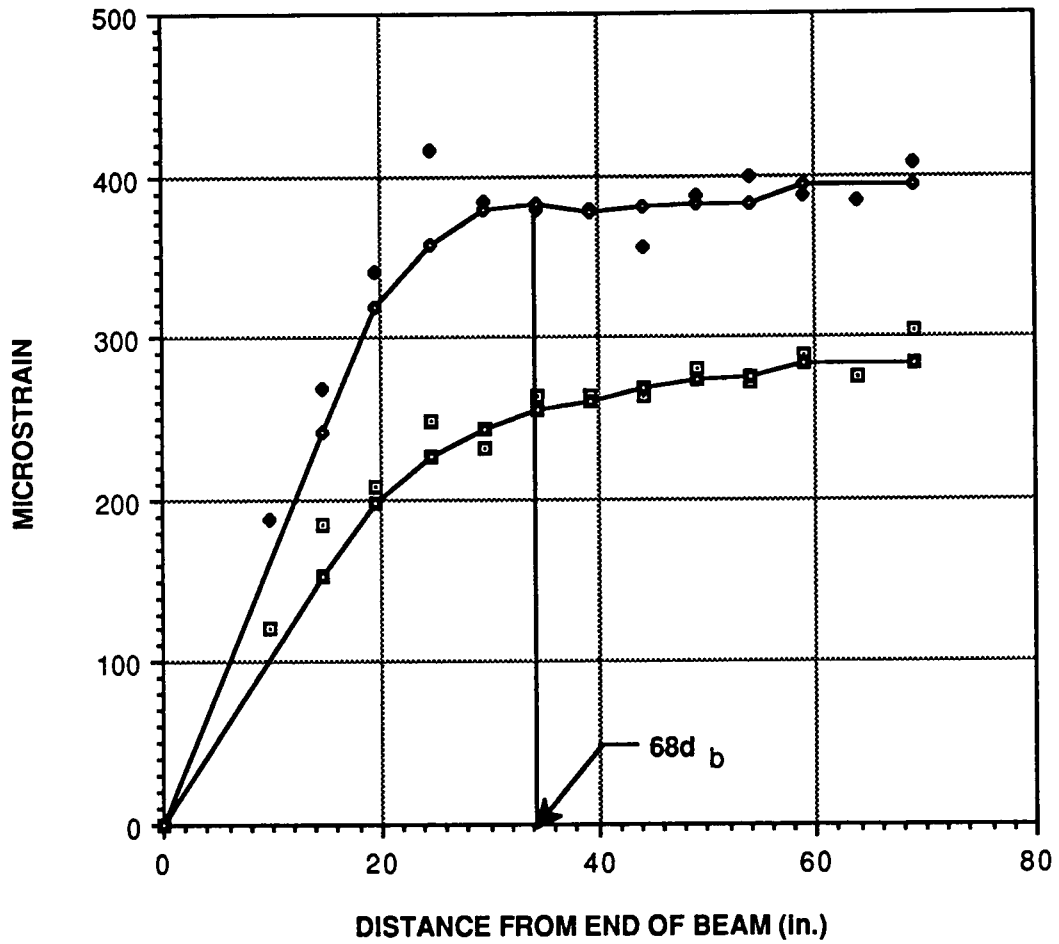
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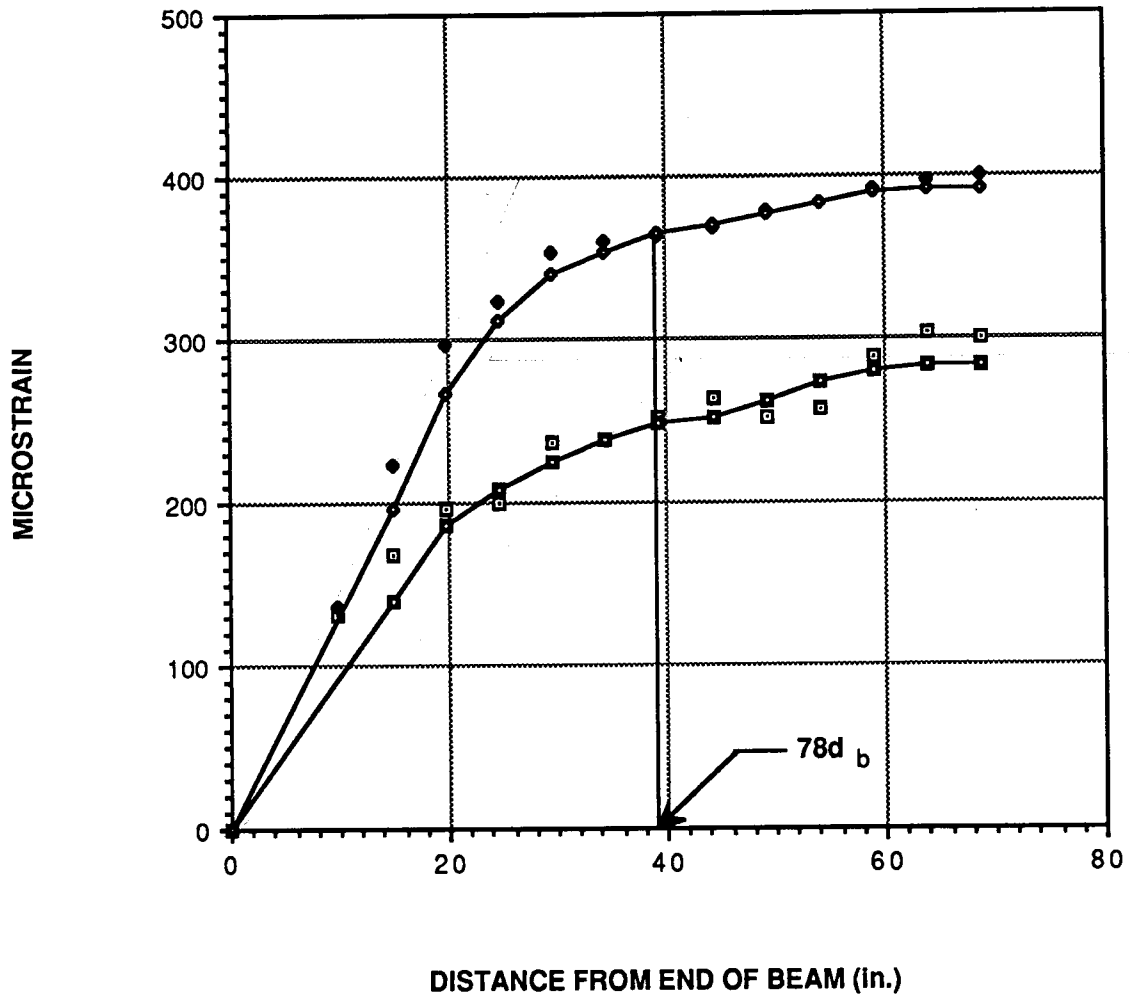
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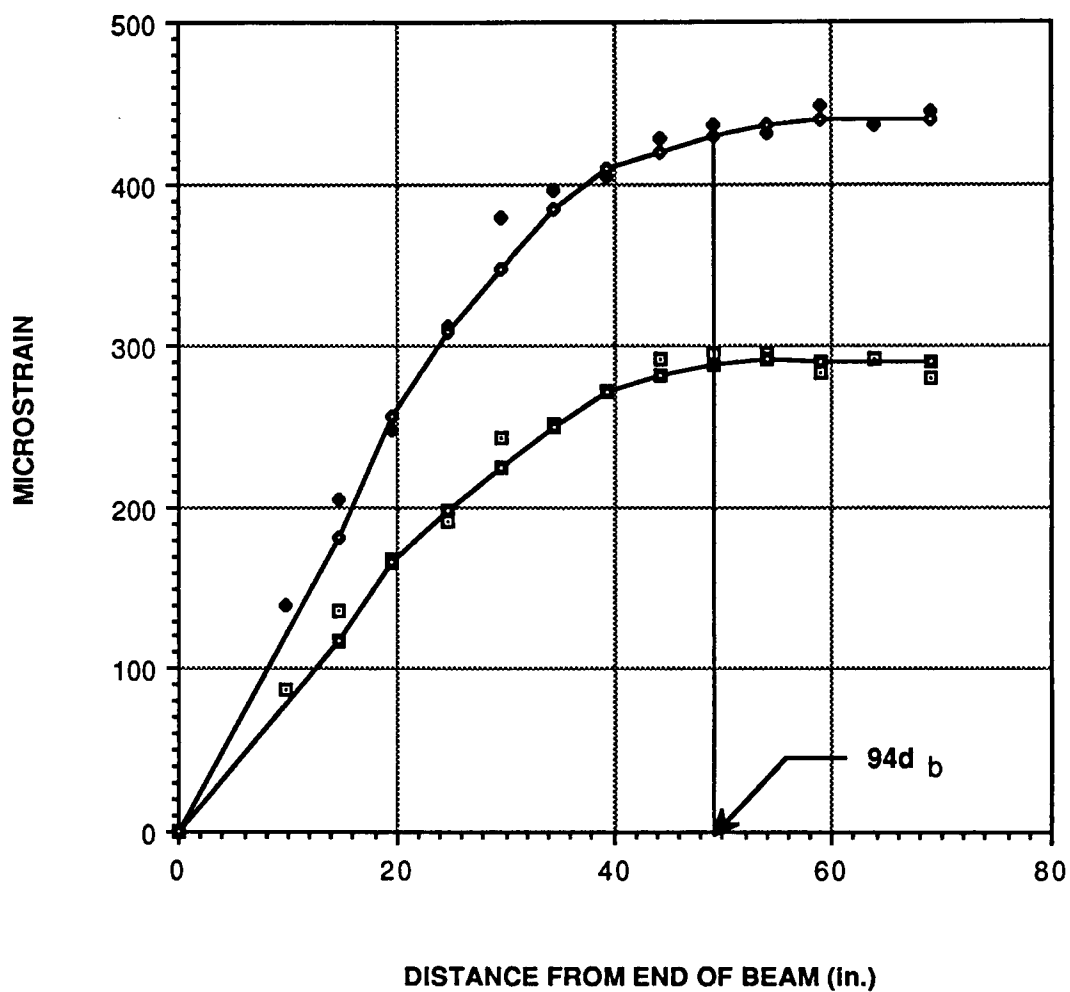
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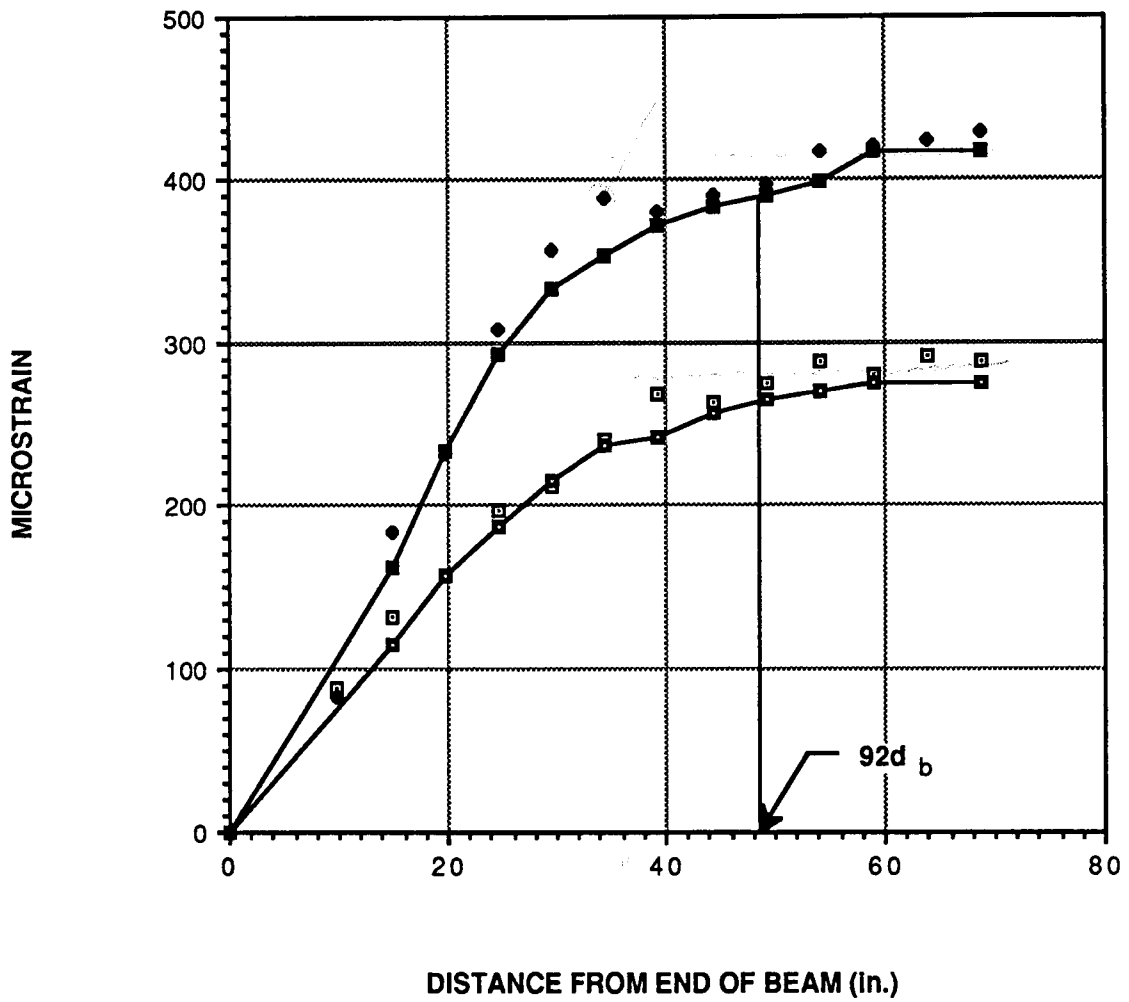
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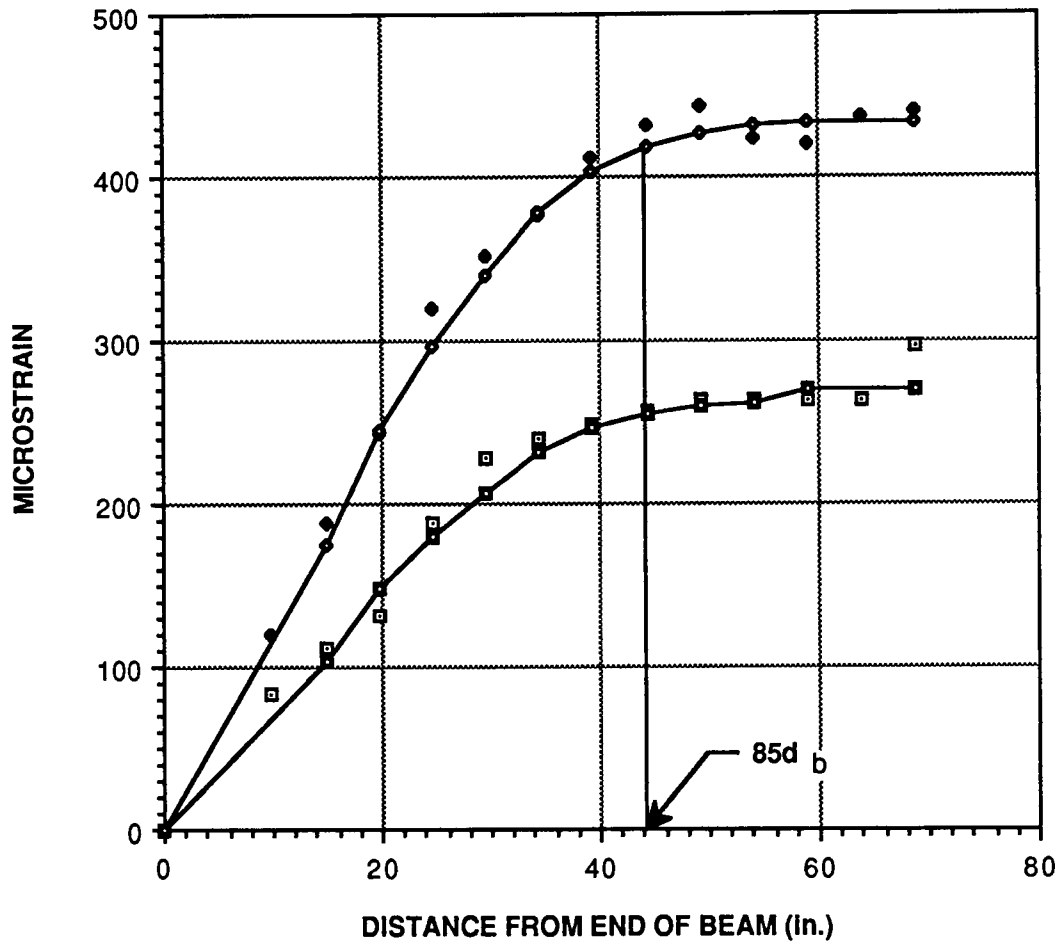
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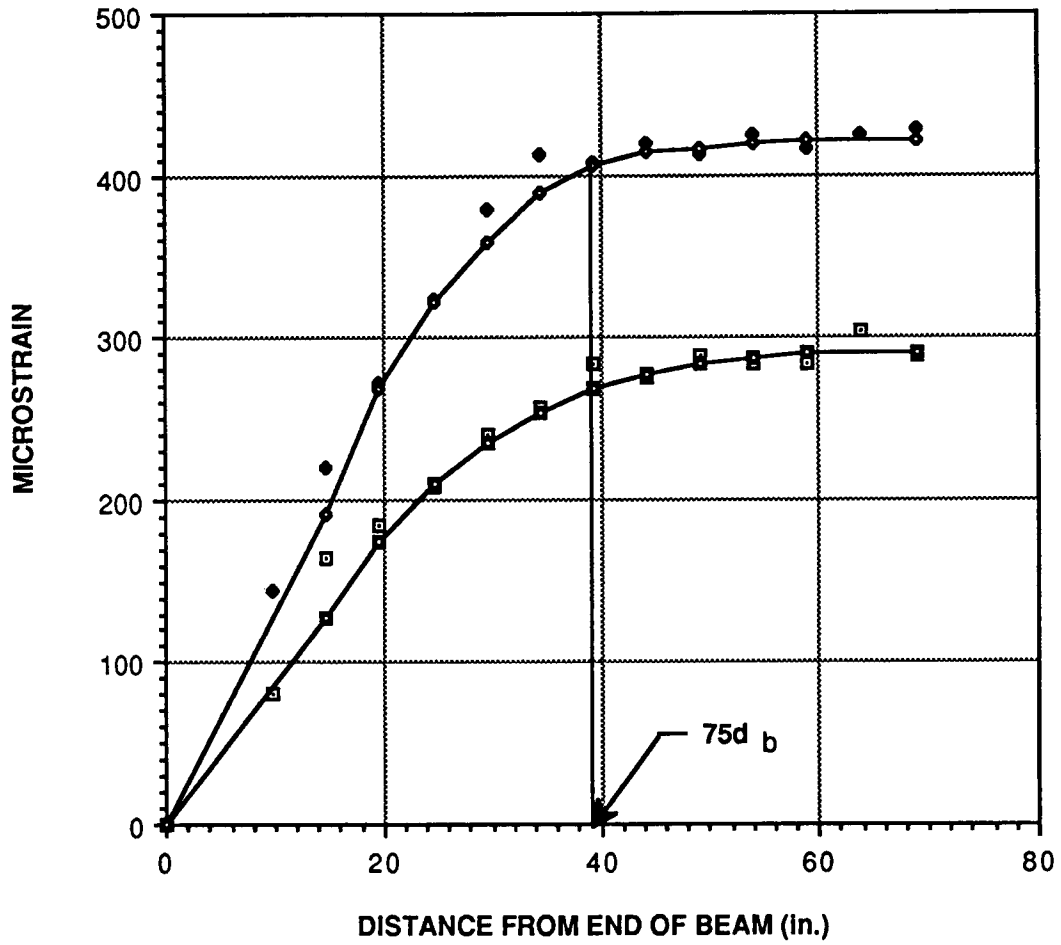
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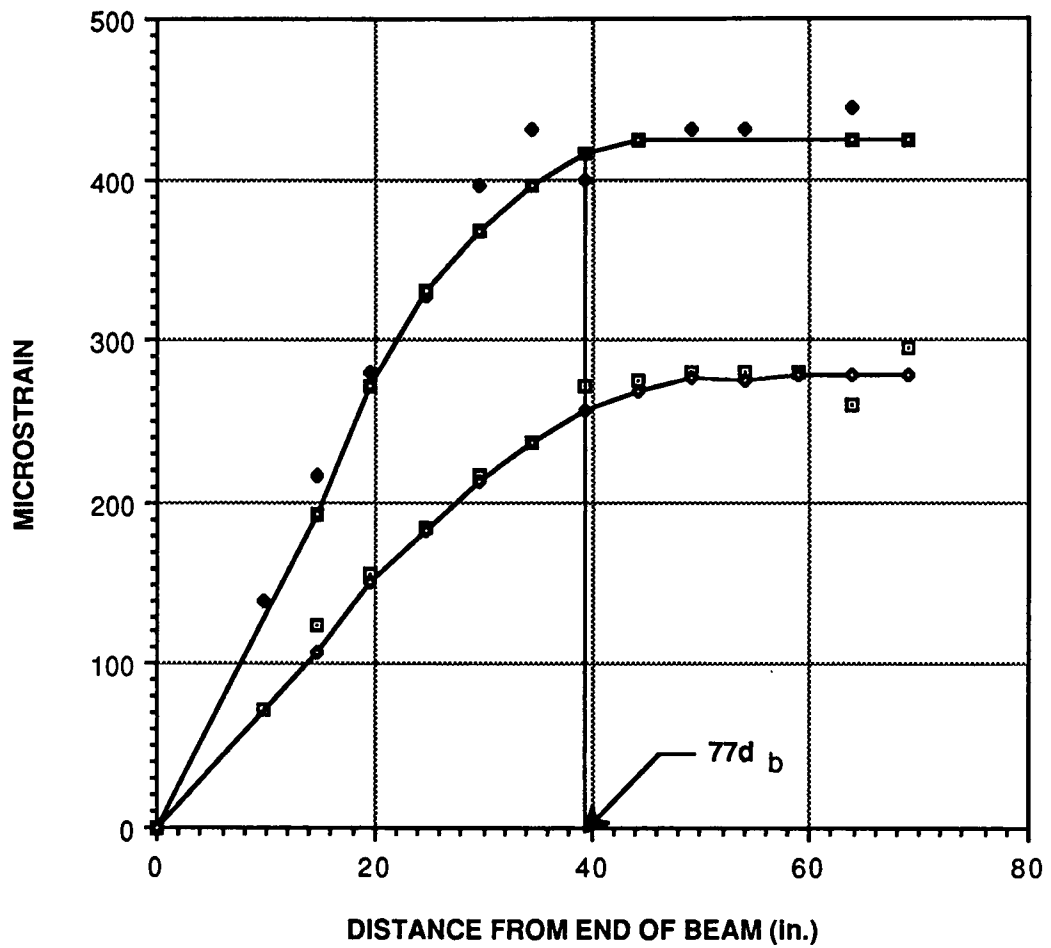
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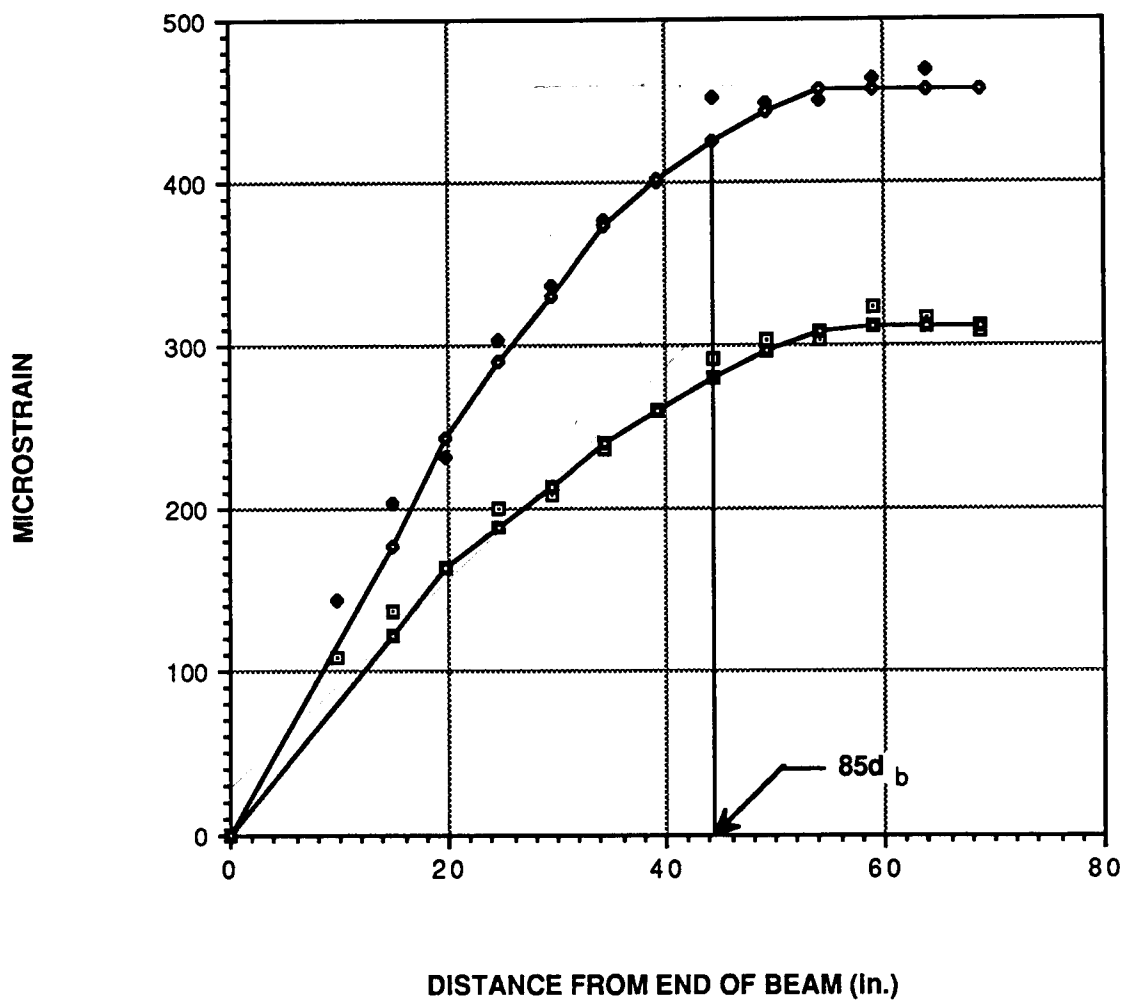
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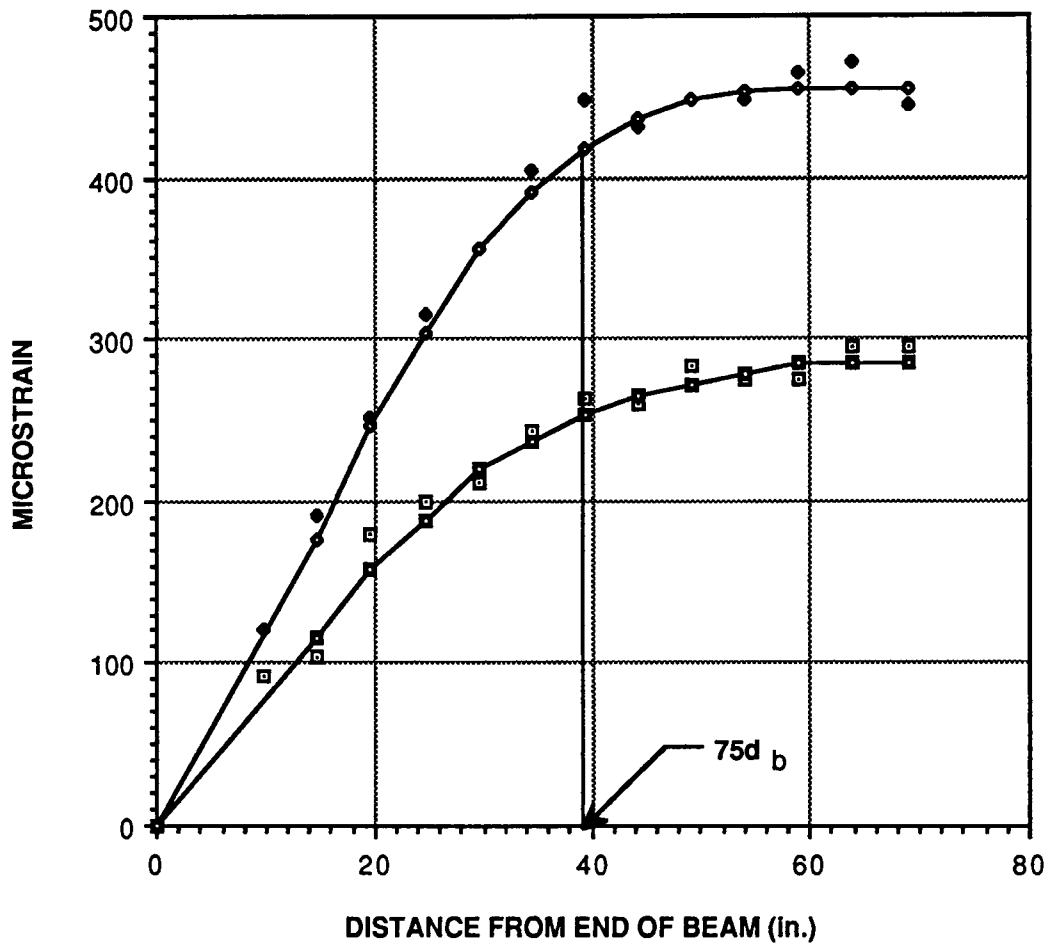
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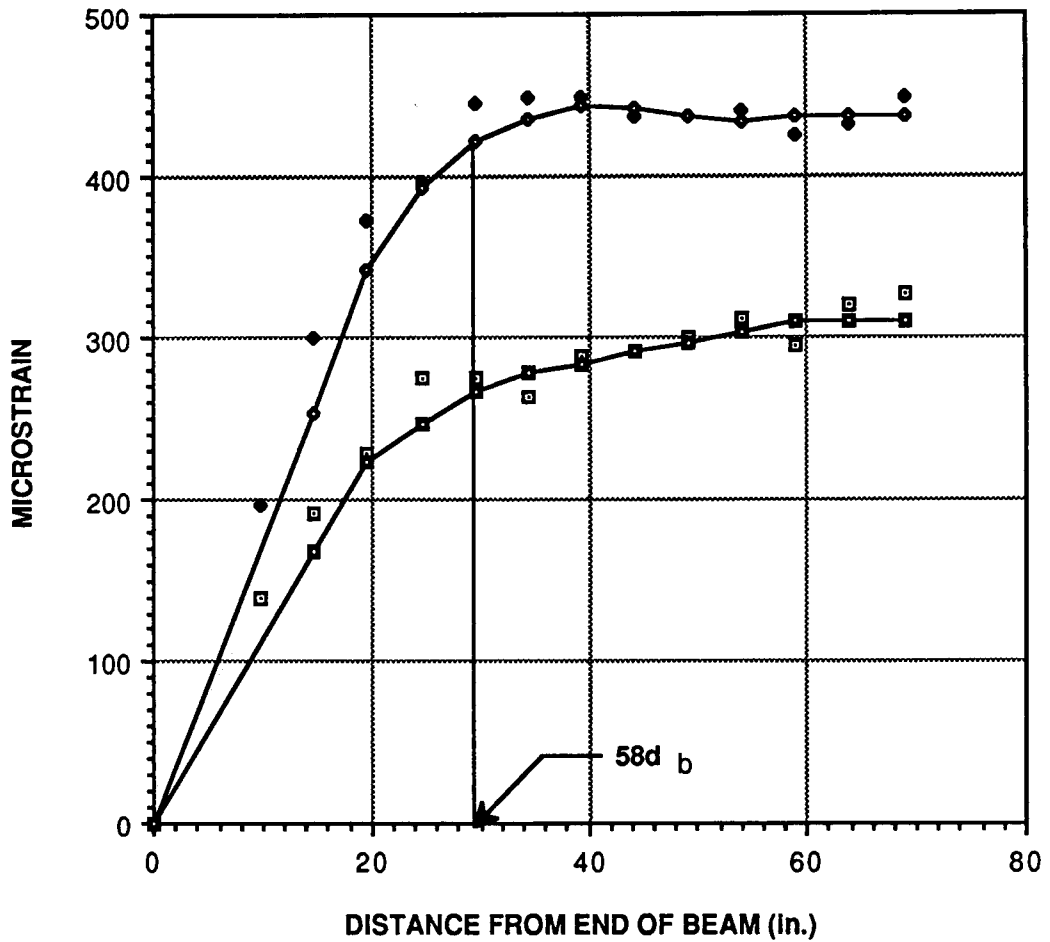
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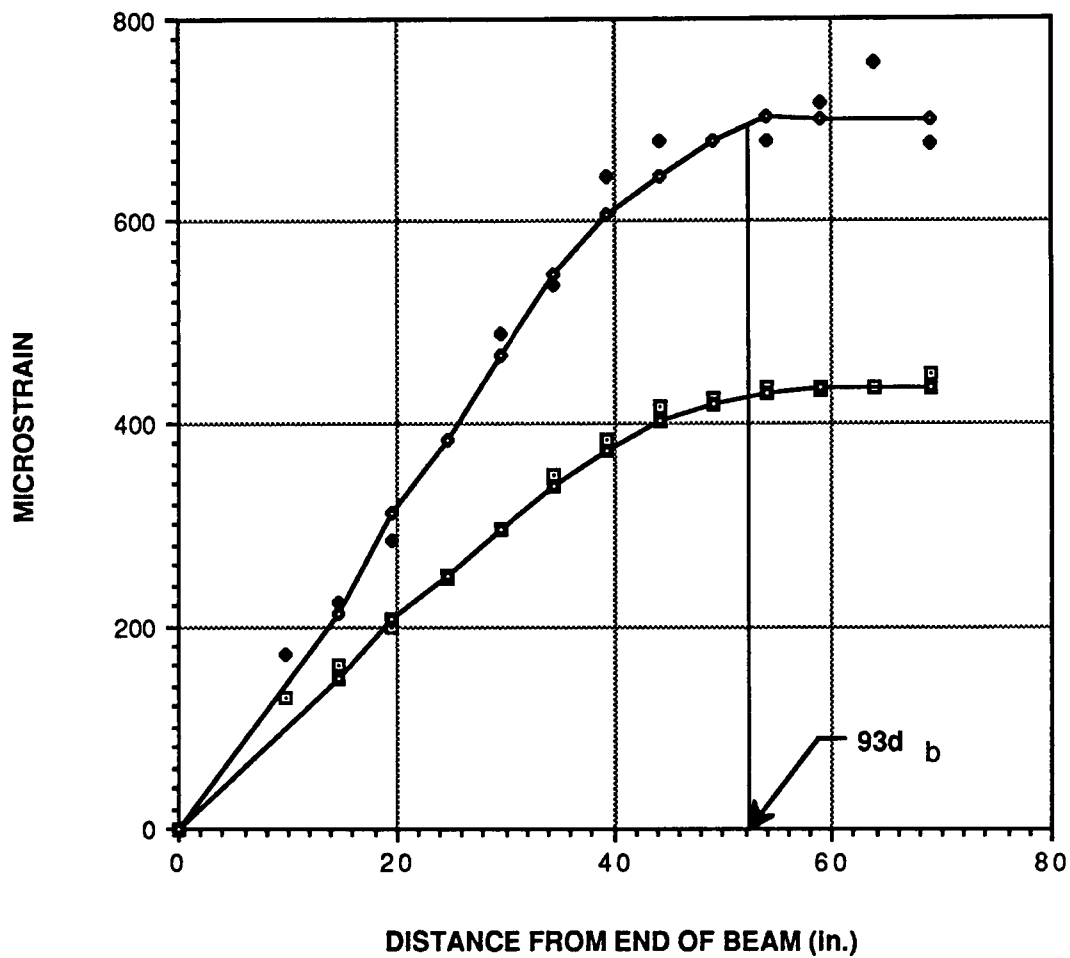
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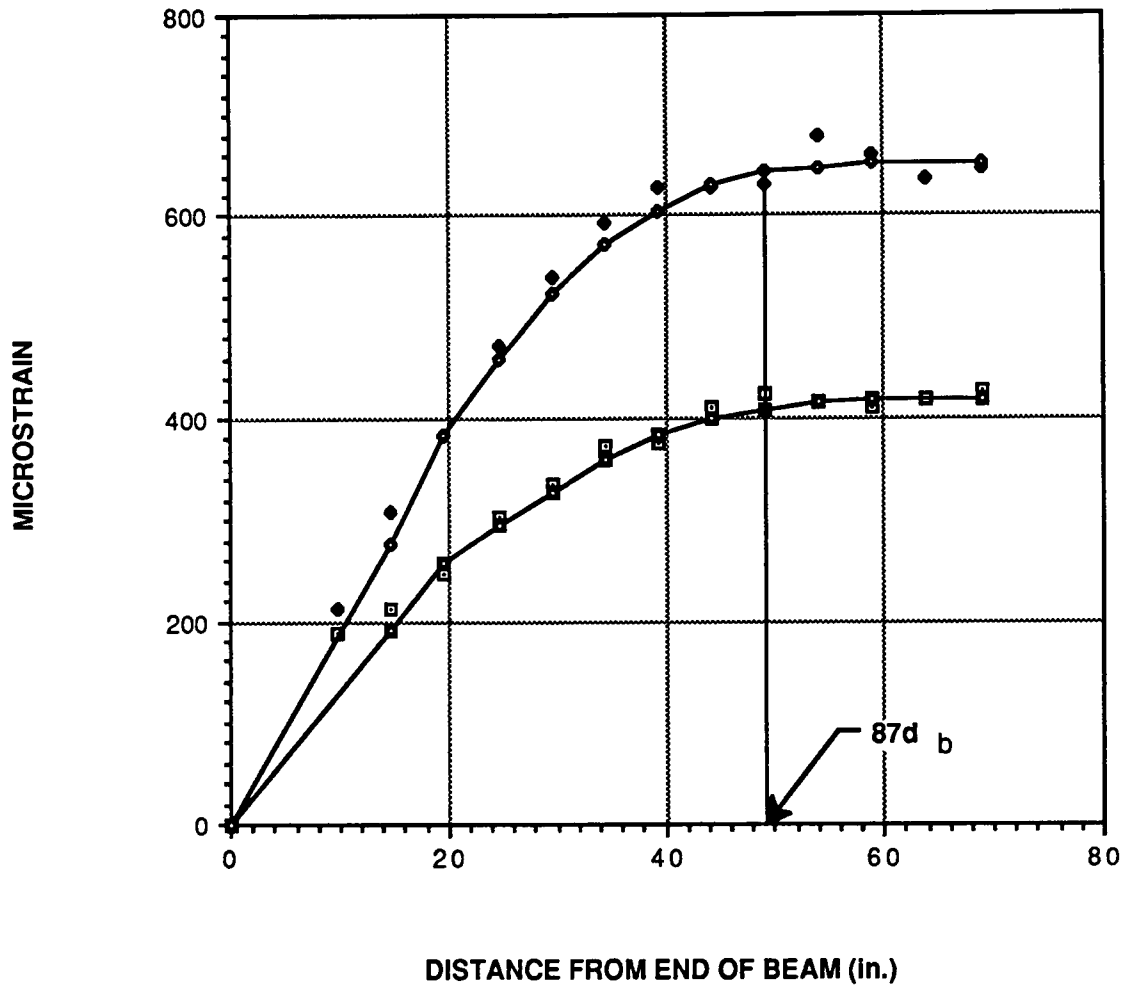
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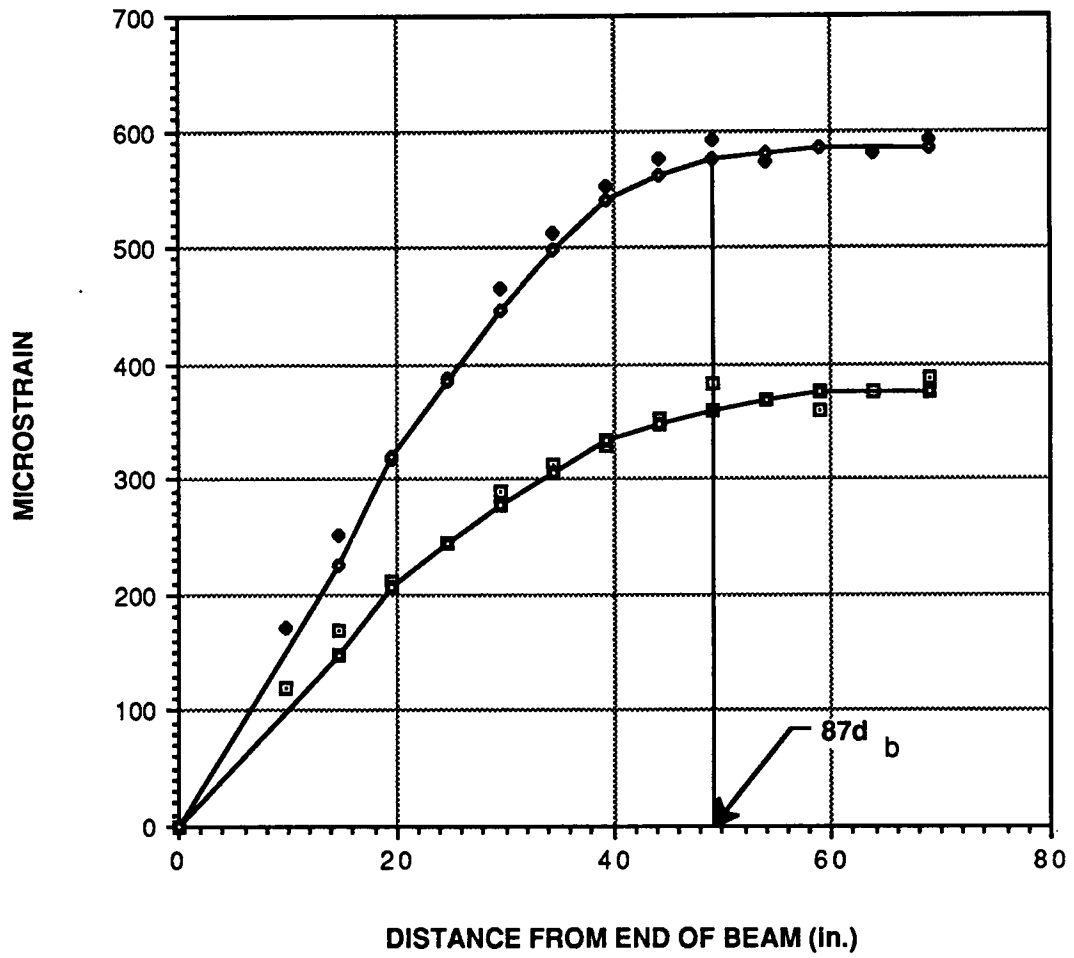
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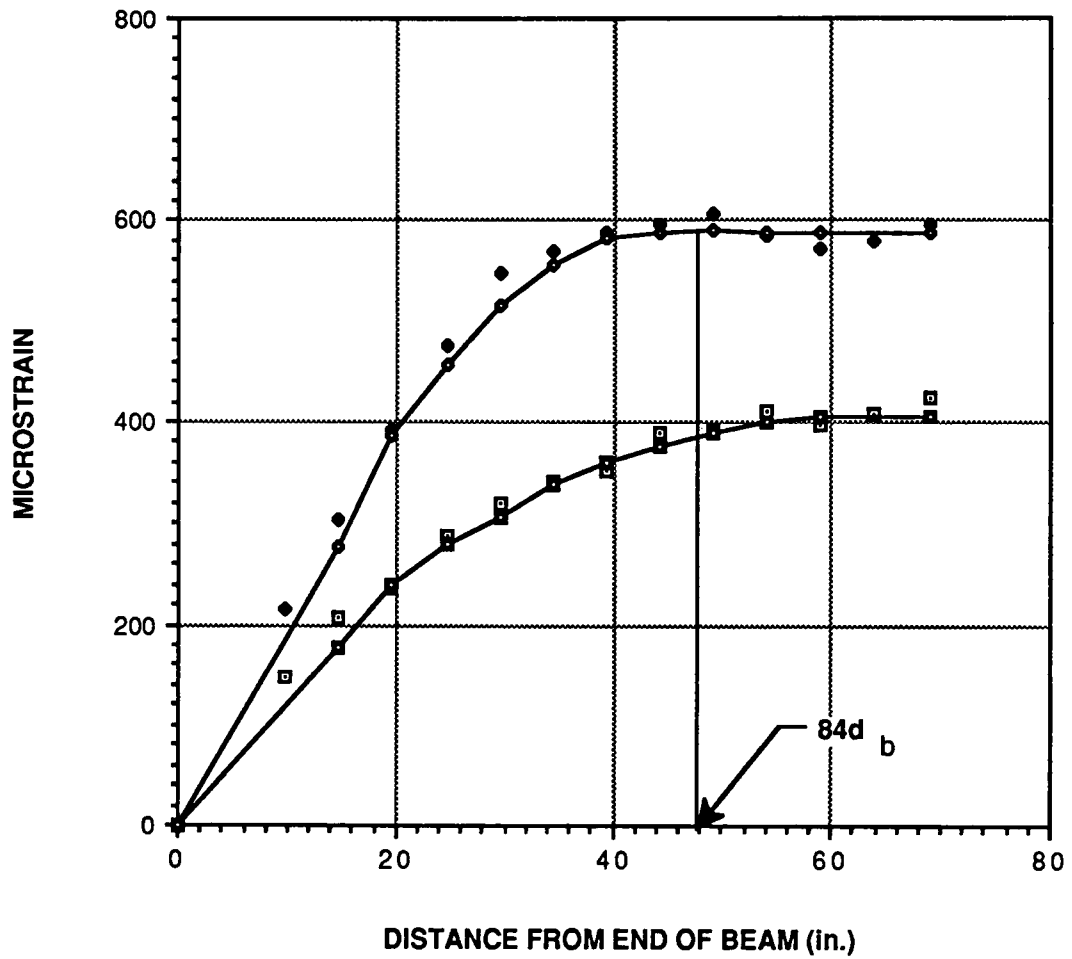
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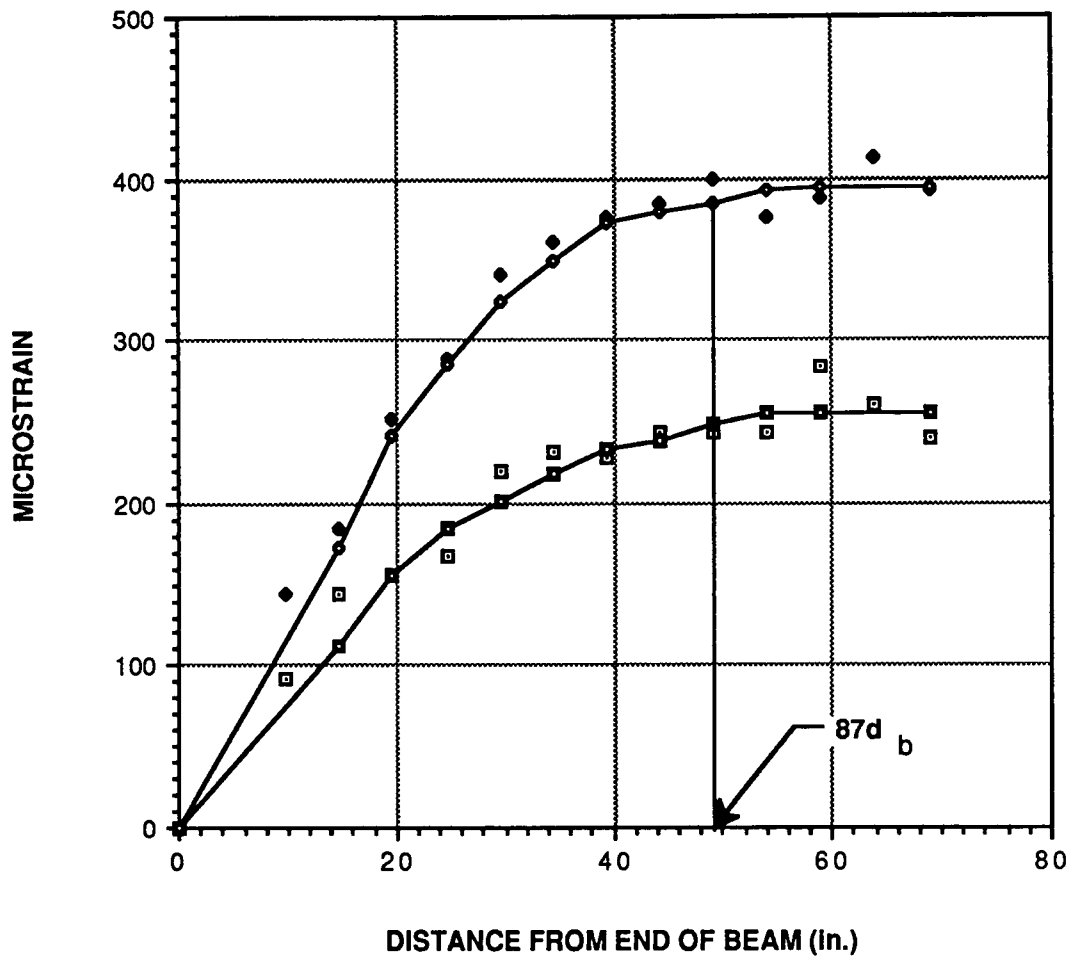
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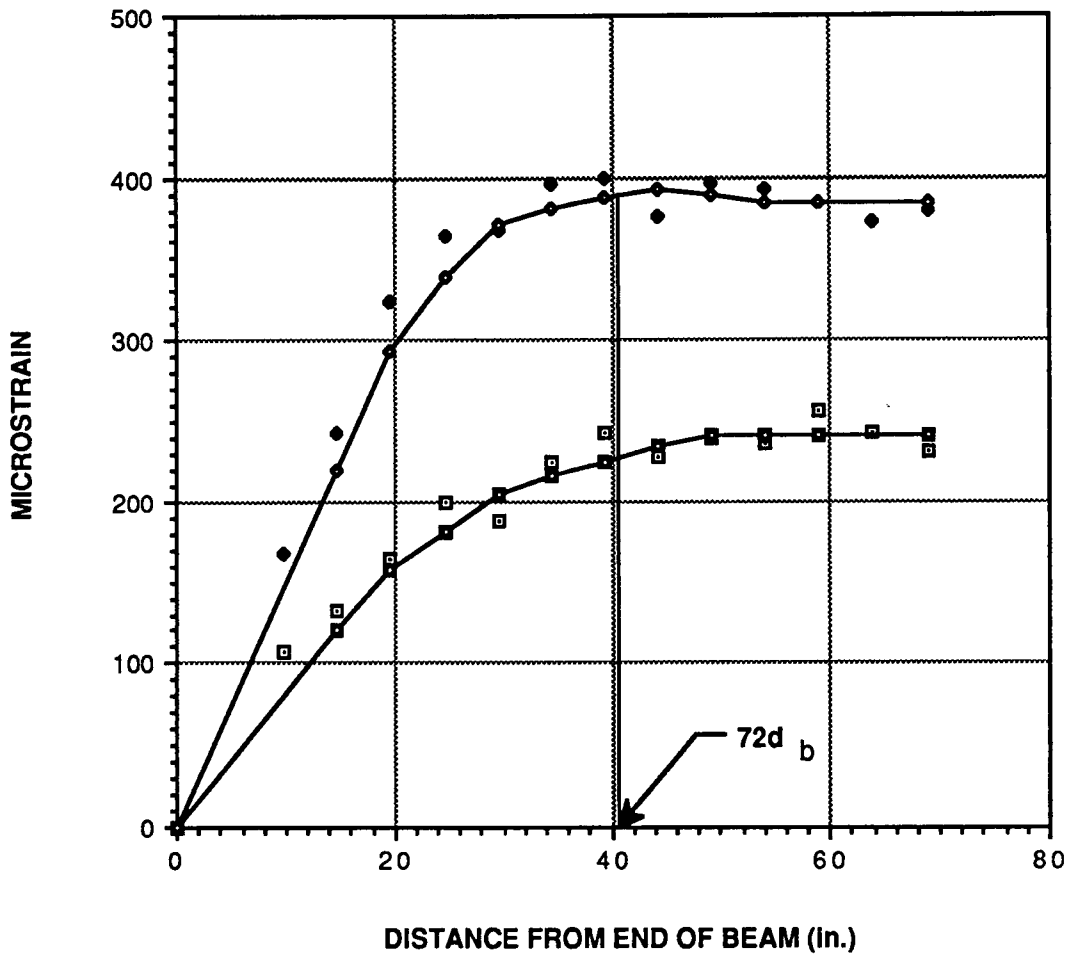
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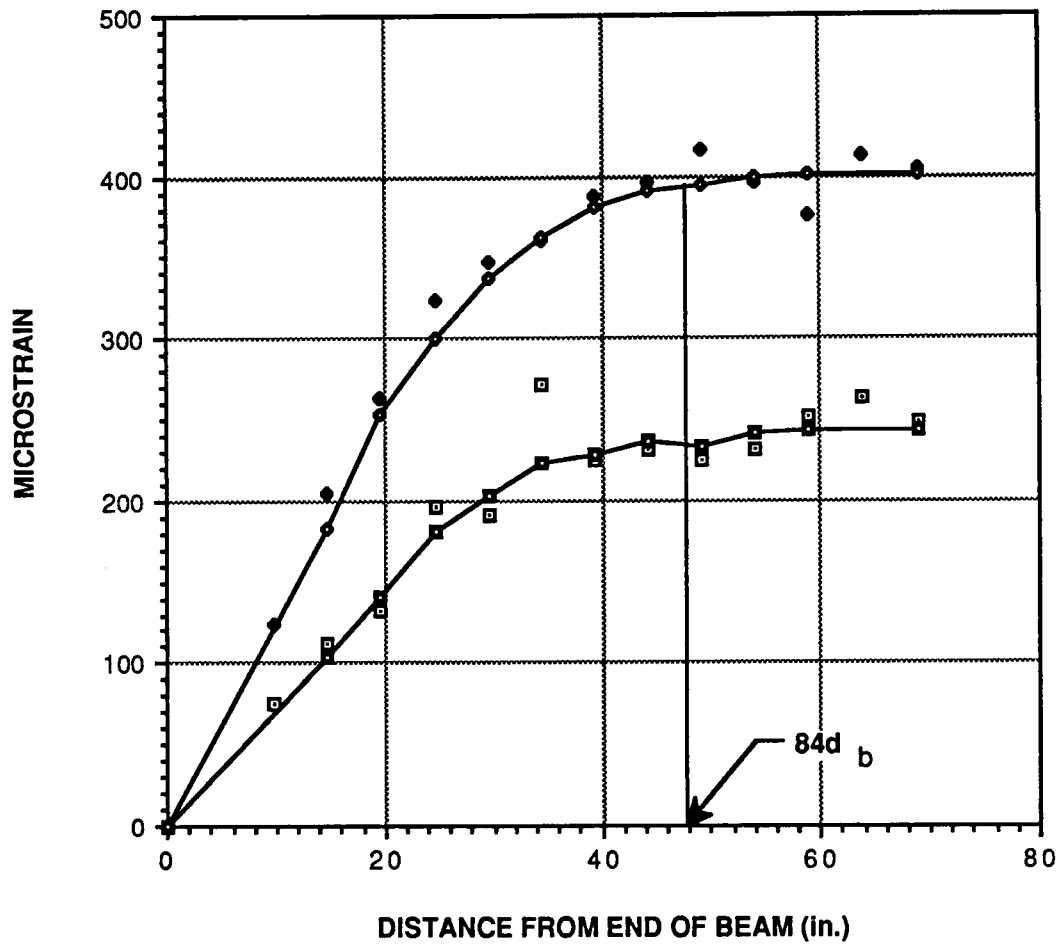
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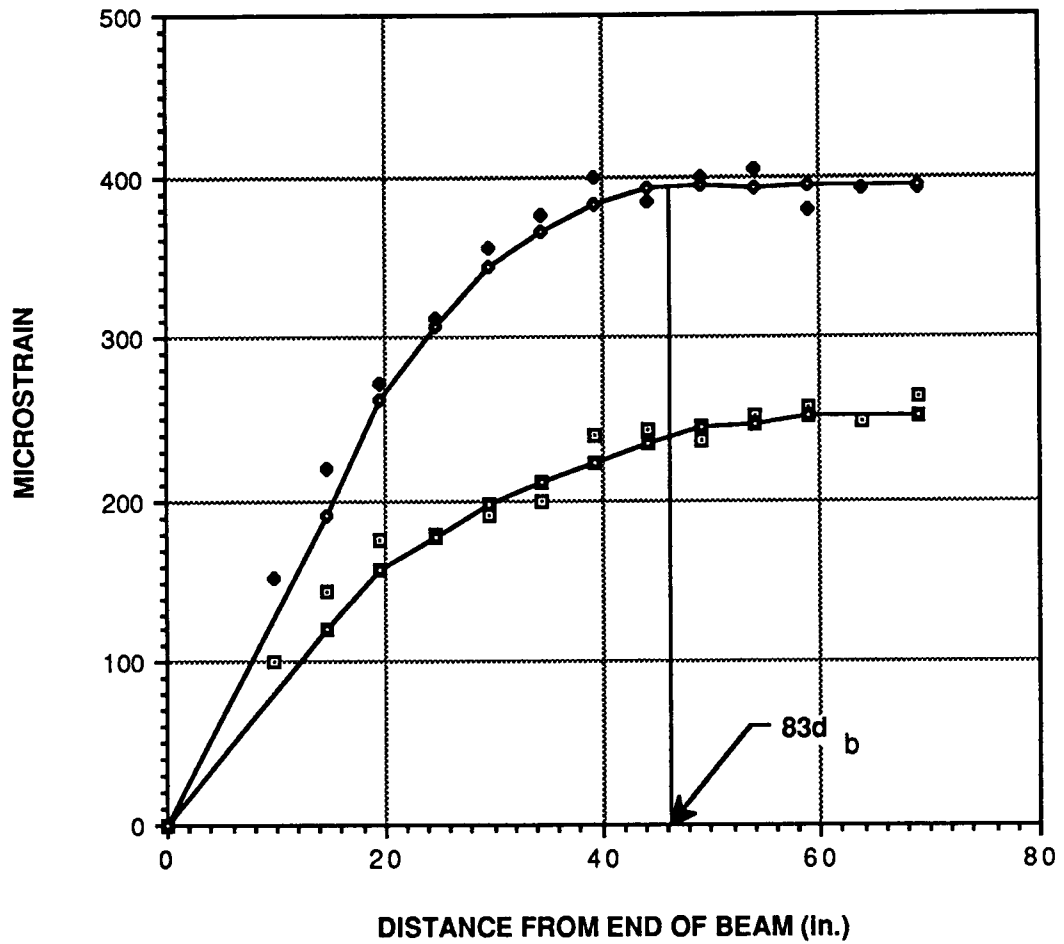
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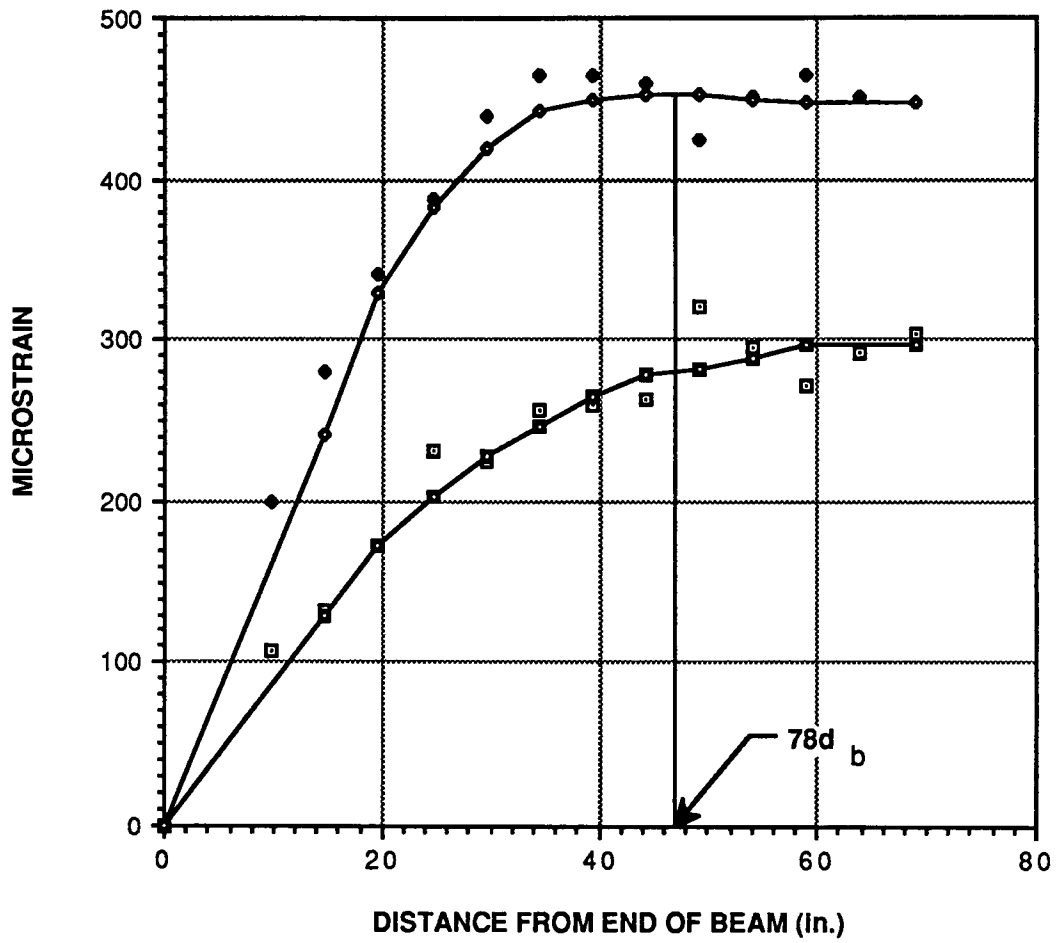
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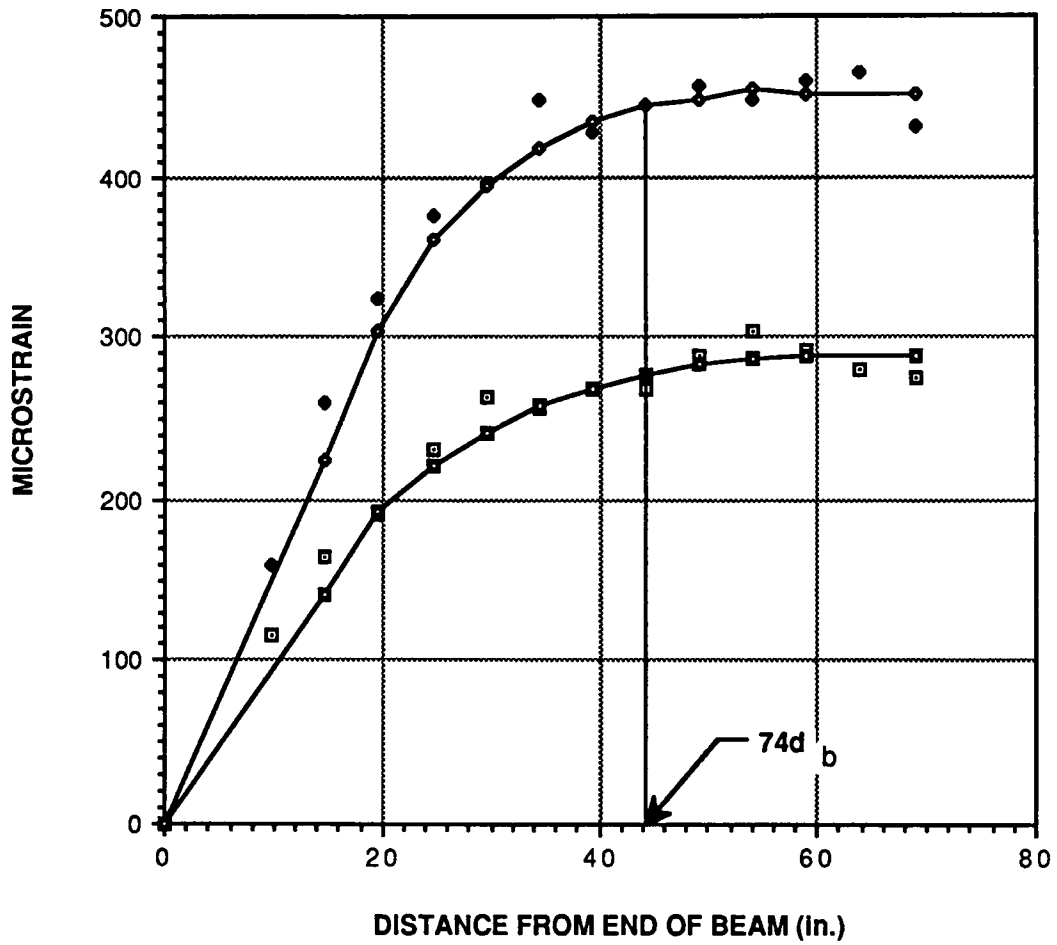
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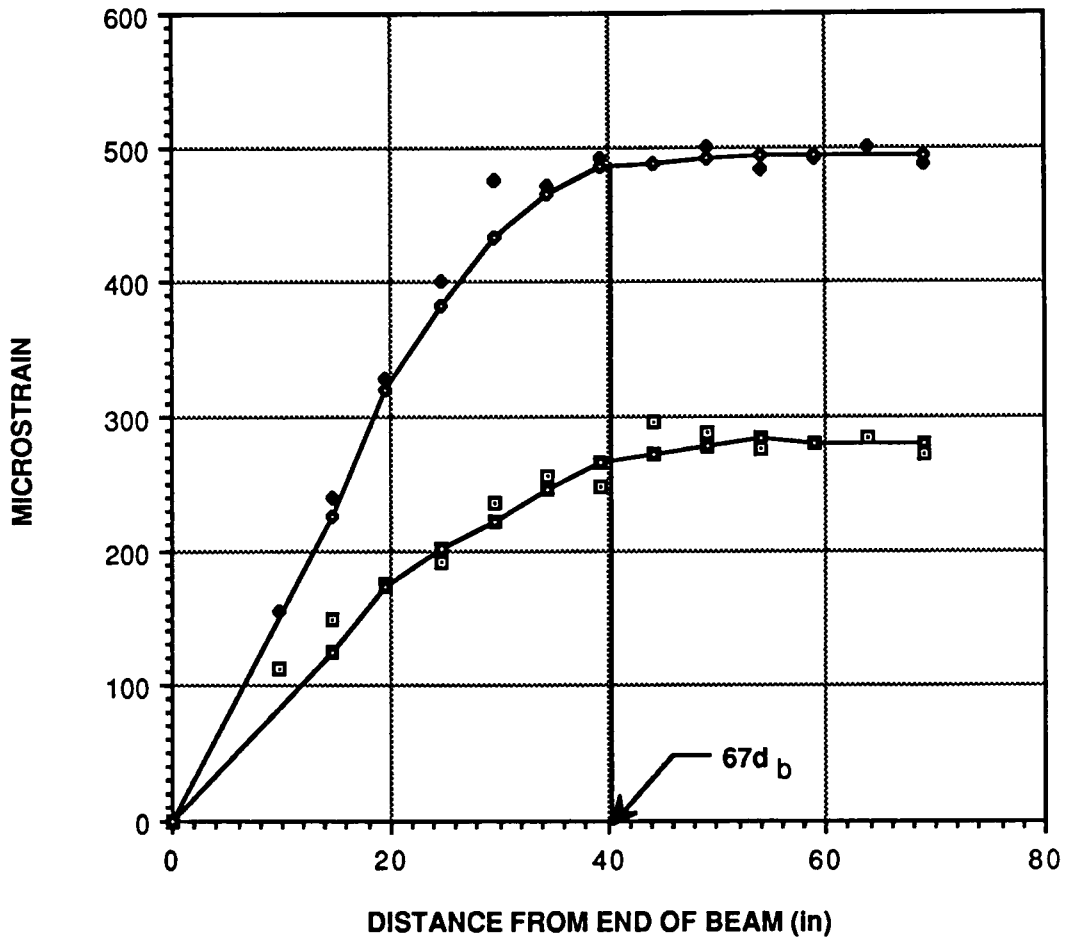
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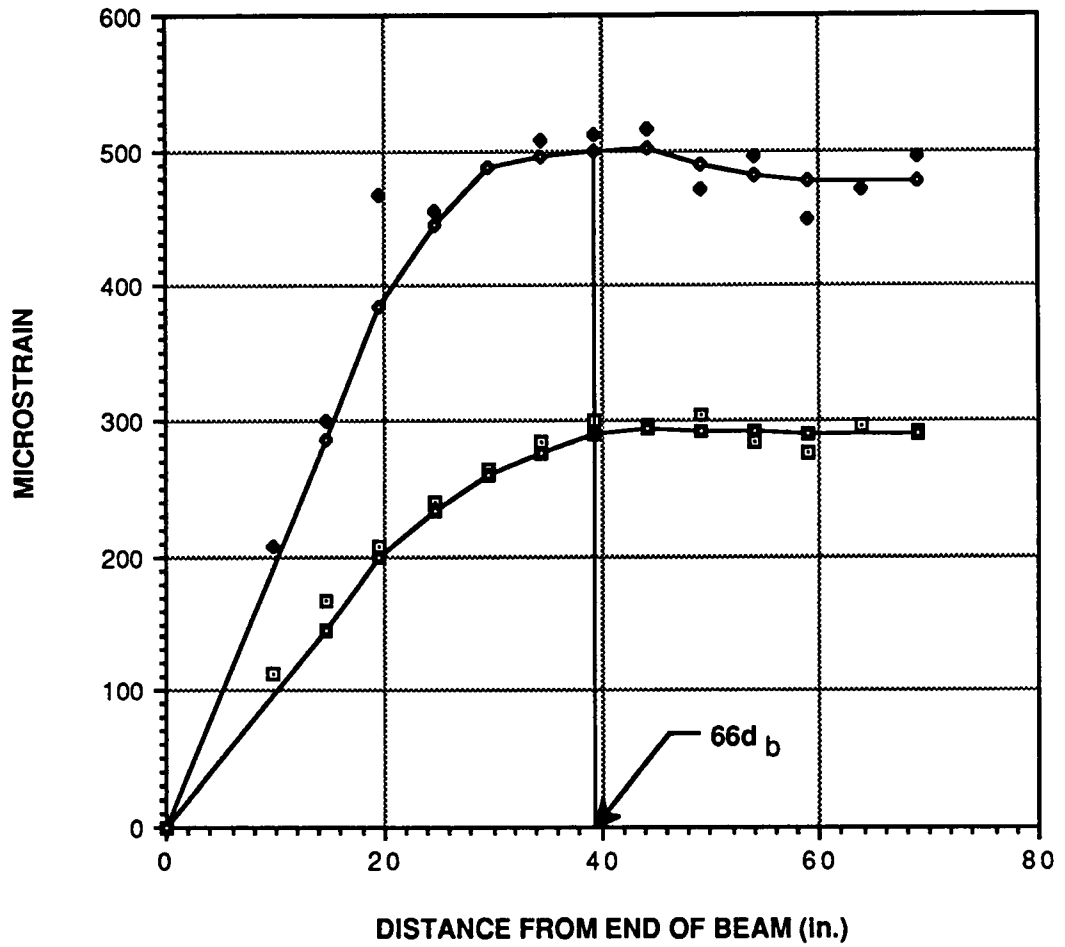
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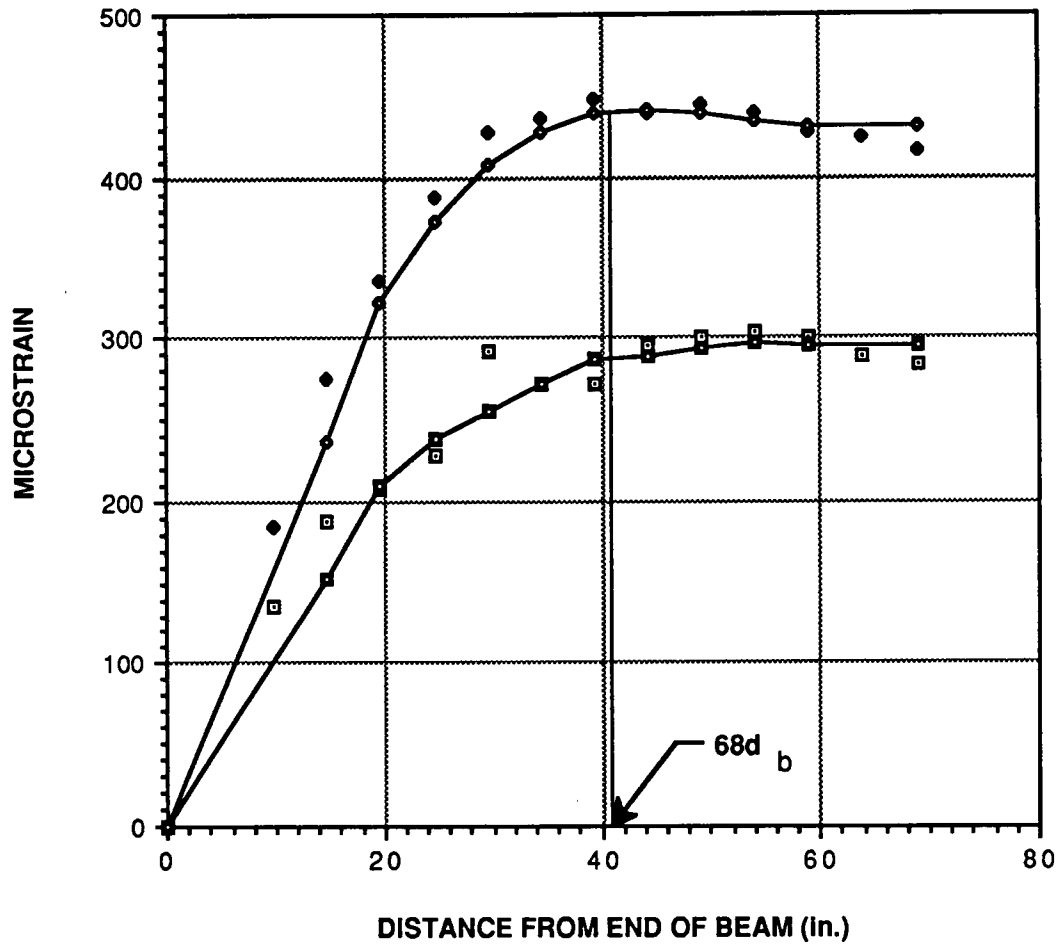
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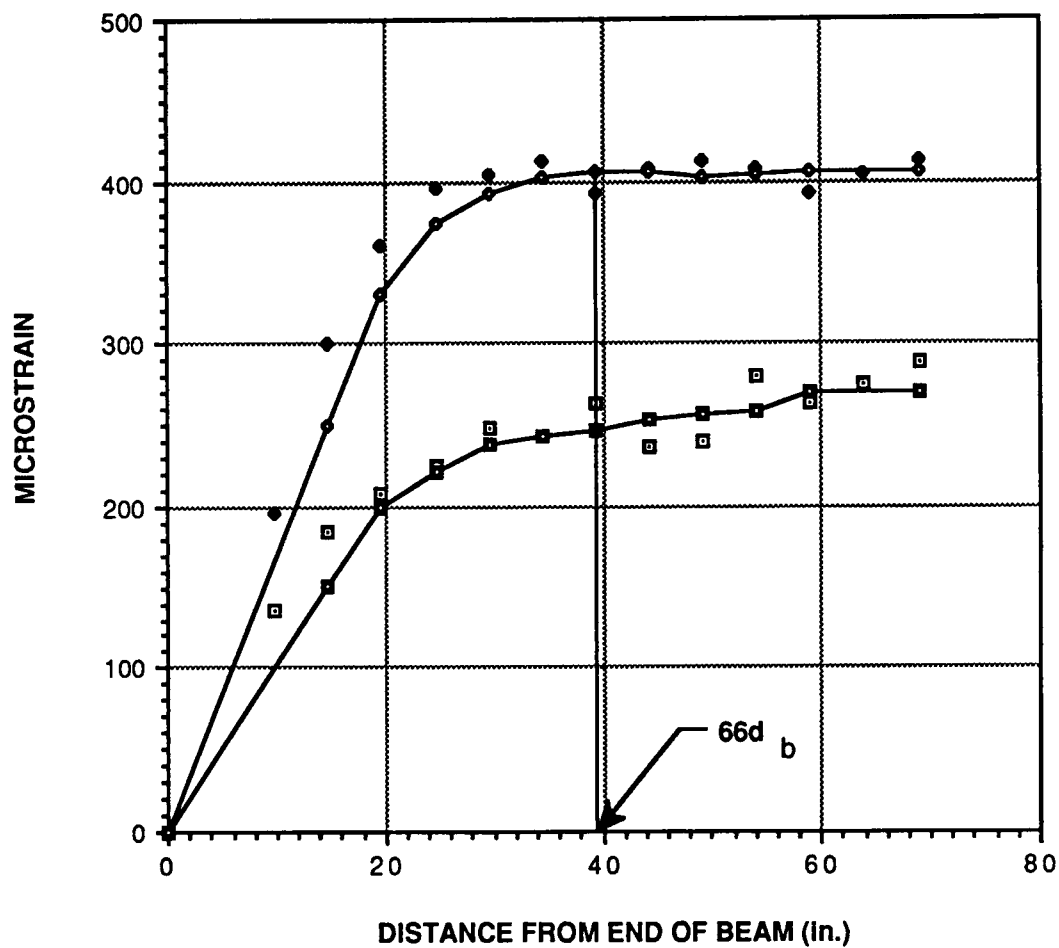
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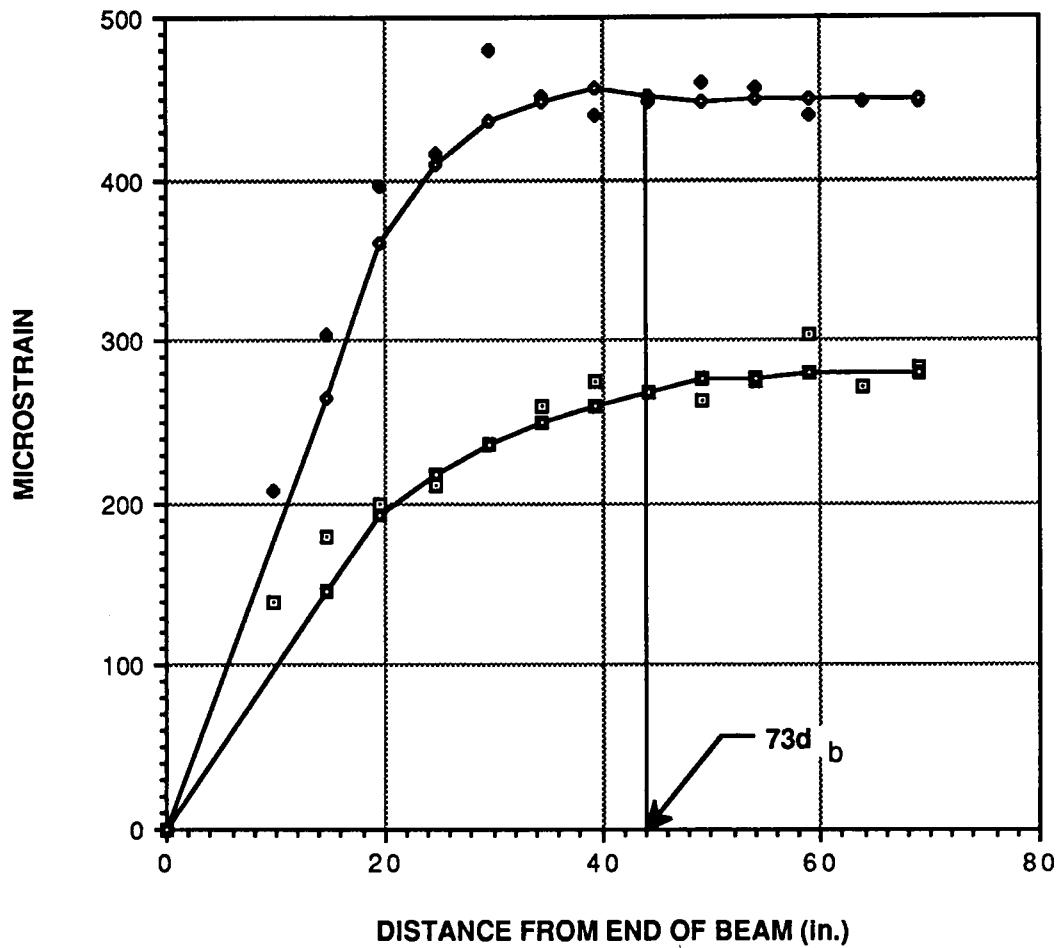
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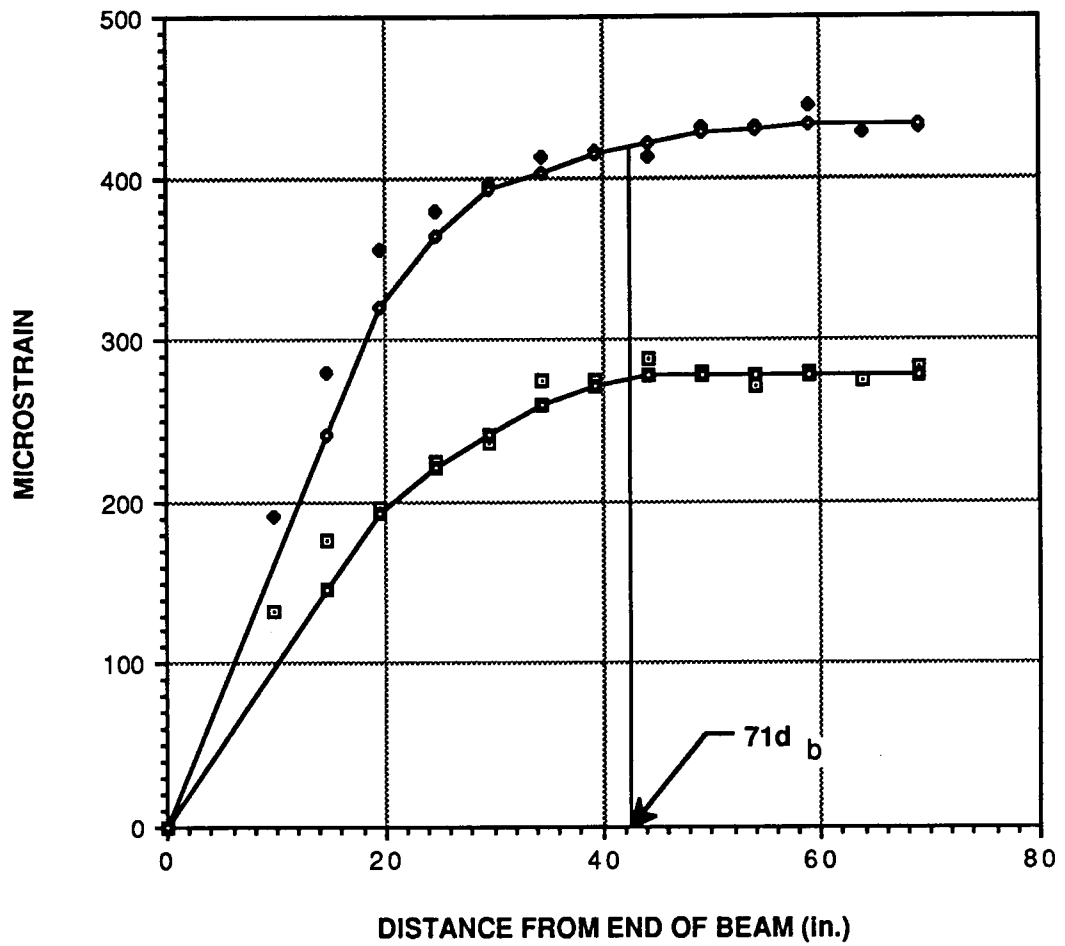
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VITA

Brian Richard Smith was born in Morristown, New Jersey on April 8, 1965. He attended elementary school in his home town of Parsippany, New Jersey and graduated from Parsippany Hills High School in June 1983. The following September he entered the University of Tennessee at Knoxville where he received a Bachelor of Architecture Degree in June 1988. He continued his education at the University of Tennessee, and in December 1989, was granted a Master of Science Degree in Civil Engineering.

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