Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-91+1210-1		

4. Title and Subtitle
MEASUREMENT OF TRANSFER LENGTH ON PRESTRESSING STRANDS IN PRESTRESSED CONCRETE SPECIMENS

5. Report Date
March 1991

6. Performing Organization Code

7. Author(s)
I. O. Unay, B. Russell, N. Burns, and M. Kreger

8. Performing Organization Report No.
Research Report 1210-1

9. Performing Organization Name and Address
Center for Transportation Research
The University of Texas at Austin
Austin, Texas 78712-1075

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
Research Study 3-5-89/1-1210

12. Sponsoring Agency Name and Address
Texas State Department of Highways and Public Transportation; Transportation Planning Division
P. O. Box 5051
Austin, Texas 78763-5051

13. Type of Report and Period Covered
Interim

14. Sponsoring Agency Code

15. Supplementary Notes
Study conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration. Research Study Title: "Influence of Debonding of Strands on Behavior of Composite Prestressed Concrete Bridge Girders"

16. Abstract

On October 26, 1988, the Federal Highway Administration (FHWA) issued a memorandum disallowing the use of 0.6-inch-diameter strand in pretensioned application. Recent studies had indicated that current AASHTO provisions for the transfer length and development length of 0.6-inch prestressing strand were unconservative. On the basis of very limited data, restrictions on 0.6-inch strand were adopted as an interim measure until additional research results were available to either substantiate or restructure code provisions. In response to this research need, this report focuses on determining the transfer length of 0.5-inch and 0.6-inch strand.

Sixty-two (62) transfer length specimens were cast and tested. Of these, 26 were single-strand specimens. Eighteen were three-strand specimens, and six were five-strand specimens. Fifty specimens had rectangular cross sections with concentric prestressing. The remaining twelve sections were I-shaped, designed to resemble the cross section for an AASHTO girder. Research variables included the number of strands, strand spacing (2-inch or 2.25-inch), strand diameter (0.5-inch or 0.6-inch), and the effects of transverse reinforcement. The transfer length of debonded strand was also studied.

Overall, test results indicated that the behavior of 0.6-inch strand is very similar to the behavior of the 0.5-inch strand. Furthermore, the transfer lengths of both 0.5-inch and 0.6-inch strand are closely predicted by AASHTO/ACI provisions.

17. Key Words
prestress, bond, transfer, development, 0.5-inch strand, 0.6-inch strand, concrete, pretensioned, prestressing strand, highways, bridges, girders

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	150	

MEASUREMENT OF TRANSFER LENGTH ON PRESTRESSING STRANDS IN PRESTRESSED CONCRETE SPECIMENS

by

I.O. Unay, B. Russell, N. Burns and M. Kreger

Research Report 1210-1

Research Project 3-5-89-1210

"Influence of Debonding of Strands of Behavior of Composite Prestressed Concrete Bridge Girders"

Conducted for

Texas

State Department of Highways and Public Transportation

In Cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

March 1991

NOT INTENDED FOR CONSTRUCTION,
PERMIT, OR BIDDING PURPOSES

Ned H. Burns, P.E. (Texas No. 20801)

Research Supervisor

Michael E. Kreger, P.E. (Texas No. 65541)

PREFACE

This report is the first in a series of four reports which discuss the transfer and development length of 0.5-inch and 0.6-inch diameter prestressing strand. This first report focuses on the transfer length of prestressing strand in pretensioned applications. Experimental procedures, data collection, previous research and possible conclusions are discussed in detail.

The second, third and fourth reports focus on development length and flexural bond behavior. The second report discusses transverse post-tensioning to strengthen shear capacity for the concrete and, at the same time, increase flexural bond capacity for prestressing strand. The third report discusses the development length of prestressing strand, both 0.5-inch and 0.6-inch, in conventional AASHTO-type sections. The fourth report focuses on flexural bond issues for debonded strands. Later reports are expected to focus on fatigue testing and more comprehensive design guidelines as a summary of results from the entire project.

This work is part of Research Project 3-5-89-1210, entitled "*Influence of Debonding of Strands on Behavior of Composite Prestressed Concrete Bridge Girders.*" This project was modified in March 1989 to include transfer and development length testing for 0.6-inch strand. The work performed under the modification is reported primarily in the first three reports. The principles learned in the research done under the modification contribute directly to the primary research objectives for debonded strands.

The research is being conducted at the Phil M. Ferguson Structural Engineering Laboratory as part of the overall research program for the Center for Transportation Research of the University of Texas at Austin. The work is sponsored jointly by the Texas SDHPT and the FHWA.

Liaison with the TSDHPT is maintained through the contact representative, Mr. David P. Hohmann. Ms. Susan N. Lane of the FHWA has been quite active in her support and consultation on the research.

This overall study is directed by Dr. Ned H. Burns who holds the Zarrow Centennial Professorship in Civil Engineering. Dr. Michael E. Kreger, Associate Professor of Civil Engineering has assisted the project by reviewing the efforts. Graduate Research Assistants who made significant contributions to this project were Raheel Malik, Bruce Russell, Asit Baxi, Bruce Lutz, Les Zumbrunnen, and Riyad Aboutaha.

SUMMARY

On October 26, 1988, the Federal Highway Administration (FHWA) issued a memorandum disallowing the use of 0.6-inch diameter strand in pretensioned application[29]. Recent studies[18] had indicated that current AASHTO provisions for the transfer length and development length of 0.6-inch prestressing strand were unconservative. On the basis of very limited data, restrictions on 0.6-inch strand were adopted as an interim measure until additional research results were available to either substantiate or restructure code provisions. In response to this research need, this report focuses on determining the transfer length of 0.5-inch and 0.6-inch strand.

Sixty-two (62) transfer length specimens were cast and tested. Of these, twenty-six (26) were single-strand specimens, eighteen (18) were three-strand specimens, and six (6) were five-strand specimens. These fifty (50) specimens all had rectangular cross sections with concentric prestressing. The remaining twelve (12) specimens were I-shaped, designed to resemble the cross section for a standard AASHTO girder.

Research variables included the number of strands, strand spacing (2 in. or 2.25 in.), strand diameter (0.5-in. or 0.6-in.) and the effects of transverse reinforcement. The transfer length of debonded strand was also studied.

These tests utilized detachable mechanical strain measuring devices (Demec) to detect before and after concrete strains at the outside face of the test specimens. The transfer length of each specimen was determined by statistical examination of the concrete strain profile. It was observed that the concrete strain increases from the end of the specimen until a plateau is achieved, signalling a fully effective prestress force. Transfer length is the distance from the beginning of bond (usually the end of the beam) to the point where the prestress force is fully effective.

The initial test series was comprised of eighteen (18) single-strand specimens. Data from these tests indicated that current AASHTO/ACI provisions were unconservative. However, the test results were scattered over a wide range of values. Similar variations are apparent in the measured transfer lengths of other research performed on single strand specimens. Unfortunately, a significant portion of the transfer length research has been performed on specimens with small cross sections and a single strand.

Subsequent multi-strand tests, eighteen (18) three-strand and six (6) five-strand specimens, and an additional eight (8) single-strand specimens, showed markedly less divergent results. Transfer length measured in these two types of specimens were only slightly longer than AASHTO/ACI provisions.

In the last series of tests, twelve (12) specimens with AASHTO-type I-sections, the measured transfer lengths were actually slightly shorter or equal to AASHTO/ACI predictions for both 0.5-inch and 0.6-inch strand. For the 0.5-inch strand, the average measured transfer length for these specimens was 19.8 inches. For the 0.6-inch strand, the average measured transfer length was 32 inches.

Overall, test results indicated that the behavior of 0.6-inch strand is very similar to the behavior of the 0.5-inch strand. Furthermore, the transfer length of both 0.5-inch and 0.6-inch strand are closely predicted by AASHTO/ACI provisions.

IMPLEMENTATION

This research project is a direct result of the Federal Highway Administration (FHWA) moratorium disallowing use of 0.6-inch prestressing strand in pretensioned application. This research clearly demonstrates that the transfer length of 0.6-inch strand is closely predicted by current AASHTO/ACI practices. Furthermore, the behavior of specimens with 0.6-inch strand is very similar to 0.5-inch strand specimens. Therefore, wholesale changes to transfer length provisions as they apply to 0.5-inch and 0.6-inch strand are not warranted.

This report is part of an ongoing research effort which extends to development length testing. In light of this transfer length test program and the forthcoming information on development length, a review of the current restrictions on use of 0.6-inch and 0.5-inch prestressing strand is warranted.

The only changes to AASHTO/ACI practices that are supported by this research are that transfer length is a function of both concrete release strength and the size and shape of the cross section, and the number of prestressing strands for the cross section.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

CHAPTER ONE
INTRODUCTION

1.1 Background and Definition of Problem

Since the concept of prestressed concrete was introduced to construction technology in the late 1920's and was actually practiced in the 1930's, there have been great improvements in the field of prestressed concrete. The transformation from the bond-wise ineffective prestressing wire to seven-wire prestressing strand which has a significant bonding capacity was a milestone. Since then, the utilization of prestressed concrete construction has increased significantly against steel and reinforced concrete construction in many types of structures, including bridges.

The tendency of the industry towards economy in construction has caused the original 1/4-inch diameter prestressing strand to be replaced by 3/8-inch diameter strand which was later replaced by 0.5-inch diameter strand, the current industry standard. Also, the characteristics of the prestressing strand have changed as the strand with higher yield strength and low relaxation characteristics has dominated the market. All these improvements together with the usage of high-strength concrete have resulted in fewer strands per beam, smaller cross sections, lighter beams and longer spans, which led to significant reduction in handling and material costs. In order to achieve further economy, 0.6-inch strand had found increasing use in pretensioned applications.

Unfortunately, preliminary research performed at North Carolina State University in 1986[18] had shown that the current AASHTO equation, number 9-32, was greatly unconservative for development length, and that the measured transfer length was much greater than standard industry guidelines. This led the Federal Highway Administration to issue a moratorium on the use of 0.6-inch strand in pretensioned applications. This action by FHWA led to a concerted research effort to establish behavioral characteristics for 0.6-inch strand that can be used as guidelines for using 0.6-in. strand in pretensioned applications. Therefore, this report is, in part, a study of the transfer length requirements for 0.6-inch strand.

In pretensioned beams, excessive tensile and compressive stresses in the concrete near the ends above code limitations might exist. In order to control these excessive stresses, generally, the strands have been draped. However, many prestressing plants don't produce beams with draped strands because of the relatively high cost of hold down devices and the time and equipment required to stress and depress the inclined strands. Debonding some of the prestressing strands in production of standard prestressed concrete bridge girders has been an alternative to draping strands. Since debonding is easy to apply, this will bring more prestressing plants into competition, which may lead to further economy. However, little research has been done in this field. Common practice of determination of debonded lengths is based on engineering judgements rather than experimental data. It has been observed in some very limited tests that cracking develops at the termination points of debonding which may lead to inclined shear cracks.

Past research has concentrated on the determination of development length. In case of debonded strands in prestressed beams, determination of development length is important. Debonding of strands shifts development length significantly towards the center of the beam.

The current code provisions for development length, provided by American Concrete Institute (ACI) and American Association of State Highways and Transportation Officials (AASHTO) are based on research, mainly conducted in the 1950s and 1960s. However, the current design practice utilizes improved materials which are quite different from materials used in past studies. Code provisions need to be adjusted for utilization of these improved materials.

Past research on debonding of strands is very inconclusive and therefore there are heavy restrictions on debonding of strands. More research is needed on the actual behavior of prestressed concrete beams utilizing debonded strands.

1.2 Objective of the Research Program

The primary objective of this research project is to develop design guidelines for pretensioned composite concrete girders. More specifically, we wish to develop design guidelines for the transfer and development of prestressing strand, both 0.5-inch and 0.6-inch diameter strand; and, building on that effort, to develop rational guidelines for the use of debonded or blanketed strand.

Transfer and development of strand both are problems concerned with the bond between concrete and the prestressing strand. Bond and its associated behavior is a complex mechanics problems involving many different components. To begin this study, the transfer length is studied first. The information gained on transfer length will lead to better understanding of transfer length, but also a better understanding of the flexural bond problems as well.

1.3 Objective of this Report

This report presents the results and conclusions of the transfer length tests. Sixty-two transfer length specimens were cast. Transfer lengths were measured for each specimen. The results and conclusions are presented in this report. Also, a review of previous research on transfer length is included.

1.4 Scope of Tests

Forty-four specimens were cast in addition to eighteen specimens which are covered in a previous report on the same project. The number and size of strands, and the dimensions of beams and debonding patterns were varied in order to investigate the effect of different variables. Transfer length of each specimen was determined by constructing the concrete strain profile for each specimen. Also, strand strains, end slip, and elongations were measured in order to verify the results and to provide additional information.

Strands of 0.5-inch and 0.6-inch diameters in both fully bonded and debonded conditions were used. The level of stress in the strand mimics standard practice.

1.5 Organization

This report starts with a review of currently available literature on bond characteristics and transfer length of prestressing strands in Chapter 2. Test setup, instrumentation, testing procedure, and material properties are covered in Chapter 3. The method of analysis and results are given in Chapter 4. The results are discussed in Chapter 5, which is followed by the comparison of results with previous research in Chapter 6. Conclusions are presented in Chapter 7. The table of notation is provided in Appendix D.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

Since the bond studies of Hoyer(1) in 1939, more than thirty such investigations have been reported. However, most of the early research was conducted with prestressing wires which are no longer in use. The focus of the rest of the research has been the study of 0.5-inch diameter and smaller seven-wire strands. The recently developed 0.6-inch diameter strand has rarely been tested for transfer or development length. Studies on the behavior of debonded strands have not been conducted on 0.6-inch diameter strand and have not revealed conclusive information in the few tests with 0.5-inch diameter strand.

This chapter covers the bond mechanism, bond types, and a literature review of currently available transfer length research.

2.2 Nature of Bond

Past research has clearly shown that in non-end-anchored pretensioned members, there are two types of bond: transfer bond and flexural bond. Transfer bond is activated at transfer of prestress, whereas flexural bond is activated only when the member undergoes loading with cracking and flexural failure. The mechanism of failure was first recognized by Janney(2) in 1954.

2.2.1 Transfer Bond. Tensile force in the prestressing strand is transferred to concrete entirely by bond in the end regions of a prestressed member. Transfer bond utilizes a part of the available tensile strength of the strand to establish compression in the concrete. The distance over which the effective prestressing stress, f_{se}, in a pretensioned strand is transferred by bond to concrete is called the transfer length (Figure 2.1). The transfer length mainly depends on the amount of prestress, surface condition of the strand, the strength of the concrete and the method of steel stress release.

The major cause of transfer bond are friction between steel and concrete, and mechanical resistance. At the time of transfer of prestress, the diameter of the strand increases along the transfer length due to Poisson's ratio effect and causes compressive forces on the interface between steel and concrete, which results in friction forces. Mechanical resistance is provided by uneven concrete strand surface due to the helical winding of wires in the strand. Since transfer of effective prestressing occurs at the end regions, there is no relative movement of the strand with respect to concrete in the central part of the beam, and the change in concrete strain, theoretically, should be the same as the change in strand strain.

2.2.2 Flexural Bond. In prestressed members, the strand develops bond stresses as a result of flexural forces. The additional bond length required to develop from the effective prestress to the ultimate stress, f_{ps}, in the prestressing strand at the ultimate flexural strength of the member is called the flexural bond length. Although the increase in steel stress due to flexural forces is not significant under normal service conditions (uncracked), it increases dramatically as cracks occur. The bond stress in the immediate vicinity of the cracks rises to some limiting stress. As slip occurs over small lengths adjacent to the cracks, the bond stresses near the cracks are reduced. With the continued increase in load, the high bond stress progresses as a wave towards the ends of the member. If the peak of the bond stress wave reaches the prestress transfer zone, the increase in steel stress resulting from the bond slip, reduces the diameter of the strand which leads to less frictional bond resistance and causes general end slip (Figure 2.2). Afterwards, mechanical resistance is the only factor which can contribute to bond between concrete and steel.

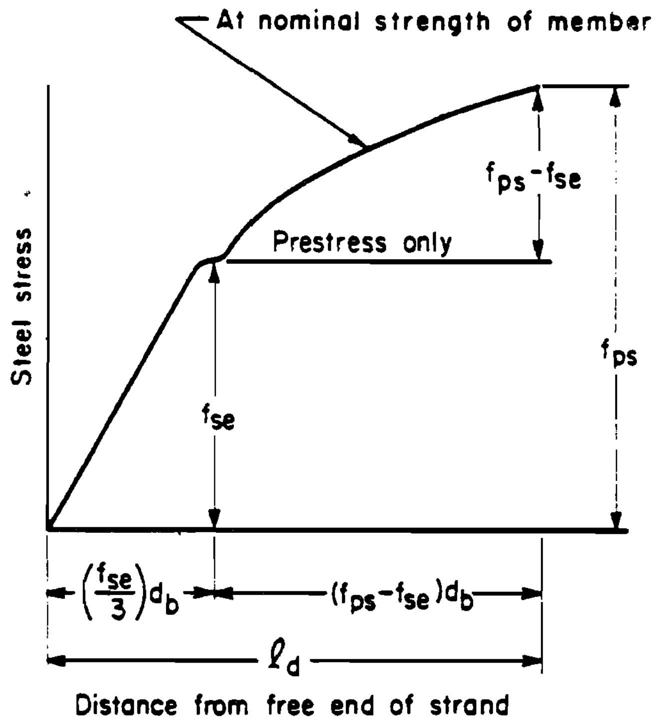


Figure 2.1 Variation of steel stress with distance from free end of strand. Used as the basis for ACI/AASHTO formula[21,22].

The sum of transfer length and flexural bond length is the development length (Figure 2.1).

2.3 Variables Which Have Been Studied

Most bond studies of pretensioned concrete beams have been confined to prestress transfer bond rather than flexural bond. In the bond studies, the effects of the following variables have been studied[15]:

1) Type of steel
2) Strand size

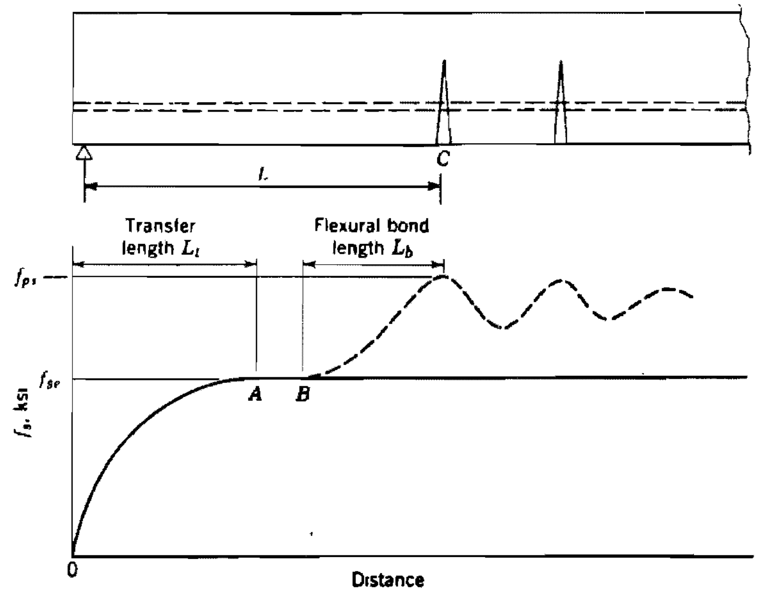


Figure 2.2 Flexural bond overlapping with transfer length[15].

4) Surface condition of steel
5) Concrete compressive strength
6) Type of loading
7) Type of release
8) Confining reinforcement around steel
9) Time dependent effects
10) Consolidation and consistency of concrete around steel
11) Amount of concrete cover around steel

A table of variables investigated in each individual research project is provided in Table 2.1

The following sections report the proposed formulas and research conducted on transfer length.

2.4 Transfer Length Studies

In this section, major studies conducted on transfer length are reported. Only studies utilizing currently used materials and material properties are reported.

In 1963 Janney[5] conducted tests on transfer length with Grade 150K and 270K seven-wire prestressing strands. Six specimens were cast and tested. Two

Table 2.1
List of Variables Investigated

Janney[5], 1963	1) 2)	Type of strand Surface condition of strand
Kaar, LaFraugh, and Mass[6], 1963	1) 2) 3) 4)	Strand size Concrete compressive strength Type of release Time dependent effects
Over and Au[7], 1965	1)	Strand size
Kaar and Magura[8], 1965	1)	Effect of strand blanketing
Kaar, Hanson, Corley and Hognestad[9], 1975	1) 2)	Surface condition of strand Type of release
Dorsten, Hunt and Preston[16], 1984	1)	Effect of coating
Cousins, Johnston and Zia[18], 1986	1) 2)	Strand size Effect of coating
Castrodale, Burns, and Kreger[20], 1988	1) 2)	Concrete compressive strength Type of release
Deatherage and Burdette[24], 1990	1) 2) 3)	Strand size Steel stress level Surface condition of strand
Malik[26], 1990	1) 2) 3) 4) 5)	Strand size Type of release Confining reinforcement around strand Amount of concrete around strand Effect of debonding

In 1963 Janney[5] conducted tests on transfer length with Grade 150K and 270K seven-wire prestressing strands. Six specimens were cast and tested. Two specimens were prestressed with Grade 250K, 0.5-inch diameter strand which was clean and bright. Two were prestressed with Grade 270K, 0.5-inch diameter strand which was clean and bright. Two were prestressed with grade 270K, 0.5-inch diameter strand which had a medium coat of rust over the surface. The specimens were of 3.5-in. x 4.5-in. cross-section and 8-ft. long, and had a single strand at the centroid of the cross-section. Mechanical gage points were used to measure concrete strain. Detensioning took place when tests on the concrete cylinders indicated that the concrete compressive strength reached 4000 psi. The only variables included in this study were the type and surface condition of the strand. The results are given in Table 2.2. Janney concluded that the transfer length was slightly longer for grad 270K strand because of the higher initial pretension stress. It was stated that as a result of the satisfactory performance from these tests, small diameter Grade 270K strand would be satisfactory with respect to stress transfer for all normal applications.

Table 2.2
Transfer Length of 0.5-in.
Strand Janney, 1963[5]

Ultimate Strength (ksi)	Surface Condition	f_{se} (ksi)	f'_c (psi)	Transfer Length (in.)
270	Clean	175.8	4115	33
270	Rusted	175.8	4090	24
250	Clean	150.0	4200	28

In 1963, Kaar, LaFraugh and Mass[6] studied the influence of concrete strength on the transfer length. Strands of 1/4-, 3/8-, 0.5-, and 0.6-inch diameter were used to prestress rectangular section members having concrete compressive strengths of 1660, 2500, 3330, 4170 and 5000 psi. Only the results for concrete compressive strengths of 4170 and 5000 psi are reviewed here because these are the strengths which are pertinent to currently used material. The ultimate strength of the strands varied between 253 ksi and 275 ksi. Strand stress immediately after transfer varied between 0.58 f_{pu} and 0.72 f_{pu}. The strands used were Grade 250K, stress-relieved seven-wire strands. The transfer lengths were obtained by plotting the change in concrete strain. The strains were measured by use of a Whittimore gage and brass discs. In order to observe the effect of time, readings were taken at the following intervals over a year: 1, 3, 7, 14, 28, 56, 90, 180 and 365 days after transfer. All transfer lengths reported were adjusted to reflect a strand tension after transfer of 175 ksi (0.7 f_{pu}). The results are reported in Table 2.3. The authors concluded that concrete strength at transfer of prestress had little influence o the transfer length of seven-wire strands up to 0.5-inch diameter. The method of flame-cutting was observed to increase transfer length by 20% for 0.5-inch strands and by 30% for 0.6-inch strands on the cut ends compared to dead ends. The average increase in transfer length over one year was 6%. Effects of strand diameter, concrete strength, and strand tension, as reported by the researchers, are illustrated in Figures 2.3, 2.4 and 2.5, respectively.

Table 2.3
Transfer Length Kaar, LaFraugh and Mass, 1963[6]

Strand Diameter (in.)	Concrete Strength (psi)	Type of Release	Transfer Length (in.)		
			1 (days)	28 (days)	365 (days)
3/8	4170	Sudden	-	-	-
		Gradual	-	-	-
	5000	Sudden	25.5	26.0	27.5
		Gradual	20.0	23.0	27.5
0.5	4170	Sudden	37.0	35.5	27.5
		Gradual	34.0	34.0	38.0
	5000	Sudden	41.0	42.0	44.0
		Gradual	34.0	36.5	37.5
0.6	4170	Sudden	39.0	38.5	40.5
		Gradual	31.5	32.5	33.5
	5000	Sudden	39.5	40.5	39.0
		Gradual	28.5	30.0	32.0

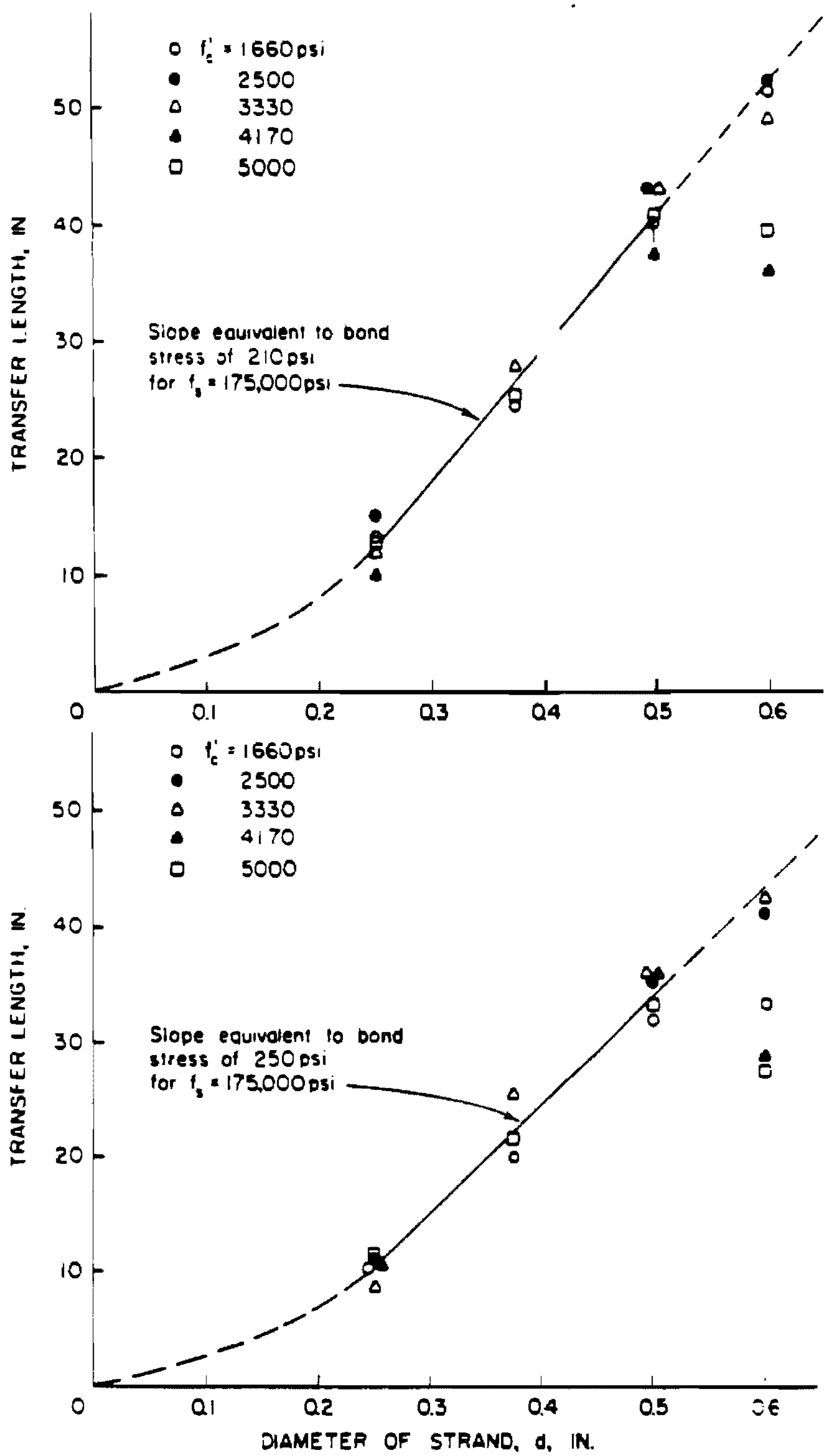


Figure 2.3 Relation of prestress transfer length to strand diameter at a) cut end and b) dead end[(6)].

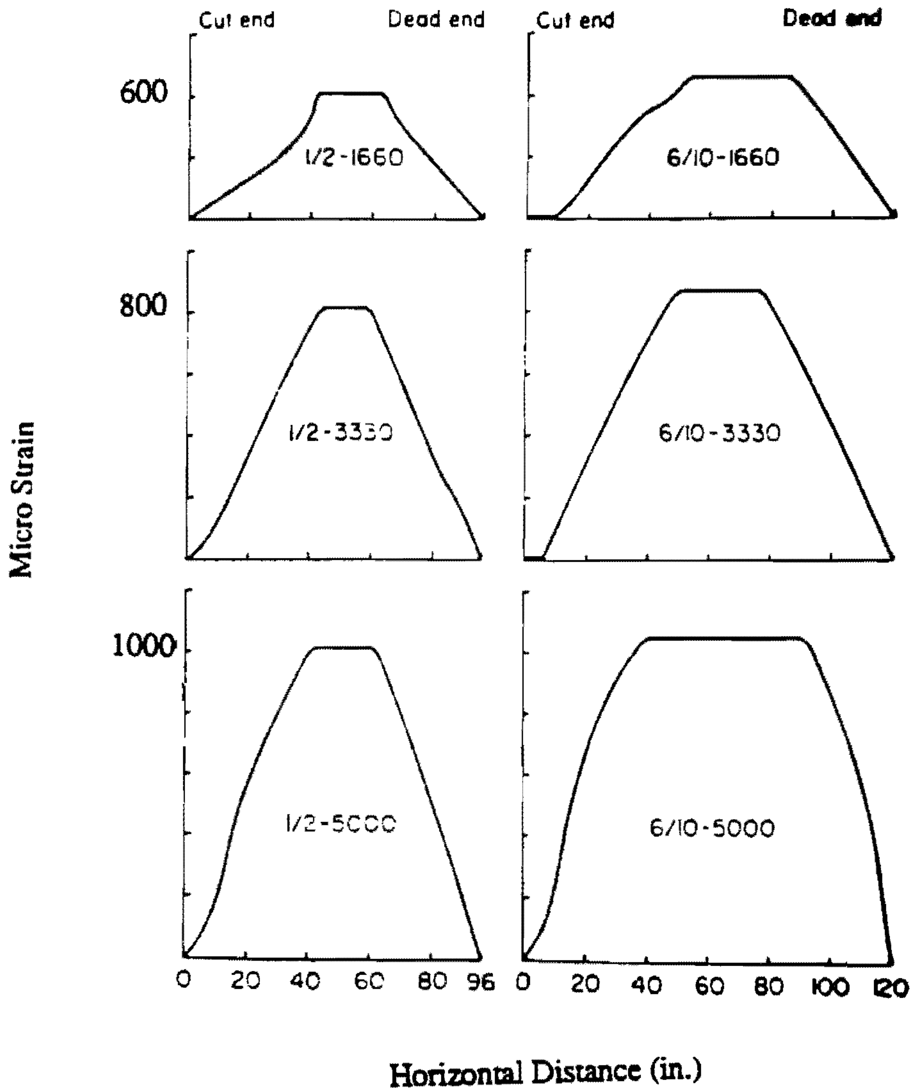


Figure 2.4 Effect of concrete strength at transfer on transfer length of 0.5-inch and 0.6-inch diameter strand[6].

In 1965, Over and Au[7] discussed the frictional and mechanical bond of seven-wire strand used in pretensioned concrete. The principal variable investigated was the size of strand. Tests were made on a limited number of specimens with pretensioned strands of 1/4-, 3/8- and 0.5-inch diameter and also on a specimen with single wire of 1/4-inch. The results are given in Table 2.4 and steel stress profiles are shown in Figure 2.6. The authors concluded that:

Table 2.4
Transfer Length
Over and Au, 1965[7]

Strand Diameter (in.)	Concrete Strength (psi)	Size of Prism (in.)	f_{se} (ksi)	Transfer Length (in.)
0.5	5500	3x3x80	170	35
3/8	4180	3x3x60	160	30
1/4	4900	3x3x60	164	20
0.25 (wire)	4720	3x3x60	192	29

1) The transfer length required is longer for strands of larger nominal diameter

2) Multi-wire strands will develop additional stress in concrete through mechanical bond after a general slip

3) Multi-wire strands require shorter transfer length than single-wires of equal strength and stress.

In the same year, Kaar and Magura[8] studied the effect of strand blanketing on performance of pretensioned girders. Plastic tubing was used to sheath the strands in the end regions of the beams to prevent bonding. If inadequate embedment length is provided, ultimate strength is governed by bond rather than flexure. The authors reported that bond slippage of strands occurs in three stages:

1) Progressive bond slip is initiated along the entire embedment length.

2) General bond slip is initiated along the entire embedment length

3) The mechanical interlocking is destroyed.

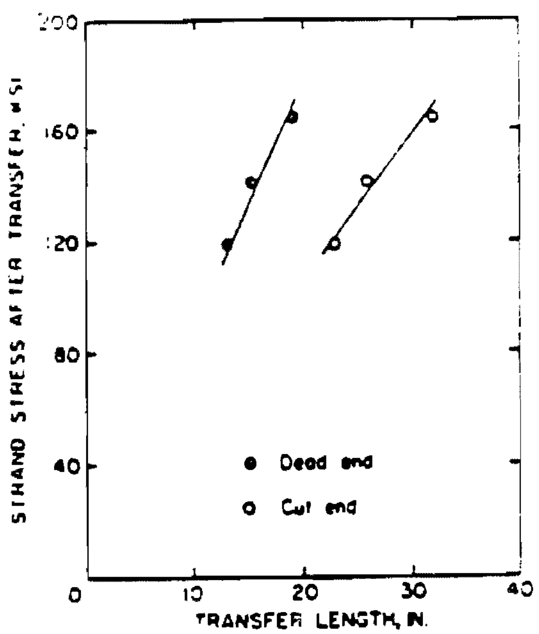


Figure 2.5 Effect of strand tension on transfer length specimens prestressed with 3/8-inch diameter strand[6].

The authors concluded that the development length obtained from the ACI/AASHTO provisions could not be applied to blanketed strand girders. However, when calculated development length was doubled, the performance of blanketed strand girders closely matched the flexural performance of similar fully bonded pretensioned girders.

In 1975, Kaar, Hanson, Corley and Hognestad[9] reported the effects of surface condition and method of release on the transfer length of prestressing strands. The strand was Grade 270K, 3/8-inch diameter strand. Three surface conditions were used: sandblasted, lightly rusted, and smooth. The specimens were 3.5 in. x 7 in. x 8.5 ft. The stress was transferred when compressive strength of concrete reached 4000 psi. Both sudden and gradual releases were investigated. The strand tension varied between 180 ksi and 185 ksi. The concrete strain readings were taken with a Whittimore gage and brass buttons. Transfer length was taken as the length required to reach 95% of the average concrete strain plateau. A summary of the results is given in Table 2.5. Even though there was a large scatter in the results, it was apparent that surface condition and type of release affected transfer length significantly. Sudden release increased transfer length by 22% on the average. Specimens with slightly rusted and sandblasted strands had respectively 51% and 36% shorter transfer lengths on the average than specimens with smooth strands.

In 1984, Dorsten, Hunt and Preston[16] reported the results of a research project on the effect of epoxy coating on transfer length. Transfer lengths of seven beams were measured. Four beams had epoxy-coated strand and three had bare strand. Both types were grade 270K, 0.5-inch diameter, low-relaxation seven-wire strand. They were tensioned to 75% of their ultimate strength before transfer and the stress was transferred when the compressive strength of concrete reached 4000 psi. The specimens were 3.5 in. x 4.5 in. x 8 ft. The test results are summarized in Table 2.6. The average transfer length for epoxy-coated strand turned out to be 16% longer than that of bare strand.

In 1986, Cousins, Johnston and Zia[18] discussed the performance of epoxy-coated strands in prestressed members. Sixty beams with uncoated, smooth epoxy-

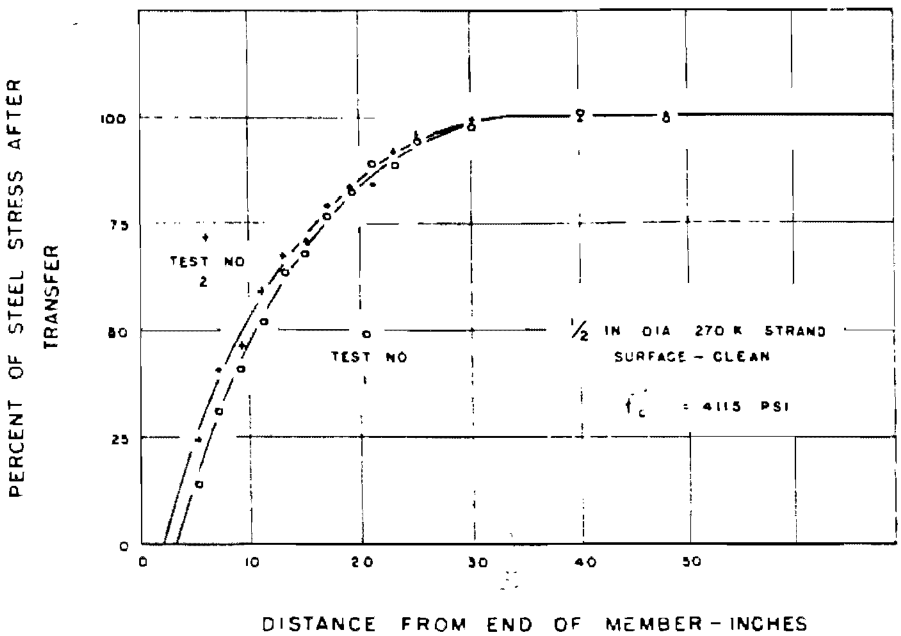


Figure 2.6 Steel stress profile of 0.5-inch diameter Grade 270K strand[7].

Table 2.5

Transfer Length* of 3/8-Inch Strand
Kaar, Hanson, Corley and Hognestad, 1975[9]

Surface Condition	Type of Release	Number of Tests	Transfer Length (in.)		
			Low	Average	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

* Defined as length to reach 95% of the average concrete strain plateau

coated, and impregnated epoxy-coated Grade 270K strand, ranging in size from 3/8-inch to 0.6-inch diameter, were cast. The stress was transferred when the compressive strength of concrete reached 4000 psi. A summary of results is given in Table 2.7. The authors concluded that transfer length of coated strand was shorter

Table 2.6

Transfer Length of Epoxy-Coated and Uncoated Strand Dorsten, Hunt and Preston, 1984[16]				
Strand Type	Type of Release	Number of Tests	Transfer Length (in.)	
			Initial	14 Months
Bare	Sudden	4	27.5	33.5
	Gradual	4	26.3	33.0
Coated	Sudden	3	29.3	29.7
	Gradual	3	33.3	35.0

than that of uncoated strand. It should be noted that the type of coating technique and coating material were different than the previously mentioned study[16]. The transfer length of uncoated strand was longer than that required by ACI/AASHTO provisions while that of coated strand was shorter than required. Sudden release resulted in 6% longer transfer length than gradual release.

In 1988 Castrodale, Burns and Kreger[20] reported a limited number of tests on transfer length of pretensioned beams as part of a research project on pretensioned high-strength concrete girders in composite highway bridges. The primary variable was the strength of concrete. The effect of method of release was also studied. Twelve specimens were cast, eight from a normal strength mix (f_c' = 5000 psi) and four from a high-strength mix (f_c' = 10,000 psi). The specimens were either 4 in. x 4 in. x 10 ft. or 6 in. x 6 in. x 10 ft., concentrically prestressed with a single strand. The prestressing strand was Grade 270K, stress-relieved, 0.5-inch diameter seven-wire prestressing strand. Concrete strain readings were taken by mechanical means. It was observed that the type of release did not have any significant effect on the transfer lengths for high-strength concrete. A summary of the results are given in Table 2.8. The authors concluded that:

1) Transfer lengths for high strength concrete are shorter than for normal strength concrete.

2) The current AASHTO expression provided a conservative yet reasonable estimate for the transfer length of strand in high-strength concrete.

Table 2.7

Transfer Length of Coated and Uncoated Strands Cousins, Johnston and Zia, 1986[18]				
Strand Diameter (in.)	Coating Type*	Avg. 1 Day Transfer Length (in.)	Number of Ends Measured	Standard Deviation
3/8	UN	34	16	4.9
	CM	14	12	2.3
0.5	UN	50	20	10.4
	CL	28	8	5.9
	CM	19	16	4.0
	CH	17	8	2.6
0.6	UN	56	10	7.6
	CM	32	12	5.4

* UN: Uncoated Strand
CL: Low Grit Density
CM: Medium Grit Density
CH: High Grit Density

In 1990, Deatherage and Burdette[24] reported the results of a research project on transfer and development length. A total of twenty Type-I AASHTO prestressed concrete I-beams and six prestressed concrete prisms were tested with Grade 270K, low-relaxation strands of 0.5-inch regular, 0.5-inch special, 9/16-inch, and 0.6-inch in diameter. All beams were 31 ft. long. All concrete prisms were 12 ft. long with a single strand prestressed concentrically through its square cross-section. The transfer of the prestressing force was made when the compressive strength of concrete reached a minimum of 4000 psi. Average measured transfer length values are given in Table 2.9. The authors concluded that:

1) Current ACI/AASHTO provisions for calculating transfer length were unconservative and needed revision.

Table 2.8

Transfer Length Castrodale, Burns and Kreger, 1988[20]				
Specimen Type (in. x in.)	Concrete Strength (ksi)	Measured Mean (in.)	Measured Maximum (in.)	AASHTO Value (in.)
4 x 4	5.1	22	41	30
4 x 4	9.4	15	19	29
6 x 6	5.1	26	33	31

Table 2.9

Average Measured Transfer Length Deatherage and Burdette, 1990[24]			
Diameter (in.)	Average Transfer Lengths (db)		
	Mill	Weather 1-day	Weather 3-day
0.5 Regular	85.50	70.50	61.00
0.5 Special	86.50	-	73.75
9/16	87.75	-	81.50
0.6	70.40	-	-

2) The surface condition of the strand was of vital importance to the transfer length and therefore, some type of surface condition quality control was needed.

3) Transfer length was directly proportional to strand stress.

4) Transfer length was directly related to strand diameter for strands ranging from 0.5-inc to 9/16-inch in diameter.

5) The stress distribution through the transfer length had two distinctive zones: a linear zone over the slip region, and a nonlinear zone over the adhesive region.

In 1990, Malik[26] studied the transfer length of 0.5-inch and 0.6-inch diameter prestressing strand and the effect of debonding on the transfer length. This study constituted the first part of this project. Eighteen specimens, 4 in. x 5 in. x 12 ft., were concentrically pretensioned with single strands. The procedure used and the variables studied were either exactly the same or very little modified from the procedure described in the following chapters. The strand used was Grade 270K, low-relaxation, 0.5-inch and 0.6-inch seven-wire prestressing strand. The concrete compressive strengths and measured transfer lengths are summarized in Table 2.10 and a detailed table of results are given in Appendix C. The author concluded that:

Table 2.10

Transfer Length Malik, 1990[26]					
Diameter (in.)	Type of Bonding	Type of Release	Number of Specimens	Ave. Transfer Length (in.)	
				95%	100%
0.5	Fully Bonded	Gradual	6	28.0	33.3
		Sudden	6	39.0	50.3
	Debonded	Gradual	2	21.0	22.5
		Sudden	2	21.0	22.5
	Fully Bonded	Gradual	6	36.0	45.2
		Sudden	6	40.3	46.5
	Debonded	Gradual	2	34.0	39.0
		Sudden	2	--	--

1) ACI/AASHTO formula used to predict transfer length was unconservative for both 0.5-inch and 0.6-inch strands.

2) The test results were generally consistent with previous research done using the same basic technique of measurement.

3) Cut end transfer length was 39% and 12% higher than dead end transfer length for 0.5-inch and 0.6-inch strands, respectively.

2.5 Approximate Equations

It should be noted that the effect of debonding and utilization of 0.6-inch strand has been the subject of limited study and all the proposed formulas are based on research on tests involving neither debond nor 0.6-inch strands.

Currently used ACI/AASHTO provisions[21,22] on transfer and development length are as follows:

12.9 - Development of prestressing strand

12.9.1 - Three- or seven-wire pretensioning strand shall be bonded beyond the critical section for a development length, in inches, not less than

$$\left(f_{ps} - \frac{2\,f_{se}}{3} \right) d_b \qquad (2.1)$$

where d_b is strand diameter in inches, and f_{ps} and f_{se} are expressed in kips per square in.

12.9.2 - Investigation may be limited to cross sections nearest each end of the member that are required to develop full design strength under specified factored loads.

12.9.3 - Where bonding of a strand does not extend to end of member, and design includes tension at service load in precompressed tensile zone as permitted by 18.4.2, development length specified in 12.9.1. shall be doubled.

In ACI Commentary[15] Section 12.9, it is mentioned that the expression for development length l_d may be rewritten as

$$l_d = \frac{f'_{se}}{3} d_b + \left(f_{ps} - f_{se} \right) d_b \qquad (2.2)$$

where:

f_{ps} = ultimate prestress force used for design
f_{se} = concrete stress at the location of the strand

The first term represents the transfer length of the strand, i.e., the distance over which the strand may be bonded to the concrete to develop the prestress, f_{se}, in the strand. The second term represents the additional length over which the strand must be bonded so that the stress, f_{ps}, may develop in the strand at nominal strength of the member.

The expressions for transfer length, and for the additional bonded length necessary to develop an increase in stress of (f_{ps} - f_{se}) are based on tests of members prestressed with clean, 1/4-, 3/9-, and 1/2-inch diameter strands for which the maximum value of f_{ps} was 275 ksi[4,6,8].

This equation is mostly based on research done by Kaar and Hanson[4], and has been virtually unchanged since 1963. The transfer length and the flexural bond length are given as functions of the effective steel stress, f_{se}, which, in turn, is dependent on the initial prestress, f_{si}, and the amount of prestress loss.

Since transfer length has been shown to vary linearly with steel prestress, and strand diameter and inversely with concrete compressive strength, the transfer length is calculated by $(f_{se}/3)d_b$. The denominator, 3, represents a conservative average concrete compressive strength in ksi.

In the flexural bond region, the strand stress varies from f_{se} to f_{ps} (Figure 2.1). This increase in stress induces the flexural bond stress. By representing the strand as a circular element of same nominal diameter, it can be shown from the condition of equilibrium that the flexural bond length is:

$$l_b \left(\frac{f_{ps} - f_{se}}{4u_{ave}} \right) d_b \tag{2.3}$$

where u_{ave} is average bond stress in the flexural bond length. In the current ACI Code it is implied that u_{ave} is 250 psi.

According to the ACI Code provisions, the transfer length would be 47 nominal strand diameters and the flexural bond length would be 110 strand diameters for Grade 250K strand, assuming an initial prestress of $0.7f_{pu}$ and a 20 percent loss of prestress. Similarly, for Grade 270K strand, the transfer length would be 51 strand diameters and the flexural bond length would be 119 strand diameters. In the shear provisions of the Code, a transfer length of 50 strand diameters is specified.

In 1977, Zia and Mostafa[12] proposed the following empirical equations for transfer length and flexural bond length, based on a linear regression analysis of research conducted prior to 1976.

For transfer length l_t:

$$l_t = 1.5\frac{f_{si}}{f_{ci}} d_b - 4.6 \quad \text{(Sudden release)} \tag{2.4}$$

$$l_t = 1.3\frac{f_{si}}{f_{ci}} d_b - 2.3 \quad \text{(Gradual release)} \tag{2.5}$$

For flexural bond length, l_b:

$$l_b = 1.25\,(f_{ps} - f_{se})\, d_b \tag{2.6}$$

where:

f_{si}	=	initial stress in strand in strand before losses (ksi)
f_{ci}	=	concrete strength at transfer (ksi)
d_b	=	diameter of prestressing strand (in.)
f_{ps}	=	ultimate stress of the prestressing strand (ksi)
f_{se}	=	effective stress of the strand after losses (ksi)

The transfer length equation accounts for the effects of strand size, initial prestress, and concrete strength at transfer, and is applicable to concrete strengths between 2000 psi and 8000 psi. The proposed equation for transfer length gave comparable results to the current ACI Code requirement for the small size strands, but was more conservative than the ACI Code, particularly for cases where the concrete strength at transfer was low.

A reevaluation of Hanson and Kaar's test data[4] suggested that the flexural bond length specified by the current ACI Code should be increased by about 25%. Comparison of Zia-Mostafa equation with experimental results is shown in Figure 2.7.

In 1979, Martin and Scott[10] proposed the following empirical equations which were developed by fitting a bilinear curve to the data obtained by Hanson and Kaar[4].

For $L_x \leq 80\ d_b$:

$$f_{ps} < \frac{L_x}{80\ d_b}\left\{\left(\frac{135}{d_b^{1/6}}\right) + 31\right\} \tag{2.7}$$

For $L_x > 80\ d_b$:

$$f_{ps} < \frac{135}{d_b^{1/6}} + \frac{0.39 L_x}{d_b}$$

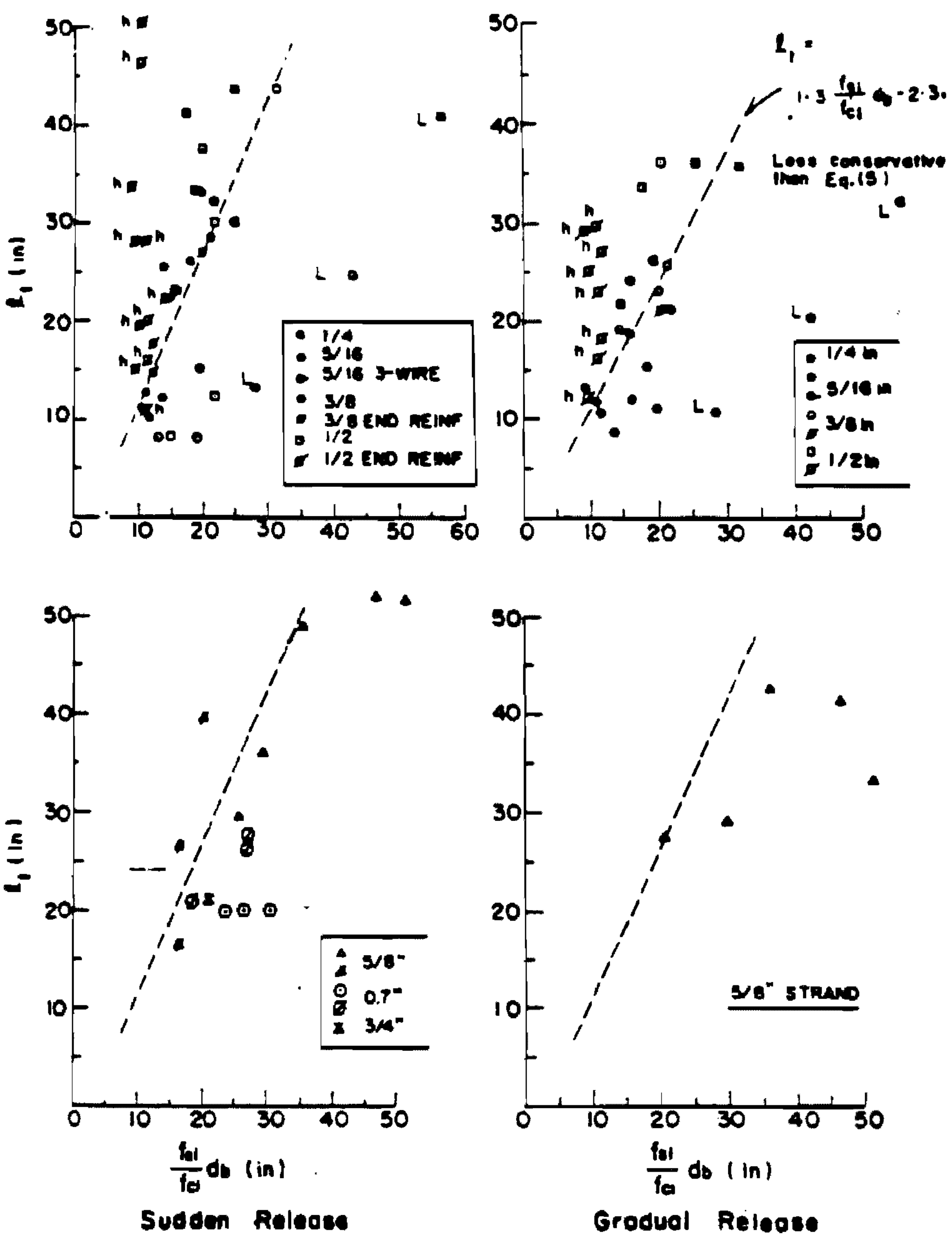


Figure 2.7 Comparison of the Zia-Mostafa equation with experimental results from various sources[12].

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 318-89 Code. The authors also concluded that the effect of mechanical interlocking should not be considered in design because of its low degree of reliability.

Average values of transfer length at the cut end of the strand, measured at transfer were 50, 69, 82, and 76 diameters for nominal strand diameters of 1/4-, 3/8-, 0.5-, and 0.6-inch strand, respectively. The suggested values are more conservative than ACI Code requirements. Comparison of Martin-Scott equations with test results by Hanson and Kaar, and by Kaar, LaFraugh and Mass, are provided in Figures 2.8 and 2.9, respectively.

In 1986, Cousins, Johnston and Zia[18] researched performance of epoxy-coated strands in prestressed members. The test program and the results are covered in Section 2.4. As part of the project, the authors have derived the following equations:

For transfer length, l_t:

$$l_t = \frac{0.5\, U_t' \sqrt{f_c'}}{B} + \frac{f_{se}\, A_s}{\pi\, (\pi\, d_b\, U_t' \sqrt{f_c'}\,)} \tag{2.9}$$

For flexural bond length, l_b:

$$l_b = \left(f_{ps} - f_{se} \right) \frac{(a_s/\pi\, d_b)}{U_d' \sqrt{f_c'}} \tag{2.10}$$

where:

U_t'	=	plastic transfer bond stress (psi)
f_c'	=	compressive strength of concrete (psi)
B	=	bond modulus (psi/in.)
f_{se}	=	effective prestressing 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)

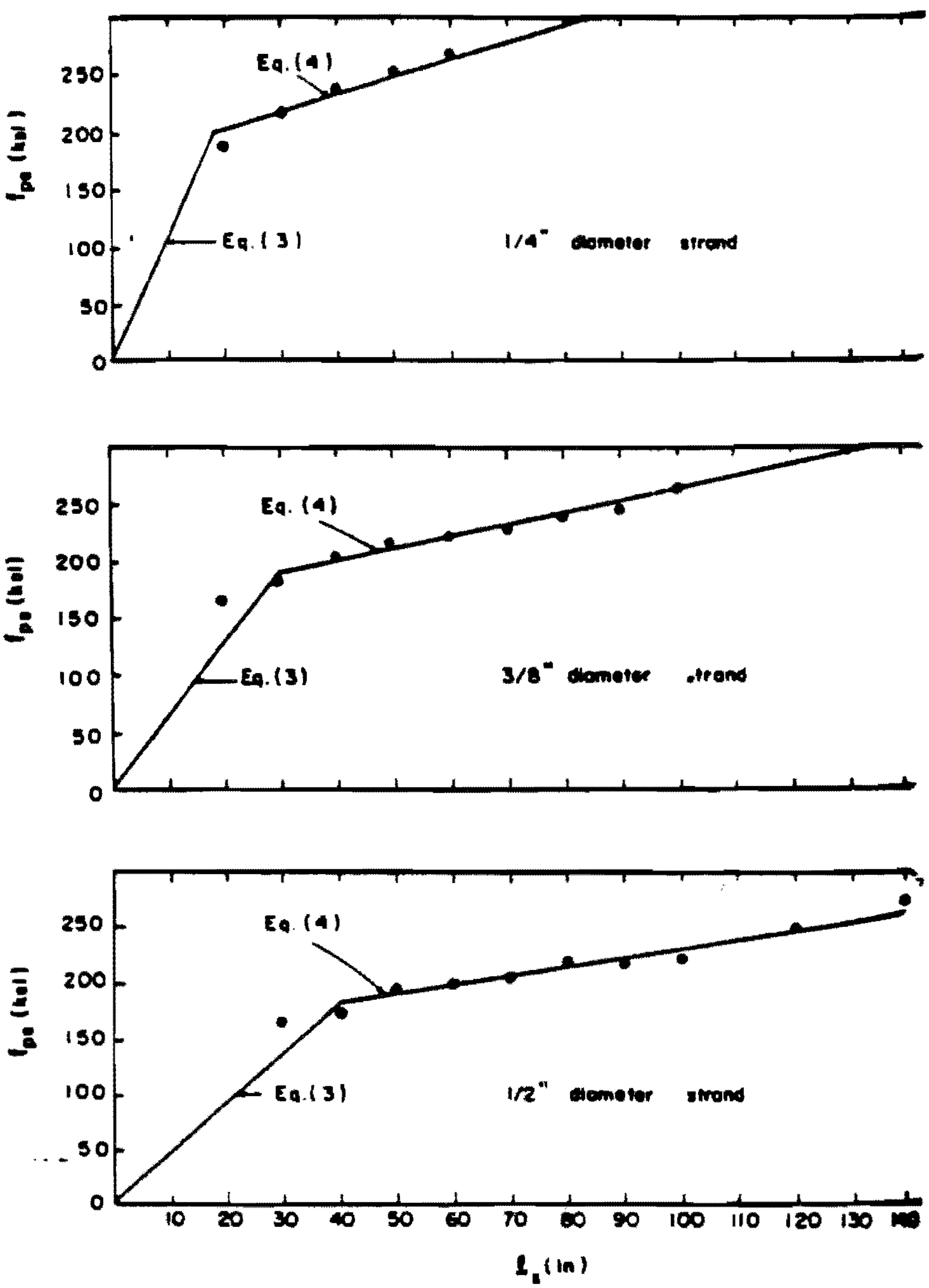


Figure 2.8 Comparison of the Martin-Scott Equations with test results by Hanson and Kaar[10].

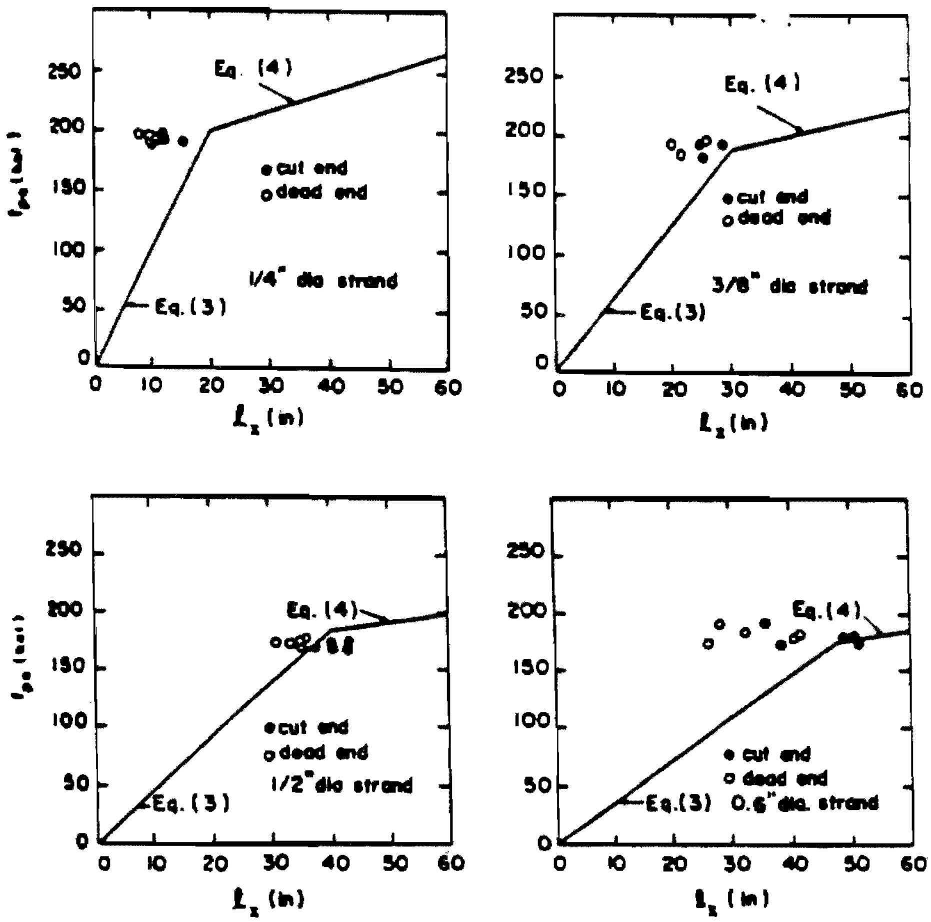


Figure 2.9 Comparison of the Martin-Scott equations with test results by Kaar, LaFraugh and Mass[10].

It should be noted that U_t', B, f_{se}, and U_d' should be determined from experimental results which were given in the report for coated and uncoated strands.

2.6 Concluding Remarks

The literature reviewed in this chapter consisted of studies utilizing currently used material. Some of the older papers utilizing prestressing wires, and the papers published in Europe were not discussed. Current ACI/AASHTO code provisions are not changed significantly since 1963. From this review of research, and including Malik [26] in 1990, it would appear that current code provisions are unconservative.

However, tests discussed later in this report demonstrate that there are additional variables that come into play with larger specimens; and that the current code may not be unconservative.

CHAPTER THREE
TEST PROGRAM

3.1 Introduction

The main purpose of the test program covered in this thesis was to determine the transfer length of fully bonded and debonded prestressing strand. The study included the effect of debonding on the transfer length of 0.5-inch diameter strands and also to investigate the transfer length of 0.6-inch prestressing strand. The variables studied were:

1) Number of strands

2) Strand spacing (2-inch and 2.25-inch)

3) Debonding (fully bonded or debonded)

4) Size of strand (0.5-inch and 0.6-inch)

5) Transverse reinforcement

6) Cross section size and shape

The data that was to be collected included the following:

1) Concrete strains on the outside faces

2) Prestressing strand strains

3) End slip

4) Visual inspection

This chapter discussed the scope of the tests, description of the test speimens, the materials used, the fabrication of the specimens, the instrumentation, and the test procedures. This chapter is partially adapted from References 25 and 26.

3.2 Scope of the Tests

Eighteen (18) single-strand specimens were cast in the initial stage of the research project. These specimens were cast and tested during the Fall of 1989. The results from these tests were presented in Technical Memo I in March 1990. Results from those tests are discussed in this report and compared to results from the later test specimens.

An additional forty-four specimens were tested for transfer length during the Spring and Summer of 1990. Of these tests, eighteen (18) were three-strand specimens, six (6) were five-strand specimens, and twelve (12) were I-shaped AASHTO-type sections. Additionally, eight (8) more single-strand specimens were cast to compare results with those from the first series of eighteen (18).

Altogether, sixty-two transfer length specimens were cast and tested. Of these sixty-two (62) specimens, twenty-nine (29) specimens tested 0.5-inch strand while the remaining thirty-three (33) specimens tested 0.6-inch strand. This represents one of the largest bodies of data on transfer length available, especially on 0.6-inch strand, with data over a broad range of variables.

Figure 3.1, 3.2, 3.3, and 3.4 illustrate the cross sectional dimensions for each of the specimens. Generally cross sectional properties were chosen to maximize concrete strains (and thereby minimize relative error in the data) without exceeding current allowable stresses.

Specimen lengths were designed to fully encompass the transfer zones at both ends. Single-strand specimens were twelve feet long. Three-strand and five-strand fully-bonded specimens were sixteen feet long. Debonded three-strand specimens were twenty-four feet long. The AASHTO-type specimens were designed for development length tests and vary in length from twenty-seven feet to forty feet.

Strands were stressed to a maximum jacking stress of approximately 0.75 f_{pu}. Due to seating losses and relaxation, the stress in the strand immediately prior to transfer was approximately 0.70 f_{pu}. Prestressing strand stresses are given in Table 4.9. Concrete strength was specified at 6000 psi at 28 days and 4000 psi at release. Concrete compressive strengths are given in Table 3.1. More detailed discussions of concrete and prestressing steel properties are included later in this report.

3.3 Test Set Up

The tests were conducted at the Ferguson Structural Engineering Laboratory, University of Texas at Austin. For the purpose of the research project and taking into account the number and nature of the specimens to be cast later in the project, a three-bay, 72-feet long, high-capacity (400 kips/bay) prestressing bed was constructed in the laboratory. Wooden formwork according to the different sizes of specimens required was constructed and secured to table tops such that the strands could pass symmetrically through the forms. The specimens were cast on tables with

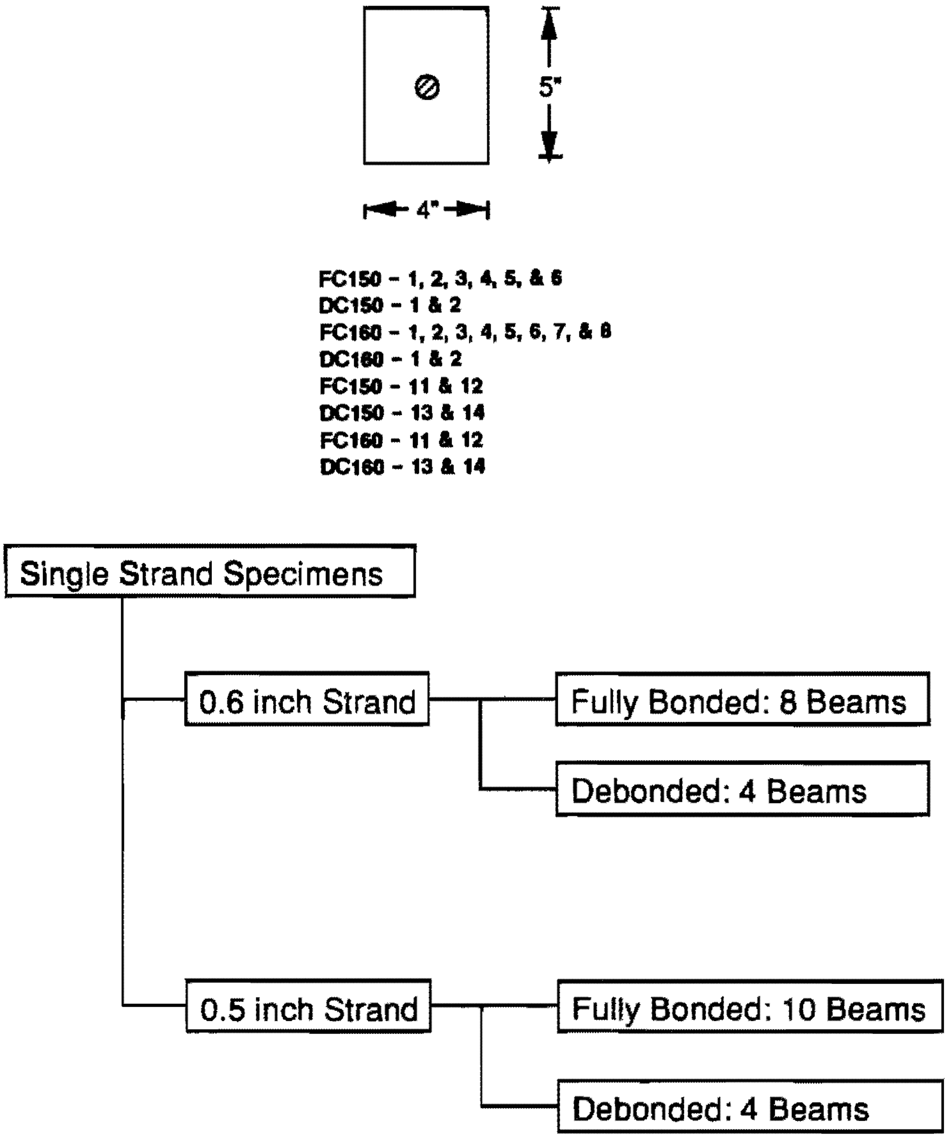


Figure 3.1 Details of single-strand specimens.

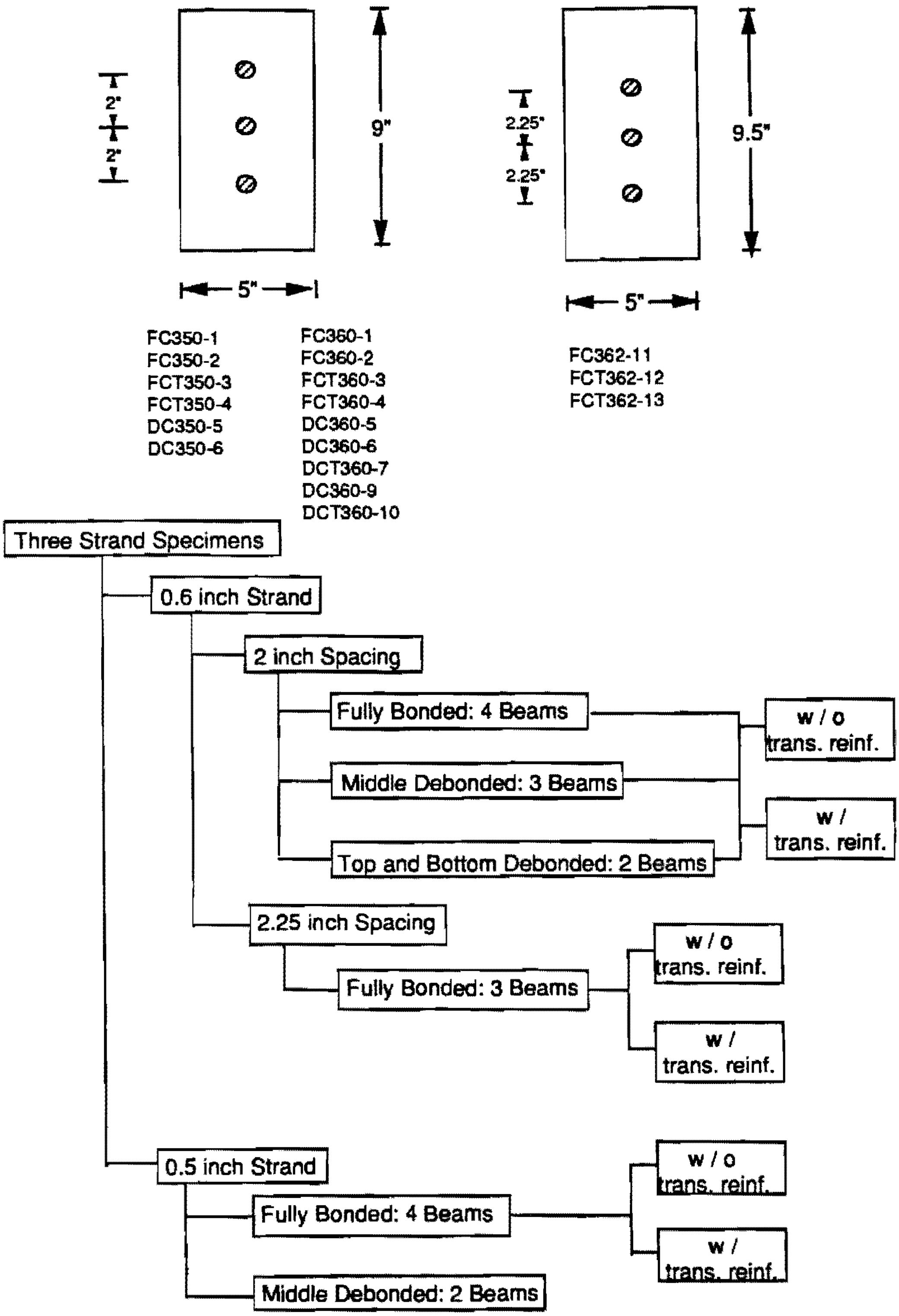


Figure 3.2 Details of three-strand specimens.

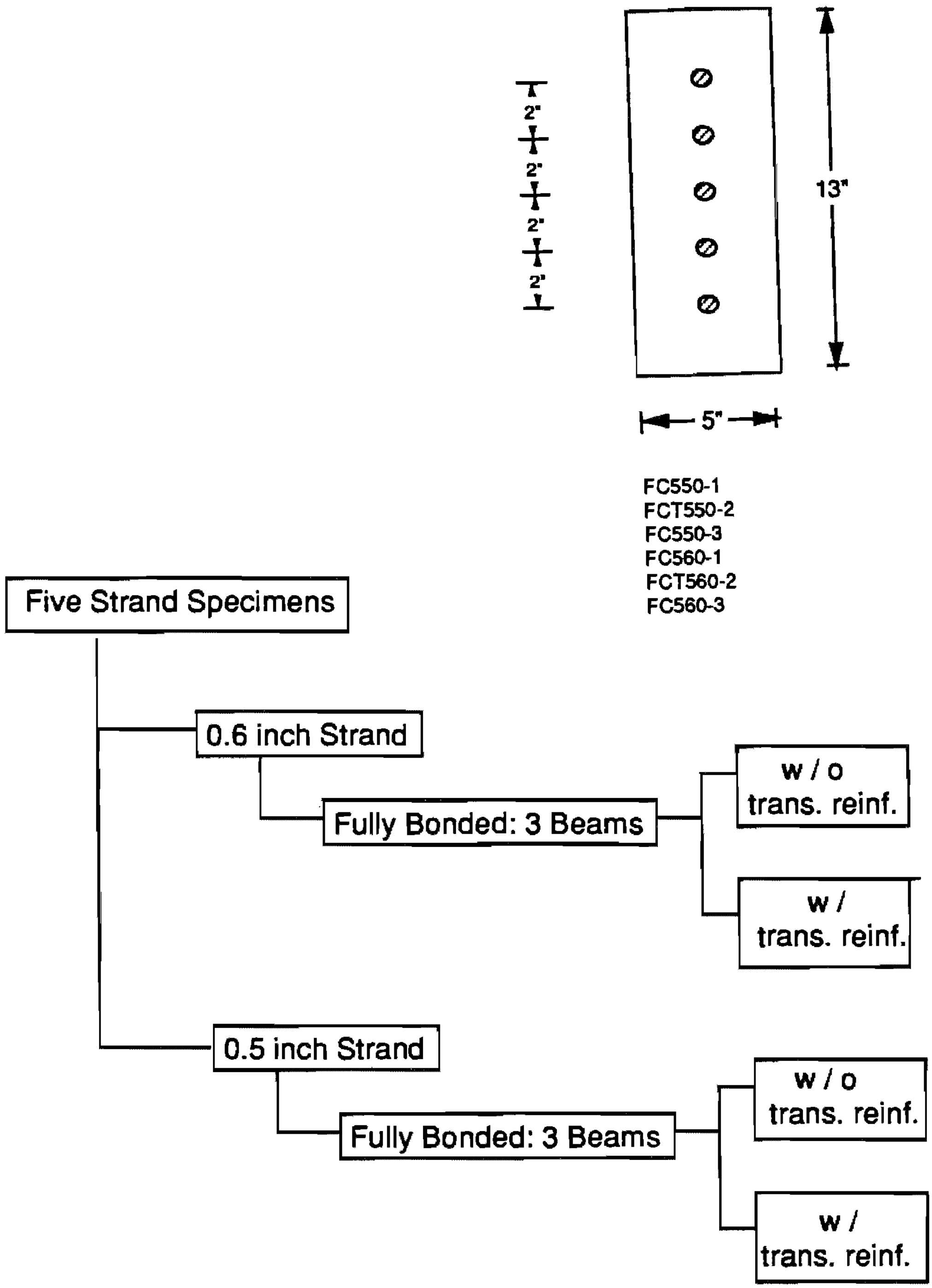


Figure 3.3 Details of five-strand specimens.

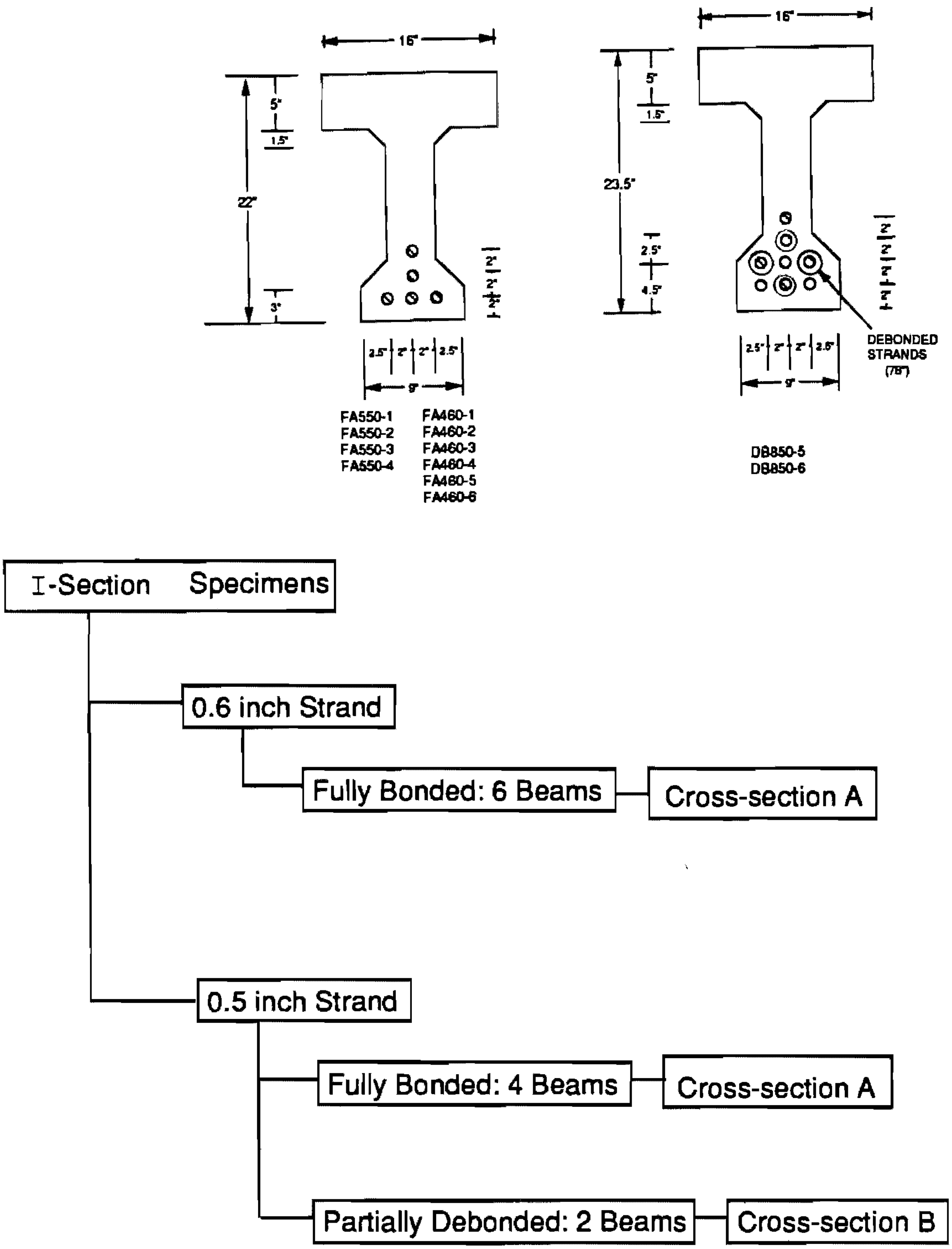


Figure 3.4 Details of I-Section Specimens.

Table 3.1
Concrete Compressive Strengths

Specimen	f_{ci}' (psi)	f_c' (psi)
FC 150-11	4481	6710
FC 150-12	4481	6710
DC 150-13	4481	6710
DC 150-14	4481	6710
FC 160-11	3853	5402
FC 160-12	3853	5402
DC 160-13	3853	5402
DC 160-14	3853	5402
FC 350-1	4315	6630
FC 350-2	4315	6630
FCT 350-3	4315	6630
FCT 350-4	4315	6630
DC 350-5	4201	6250
DC 350-6	4201	6250
FC 360-1	4201	6250
FC 360-2	4201	6250
FCT 360-3	4201	6250
FCT 360-4	4792	7298
DC 360-5	4792	7298
DC 360-6	4792	7298
DCT 360-7	4792	7298
DC 360-9	4759	7525
DCT 360-10	4759	7525
FC 362-11	4759	7525
FCT 362-12	4759	7525
FCT 362-13	4759	7525
FC 550-1	3853	5402
FCT 550-2	3853	5402
FC 550-3	3853	5402
FC 560-1	4481	6603
FCT 560-2	4481	6603
FC 560-3	4481	6603
FA 550-1	4639	5107
FA 550-2	4639	5107
FA 550-3	4040	5281
FA 550-4	4040	5281
FA 460-1	4880	6362
FA 460-2	4458	6573
FA 460-3	4458	6573
FA 460-4	4836	6458
FA 460-5	4661	7020
FA 460-6	4661	7020
DB 850-5	5578	7217
DB 850-6	5152	6878

plexi-glass tops to reduce friction between the specimens and the tables when cutting the strands (Figure 3.5).

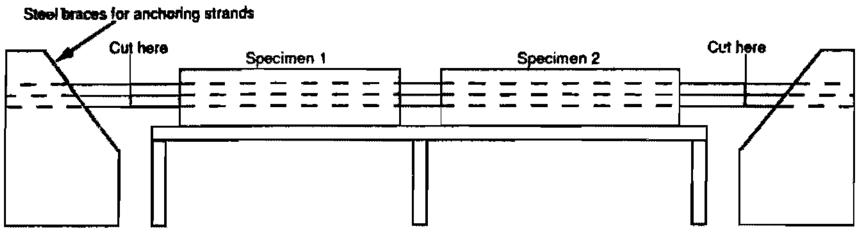


Figure 3.5 Test setup (figure not drawn to scale).

3.4 Instrumentation

Transfer length data was acquired from three primary sources: concrete strains, prestressing steel strains and end slip measurements. Of these three, measurement of concrete strains proved to be the most accurate and reliable data. Steel strain and end slip measurement were found to have a high degree of scatter, and were therefore limited in their overall value.

3.4.1 Instrumentation for Concrete Strains. Concrete strains at transfer were the main source of information in obtaining the transfer length. After the formwork was removed and prior to transfer, mechanical gage points (sometimes known as DEMEC points) were attached to both sides of the test specimens by using epoxy glue. The DEMEC gage points are stainless steel discs, each with a small hole in the center designed to receive the DEMEC strain gage. Gage points were attached at the centroid of the cross section on opposing faces of the concrete to allow correction for the stresses produced by moments which resulted in regions where the strand drifted slightly off the center.

The DEMEC gage measures the relative distances between two points so that the change in relative distance before and after transfer is a measure of the concrete strain within the mesurement length of the strain gage. The DEMEC strain gage had 0.0002 mm (8×10^{-6} inch) subdivisions.

This system has been used in the FSEL prior to this project and has proved to be reliable and reasnably accurate within 20 or 30 microstrains[20].

3.4.2 Instrumentation for Steel Strains. Electrical strain gages were installed on the strands before tensioning. Electrical strain gages were used as a secondary source of information in order to provide additional transfer length data. Strain gage locations were chosen such that they would give the strain profile over the transfer zone. However, their usage was limited because the gages interfere with the bond between the strand and the concrete, thus affecting the results. The steel strains also provided a measure of the prestressing force. For 0.5-inch and 0.6-inch diameter, fully bonded and debonded strands all strain gage readings were combined together separately and four graphs were generated by plotting the change in steel strain vs. the distance. This procedure is further explained in Section 4.3 and the plots are provided in Appendix B.

3.4.3 End Slip Measurement. Prior to transfer, end slip devices wre attached to the strands. The end slip device is a simple assembly which consists of aluminum clamps and a dial gage (Figure 3.6). The dial gage sensor rested on the end surface of specimen. Readings were taken before and after transfer in order to measure the end slip. This method was discontinued for most of the later tests because of damage caused to the end slip device at release. Instead, a strip of tape was placed on the strand prior to release. The relative movement of the tape to the concrete surface provided the end slip measurement. This method proved to be very reliable. Results from this method had a relatively high degree of repeatability and accuracy within 0.03 inches.

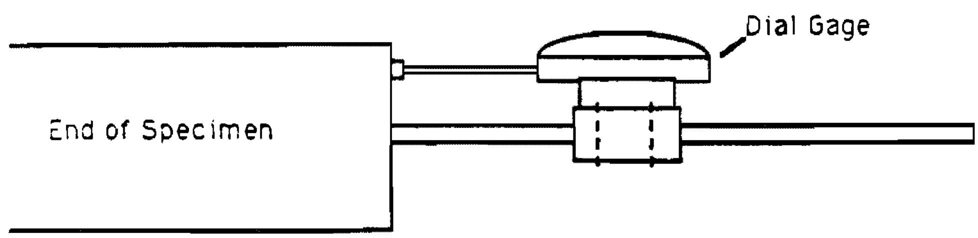


Figure 3.6 End slip device.

3.4.4 Other Instrumentation. The strands were stressed individually using a Velzey Ram which could seat the chuck at transfer with minimum seating losses of 2 to 5%. The prestressing force (the force exerted by the ram) was monitored by a pressure gage on the ram itself, a pressure transducer connected to the ram, a load cell, and measurement of elongation of the strand. A load cell was attached to the holding end of one of the strands, in order to be able to measure the force exerted by the ram at the jacking end. A piece of tape was wrapped around each strand at the end of the bay and the distnace to this reference line was measured with a steel ruler before and after stressing in order to obtain the elongation of the strand.

3.5 Procedure

Generally, the following procedure was used for construction and testing:

1) Stressing of the prestressing strand(s)

2) Casting of the concrete

3) Instrumentation of the specimens and initial readings

4) Detensioning

5) Final readings

3.5.1 Stressing the strands. Initially, the strands were stressed to approximately 10% of their target stress. At this time, the strain gages were installed. The purpose of this initial prestress was simply to "lock in" the geometry of the strand respective to the prestressing bed and facilitate working with the strands. After the gages were installed and the prestressing chucks were set, the stress was relieved.

Prestressing strands were stressed to an initial stress of approximately 0.75 f_{pu}. Stressing was done incrementally and data recorded accordingly. Stressing was performed with the Velzey Double Hydraulic Cylinder Ram which was donated to Ferguson Structural Engineering Laboratory by the Velzy Engineering and Machine, Inc.

Prestressing strands were laid out in the prestressing bed and load cells and chucks were installed. The strands were initially tensioned to 10% of the target prestress with the ram in order to facilitate working with the strands. The electrical strain gages were installed on an individual wire of the seven-wire strand. The strand stressing procedure was as follows:

1) Shims were placed between the chuck wedges and the bay. The total thickness of the shims varied between 0.5-inch and 1.0-inch, according to the length of the exposed strand. Later, the shims were taken out during detensioning.

2) The strand was stressed by the ram in stages, in order to obtain a load-elongation curve.

3) Finally, the strand was stressed to desired stress ($0.75f_{pu}$)

4) The Velzey Double Hydraulic Cylinder Ram automatically seated the chuck wedges by its nose piece and the prestressing force was transferred from the ram to the chuck by the Velzey Ram.

The strands were stressed to approximately 75% of the ultimate stress, (about 202.5 ksi) before casting. This level of prestressing complies with AASHTO specifications.

After prestressing, forms were placed and the concrete was cast. During casting, concrete was vibrated carefully in order to ensure the proper placement of the concrete around the strand. In turn, this ensures the bond between the concrete and the strand. A few hours later, the specimen was covered with plastic sheets to avoid rapid moisture loss during curing. No other furing procedures were used. Up to 21.6 in. x 12 in. cylinders were cast at each pour to be tested for concrete compressive strength at transfer, 7 days, and 28 days.

Generally, two days after casting, the forms were removed. However, occasionally, this period had to be prolonged for the concrete to attain a certain compressive strength. DEMEC gage point locations were marked over a length that stretched beyond the expected transfer on both ends and on both sides. The intervals were either 50 mm (1-31/32 inches) or 100 mm (3-15/16 inches). The DEMEC gage points were set by epoxy glue. After allowing enough time for the epoxy to dry, initial concrete strain readings were taken. After testing concrete cylinders to verify that the concrete had attained sufficient cocnrete compressive strength, detensioning took place. The detensioning technique was modified before this stage of the project due to the excessive shocks observed during the initial single strand specimens. Instead of releasing the strands suddenly, first the shims were taken out, causing approximately 30% reduction in strand stresses. For multi-strand specimens, cutting was done by alternating cutting from one end of the bay to the other. The cutting sequence of typical multistrand specimens in a bay is illustrated in Figure 3.7. After transfer, final readings were taken for concrete strains, steel strains, and end slips.

Two sets of readings were taken for concrete strains by two different individuals both before and after transfer. All individual readings which did not fall within 40 microstrains of each other were retaken to maintain a high degree of accuracy.

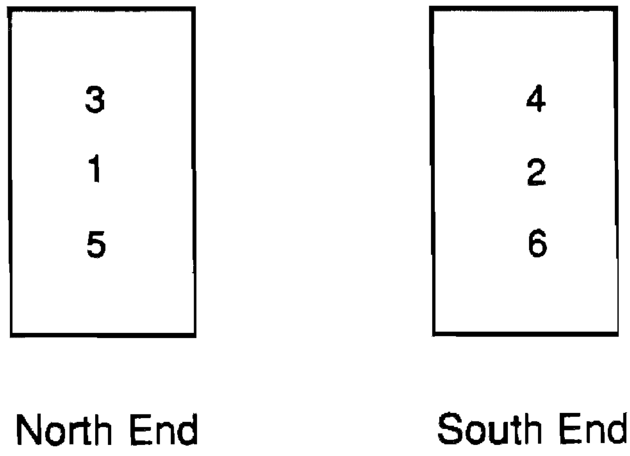


Figure 3.7 Cutting sequence of typical multi-strand specimens in a bay.

3.6 Material Properties

3.6.1 Concrete. The concrete mix was designed to match as closely as possible the concrete that is cast in fabrication plants for pretensioned prestressed concrete members. The concrete was batched and delivered by a ready-mix concrete supplier. Concrete cylinders were cast and tested at transfer, at 28 days, and at other ages as deemed necessary. The concrete mix was designed to have a compressive strength of about 4000 psi at transfer and about 6500 psi at 28 days. The results of the concrete cylinder tests are reported in Table 3.1.

The specified maximum aggregate size was 3/8-inch for most of the beam specimens. However, 5/8-inch aggregate was specified for I-section beams. Although 3/4-inch aggregate would be allowed by the Code, a smaller size aggreaget was specified in order to accommodate the small cross-section of the specimens. All of the mixes used water-reducing admixture. Air entrainment was not included and total air content was measured at 2% to 8%. Slump was controlled between four inches and six inches to provide adequate workability. Following is a typical design mix:

Cement	611 lbs.
Coarse aggregate (5/8-in.)	1680 lbs.
Fine aggregate	1355 lbs.
Water	290 lbs.
761-N Admixture	37 ozs.

3.6.2 Steel. The prestressing strand used on this project was donated by Florida Wire and Cable. All prestressing steel used for this research project was Grad 270K, uncoated, seven-wire, low-relaxation strand, which is becoming the industry standard. Two different size, 0.5-inch and 0.6-inch nominal diameter, were used. The strand was not treated in any special manner such as wiping or cleaning with acid before casting. However, care was taken not to drag the strand on the floor. No form oil was ued on this project. The researchers agreed that by not treating the strand, standard industry practice would be best simulated and the "worst case" effect would be provided. Slight differences in the surface conditions of the strands provided at different times were observed. The strand used for the initial series was covered with a slight film. However, no cleaning of the strand was done prior to casting, and the surface condition of all strand used was that of bright mill condition.

CHAPTER FOUR
METHOD OF ANALYSIS AND RESULTS

4.1 Introduction

The objective of the project was to investigate the transfer length of 0.5-inch and 0.6-inch diameter prestressing strand under fully bonded and debonded conditions. Transfer lengths were obtained by measured concrete strain profiles along the length of the specimens. Also, strand strain profiles were obtained to supply supporting information.

In this chapter the method of analysis is explained and the results are presented.

4.2 Concrete Strain Analysis

4.2.1 Method of Plotting. Two sets of DEMEC gage readings were taken for each end on both sides of the specimens by two different people working together, both before and after transfer. Therefore, the absolute strain readings are represented by the average of four independent sets of data. The concrete strain profiles obtained are the profiles of the change in concrete strains immediately following the prestress force transfer. The length over which the readings were taken started at the ends of each specimen and continued well past the expected transfer length zone. In fact, strain readings were taken along the entire length of each specimen, except the I-shaped specimens.

The difference between the initial and final readings at every gage point for each individual was calculated from the data obtained. The maximum acceptable difference between two individuals' readings was established as 32 microstrains. Then the average of the two sets of readings were taken. In a very few instances, readings which were well off the trend set by other readings (possibly the result of an unstable DEMEC gage point or a surface imperfection at a certain spot close to the strand) was discarded. This procedure was followed for all sets of points on both ends and on both sides. After this, the corresponding strain changes on opposite sides were averaged and each average strain change result was taken as the true concrete strain reading for the gage length corresponding to those DEMEC gage points. The corresponding strains in absolute terms were calculated by multiplying all strain gage readings by a factor of $8.0x10^{-6}$ for one DEMEC gage and by $8.1x10^{-6}$ for the other and the results obtained were in strain-in./in. The preset calibrations for the individual gages are 8.0×10^{-6} in. and 8.1×10^{-6} in.

Using the above mentioned procedure, two sets of concrete strain readings were obtained for each end of each specimen. These sets of readings were smoothed and the concrete strain profiles were obtained by using Microsoft Cricket Graph[23]. The smoothing technique utilized by this software is a "sliding average smoothing" technique. This technique averages a number of data points in an overlapping manner (Figure 4.1). A width of three data points was used in the smoothing application in this study.

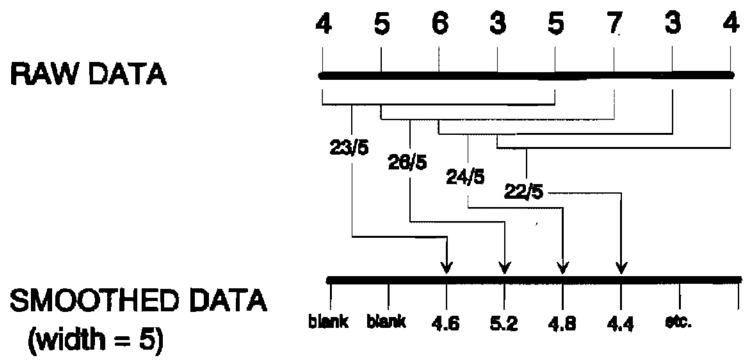


Figure 4.1 Schematic showing smoothing techniques on Cricket Graph using width = 5 (for analysis of concrete strains width = 3 is used)[23].

A typical plot before and after smoothing is illustrated in Figures 4.2 and 4.3. The smoothed concrete strain profiles for all tests are presented in Appendix A.

Due to the application of the smoothing technique, two points on each plot were lot, one point at the beginning and a second point at the end of the distance over which the readings were taken. Also, the first reading was taken at an inch from the end of the beam.

4.2.2 Method of Obtaining Transfer Length. After the concrete strain profile was obtained, a strain was chosen visually as the strain at which the slope of the concrete strain curve became horizontal. Then the average of the strains beyond that point was calculated and a horizontal line parallel to the x-axis was drawn, representing the mean strain of the portion of the specimen between the transfer zones at both ends. However, in some specimens, this procedure was applied at each end separately because there were cases where the plateau was observed at different strains at each end of the same specimen. Another horizontal line was drawn at 95% of the strain for the line mentioned above. Then two vertical lines were drawn from the points where these horizontal lines intersected the concrete strain curve to the

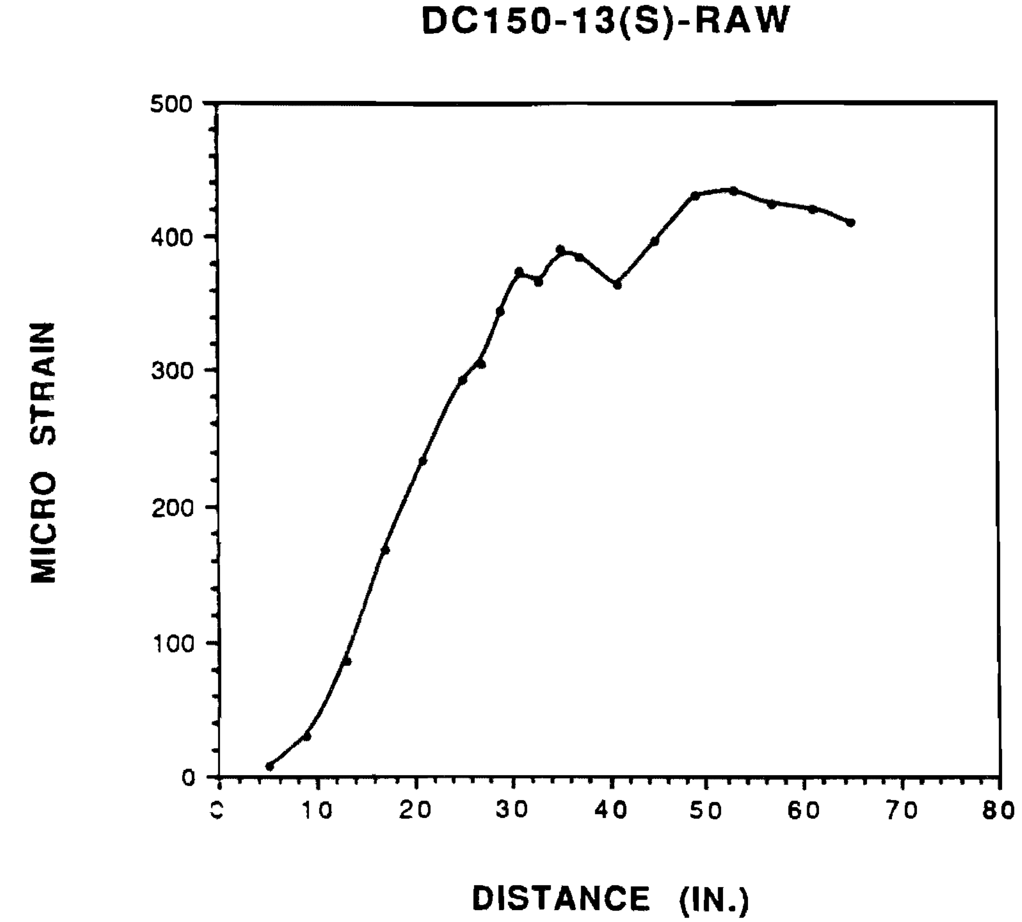


Figure 4.2 Typical concrete strain profile obtained by raw data.

x-axis. Thus, the transfer lengths representing the distance at which 95% and 100% of the prestressing stress was transferred were obtained. Since the spacing between DEMEC gage points were less than assumed (assumed 2 and 4 inches, actual 1-31/32 and 3-15/16 inches), transfer lengths obtained from concrete strain profiles were multiplied by a correction factor of 0.984.

Figure 4.4 illustrates the technique of obtaining the transfer length from the concrete strain profiles. The values in parentheses indicate the actual readings from the profile and other values are the corrected transfer length values.

For the debonded multi-strand specimens, two transfer zones exist. The first transfer zone is due to the fully bonded strands. There is a second transfer zone which starts at the point where debond is terminated and this is the transfer zone for debonded strands.

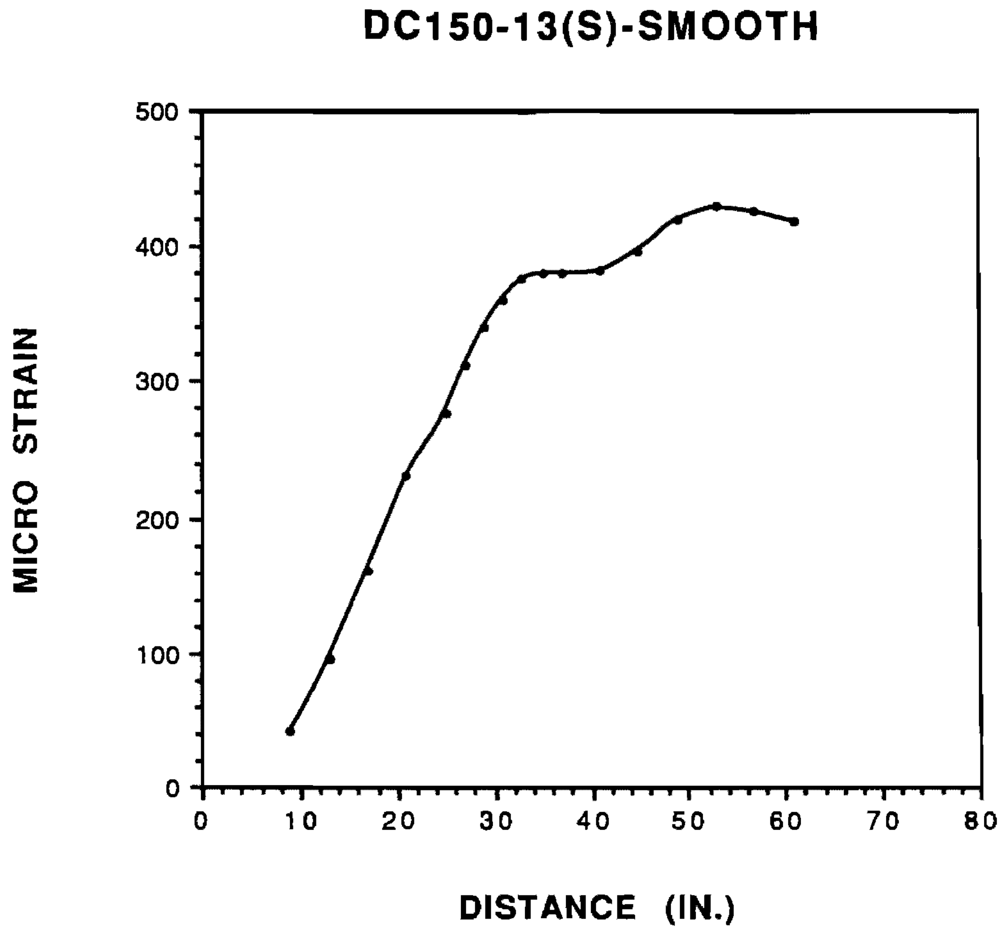


Figure 4.3 Typical concrete strain profile obtained by smoothed data.

The mean transfer length is 30.1 inches for 0.5-inch diameter strand and 39.4 inches for 0.6-inch diameter strand. It should be noted that the mentioned values are transfer lengths for 95% of prestress transfer. The minimum, mean, and maximum measured transfer lengths for each different series are illustrated and compared against the ACI/AASHTO required value in Figures 4.5 through 4.8.

4.2.3 Transfer Lengths. The measured transfer lengths are reported in Tables 4.1 through 4.4. The tables indicate transfer lengths for both 95% and 100% of the prestress force. The 95% transfer is used throughout this report as the actual measured transfer length.

Tables 4.1 and 4.2 report the transfer lengths for all fully bonded specimens and for the fully bonded strands of the debonded specimens. Tables 4.3 and 4.4 report the transfer lengths of debonded strands only.

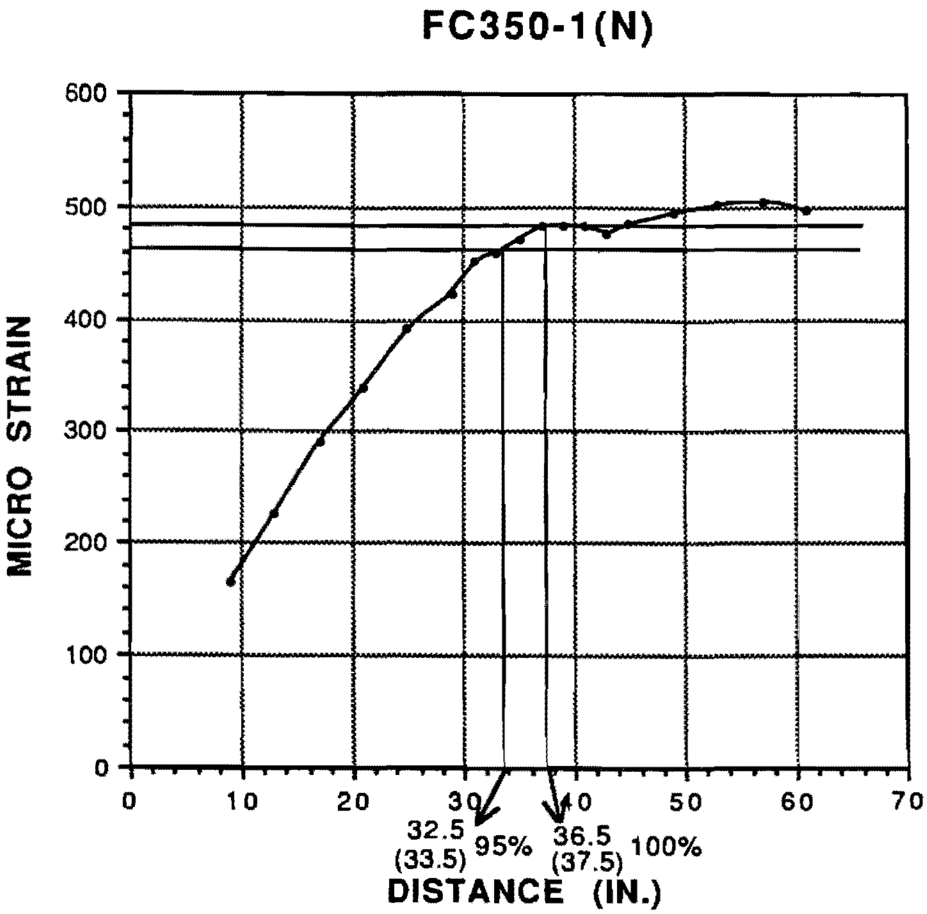


Figure 4.4 Typical concrete strain profile and techniques of obtaining transfer length.

The average transfer length for all 0.5-inch strand specimens is 30.1 inches. For the four AASHTO-type specimens (FA550 - 1, 2, 3, and 4), the average transfer length is 19.8 inches. Results for 0.5-inch strand are presented graphically in Figure 4.5. This figure illustrates the data by specimen series number. The values labeled "RM" represent the original single-strand specimens reported earlier by Malik[26]. Note the high degree of scatter in these results.

The average transfer length for all 0.6-inch strand specimens is 39.4 inches. For the six AASHTO-type specimens (FA460-1 through 6), the average transfer length is 32.0 inches. Results for 0.6-inch strand are presented graphically in Figure 4.6. Results from each specimen series are shown separately for comparison. Again, note the relatively large degree of scatter in the original single strand specimens (RM).

Table 4.1
Measured transfer length, 0.5-inch, fully bonded specimens

Specimen	95% Transfer		100% Transfer	
	North End	South End	North End	South End
FC150-11	27.0	34.0	31.0	38.0
FC150-12	28.5	28.0	32.5	33.5
Mean	29.4		33.8	
FC350-1	32.5	27.5	36.5	30.0
FC350-2	27.5	27.5	31.0	31.0
FCT-350-3	30.5	30.0	34.0	32.5
FCT350-4	29.0	32.0	31.0	34.0
Mean	29.6		32.5	
DC350-5	26.5	28.0	29.5	30.5
DC350-6	28.5	30.5	35.5	33.5
Mean	28.4		32.3	
FC550-1	39.5	36.5	46.0	44.0
FCT550-2	36.0	39.5	40.5	52.0
FC550-3	33.0	44.0	36.0	51.5
Mean	38.1		45.0	
FA550-1	18.0	16.0	33.5	19.0
FA550-2	20.5	-	24.5	-
FA550-3	21.5	22.0	30.0	29.0
FA550-4	21.0	-	24.5	-
Mean	19.8		26.8	
DB850-5	30.5	44.0	32.0	46.5
DB850-6	36.5	35.5	38.0	39.0
Mean	36.6		38.9	

Table 4.2
Measured transfer length, 0.6-inch, fully bonded specimens

Specimen	95% Transfer		100% Transfer	
	North End	South End	North End	South End
FC160-11	--	--	--	--
FC160-12	48.0	46.0	60.0	50.5
Mean	47.0		55.3	
FC360-1	42.0	40.5	47.0	47.0
FC360-2	37.0	48.0	42.0	57.5
FCT360-3	39.5	45.5	46.0	54.0
FCT360-4	50.5	42.0	60.0	51.5
FC362-11	46.0	44.0	54.0	49.5
FCT362-12	44.0	42.0	46.0	44.5
FCT362-13	44.0	40.0	47.0	44.0
	43.2		48.6	
DC360-5	42.0	36.0	46.5	40.0
DC360-6	34.5	41.0	39.0	45.0
DCT360-7	40.5	34.5	46.5	42.0
DC360-9	37.0	35.0	39.0	37.0
DCT360-10	34.5	36.5	37.0	38.0
Mean	37.2		41.0	
FC560-1	45.5	47.0	52.0	56.5
FCT560-2	48.0	51.5	54.0	59.0
FC560-3	48.0	-	57.5	-
Mean	48.0		55.8	
FA460-1	29.5	37.0	32.0	42.0
FA460-2	34.0	37.0	37.0	44.0
FA460-3	33.0	32.5	35.5	40.5
FA460-4	27.5	28.5	31.0	32.0
FA460-5	31.5	31.0	35.5	36.5
FA460-6	31.5	31.0	36.0	36.5
Mean	32.0		36.5	

Table 4.3
Measured transfer length, 0.5-inch debonded specimens

Specimen	95% Transfer		100% Transfer	
	North End	South End	North End	South End
DC150-13 DC150-14	23.0 27.0	23.5 17.0	29.0 32.5	27.5 20.0
Mean	22.6		27.3	
DC350-5 DC350-6	2.5 30.0	20.5 26.5	24.5 39.0	23.5 28.0
Mean	24.9		28.8	
DB850-5 DB850-6	35.5 25.5	30.0 29.0	41.5 29.5	34.5 31.5
Mean	30.0		34.3	

Table 4.4
Measured transfer length, 0.6-inch debonded specimens

Specimen	95% Transfer		100% Transfer	
	North End	South End	North End	South End
DC160-13 DC160-14	-- 37.5	31.5 37.5	-- 41.5	39.0 41.5
Mean	35.5		40.7	
DC360-5 DC360-6 DCT360-7 DC360-9 DCT360-10	31.5 28.0 29.5 32.0 31.5	20.0 21.0 26.5 26.5 41.0	40.0 32.5 30.5 35.0 39.0	21.5 22.0 28.0 28.0 44.0
Mean	28.8		32.1	

For debonded strand, the average transfer length values are 25.8 inches for 0.5-inch strand and 30.3 inches for 0.6-inch strand. These results are shown graphically in Figures 4.7 and 4.8.

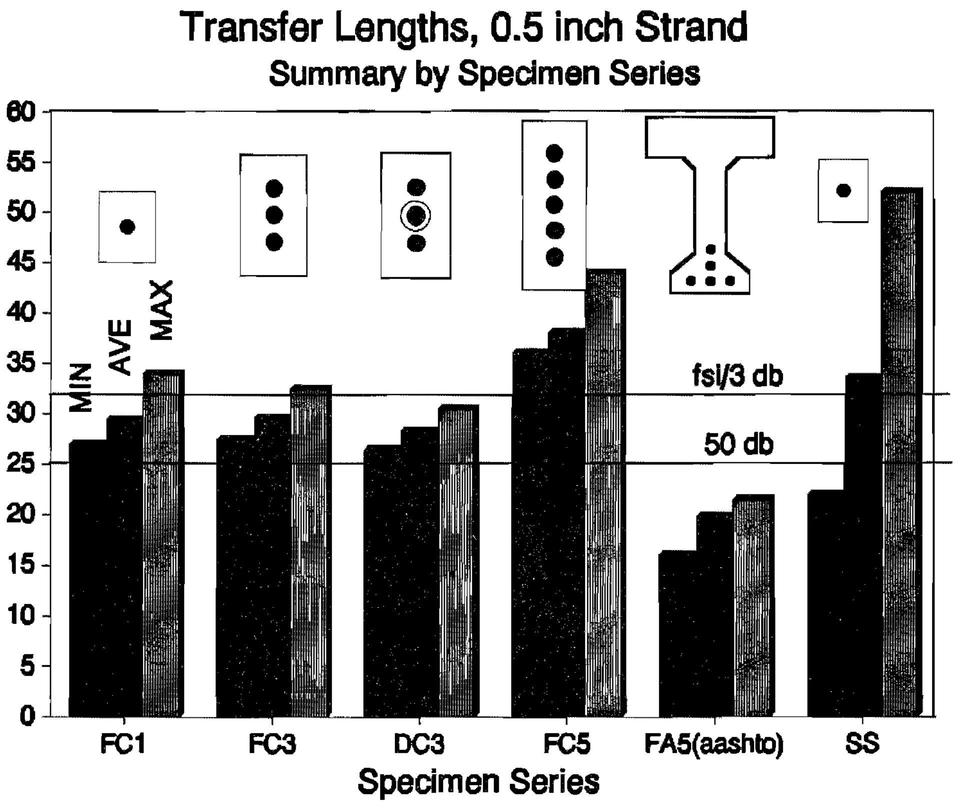


Figure 4.5 Measured transfer length, 0.5-inch fully bonded strand (minimum, mean and maximum values compared with ACI required value).

4.3 Steel Strains

Strain gages were located on the strands in order to be able to plot the change in steel stresses in all beams in each series. The change in steel stresses at transfer are plotted for 0.5-inch fully bonded, 0.6-inch fully bonded, 0.5-inch debonded, and 0.6-inch debonded specimens in Appendix B.

In the plots, the x-axis represents the length over which the strain gages were located and the y-axis represents the change in steel stress at transfer. An extra data point was added to be able to generate a second degree polynomial curve. A horizontal line was drawn from the y-axis intersecting the bottom of the curve. Another horizontal line was drawn at 95% of the change in stress. Two vertical lines were drawn from the points of intersection. The locations of the points of

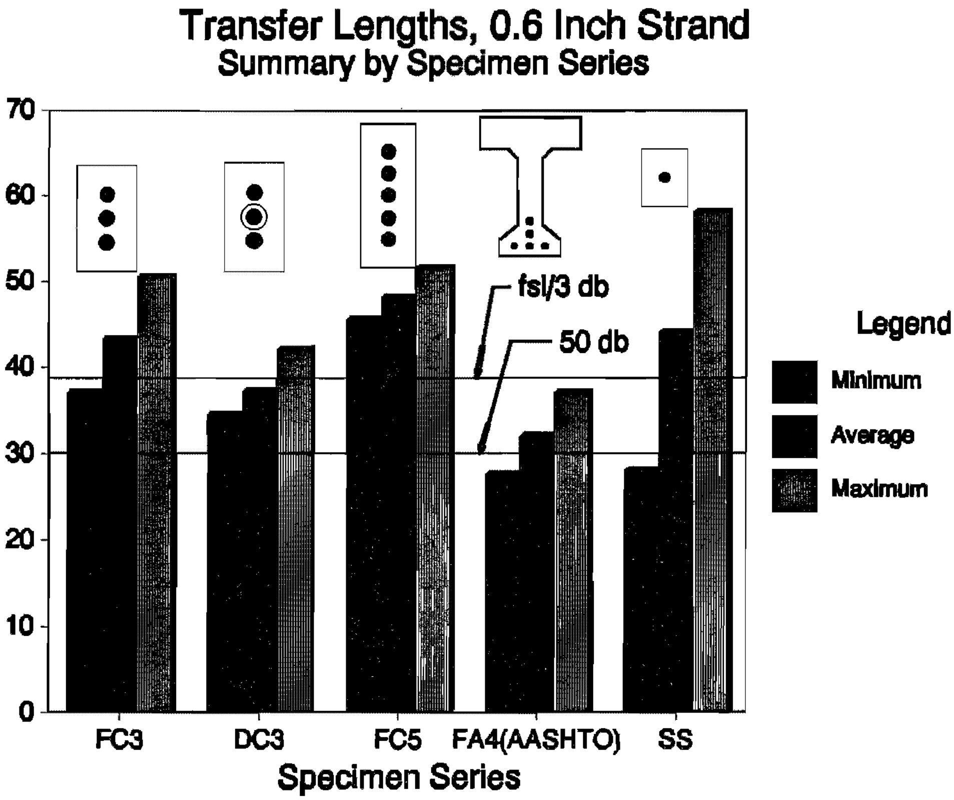


Figure 4.6 Measured transfer length, 0.6-inch fully bonded strand (minimum mean and maximum values compared with ACI required value).

intersection of the vertical lines and the x-axis represent the transfer lengths for 95% and 100% of prestress transfer.

Usage of steel strain gages was limited due to the fact that they didn't provide useful information in the initial part of the research project[26]. Also, some of the strain gages were damaged at transfer and there weren't enough gages to obtain accurate results. The transfer lengths obtained are 26 inches for 0.5-inch fully bonded specimens, 42.5 inches for 0.6-inch fully bonded specimens, 11 inches for 0.5-inch debonded specimens, and 31.5 inches for 0.6-inch debonded specimens.

4.4 End Slip

End slip measurements were taken to estimate transfer lengths. However, as the results in Ref. 26 clearly indicate, the scatter of the ratios of the estimated transfer lengths from end slip to measured transfer lengths was excessive. The ratios were between 0.46 and 1.26 for all bonded specimens and it was felt that the scatter was too excessive to develop a unifying relationship between transfer length and slip.

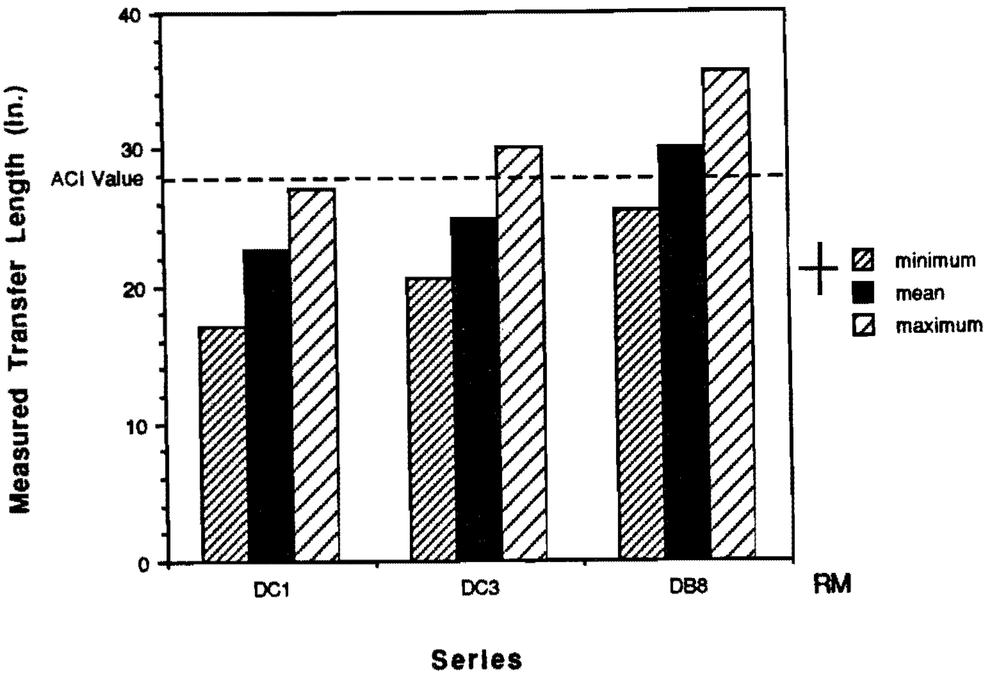


Figure 4.7 Measured transfer length, 0.5-inch debonded strand (minimum, mean and maximum values compared with ACI required value).

Therefore, only the measured end slips are reported in Tables 4.5 through 4.8. In all tables, measurements are reported separately for both ends of each specimen and the values reported for multi-strand specimens are the average values of all strands in each specimen. Plots of initial end slip vs. measured transfer length are given in Chapter 5.

4.5 Steel Stress

The equations developed in the past to predict transfer length, require the use of f_{si}, initial stress in steel, and f_{se}, effective stress in steel i the central portion of the specimen after transfer. Two different sources were used to predict steel stresses; electrical strain gage readings and elongations. In both cases, the moduli of elasticity, supplied by the manufacturer (28.2 x 10^6 psi for 0.5-inch strand and 28.5 x 10^6 psi for 0.6-inch strand) were used in the calculations.

A mean value of electrical strain gage readings for each specimen before transfer was multiplied by the modulus of elasticity of steel and f_{si} was calculated. The calculate f_{se}, only the strain gages which were in the central portion of the specimens were taken into account and f_{se} was calculated by multiplying the strain gage readings by the modulus of elasticity of steel. However, usually there was only one strain gage in the central portion of each beam, and some of these were

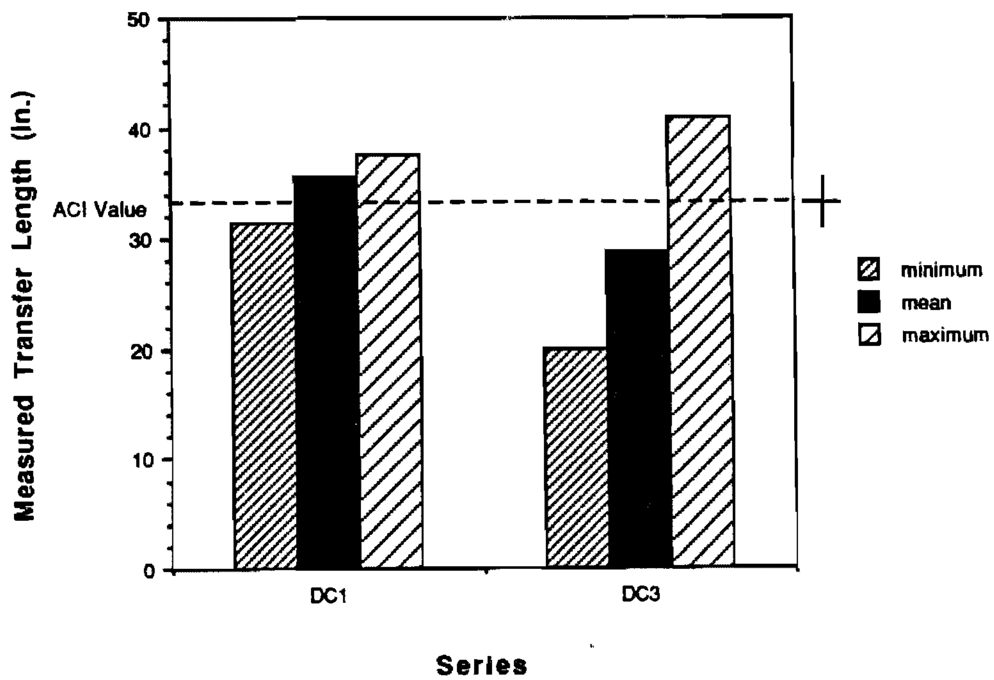


Figure 4.8 Measured transfer length, 0.6-inch debonded strand (minimum, mean and maximum values compared with ACI required value).

destroyed as a result of shock due to cutting. The calculated values of f_{se} did not seem to be realistic. Steel stresses after transfer are reported in Table 4.9.

In Table 4.10, the elongations and the stresses computed from the elongations are reported.

4.6 Concluding Remarks

In this chapter the data were reported. The data obtained from concrete strains were considered as the most reliable data. Average transfer lengths were measured as 30.1 inches for 0.5-inch fully bonded strands and 39.4 inches for 0.6-inch fully bonded strands.

Table 4.5
End slip data, 0.5-inch fully bonded strands

Specimen	End Slip (in.)	
	North End	South End
FC150-11	0.125	0.125
FC150-12	0.125	0.125
FC350-1	--	--
FC350-2	--	--
FCT350-3	--	--
FCT350-4	--	--
DC350-5	0.063	0.063
DC350-6	0.063	0.063
FC550-1	0.031	0.125
FCT550-2	--	--
FC550-3	--	--
FA550-1	0.075	--
FA550-2	0.088	--
FA550-3	0.056	0.063
FA550-4	0.081	0.069
DB850-5	0.125	0.176
DB850-6	0.250	0.125

Table 4.6
End slip data, 0.6-inch fully bonded strands

Specimen	End Slip (in.)	
	North End	South End
FC160-11	0.031	0.031
FC160-12	0.031	0.063
FC360-1	0.094	0.135
FC360-2	0.094	0.156
FCT360-3	0.073	0.135
FCT360-4	0.146	0.115
DC360-5	0.094	0.125
DC360-6	0.125	0.125
DCT360-7	0.109	0.156
DC360-9	0.188	0.125
DCT360-10	0.125	0.219
FC362-11	0.125	0.141
FCT362-12	0.125	0.146
FCT362-13	0.135	0.146
FC560-1	0.163	0.156
FCT560-2	0.169	0.144
FC560-3	0.169	0.150
FA460-1	0.102	0.094
FA460-2	--	--
FA460-3	--	--
FA460-4	0.125	0.133
FA460-5	0.125	0.117
FA460-6	0.117	0.086

Table 4.7
End slip data, 0.5-inch debonded strands

Specimen	End Slip (in.)	
	North End	South End
DC150-13	0.094	0.063
DC150-14	0.125	0.063
DC350-5	0.156	0.094
DC350-6	0.156	0.094
DB850-5	0.344	0.445
DB850-6	0.422	0.582

Table 4.8
End slip data, 0.6-inch debonded strands

Specimen	End Slip (in.)	
	North End	South End
DC160-13	0.063	0.063
DC160-14	0.063	0.063
DC360-5	0.500	0.500
DC360-6	0.500	0.500
DCT360-7	0.500	0.500
DC360-9	0.594	0.688
DCT360-10	0.578	0.438

Table 4.9 Steel stresses after transfer.	
Specimen	After Transfer (ksi)
FC350-1	188.2
FC350-2	185.7
FCT350-3	168.9
FCT350-4	189.9
DC350-5	188.2
DC350-6	185.7
FC360-1	194.4
FC360-2	197/4
FCT360-3	175.6
FCT360-4	188.4
DC360-5	189.3
DC360-6	194.3
DCT360-7	186.3
DC360-9	184.5
DCT360-10	189.5
FC362-11	187.3
FCT362-12	184.1
FCT362-13	179.9

Table 4.10
Elongations and corresponding stresses.

Specimen	Elongation (in.)	Stress (kips)
FC350-1	6.026	198.1
FC350-2	6.026	198.1
FCT350-3	6.026	198.1
FCT350-4	6.026	198.1
DC350-5	5.941	195.3
DC350-6	5.941	195.3
FC360-1	5.880	195.3
FC360-2	5.880	195.3
FCT360-3	5.880	195.3
FCT360-4	5.818	193.3
DC360-5	5.901	196.0
DC360-6	5.901	196.0
DCT460-7	5.818	193.3
DC360-9	5.943	197.4
DCT360-10	5.943	197.4
FC362-11	5.464	181.5
FCT362-12	5.464	181.5
FCT362-13	5.464	181.5
FA550-1	5.976	196.3
FA550-2	5.976	196.3
FA550-3	5.941	195.3
FA550-4	5.941	195.3
FA460-1	5.867	194.9
FA460-2	5.945	197.5
FA460-3	5.945	197.5
FA460-4	5.995	199.1
FA460-5	6.219	206.6
FA460-6	6.219	206.6
DB850-5	5.761	189.4
DB850-6	5.865	192.8

CHAPTER FIVE
DISCUSSION OF RESULTS

5.1 Introduction

In the preceding chapter, data obtained from three different sources (concrete strains, strand strands and end slips) are reported. In this chapter the results are discussed. The effects of each variable on transfer length are explained. Also, the validity and limitations of the reported data are discussed.

5.2 Effects of Variables

The nature of transfer bond and major factors contributing to transfer bond are explained in Chapter 2. As determined by Janney[2] in 1954, adhesion, friction and mechanical resistance are the three independent factors which may contribute to bond between steel and concrete. In this section the effects of each variable are discussed.

5.2.1 Size of Strand. Two different sizes of seven-wire prestressing strand, 0.5-inch and 0.6-inch diameter, were used in this project. The bond characteristics of prestressing strand are effected by dimensional properties. Properties of 0.5-inch and 0.6-inch diameter prestressing strands are tabulated in Table 5.1. The significance of this comparison is that the ratio of area to perimeter is approximately 18% greater for 0.6-inch diameter strand than for 0.5-inch strand. Therefore, it follows that 0.6-inch strand should have a longer transfer length than the 0.5-inch strand.

It should be noted that, according to previous research and by calculation, the perimeter of seven-wire prestressing strand is taken as $(4/3)\pi d_b$[24]. The results of transfer length for each different series for both sizes of strand are summarized in Table 5.2.

Table 5.1
Properties of prestressing strands

Strand Diameter (in.)	A_s (sq. in.)	Perimeter (in.)
0.5	0.153	2.094
0.6	0.217	2.513

The results reveal that the average transfer length of 0.6-inch strand is 31% longer than that of 0.5-inch strand. The average transfer lengths are 30.1 inches and 39.4 inches for 0.5-inch and 0.6-inch strands, respectively.

The data clearly supporta larger transfer length for 0.6-inch strand than for 0.5-inch strand. This is due in large part to the relative area/perimenter ratios of the two strands. While the 0.6-inch strand has a 42% greater area, and likewise a larger prestressing force, it has only about 20% more surface area to develop bond.

Current AASHTO and ACI practice would include a 20% longer transfer length for 0.6-inch strand (the ratio of d_b). However, these test results indicate a higher factor be included, on the order of 30%.

Table 5.2
Fully bonded strands

Series	Transfer Length (in.)[1]	
	0.5-inch	0.6-inch
FC1	29.4	47.0[2]
FC3	29.6	43.2
DC3	28.4	37.2
FC5	38.1[2]	48.0[3]
FA5-FA4	19.8	32.0
DB8	36.6	--
Mean	30.1	39.4

1 The transfer length values are at 95% of prestress transfer and the numbers in parentheses represent the number of ends measured.
2 Low concrete strength f'_{ci} = 3853
3 $f_{ce} \leq$ 3090 psi > 0.6 f'_{ci} = 2690 psi

5.2.2 Concrete Compressive Strength. Even though the study initially was not designed to evaluate the effects of concrete compressive strength, it was observed that there was enough variation in concrete compressive strengths of specimens to warrant a statistical examination. The variation in concrete strength were generally caused by unintentional differences in concrete mixes from the supplier to differences such as ambient temperature or moisture content of the aggregates. It should be noted that since several variables were involved and the specimens were not designed for this evaluation, the observations are not conclusive.

There have been different observations about the effect of concrete compressive strength on transfer length in the past. While researchers[2, 12, 20] observed that transfer length decreased as concrete compressive strength increased, Kaar, LaFraugh and Mass[6] reported that concrete compressive strength did not have a significant effect on transfer length.

In Figures 5.1 and 5.2, transfer length vs. concrete compressive strength is plotted. For 0.5-inch specimens (Figure 5.1) there is a slight increase in transfer length as concrete compressive strength increases. For 0.6-inch specimens (Figure 5.2) there is a clear trend of reduction in transfer length as concrete compressive strength increases. The author believes that, generally, as concrete compressive strength increases, the transfer length decreases. However, since the data for 0.5-inch specimens does not support this, no conclusion can be made.

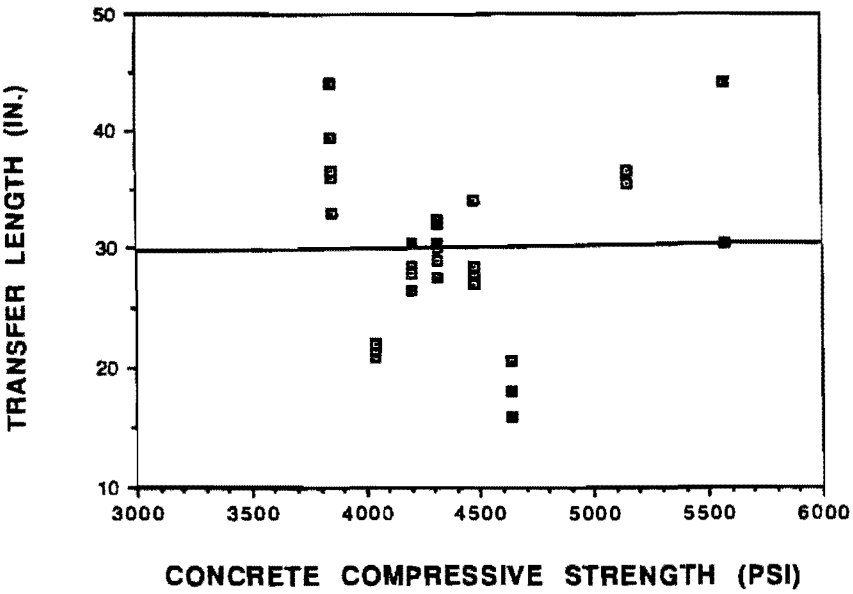


Figure 5.1 Measured transfer length vs. concrete compressive strength, 0.5-inch diameter strand.

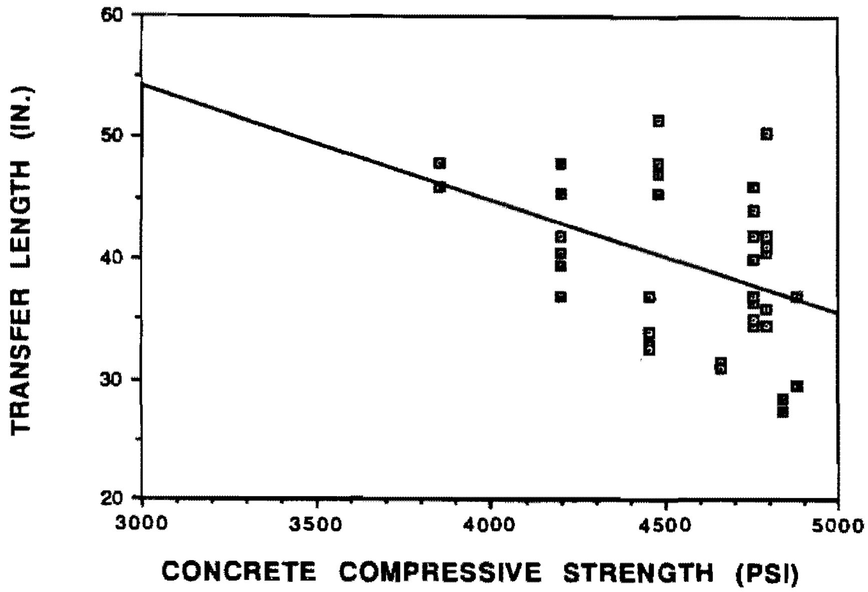


Figure 5.2 Measured transfer length vs. concrete compressive strength, 0.6-inch diameter strand.

5.2.3 Consolidation of Concrete Around Strands. Concrete consolidation and consistency around the strands is one of the major factors affecting transfer length. Concrete consolidation is provided by vibration immediately after pouring. Consolidation reduces the amount of voids and air pockets and helps the cement paste to work into the grooves of the strand. Consolidation aids adhesion and friction between concrete and steel and increases mechanical resistance. Good consolidation results in reduced transfer lengths.

In specimens FA550-1 (south end) and FA550-2 (south end) the effects of poor consolidation may be observed. Even though the point of transfer is well defined, a sudden increase and then a decrease in concrete strains is observed even well beyond the transfer length, due to poor consolidation.

5.2.4 Debonding and Debonding Patterns. The mean transfer length values for debonded strands supported the general trend that the transfer length for 0.6-inch strand was longer than that of 0.5-inch strand. The results are tabulated in Table 5.3. It is observed that the transfer lengths of debonded specimens were shorter than those of fully bonded specimens. It is unlikely, although possible, that transfer bond was not totally prevented over the transfer zone by plastic tubing and that some concrete might have gotten into the plastic tubing from the ends. A more likely explanation is that the transfer of debonded strands is not affected by undesirable end effects.

The effect of debonding patterns can be observed by comparing the concrete strain profiles of DC360-5, DC360-6, DCT360-7, DC360-9, and DC360-10. The slope of the strain vs. transfer length curves for specimens in which only the middle strand was debonded is twice as steep as the specimens in which the bottom and the top strands were debonded. As expected, the maximum concrete strain was the same for all similar debonded specimens.

Table 5.3
Debonded strands

Series	Transfer Length (in.)*	
	0.5-inch	0.6-inch
DC1	22.6 (4)	35.5 (3)
DC3	24.9 (4)	28.8 (10)
DB8	30.0 (4)	–
Mean	25.8 (12)	30.3 (13)

* The transfer length values are at 95% of prestress transfer and the numbers in parentheses represent the number of ends measured.

5.2.5 Strand Spacing. Two different strand spacings were used: 2-inch and 2.25-inch. The original intention was to determine if cracking would occur for 2-inch spacing, especially with 0.6-inch diameter prestressing strand. However, no such cracking was observed in the specimens. Also, transfer lengths did not significantly change between specimens with 2-inch spacing and those with 2.25-inch spacing.

5.2.6 Transverse Reinforcement. Although, theoretically, it is possible that providing transverse reinforcement will reduce transfer length, it was reported to have no significant effect on transfer length by Dane and Bruce[28], and to reduce transfer length only at the cut end of 15% by Kaar, LaFraugh and Mass[6].

Results from these tests also show that transverse reinforcement has no significant effect on transfer length. It should be noted that in cases where longitudinal cracking occurs in the transfer zone, transverse reinforcement will be required to arrest crack propagation.

Table 5.4
Transversely reinforced specimens vs. others
(similar specimens)

Series	0.5-inch		0.6-inch	
	Simple	T.R.**	Simple	T.R.**
FC3	28.8 (4)	30.4 (4)	42.9 (6)	43.4 (8)
FC5	28.3 (4)	37.8 (2)	46.8 (3)	49.3 (2)
Mean	33.6 (8)	32.9 (6)	44.2 (9)	44.6 (10)

* The transfer length values are at 95% of prestress transfer and the number in parentheses represent the number of ends measured.

** Specimens for which transverse reinforcement was provided.

5.2.7 Method of Release. Two methods of release were used in this research work. The first method employed conventional flame cutting at full tension. This method was used on the initial eighteen (18) single-strand specimens reported by Malik[26]. In these tests, the transfer length at the cut end was significantly larger than the transfer length at the dead end. Unfortunately, at release, the specimens experienced a very large amount of violence and movement. The high degree of scatter in the results is a likely consequence of this method of release on small specimens.

Of the remaining forty-four (44) specimens, the three strand specimens and the five-strand specimens used a second method of release that can best be described as a hybrid between flame cutting, or sudden release, and a gradual detensioning. The single-strand specimens numbered -11 or higher also employed this method.

The researchers theorized that specimens with a single-strand and/or a small cross section undergo an extreme level of shock when prestressing strands are suddenly detensioned. Consequently, it was felt that these small cross sections with a small number of strands do not provide highly reliable data on transfer length if strands are suddenly detensioned. It is reasoned that a specimen with a large number of strands enjoys some confinement and reinforcement effects from the other prestressing strands, particularly those strands which have previously been cut and would be actively precompressing the concrete. Also, larger cross-sections would be less susceptible to shock and other dynamic effects from the cutting of a single strand.

Considering all of these things, the researchers still wanted to emulate a "worst cast" transfer. Therefore, the hybrid method of release was adopted for use for the multi-strand specimens designated above. This method of release more clearly approximates the sudden release of full-size specimens.

The hybrid release method employed a set of shims at the jacking end of the prestressing bed. These shims were removed as the first step towards detensioning prior to cutting the strands. The thickness of the shims accounted for approximately 40% of the total tensile force. Therefore, detensioning the strands had the effect of gradually detensioning approximately 40% of the total tensile force. Actual elongation measurements indicate that real detensioning was only about 30% leaving 70% of the total tensile force to be relieved by flame cutting. Upon flame cutting, the force and shock to the test specimens was very similar to that when flame cutting was done at 100% tension. There was, however, noticeably less violence and movement of the specimens.

The twelve AASHTO-type specimens were flame cut at full tension. Because these specimens resemble actual AASHTO girders in shape and size, the measured transfer length from from these specimens should closely match the actual transfer length of highway girders. These specimens also provide interesting comparisons with the smaller cross sections that were released by the hybrid method.

The results of the detensioning method are readily apparent from the data. For the 0.5-inch diameter strand, the "FA5" specimens averaged a transfer length of twenty inches, whereas the other specimen, "FC1", FC3", and "DC3", averaged a transfer length of about twenty-nine. The original single-strand specimens that were flame cut at full tension had an average transfer length of 33.5. Also note the scatter in results from these specimens. These data are clearly shown in Figure 4.6.

For the 0.6-inch diameter strand, the "FA4" specimens averaged a transfer length of thirty-two inches, whereas the other specimen, "FC1", "FC3", and "DC3", averaged a transfer length of forty-one inches. The original single-strand specimens that were flame cut at full tension had an average transfer length of forty-four inches, but again with a high degree of scatter.

The conclusions that can be drawn from this is that:

1) The specimens with larger cross sections enjoy a much lower transfer length, even though the release was at greater tension,

2) The hybrid release method (a combination of gradual detensioning and flame cutting) provides reliable data for transfer length and more closely emulates transfer of full-size speciimens, and

3) Single-strand specimens released at full tension do not provide accurate or reliable data. The variation in result is much larger than normal and the measured transfer length is 67.5% larger for 0.5-inch strand and 37.5% greater for 0.6-inch strand than the AASHTO-=type sections. Furthermore, it is likely that a similar unreliability and

accuracy may be inferred to development length tests on single-strand specimens that were flame cut at full tension.

Series	Transfer Length (in.)*			
	0.5-inch		0.6-inch	
	Cut	Dead	Cut	Dead
FC1	27.0 (1)	30.2 (3)	-	-
FC3	32.3 (2)	28.7 (6)	44.8 (5)	42.3 (9)
DC3	28.3 (2)	28.5 (2)	38.2 (5)	36.1 (5)
FC5	41.8 (2)	36.3 (4)	45.5 (1)	48.6 (4)
FA5-FA4	19.8 (2)	19.4 (4)	31.4 (8)	33.1 (4)
Mean	30.2 (9)	28.6 (19)	37.5 (19)	40.4 (22)

Table 5.5
Cut end vs. dead end

* The transfer length values are at 95% of prestress transfer and the numbers in parentheses represent the number of ends measured.

5.2.8 Number of Strands. In this study, number of strands and accordingly, cross-sections, were varied. Most of the previous research was conducted using single-strand specimens. However, the researchers were concerned about how well the behavior of single-strand specimens represents the behavior of actual beams and girders. Although, the transfer lengths of single-strand and multi-strand specimens were not very different, it was observed that the scatter of the data obtained from single-strand specimens was high compared to multi-strand specimens. The effect of method of release is high in single-strand specimens and is the main cause of such excessive scatter of data. Also, some averaging effects quite likely reduce scatter for specimens with multiple strands.

5.3 Discussion of Methods

In measuring the transfer length, only the concrete strains out of three sources proved to be reliable. In this section, the reliability and limitations of the three sources of information are discussed.

5.3.1 Concrete Strain Profiles. Concrete strains were the major source of information in measuring the transfer length. The measured transfer lengths compare well and are consistent with previous research. However, there is some concern about strain profiles. In most cases it is difficult to determine the location of full transfer on the strain profiles. Also, beyond the transfer length, the strain profiles usually did not have a smooth plateau. The points were slightly scattered and a smoothing technique, explained in Section 4.2.1, was applied to raw data. The difference between a raw and a smoothed profile can be observed by comparing Figures 4.2 and 4.3. Also, the reported transfer lengths correspond to 95% of prestress transfer. This technique was developed to obtain more consistent results, especially in cases where the horizontal line passing through the mean of the plateau give rather excessive transfer length values compared to a horizontal line passing through a plateau slightly below the mean where the prestress transfer is considered nearly 100% effective.

5.3.2 Steel Strain Profiles. Steel strains were plotted four times (Appendix B) and mean transfer length values were obtained for 0.5-inch and 0.6-inch, fully bonded and debonded strands. The results are consistent with values obtained from concrete strains, except for the transfer length for 0.5-inch debonded strands which is lower than measured. Certainly, in a qualitative sense, the transfer length derived from steel strain gage data show a solid correlation with results obtained from concrete strain readings.

The steel strain data was intended to be supplemental. Even though the results were consistent with those of concrete strains and showed the same trends, the author believes that the steel strain data is not as reliable as the concrete strain data.

5.3.3 End Slip. End slip was measured in two ways: manually by a steel ruler and by end slip devices. End slip was measured to provide supplemental data. As demonstrated by Malik[26], there was a lot of scatter in end slip data and the scatter was too excessive to develop a unifying relationship between transfer length and end slip. Also, since end slip devices were mostly destroyed at transfer, they did not turn out to be useful.

Two plots of end slip vs. transfer length for 0.5-inch and 0.6-inch strands are given in Figures 5.3 and 5.4. Although the slips of the two plots are slightly different, they demonstrate that there is a trend for transfer length to increase as end slip increases. This is mostly due to the fact that the adhesive bond is broken over a length directly proportional to the amount of end slip. Also, mechanical resistance is reduced by increased end slip because the concrete in the grooves of the strand is broken over a certain length. However, as end slip increases, steel stresses in the slip region are reduced and this increases friction due to the swelling of the strand.

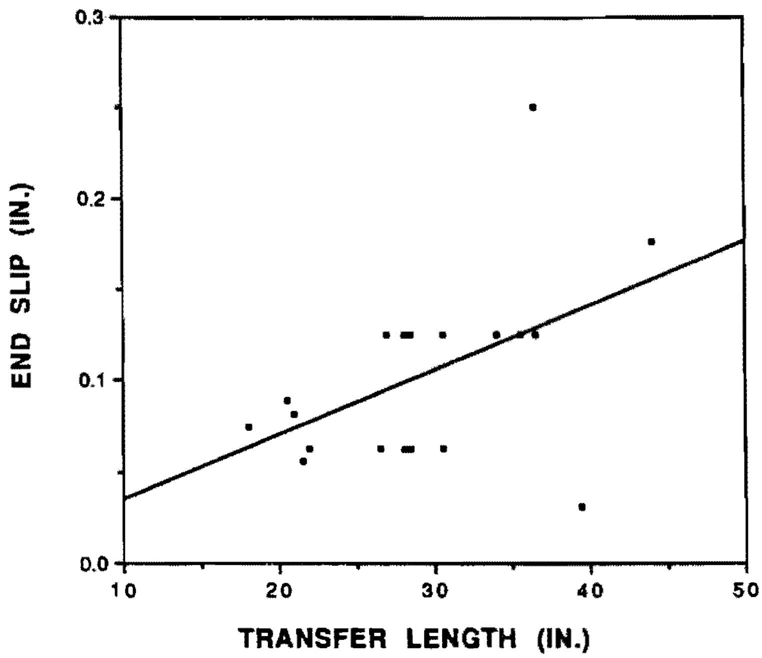


Figure 5.3 Measured transfer length vs. end slip, 0.5-inch diameter strand.

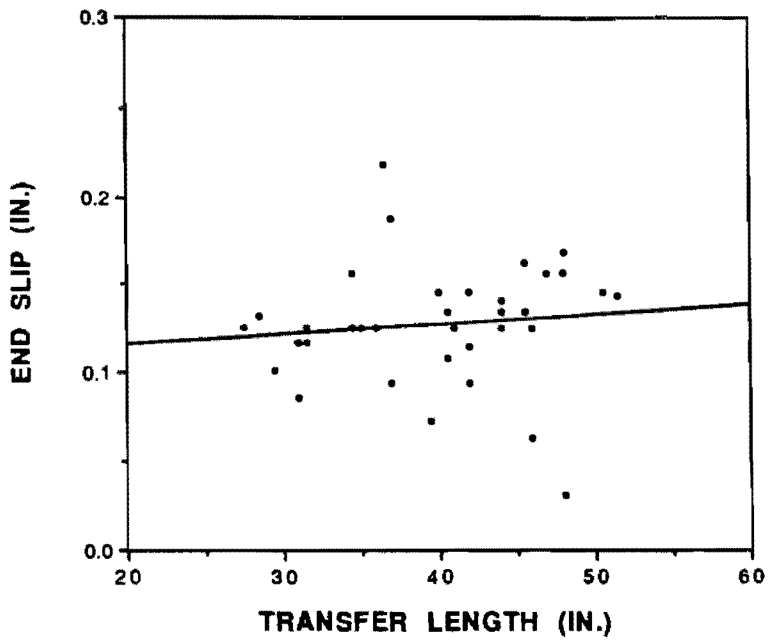


Figure 5.4 Measured transfer length vs. end slip, 0.6-inch diameter strand.

CHAPTER SIX
COMPARISON WITH PREVIOUS RESEARCH

6.1 Introduction

The research project covered here differs from previous research in several aspects. Strand with 0.6-inch diameter has rarely been tested and the materials were different than the materials utilized in this project. Also, in several project the main source of information was steel strains, whereas concrete strains were used as the main source of information in this project.

This chapter compares the results with results from previous research. Also, results are compared with computed results from approximate equations.

6.2 Comparison with Experimental Work

The experimental work conducted in the past was reported in Chapter 2. In this section the test results are compared with previous experimental results.

Tests conducted by Janney(5) included Grade 270K, 0.5-inch diameter seven-wire prestressing strand. Only the results of the two specimens utilizing clean and bright strand are compared. Janney reported the transfer length to be 33 inches, which was measured to be 30.1 inches at 95% prestress transfer and 34.7 inches at full transfer for 0.5-inch strand in this project.

Kaar, LaFraugh and Mass(6) experimented with 0.5-inch and 0.6-inch strands and concrete of compressive strengths of 4170 psi and 5000 psi. They concluded that concrete compressive strength had little influence on the transfer length of seven wire strands up to 0.5-inch diameter. Similar to the specimens tested in this project, multi-strand specimens with more massive sections were tested. However, Grade 250K, stress-relieved strand was used. The results are compared in Table 6.1. It is noted that Kaar et al. results are higher for 0.5-inch strand and almost the same for 0.6-inch strand at full transfer. The difference for 0.5-inch strand results is partly due to the fact that Kaar et al. measured transfer length at full transfer and the method of cutting was different.

Over and Au(7) conducted tests on the transfer length of 0.5-inch diameter strand. They measured the transfer length to be 35 inches which compares well with the measured 34.7 inches for full transfer on this project.

Table 6.1 Comparison of results with Kaar et al.					
		Kaar et al.		Present Project	
		Cut (in.)	Dead (in.)	95% (in.)	100% (in.)
0.5-inch	Minimum	37.5	32.0	16.0	19.0
	Mean	41.0	34.5	30.1	34.7
	Maximum	43.5	36.0	44.0	52.0
0.6-inch	Minimum	36.0	27.5	27.5	31.0
	Mean	45.5	35.0	39.4	44.6
	Maximum	52.0	42.5	51.5	60.0

Kaar, Hanson, Corley and Hognestad(9) tested with 3/8 inch diameter strand which is not comparable to the results reported here. However, their work was significant due to the fact that they took transfer length as the length required to reach 95% of the average concrete strain plateau.

Dorsten, Hunt and Preston(16) tested three beams with uncoated Grade 270K, 0.5-inch diameter, low-relaxation seven-wire prestressing strand as part of a research project on the effect of epoxy-coating on transfer length. Their results are slightly lower than the results reported here. The transfer length was 27.5 inches compared to 30.1 inches at 95% transfer on this project.

Cousins, Johnston and Zia(18) tested some specimens prestressed with uncoated 0.5-inc and 0.6-inch strands. They had transfer lengths of 50 inches and 56 inches, respectively. These values are considerably higher than those reported here. It should be noted that the technique of measuring the transfer length was different and all the transfer lengths reported correspond to 100% prestress transfer.

Castrodale, Burns and Kreger(20) reported values which were below ACI/AASHTO provisions. They reported transfer lengths of 22 inches and 26 inches for 0.5-inch strand in two series of specimens with different cross-sections. This may be partly due to the fact that they utilized stress-relieved prestressing strand. Also, the strands were initially stressed to $0.7f_{pu}$. If a comparison is made between those results and current test results, taking into account the facts mentioned above, the results are similar.

Deatherage and Burdette[24] reported tests on concrete prisms and I-beams prestressed with 0.5-inch and 0.6-inch strands. They measured transfer lengths to be 42.8 inches and 42.2 inches, respectively. If the technique utilized in the present project is applied to their concrete strain profiles, the results would be slightly higher for 0.5-inch strand and almost the same for 0.6-inch strand compared to the present results.

6.3 Comparison with Approximate Equations

The ACI Commentary[21], section 12.9, recommends a transfer length,

$$l_t = \frac{f_{se}}{3} d_b$$

Using the mean values for f_{se} as 165.8, the ACI equation predicts a transfer length for 0.5-inch strand and 0.6-inch strand as 27.6 inches and 33.2 inches, respectively.

For 0.5-inch strand, the average transfer length is 30.1 inches, and the formula presented in ACI commentary would be unconservative by nine percent. For 0.6-inch strand, the average transfer length is 39.4 inches. Again, the ACI provision would be unconservative, in this case by nineteen percent.

On the other hand, if only the AASHTO-type specimens are considered, the average transfer lengths are 19.8 inches for 0.5-inch strand and 32.0 inches for 0.6-inch strand. These values make the ACI formula conservative by twenty-eight percent and four percent, respectively.

Current AASHTO practices use a transfer length equal to 50 strand diameters. This can be slightly less conservative than ACI predictions if f_{se} is greater than 150 ksi. Comparison of these test results to AASHTO yields very similar results. In fact, AASHTO predicts quite well the transfer length of AASHTO-type girders.

Zia and Mostafa[12] proposed two equations for transfer length based on a linear regression analysis of research conducted prior to 1976. Actually, a comparison of current results with the Zia-Mostafa equation (sudden release) is a comparison with all the research conducted prior to 1976. The comparison of current measured results with those predicted by the equation is given in Table 6.2. It should be noted that the initial prestress values are obtained from the elongations. Although the ratios of measured and calculated values are close in some specimens, there are differences as high as 78%. The scatter of the ratios is not startling since the equation was derived from an analysis of highly scattered data. The Zia-Mostafa equation is not a unifying equation. It is rather an attempt to predict the mean value

Table 6.2
Comparison of results with the Zia-Mostafa equation

Specimen	f_{si} (ksi)	f_{ci}' (psi)	Transfer Length (in.)		Measured / Z-M
			Z-M	Measured	
FC350-1	198.1	4315	29.8	30.90	1.01
FC350-2	198.1	4315	29.8	27.5	0.92
FCT350-3	198.1	4315	29.8	30.3	1.02
FCT350-4	198.1	4315	29.8	30.5	1.02
DC350-5	195.3	4201	30.3	27.3	0.90
DC350-6	195.3	4201	30.3	29.5	0.97
FC360-1	195.3	4201	37.2	41.3	1.11
FC360-2	195.3	4201	37.2	42.5	1.14
FCT360-3	195.3	4201	37.2	42.5	1.14
FCT360-4	193.3	4792	31.7	46.3	1.46
DC360-5	196.0	4792	32.2	39.0	1.21
DC360-6	196.0	4792	32.2	37.8	1.17
DCT360-7	193.3	4792	31.7	37.5	1.18
DC360-9	197.4	4759	32.7	36.0	1.10
DCT360-10	197.4	4759	32.7	35.5	1.09
FC362-11	181.5	4759	29.7	45.0	1.52
FCT362-12	181.5	4759	29.7	43.0	1.45
FCT362-13	181.5	4759	29.7	42.0	1.41
FA550-1	196.3	4639	27.1	17.0	0.63
FA550-2	196.3	4639	27.1	20.5	0.76
FA550-3	195.3	4040	31.7	21.8	0.69
FA550-4	195.3	4040	31.7	21.0	0.66
FA460-1	194.9	4880	31.3	33.3	1.06
FA460-2	197.5	4458	35.3	35.5	1.01
FA460-3	197.5	4458	35.3	32.8	0.93
FA460-4	199.1	4836	32.5	28.0	0.86
FA460-5	206.6	4661	35.3	31.3	0.89
FA460-6	206.6	4661	35.3	31.3	0.89
DB850-5	189.4	5578	20.9	37.3	1.78
DB850-6	192.8	5152	23.5	36.0	1.53

of transfer length. It is by no means conservative since 63% of the measured values are higher.

Martin and Scott[10] proposed two empirical equations by fitting a bilinear curve to the data obtained by Hanson and Kaar. They proposed a transfer length of 80 strand diameters for all conditions. Comparison of measured and calculated values from the Martin-Scott equation are given in Table 6.3. It should be noted that the measured values are the minimum, mean and maximum values corresponding to 95% transfer. The suggested transfer length of 870 strand diameter is a conservative upper limit. However, since the transfer length is shorter for massive beams, it is slightly overconservative.

Table 6.3
Comparison of results with the Martin-Scott equation

	Martin-Scott	Minimum	Mean	Maximum
0.5-inch	40.0	16.0	30.1	44.0
0.6-inch	48.0	27.5	39.4	51.5

CHAPTER SEVEN
SUMMARY AND CONCLUSIONS

On October 26, 1988, the Federal Highway Administration (FHWA) issued a memorandum disallowing the use of 0.6-inch diameter strand in pretensioned application[29]. Recent studies[18] had indicated that current AASHTO provisions for the transfer length and development length of 0.6-inch prestressing strand were unconservative. On the basis of very limited data, restrictions on 0.6-inch strand were adopted as an interim measure until additional research results were available to either substantiate or restructure code provisions. In response to this research need, this report focuses on determining the transfer length of 0.5-inch and 0.6-inch strand.

Sixty-two (62) transfer length specimens were cast and tested. Of these, twenty-six (26) were single-strand specimens, eighteen (18) were three-strand specimens, and six (6) were five-strand specimens. These fifty (50) specimens all had rectangular cross sections with concentric prestressing. The remaining twelve (12) specimens were I-shaped, designed to resemble the cross section for an AASHTO section.

Research variables included the number of strands, strand spacing (2 in. or 2.25 in.), strand diameter (0.5-in. or 0.6-in.) and the effects of transverse reinforcement. The transfer length of debonded strand was also studied.

These tests utilized mechanical strain measuring devices (Demec) to detect concrete strains at the outside face of the test specimens when pretensioned strand were out. The transfer length of each specimen was determined by statistical examination of the concrete strain profile. It was observed that the concrete strain increases from the end of the specimen until a plateau is achieved, signalling a fully effective prestress force. Transfer length is the distance from the beginning of bond (usually the end of the beam) to the point where the prestress force is fully effective.

The initial test series was comprised of eighteen (18) single-strand specimens. Data from these tests indicated that current AASHTO/ACI provisions were unconservative. However, the test results were scattered over a wide range of values. Similar variations are apparent in the measured transfer lengths if other research performed on single strand specimens. Unfortunately, a significant portion of the transfer length research has been performed on specimens with small cross sections and a single strand.

Subsequent multi-strand tests, eighteen (18) three-strand and six (6) five-strand specimens, and an additional eight (8) single-strand specimens, showed markedly less divergent results. These strands were detensioned using the hybrid release method described in sectoin 5.2.7. Transfer length measured in these two types of specimens were only slightly longer than AASHTO/ACI provisions.

In the last series of tests, twelve (12) specimens with AASHTO-type I-sections, the measured transfer lengths were actually slightly shorter or equal to AASHTO/ACI predictions for both 0.5-inch and 0.6-inch strand. For the 0.5-inch strand, the average measured transfer length for these specimens was 19.8 inches. For the 0.6-inch strand, the average measured transfer length was 32 inches. Strands for these specimens were flame cut at full tension.

Overall, test results indicated that the behavior of 0.6-inch strand is very similar to the behavior of the 0.5-inch strand. Furthermore, the transfer length of both 0.5-inch and 0.6-inch strand are closely predicted by AASHTO/ACI provisions. Although the codes may be slightly unconservative, they are conservative to a small degree. Only slight modifications to current practice are warranted, if at all.

Following is a summary list detailing the conclusions which are made:

1) The large AASHTO-type specimens demonstrated significantly shorter transfer lengths than the smaller "transfer length prisms." This is significant because much of the past and concurrent research is being conducted on rectangular prisms. From these data, pretensioned specimens with large cross-sections and multiple strands have significantly shorter transfer lengths.

2) Current AASHTO/ACI transfer length expressions are only slightly unconservative and require little or no modification. Even though average transfer lengths were 30.1 inches (20% high[1]) for 0.5-inch strand and 39.4 inches (30% high[1]) for 0.6-inch strand, tests on the larger AASHTO-type specimens revealed significantly lower transfer lengths: 19.8 inches (20% low[1]) for 0.5-inch strand and 32 inches (7% high[1]) for 0.6-inch strand.

3) The behavior of specimens with 0.6-inch strands is nearly the same as behavior of specimens with 0.5-inch strands. Behavioral similarity is very significant because current design and construction practices for other sizes of pretensioned strand should be transferable to 0.6-inch strand. Data from these test results indicate that the restrictions currently placed on 0.6-inch strand should be considered for review.

4) Higher concrete strengths at release result in shorter transfer lengths. Although no quantitative assessment can be formalized, the data clearly demonstrate in general terms that weaker concrete results in longer transfer lengths.

5) Transverse reinforcement has little or no effect on transfer length. This is certainly true for specimens which do not crack upon transfer. For specimens which do experience cracking at transfer, transverse reinforcement must still be required.

6) The 2.25-inch spacing of 0.6-inch strand had no effect on transfer length.

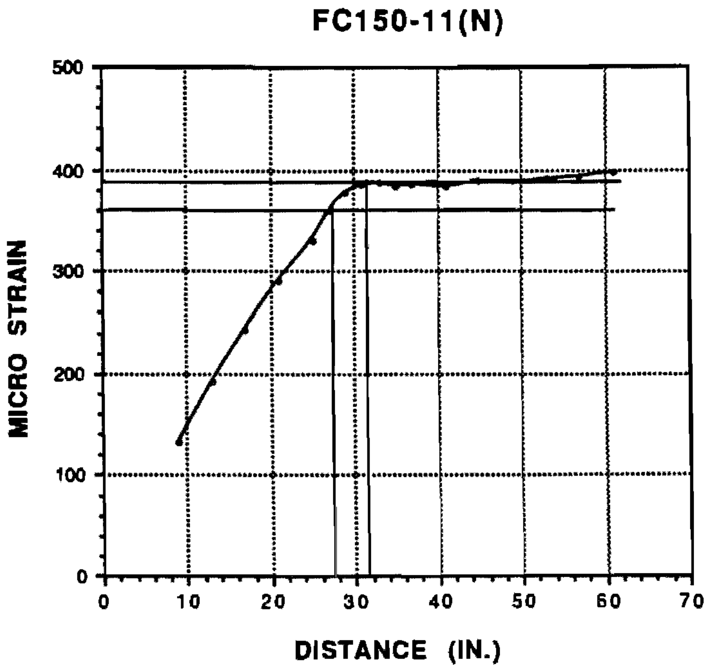
---

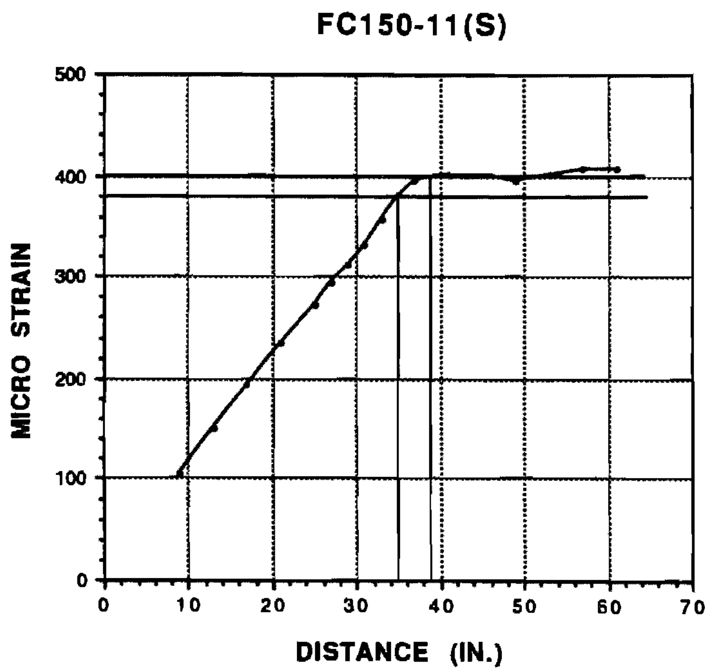
[1] Comparison is to the AASHTO practice of 30 d_b

APPENDIX A

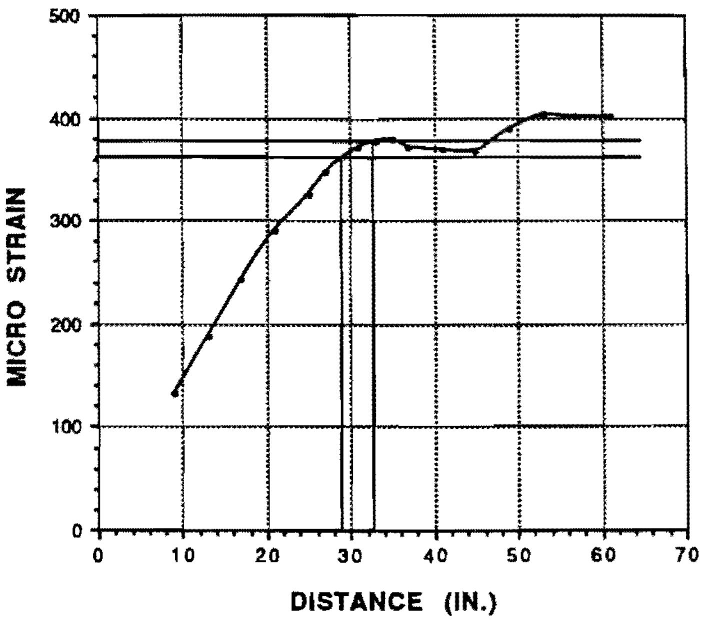
CONCRETE STRAIN PROFILES

The appendix shows concrete strain profiles of all the 44 specimens tested. Method of obtaining transfer length is explained in detail in Section 4.2.2.

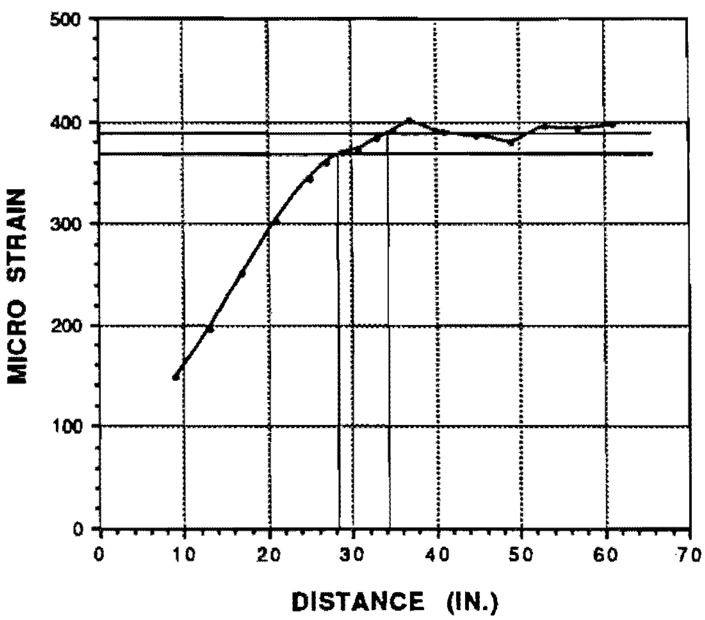

FC150-11(N)
MICRO STRAIN
500
400
300
200
100
0
0
10
20
30
40
50
60
70
DISTANCE (IN.)

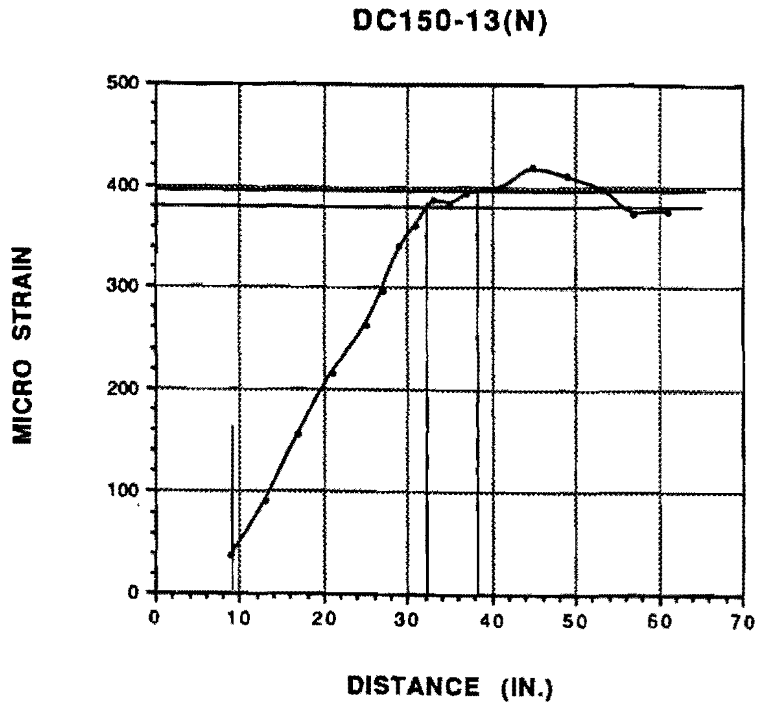

FC150-11(S)
MICRO STRAIN
500
400
300
200
100
0
0
10
20
30
40
50
60
70
DISTANCE (IN.)

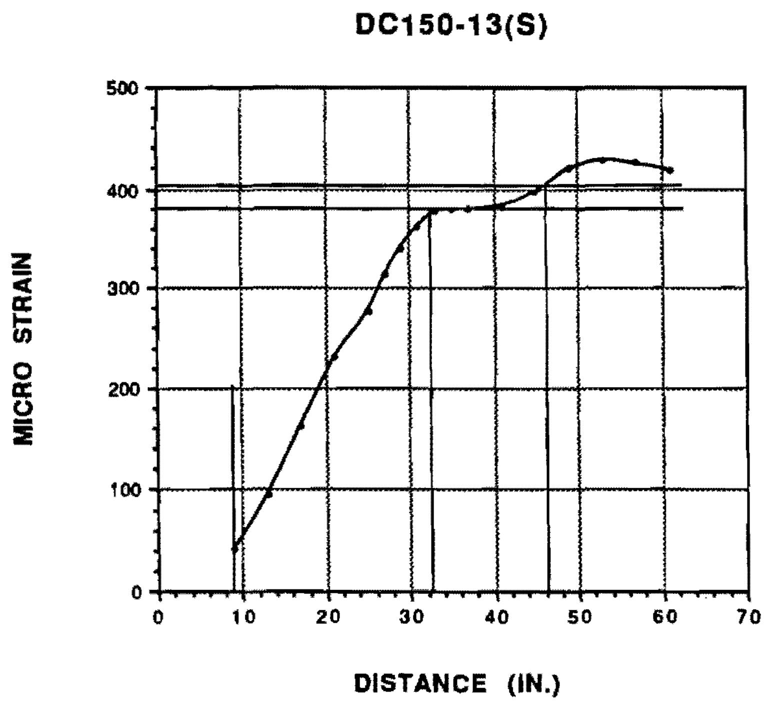
FC150-12(N)

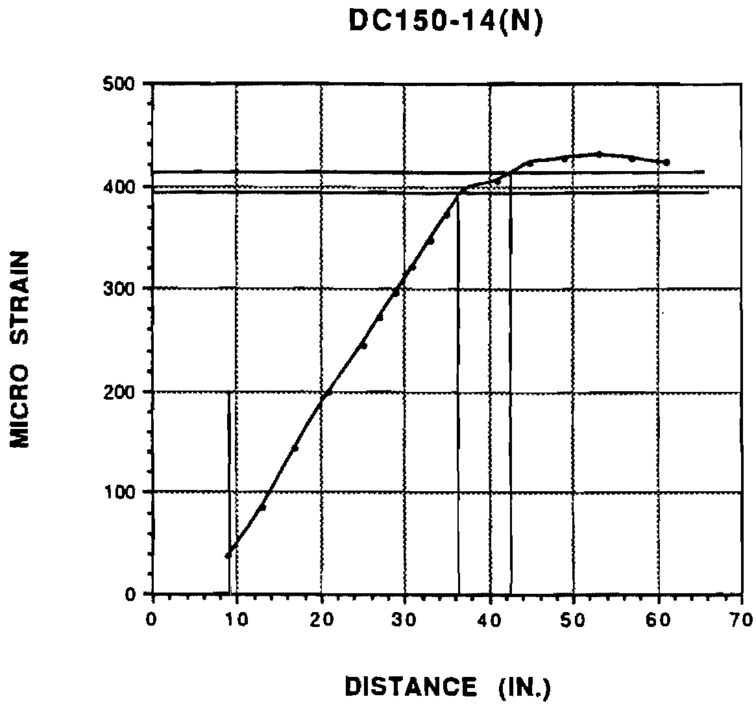


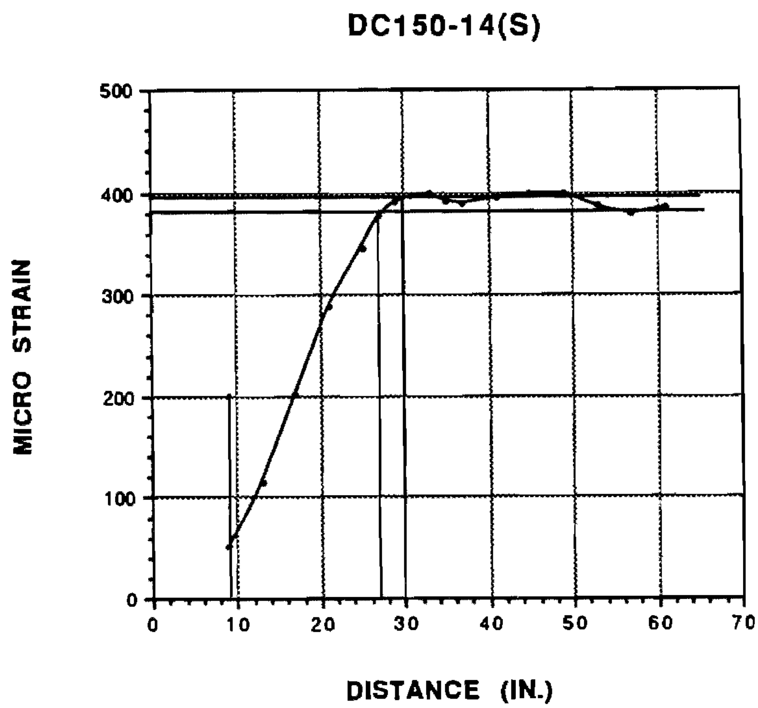
FC150-12(S)

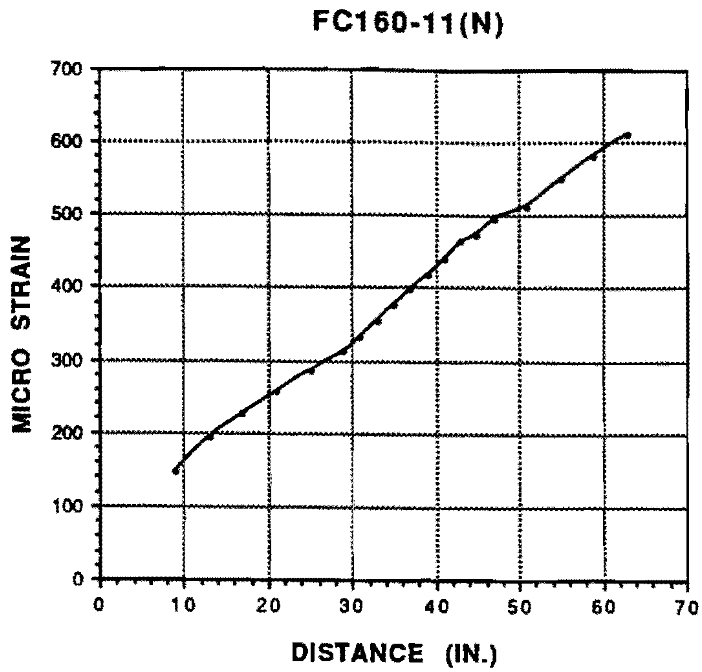


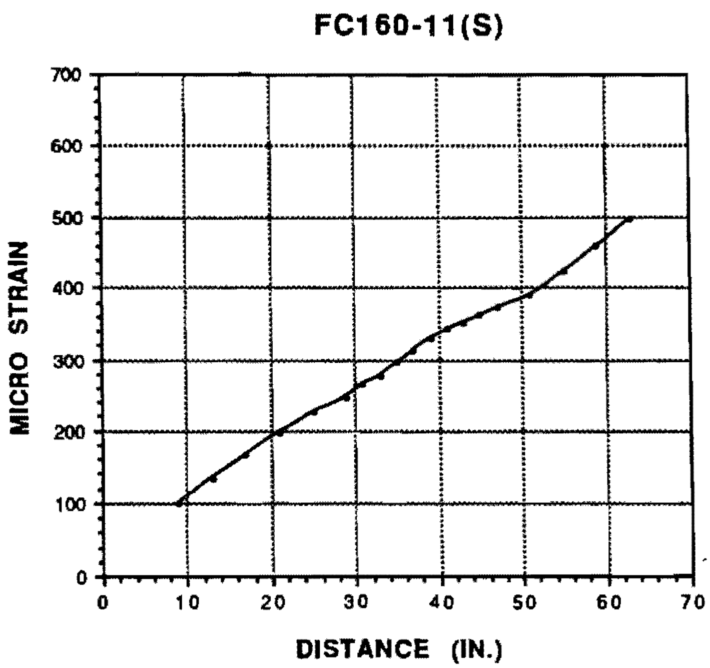

DC150-13(N)
MICRO STRAIN
DISTANCE (IN.)
0
100
200
300
400
500
0
10
20
30
40
50
60
70

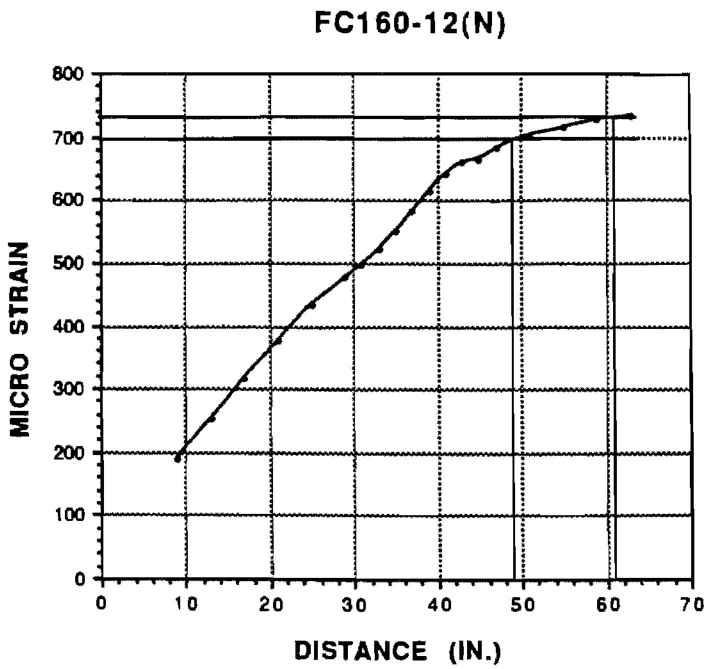

DC150-13(S)
MICRO STRAIN
DISTANCE (IN.)
0
100
200
300
400
500
0
10
20
30
40
50
60
70

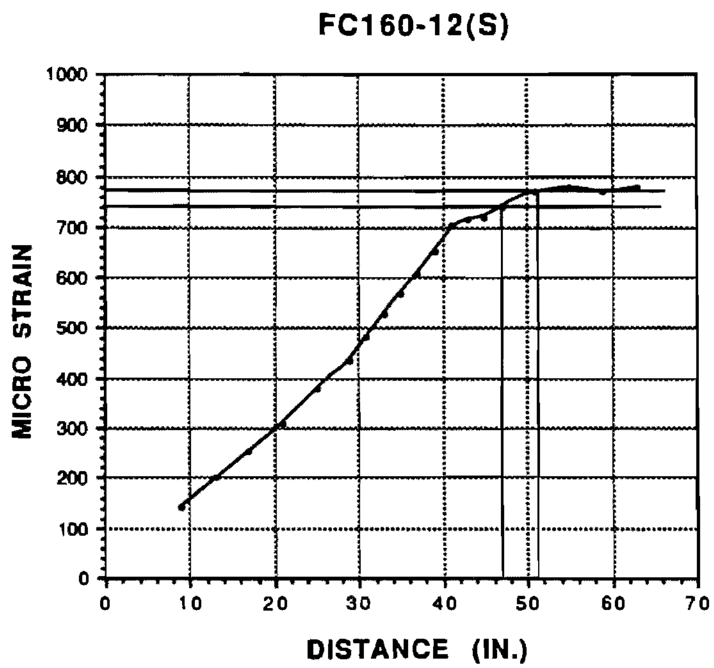

DC150-14(N)
MICRO STRAIN
500
400
300
200
100
0
0
10
20
30
40
50
60
70
DISTANCE (IN.)


DC150-14(S)
MICRO STRAIN
500
400
300
200
100
0
0
10
20
30
40
50
60
70
DISTANCE (IN.)

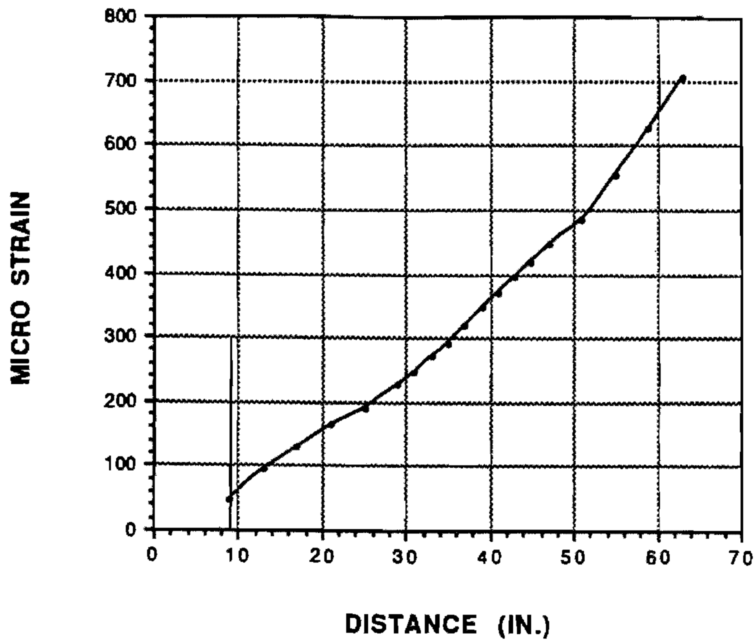

FC160-11(N)
MICRO STRAIN
DISTANCE (IN.)
0
100
200
300
400
500
600
700
10
20
30
40
50
60
70


FC160-11(S)
MICRO STRAIN
DISTANCE (IN.)
0
100
200
300
400
500
600
700
10
20
30
40
50
60
70

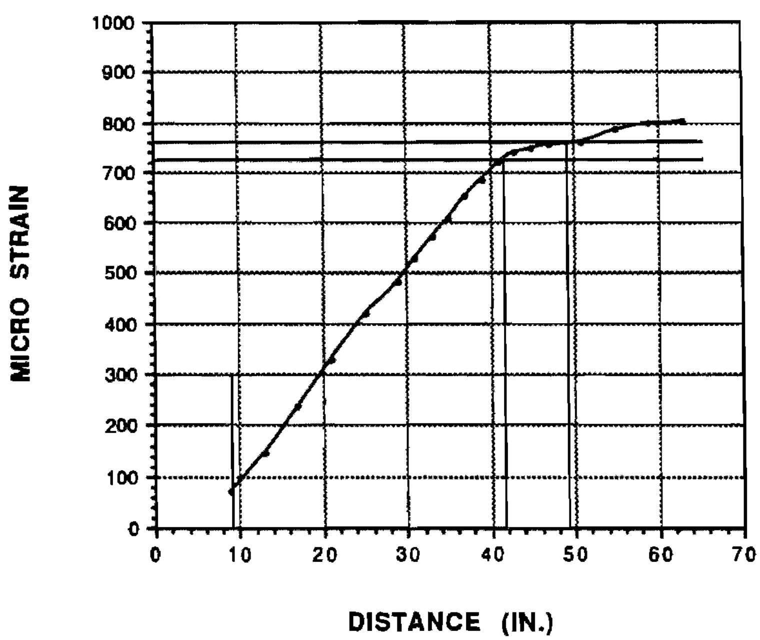

FC160-12(N)
MICRO STRAIN
0
100
200
300
400
500
600
700
800
0
10
20
30
40
50
60
70
DISTANCE (IN.)


FC160-12(S)
MICRO STRAIN
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
DISTANCE (IN.)

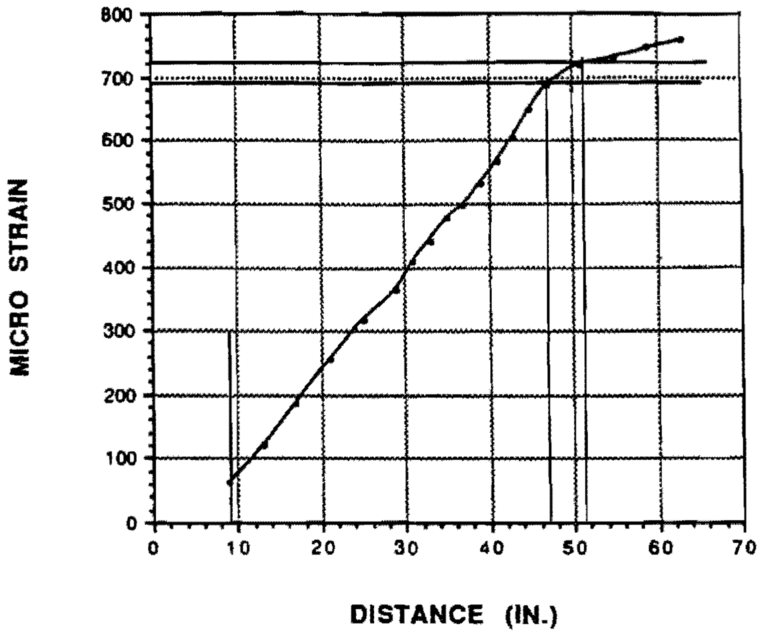
DC160-13(N)



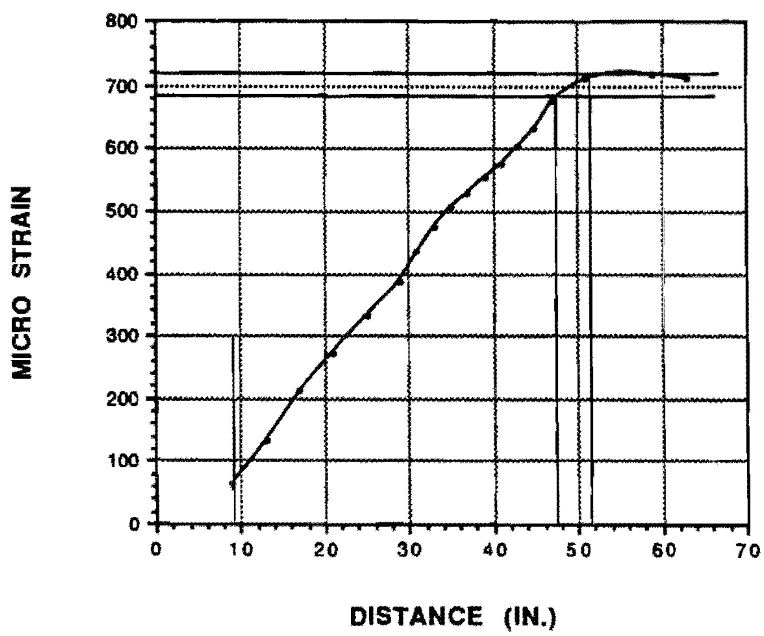
DC160-13(S)

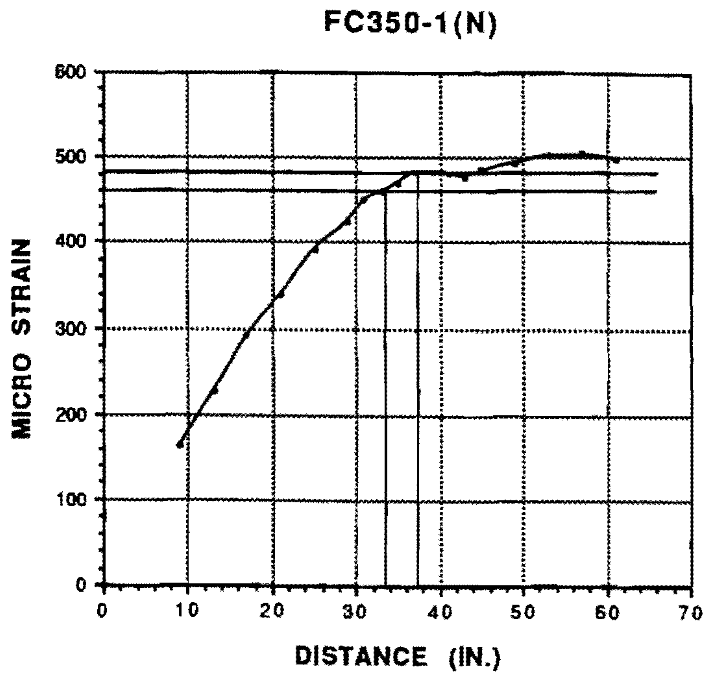


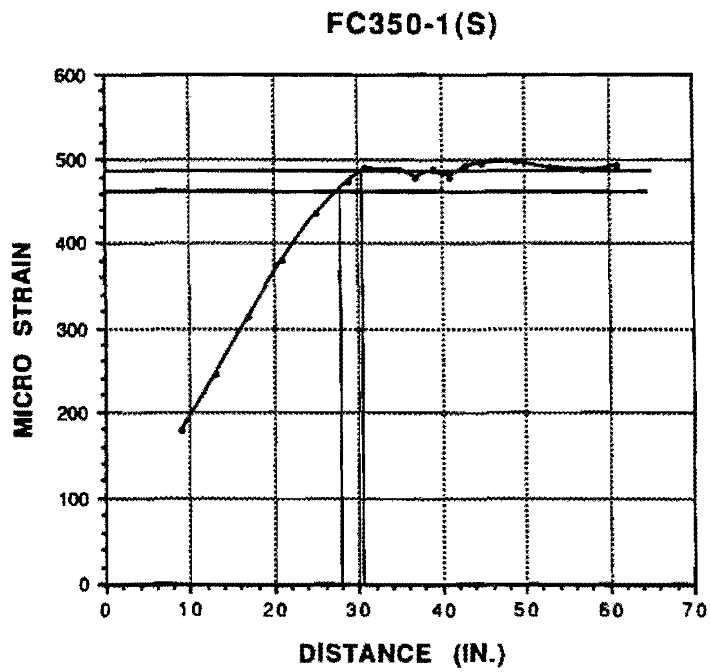
DC160-14(N)



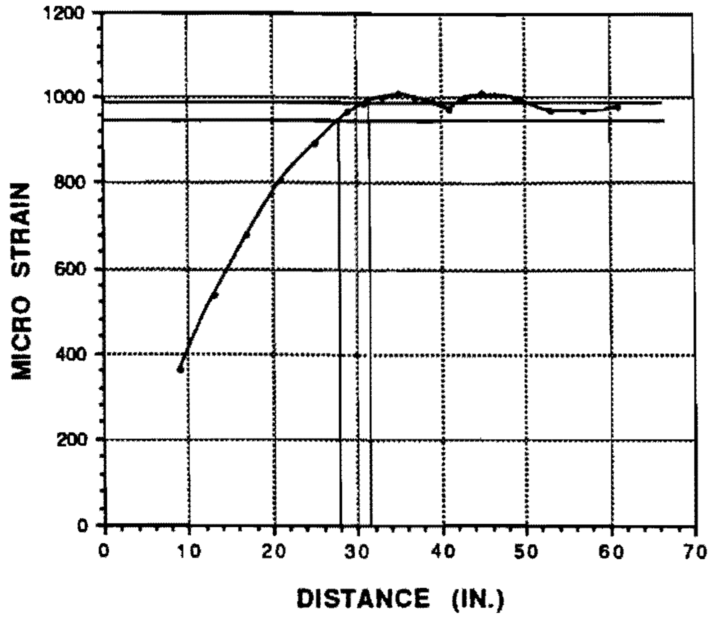
DC160-14(S)



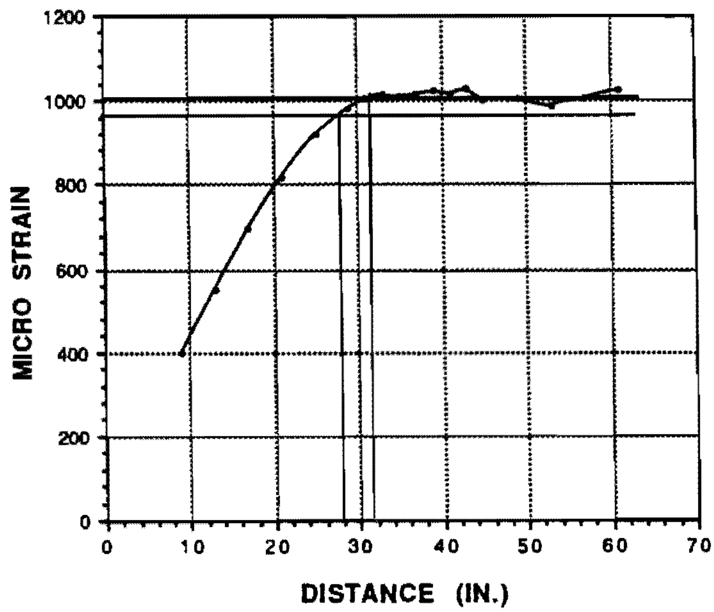

FC350-1(N)
MICRO STRAIN
0
100
200
300
400
500
600
0
10
20
30
40
50
60
70
DISTANCE (IN.)

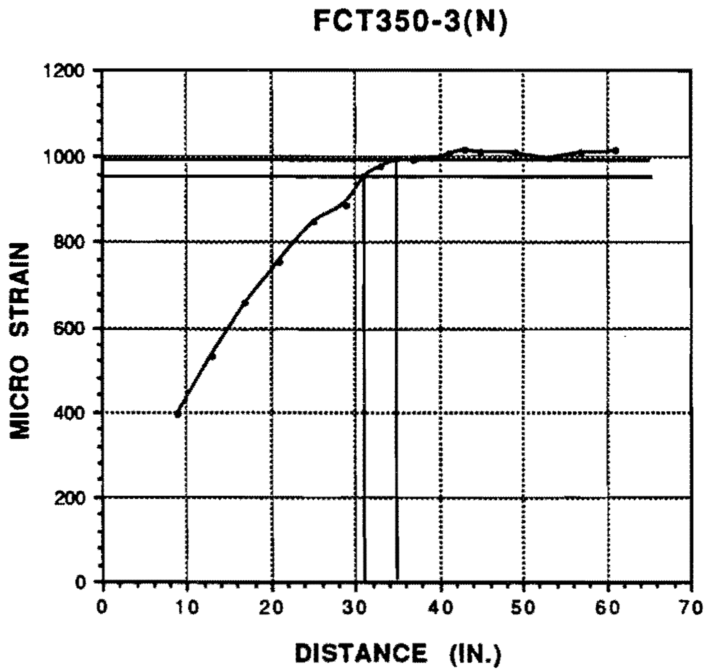

FC350-1(S)
MICRO STRAIN
0
100
200
300
400
500
600
0
10
20
30
40
50
60
70
DISTANCE (IN.)

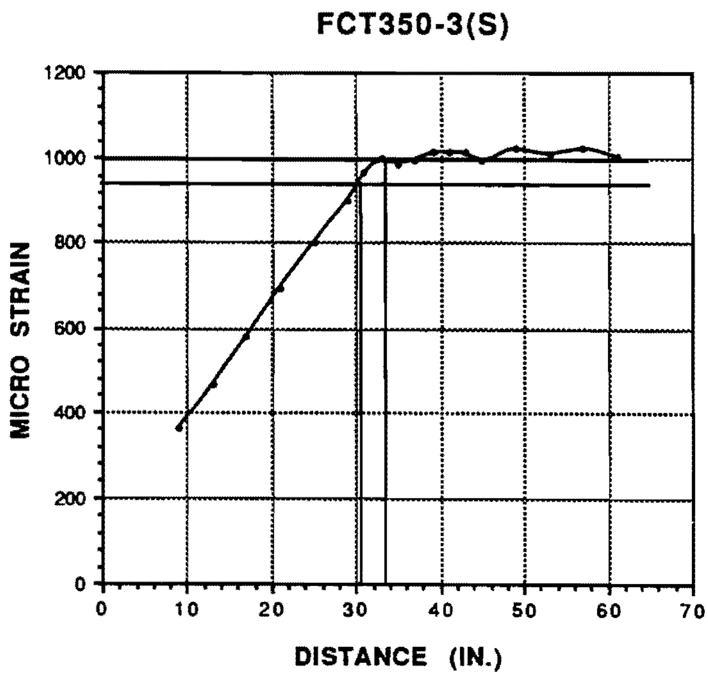
FC350-2(N)

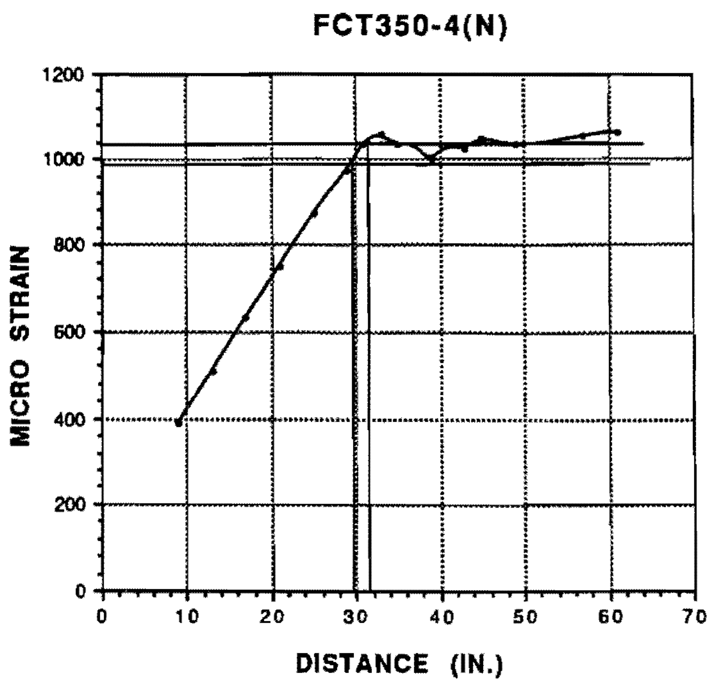


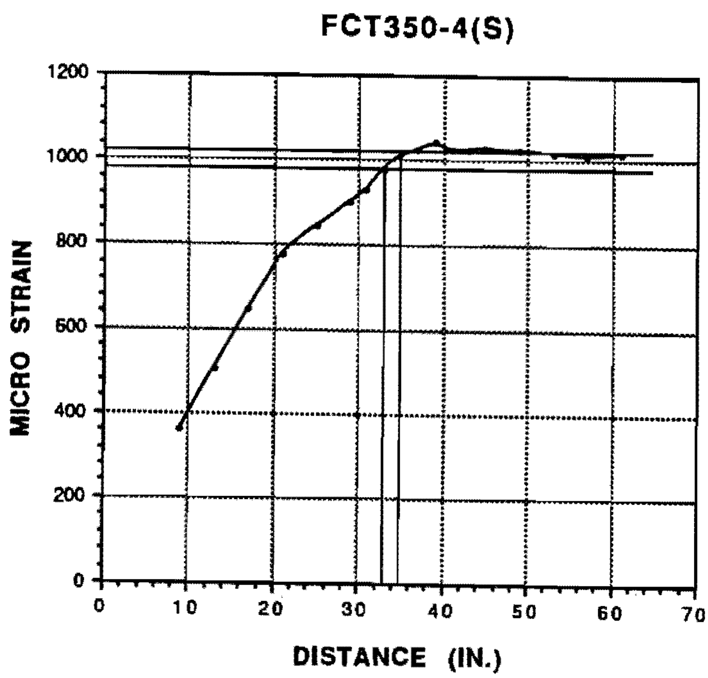
FC350-2(S)

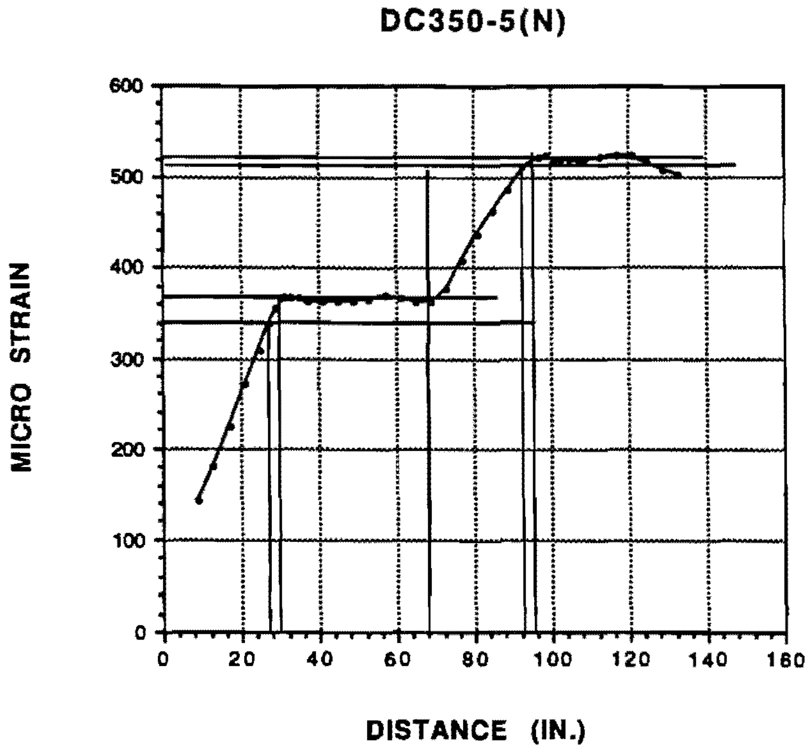


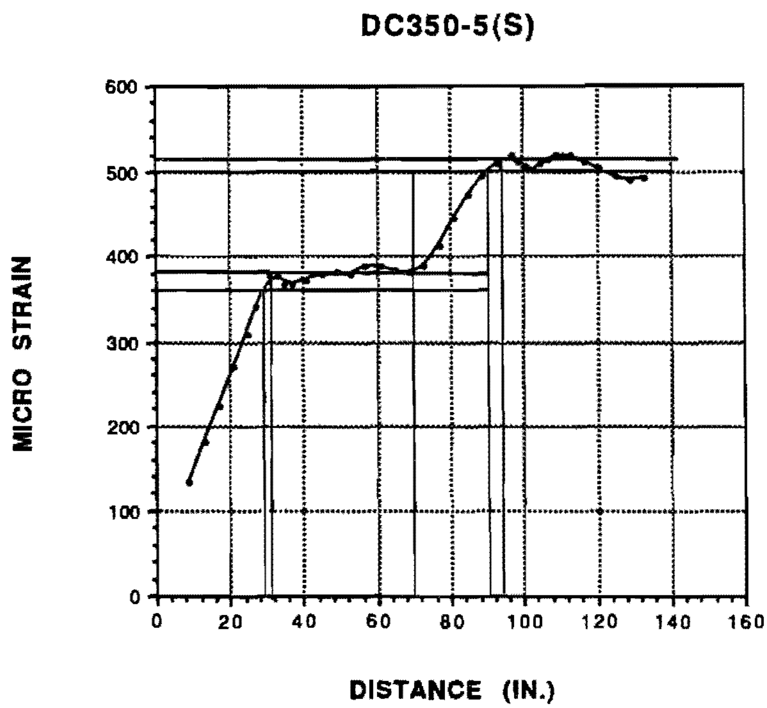

FCT350-3(N)
MICRO STRAIN
DISTANCE (IN.)
0
200
400
600
800
1000
1200
0
10
20
30
40
50
60
70

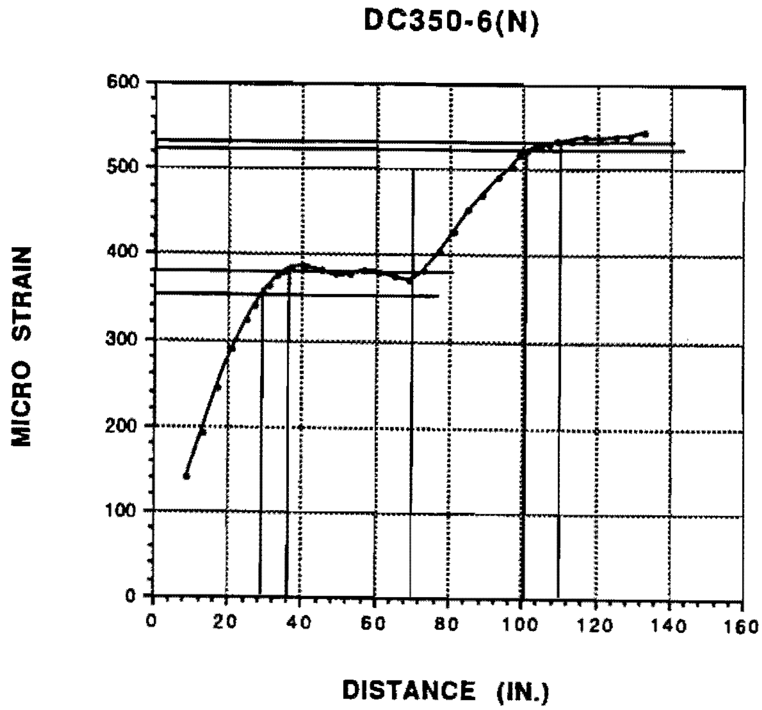

FCT350-3(S)
MICRO STRAIN
DISTANCE (IN.)
0
200
400
600
800
1000
1200
0
10
20
30
40
50
60
70

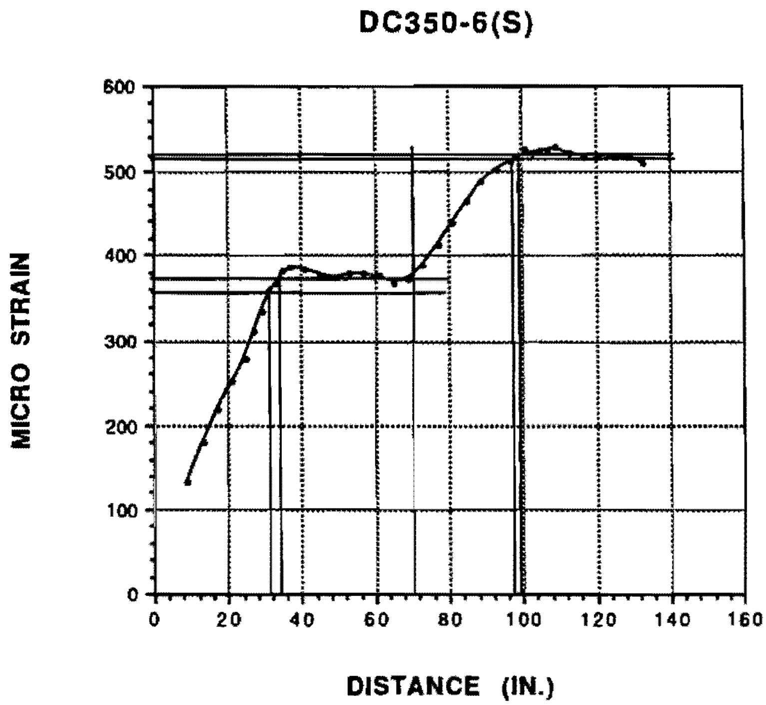

FCT350-4(N)
MICRO STRAIN
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
DISTANCE (IN.)

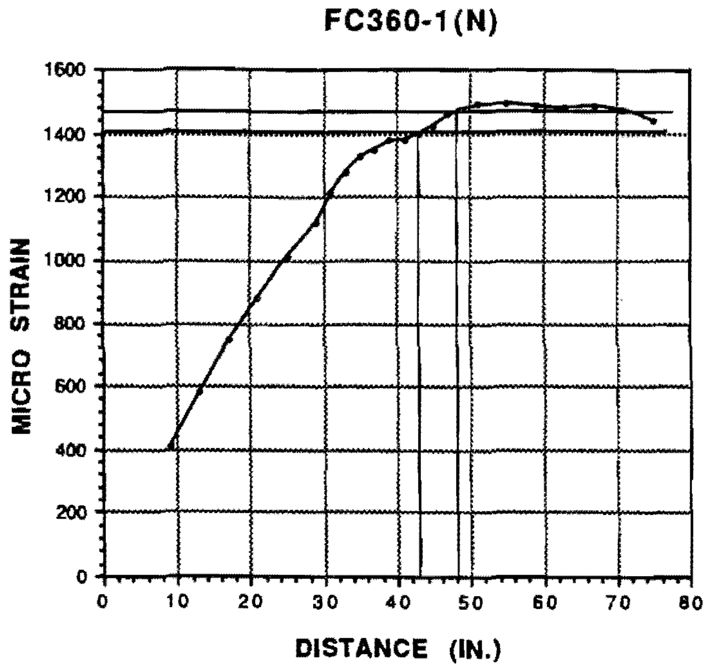

FCT350-4(S)
MICRO STRAIN
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
DISTANCE (IN.)

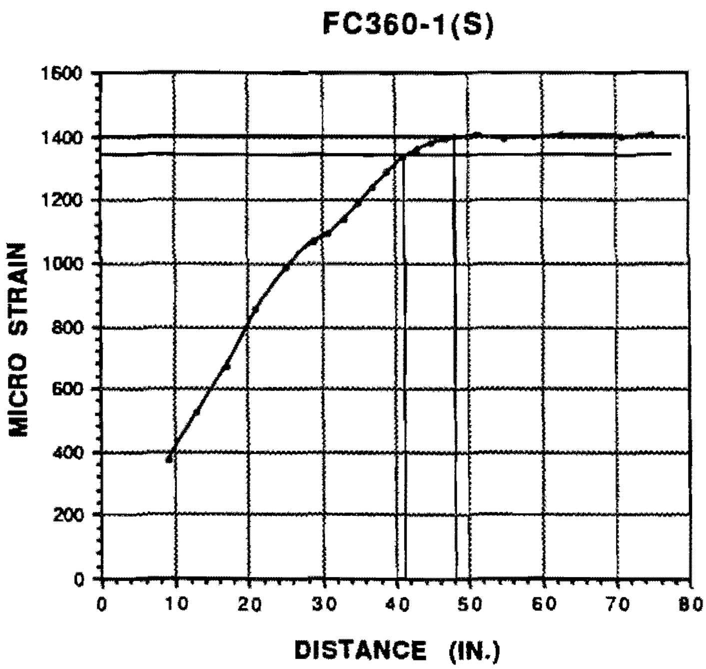

DC350-5(N)
MICRO STRAIN
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
DISTANCE (IN.)

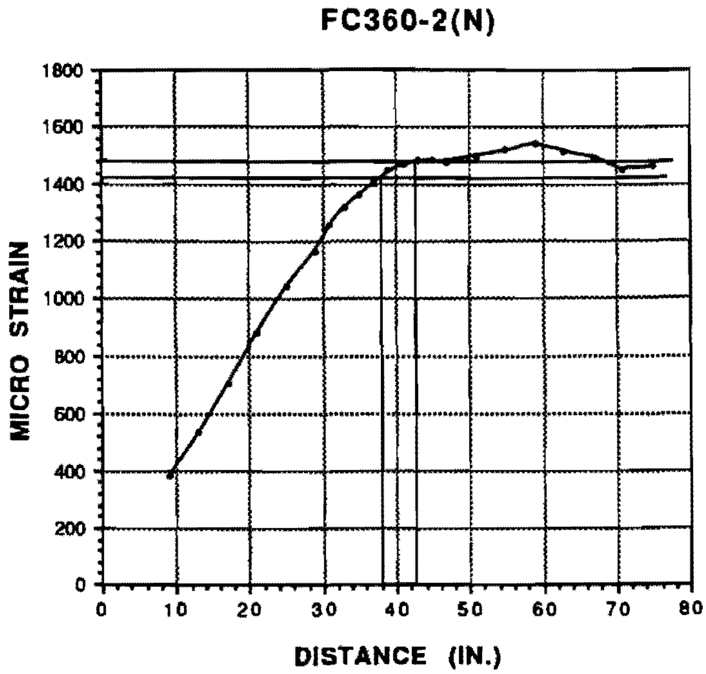

DC350-5(S)
MICRO STRAIN
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
DISTANCE (IN.)

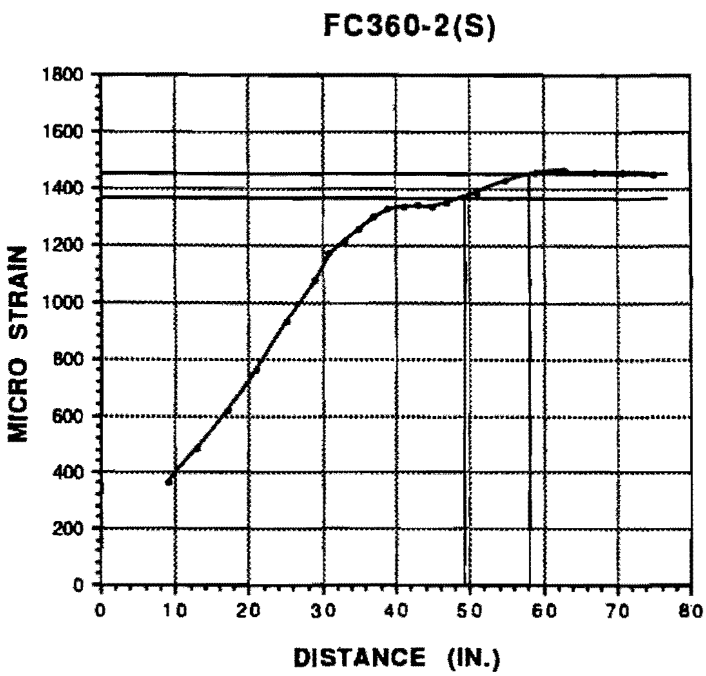

DC350-6(N)
MICRO STRAIN
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160
DISTANCE (IN.)

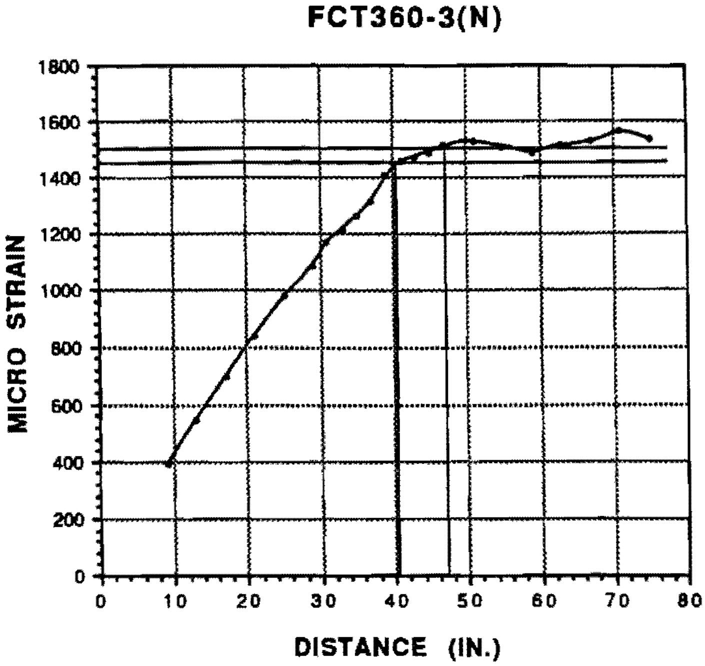

DC350-6(S)
MICRO STRAIN
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160
DISTANCE (IN.)

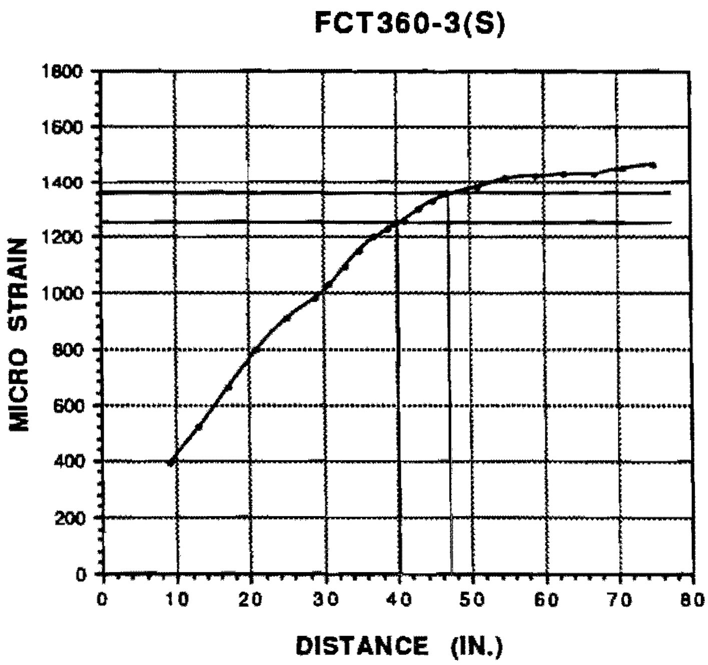

FC360-1(N)
MICRO STRAIN
0
200
400
600
800
1000
1200
1400
1600
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)

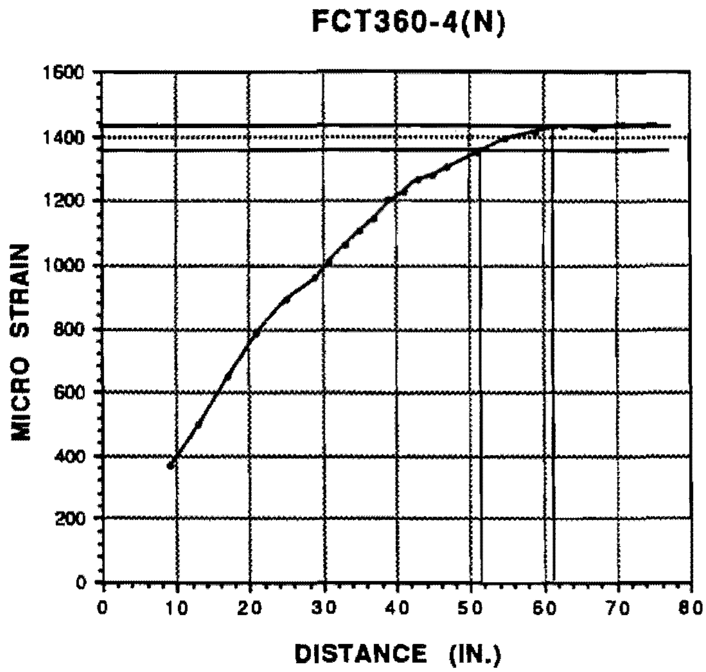

FC360-1(S)
MICRO STRAIN
0
200
400
600
800
1000
1200
1400
1600
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)

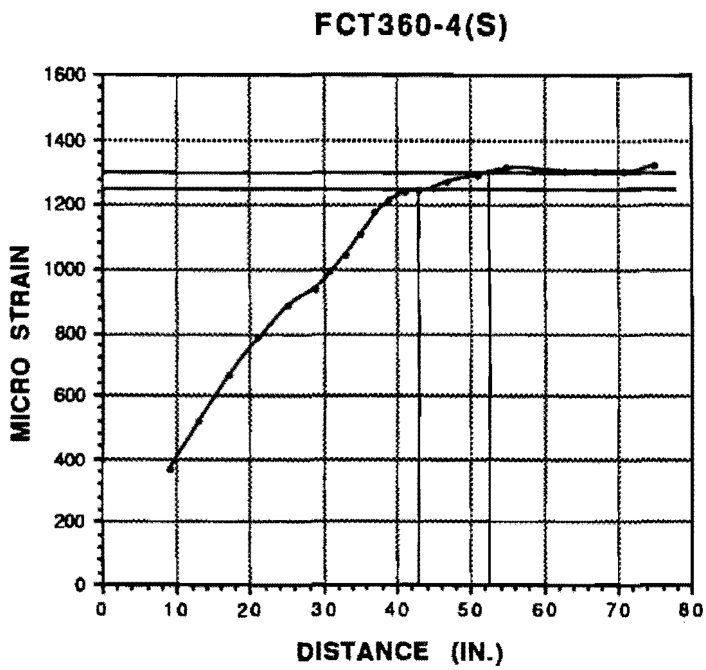

FC360-2(N)
MICRO STRAIN
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)

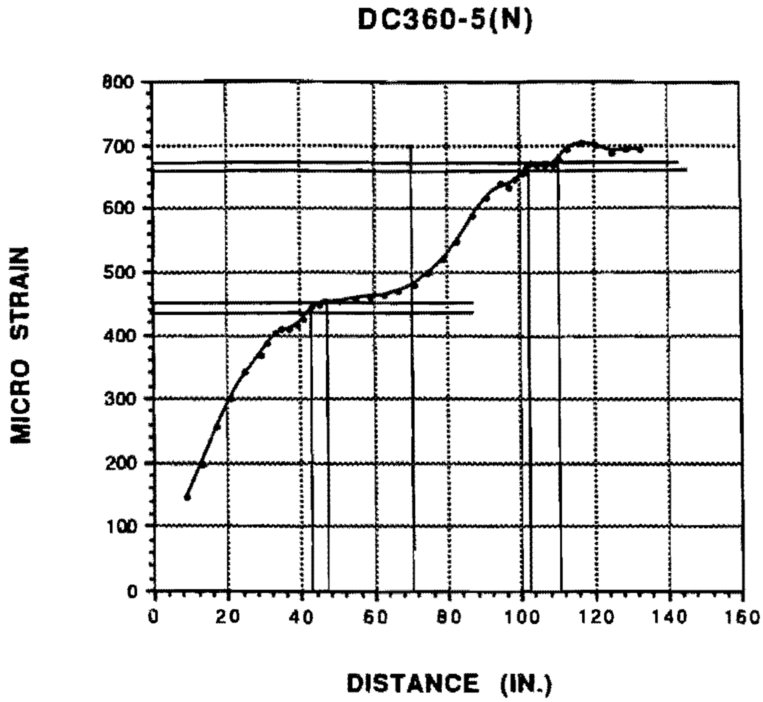

FC360-2(S)
MICRO STRAIN
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)

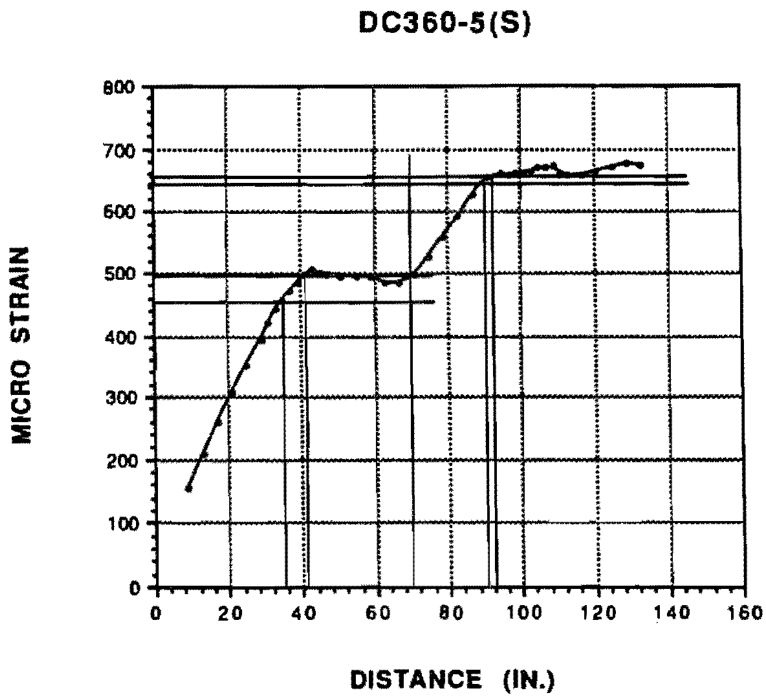

FCT360-3(N)
MICRO STRAIN
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)


FCT360-3(S)
MICRO STRAIN
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)

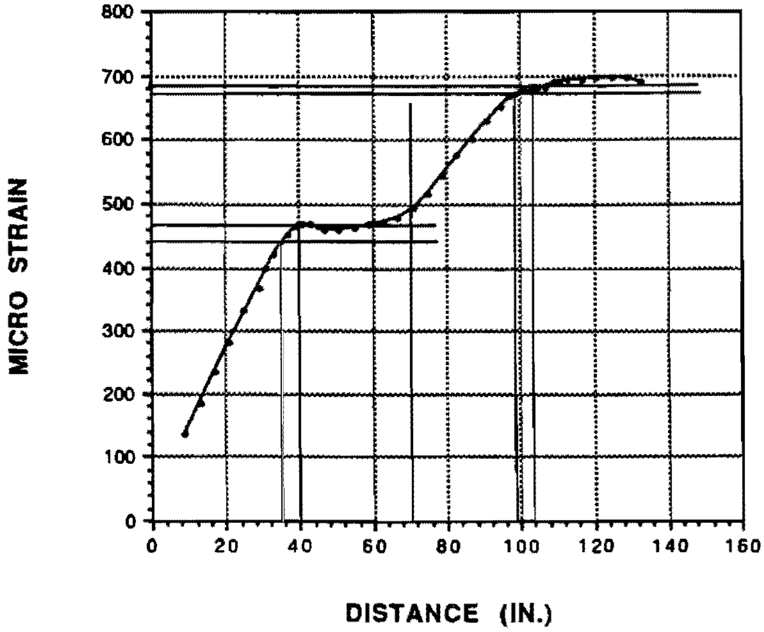

FCT360-4(N)
MICRO STRAIN
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)


FCT360-4(S)
MICRO STRAIN
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)

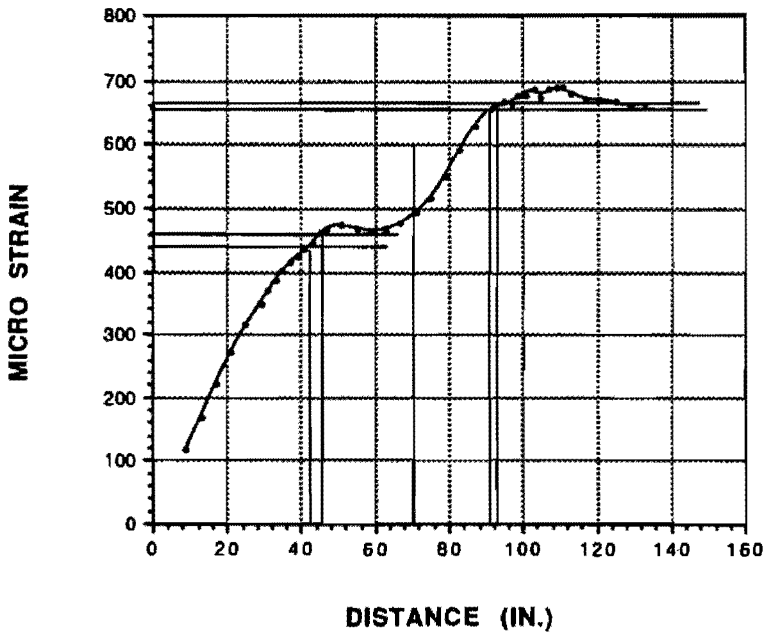

DC360-5(N)
MICRO STRAIN
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160
DISTANCE (IN.)

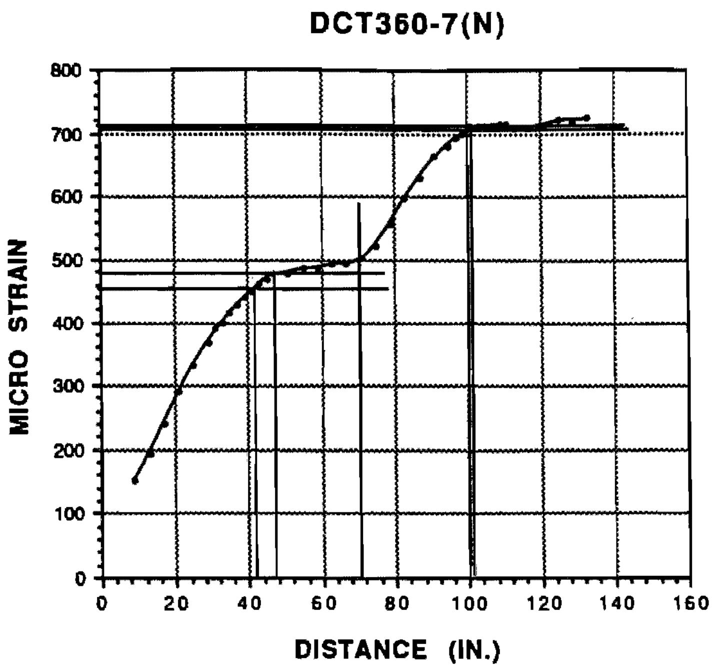

DC360-5(S)
MICRO STRAIN
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160
DISTANCE (IN.)

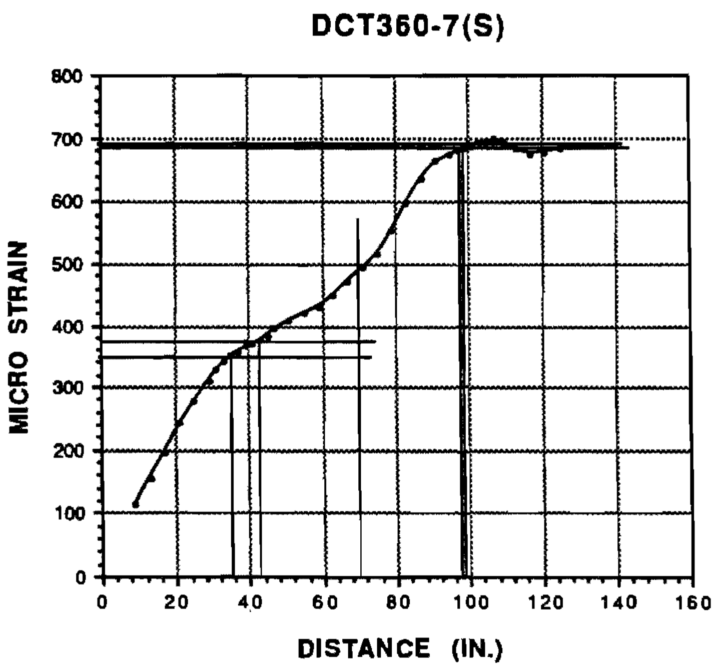
DC360-6(N)

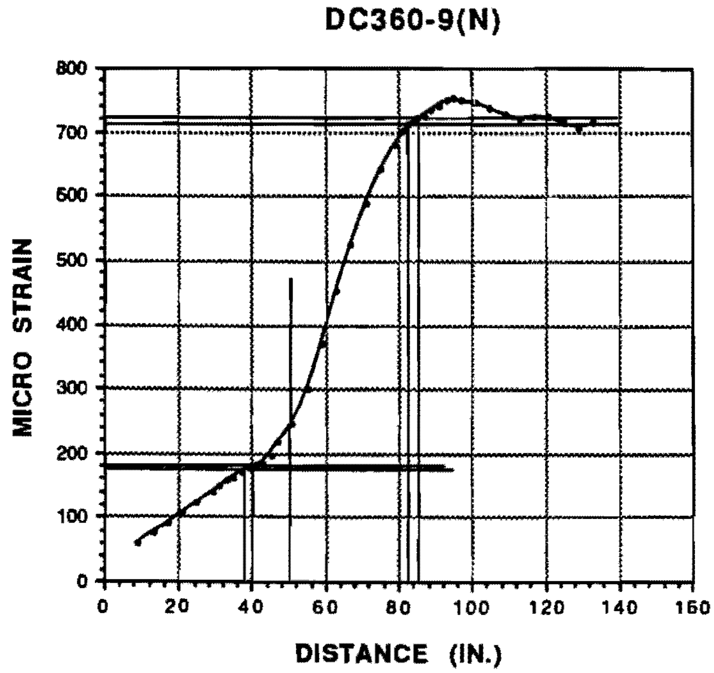


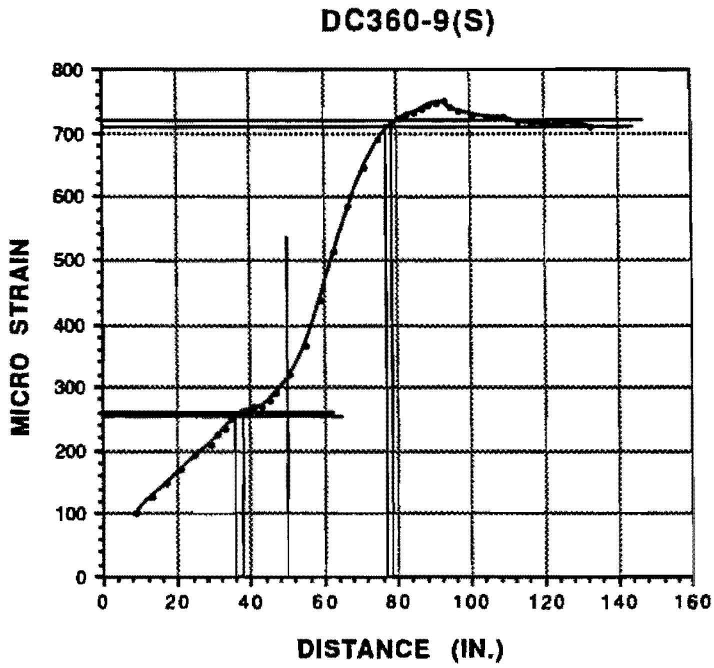
DC360-6(S)

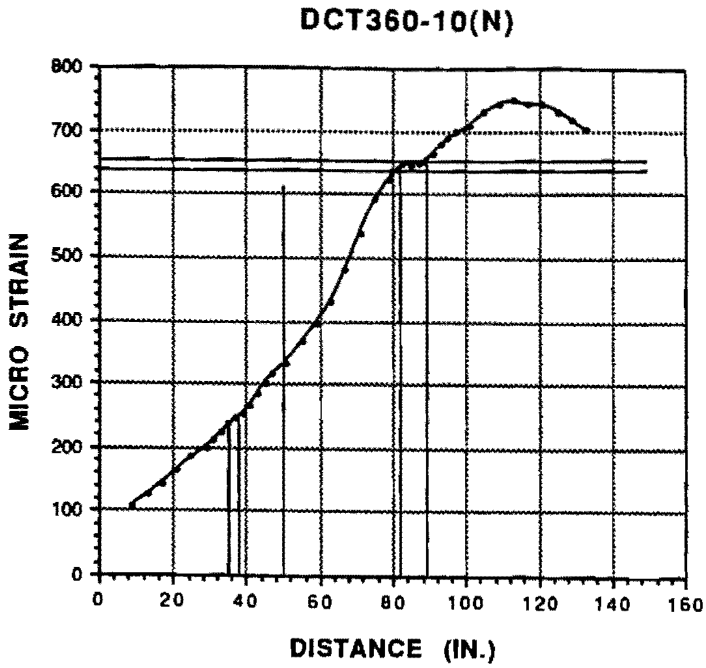


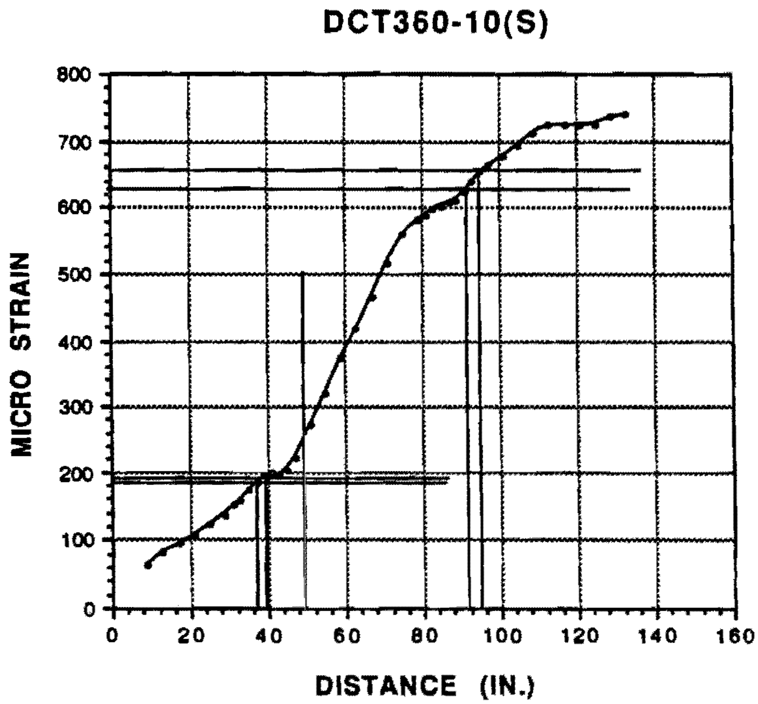

DCT360-7(N)
MICRO STRAIN
DISTANCE (IN.)
0
100
200
300
400
500
600
700
800
0
20
40
60
80
100
120
140
160

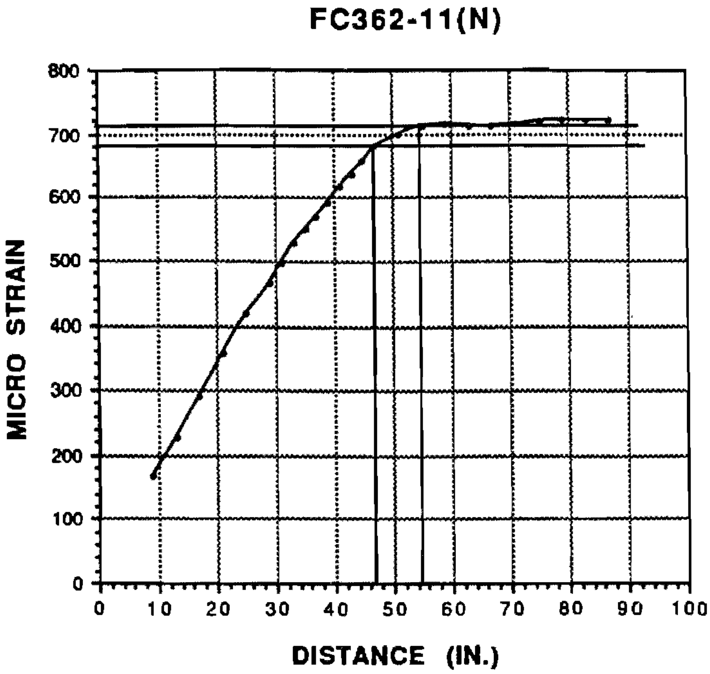

DCT360-7(S)
MICRO STRAIN
DISTANCE (IN.)
0
100
200
300
400
500
600
700
800
0
20
40
60
80
100
120
140
160

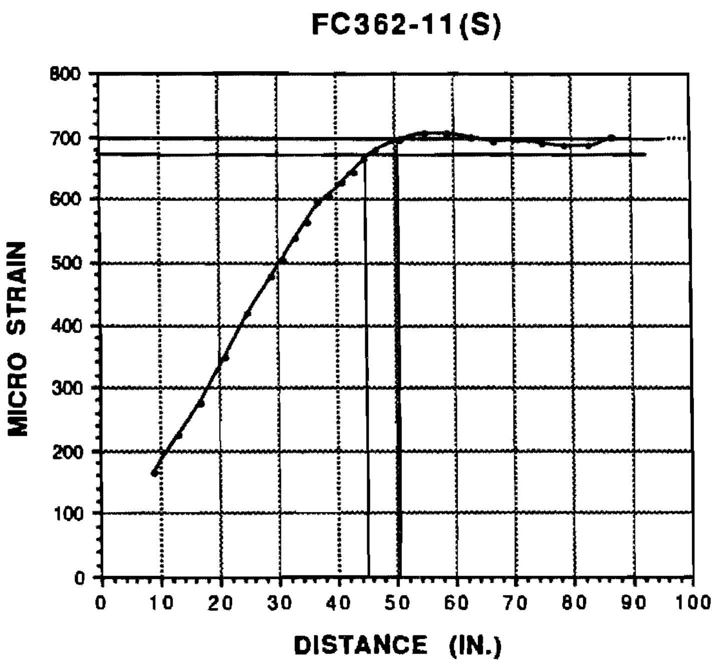

DC360-9(N)
MICRO STRAIN
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160
DISTANCE (IN.)

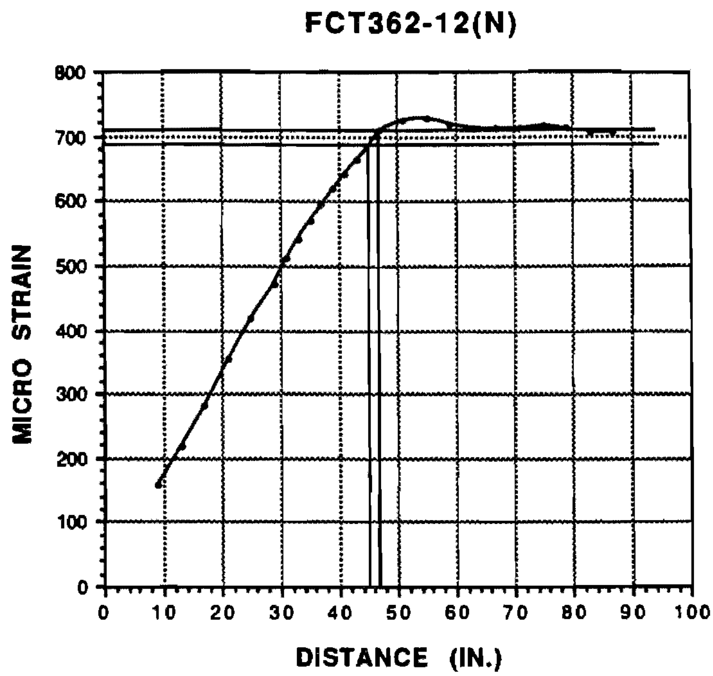

DC360-9(S)
MICRO STRAIN
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160
DISTANCE (IN.)

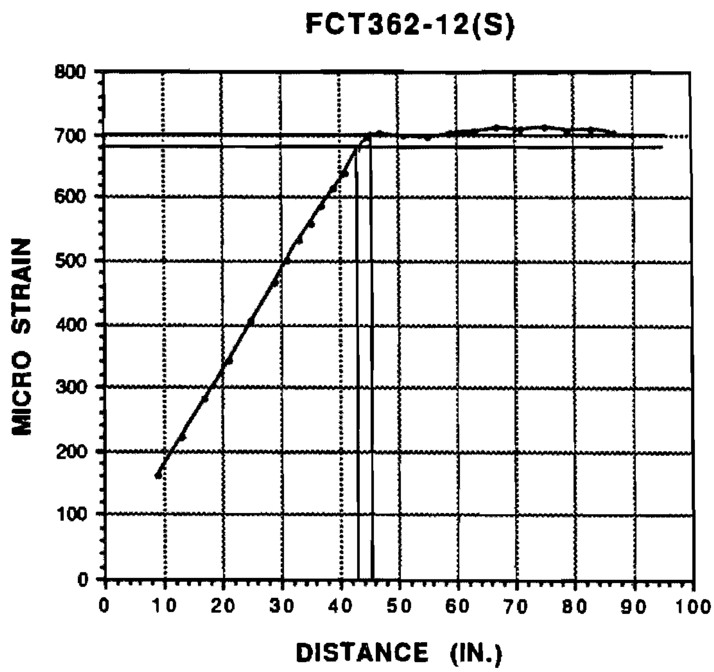

DCT360-10(N)
MICRO STRAIN
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160
DISTANCE (IN.)

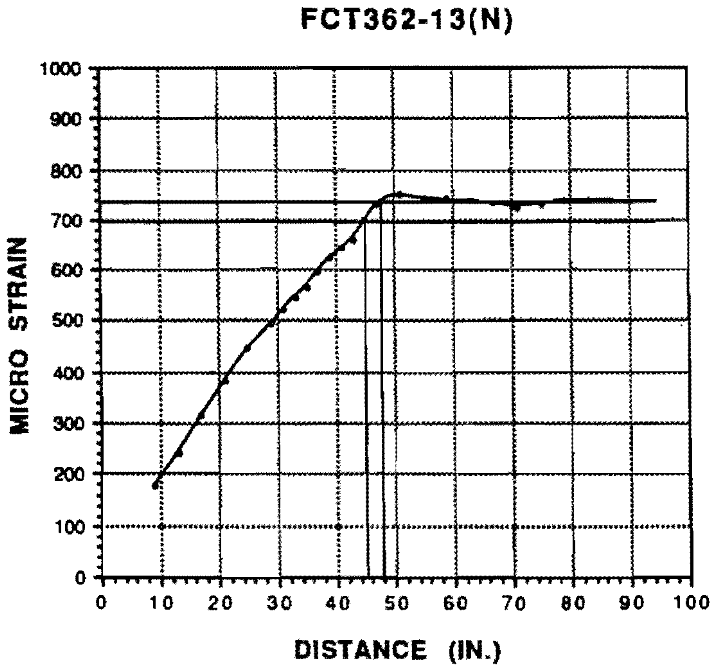

DCT360-10(S)
MICRO STRAIN
800
700
600
500
400
300
200
100
0
0
20
40
60
80
100
120
140
160
DISTANCE (IN.)

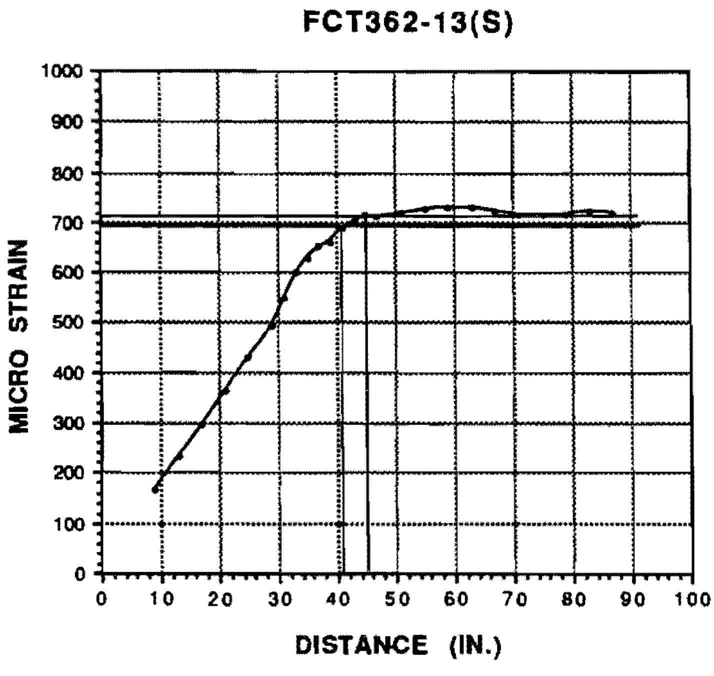

FC362-11(N)
MICRO STRAIN
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
DISTANCE (IN.)


FC362-11(S)
MICRO STRAIN
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
DISTANCE (IN.)

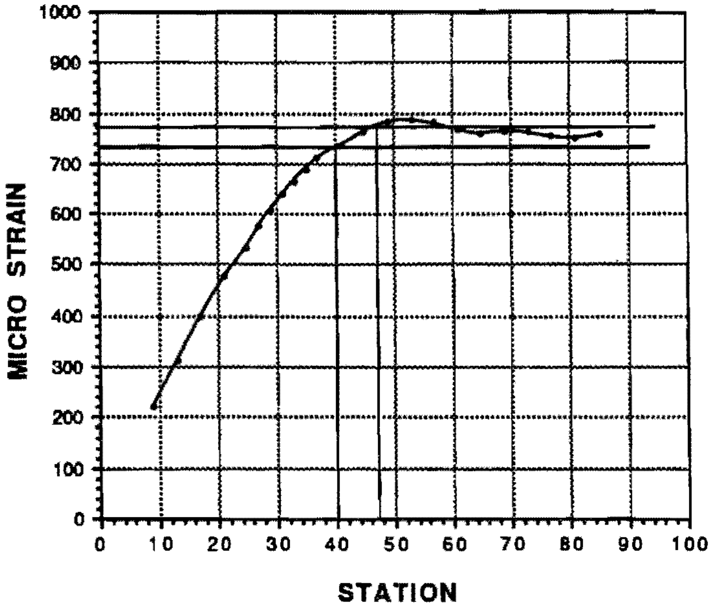

FCT362-12(N)
800
700
600
500
400
300
200
100
0
MICRO STRAIN
0
10
20
30
40
50
60
70
80
90
100
DISTANCE (IN.)


FCT362-12(S)
800
700
600
500
400
300
200
100
0
MICRO STRAIN
0
10
20
30
40
50
60
70
80
90
100
DISTANCE (IN.)

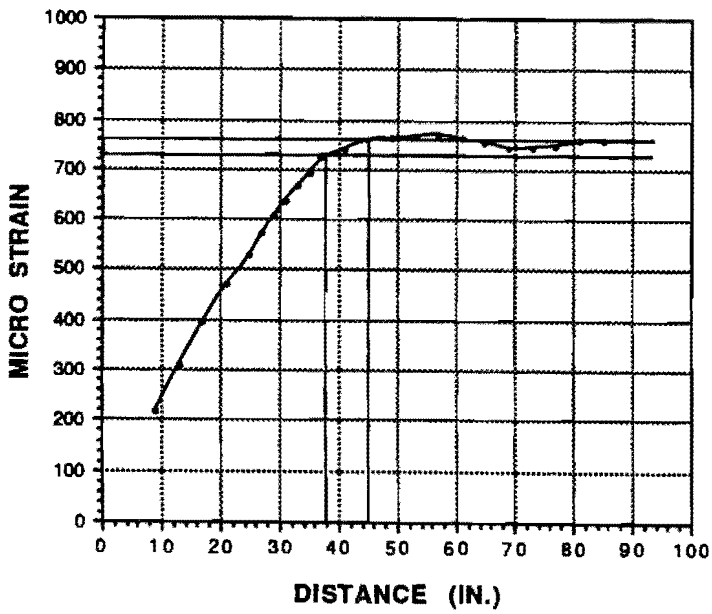

FCT362-13(N)
MICRO STRAIN
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
DISTANCE (IN.)


FCT362-13(S)
MICRO STRAIN
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
DISTANCE (IN.)

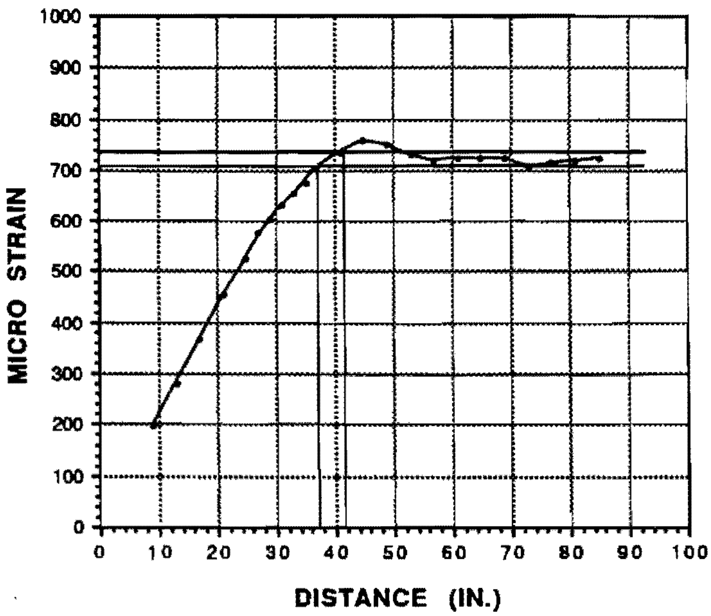
FC550-1(N)



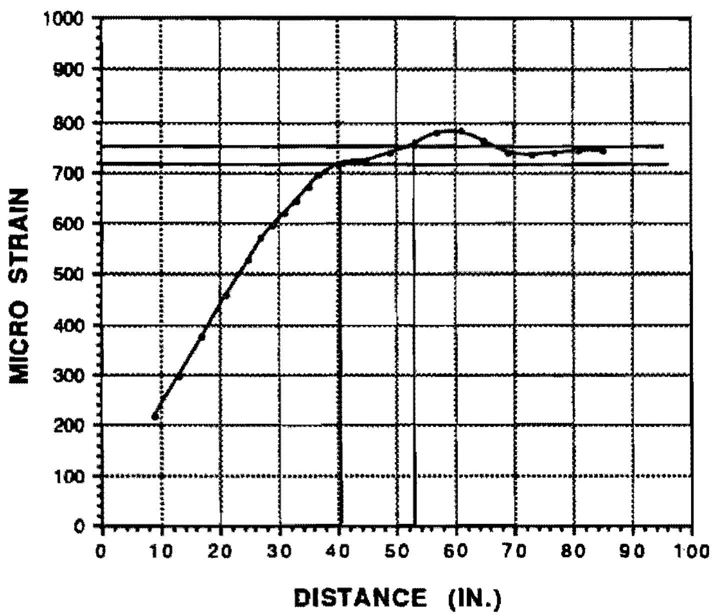
FC550-1(S)

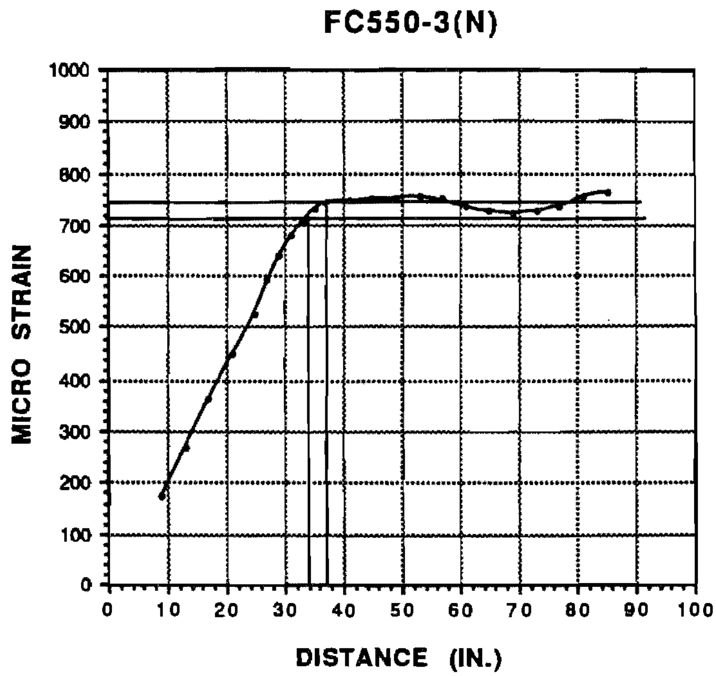


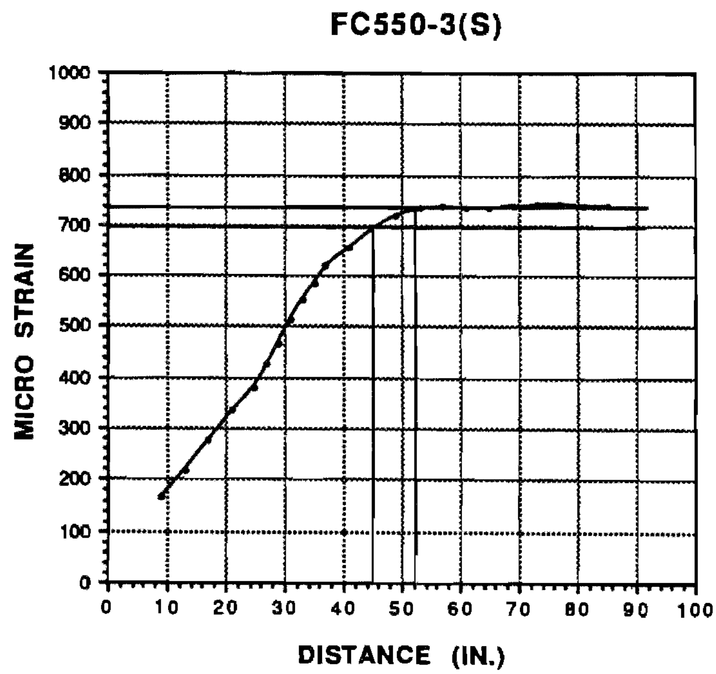
FCT550-2(N)



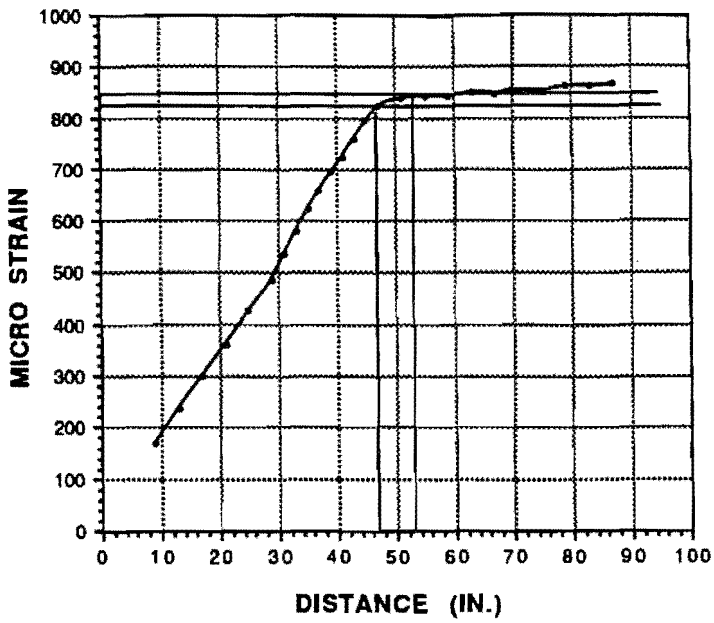
FCT550-2(S)



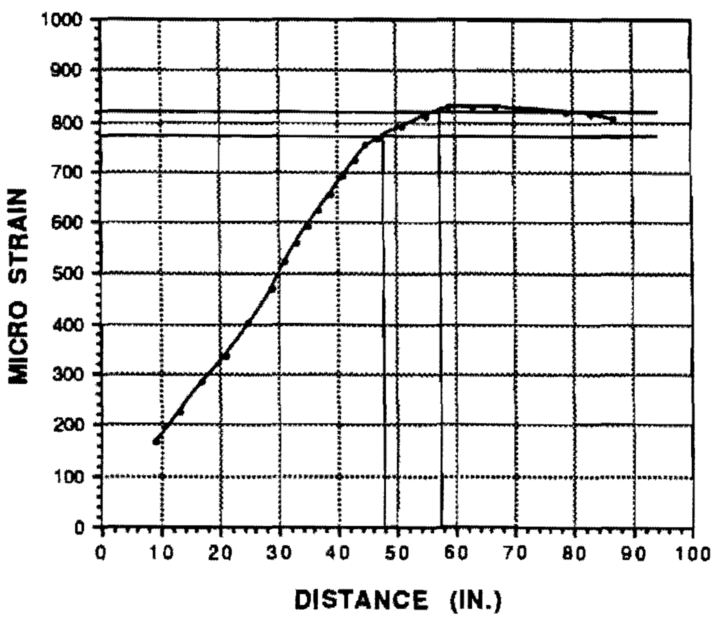

FC550-3(N)
MICRO STRAIN
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
DISTANCE (IN.)

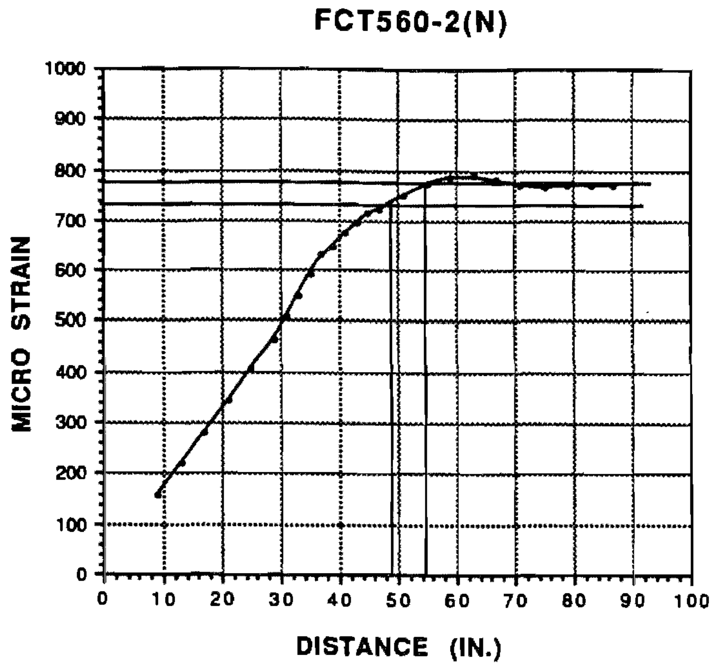

FC550-3(S)
MICRO STRAIN
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
DISTANCE (IN.)

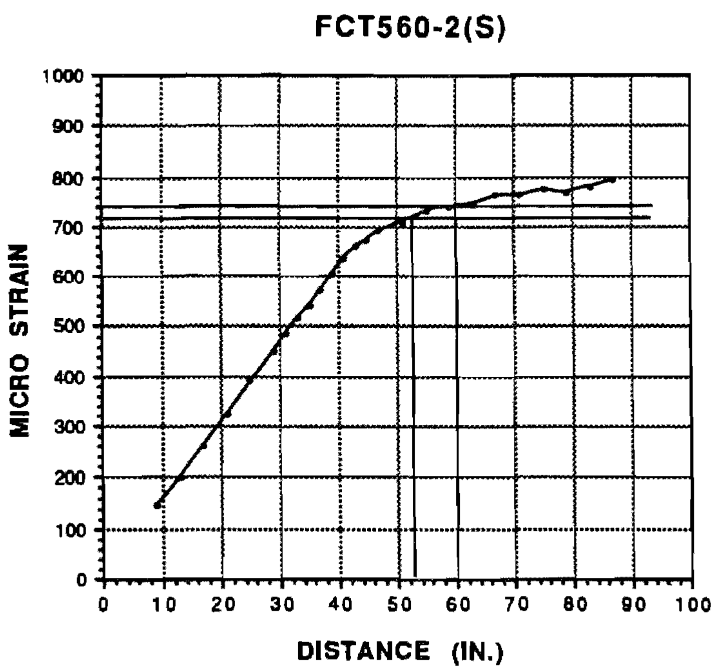
FC560-1(N)

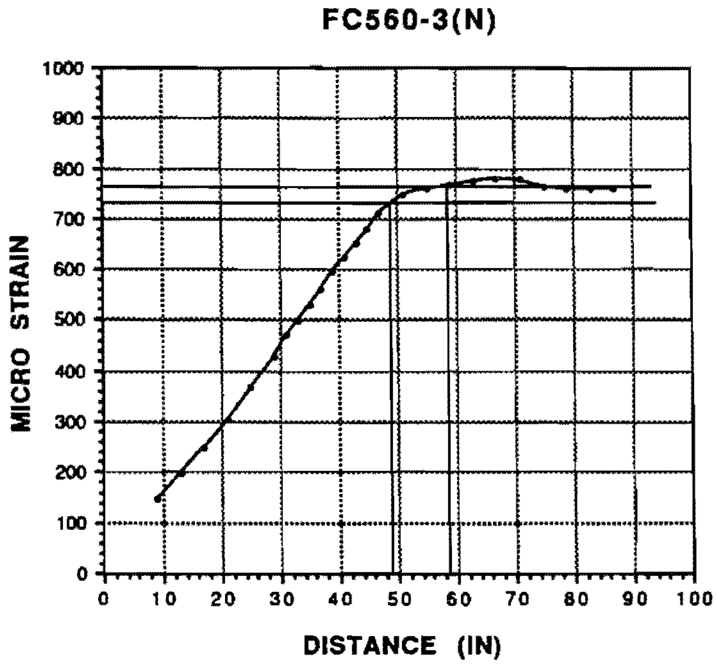


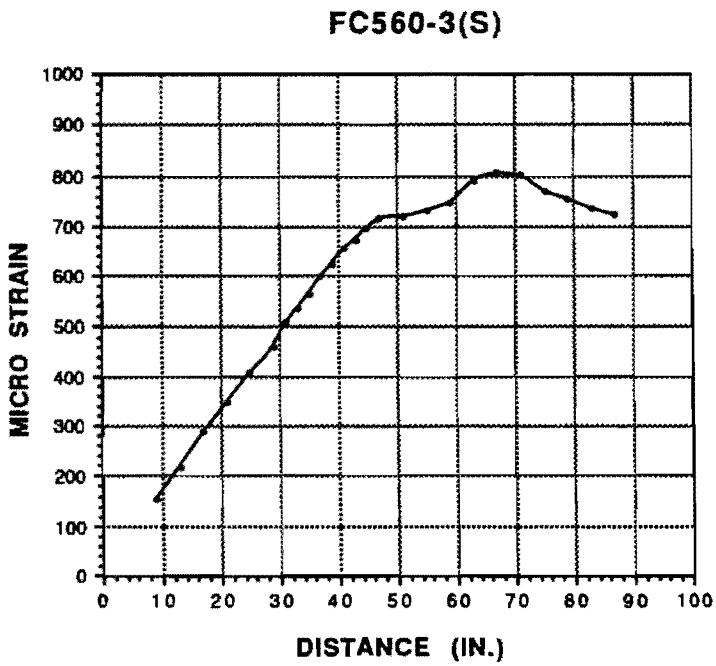
FC560-1(S)

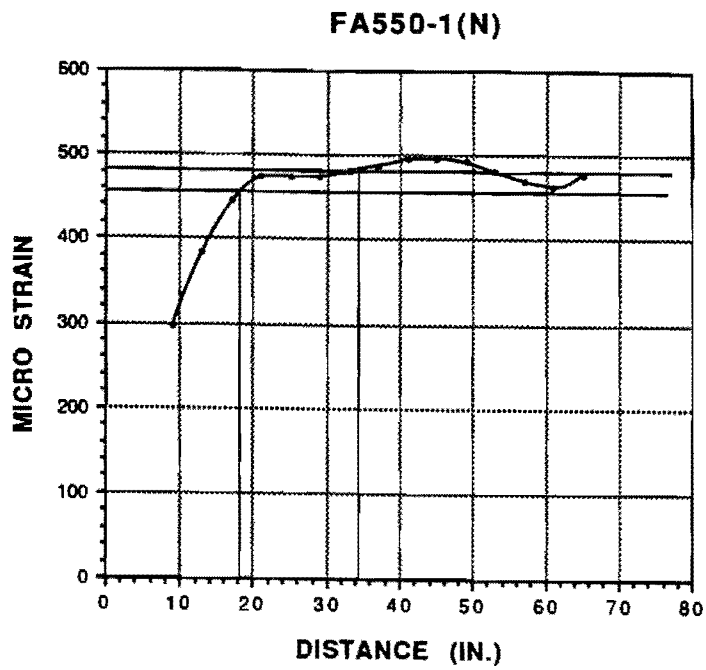


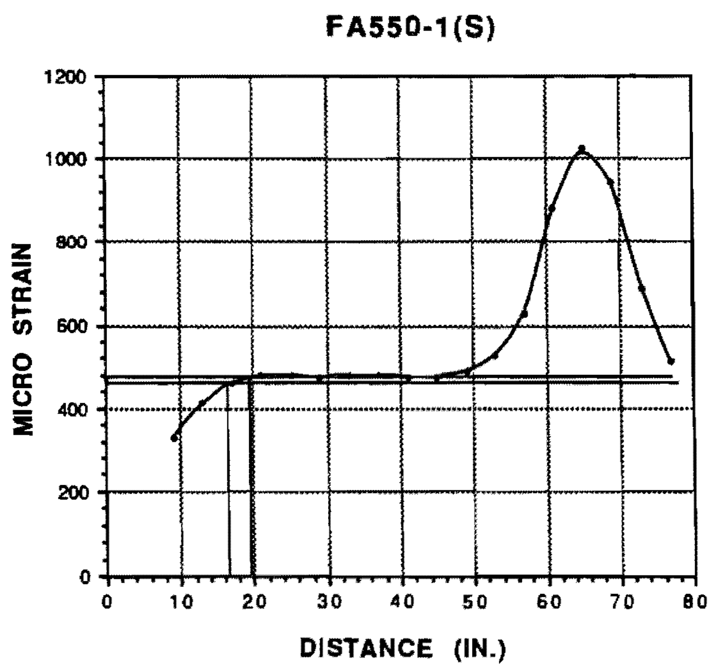

FCT560-2(N)
MICRO STRAIN
DISTANCE (IN.)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100


FCT560-2(S)
MICRO STRAIN
DISTANCE (IN.)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
80
90
100

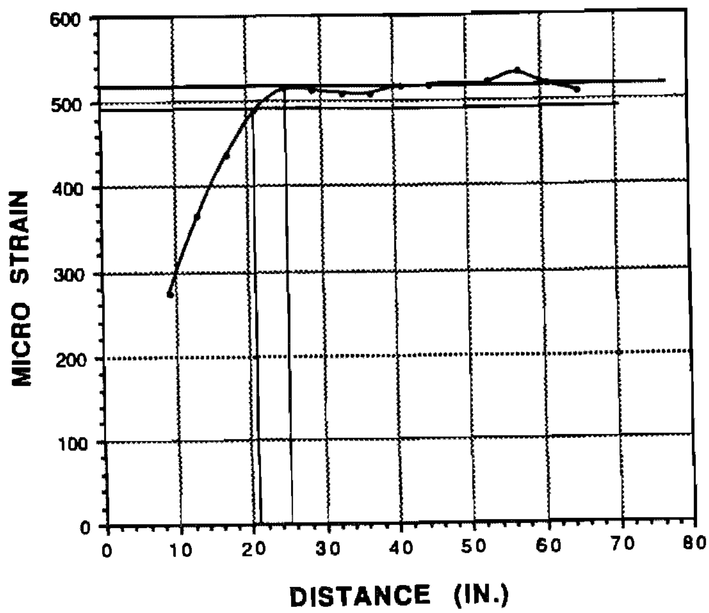

FC560-3(N)
MICRO STRAIN
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
DISTANCE (IN)


FC560-3(S)
MICRO STRAIN
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
DISTANCE (IN.)

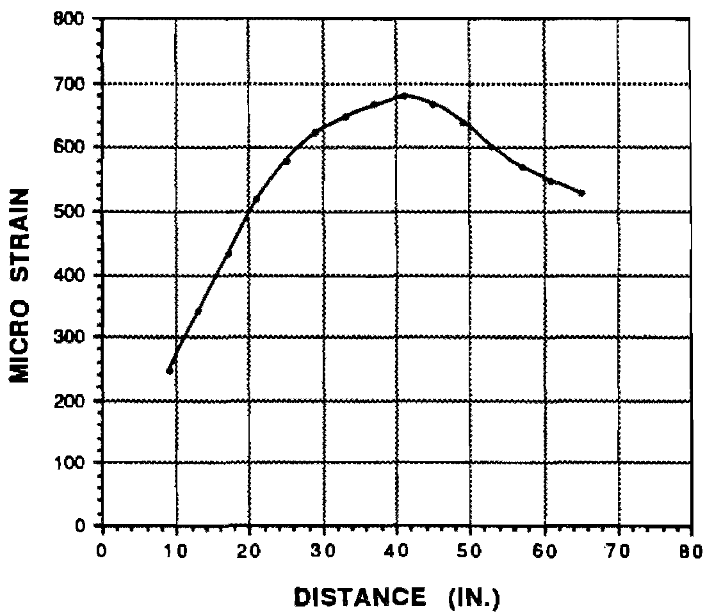

FA550-1(N)
MICRO STRAIN
0
100
200
300
400
500
600
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)


FA550-1(S)
MICRO STRAIN
0
200
400
600
800
1000
1200
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)

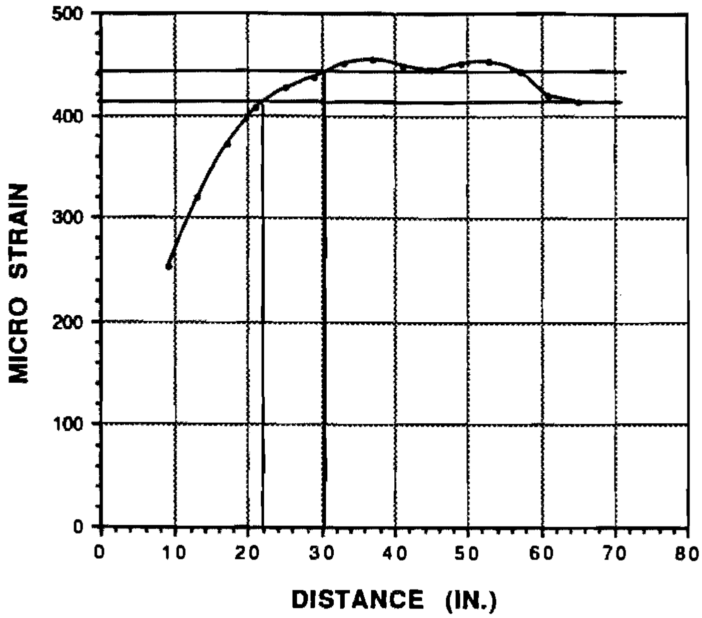
FA550-2(N)



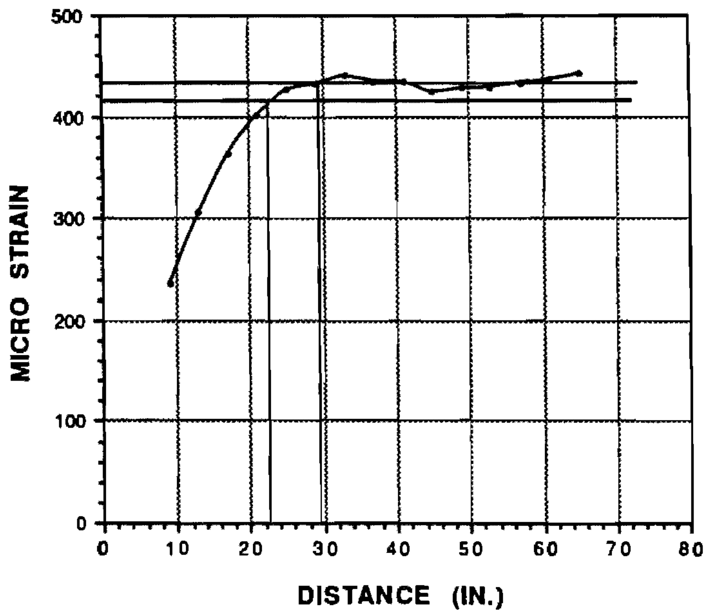
FA550-2(S)



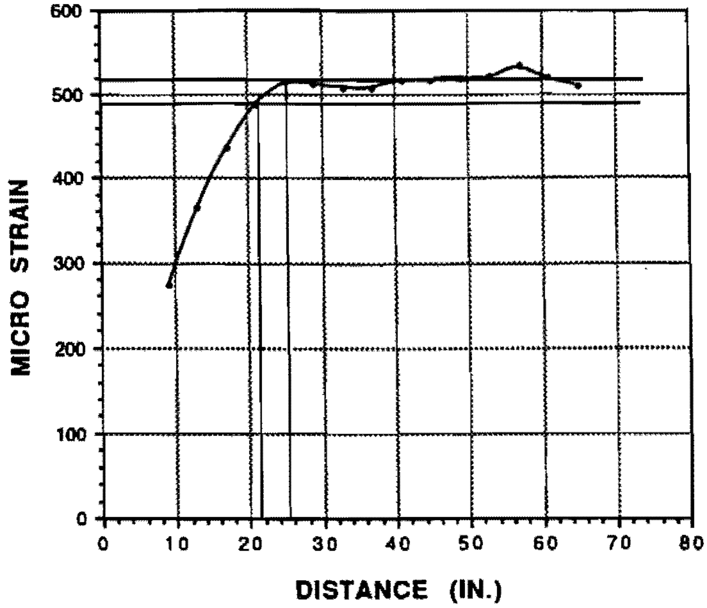
FA550-3(N)



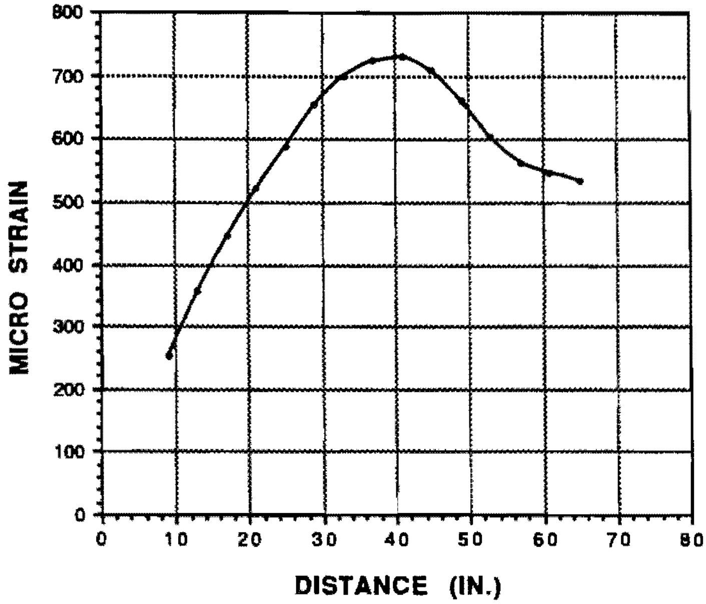
FA550-3(S)



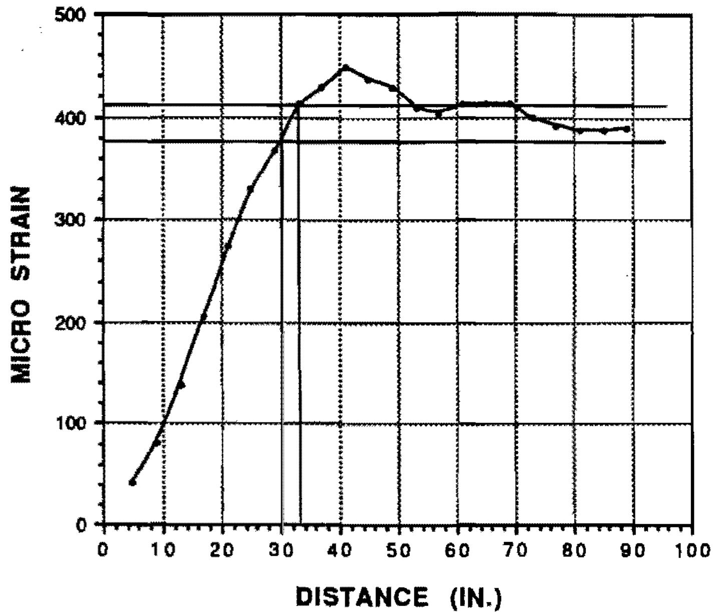
FA550-4(N)



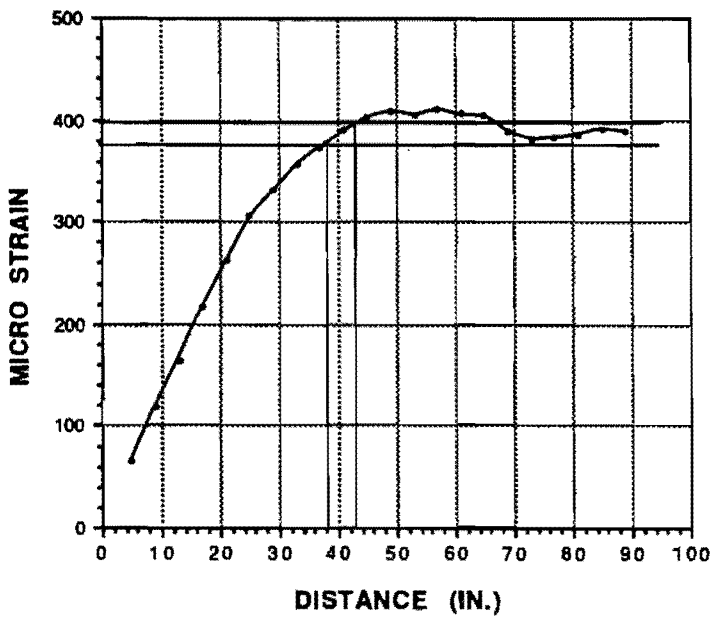
FA550-4(S)

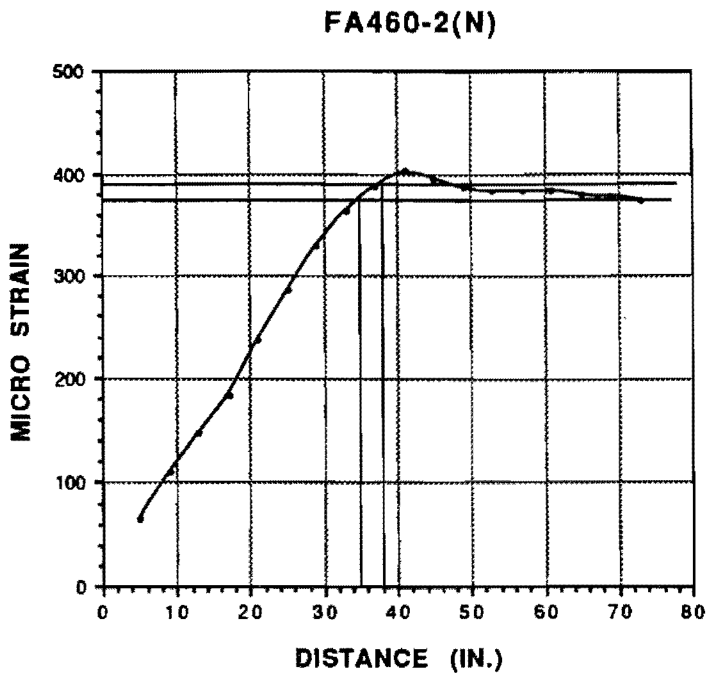


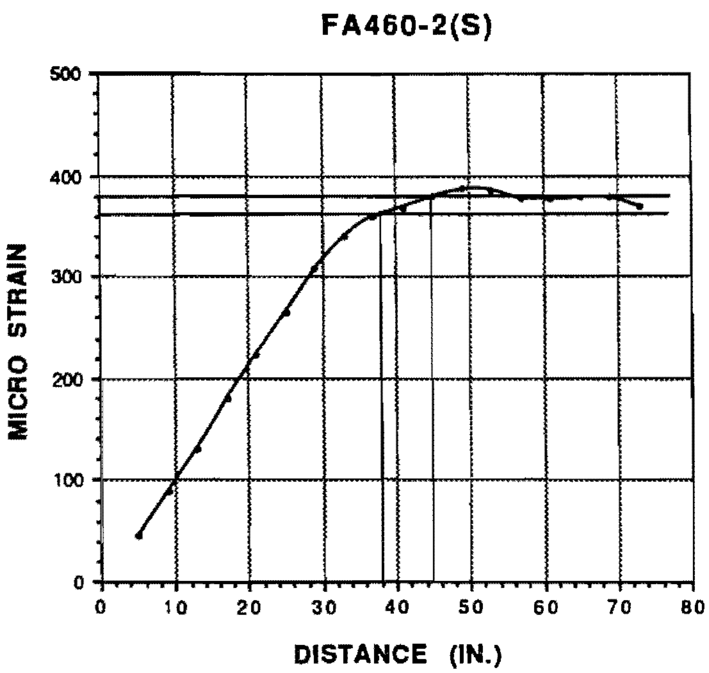
FA460-1(N)



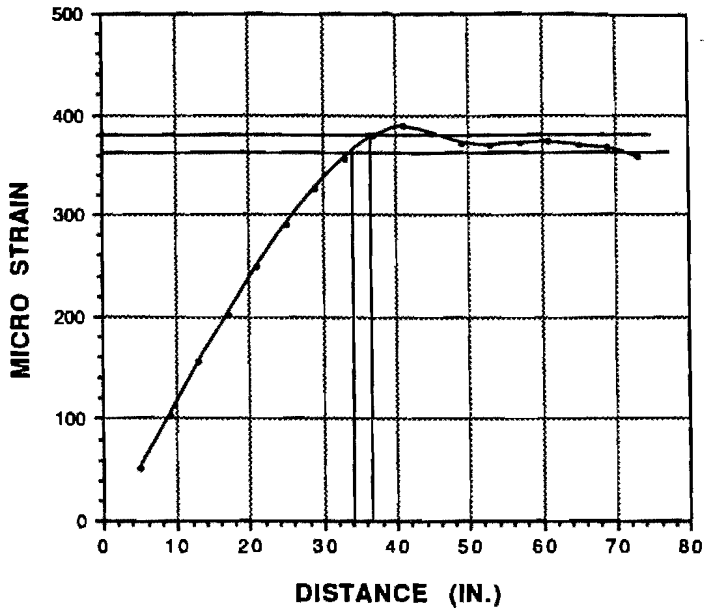
FA460-1(S)



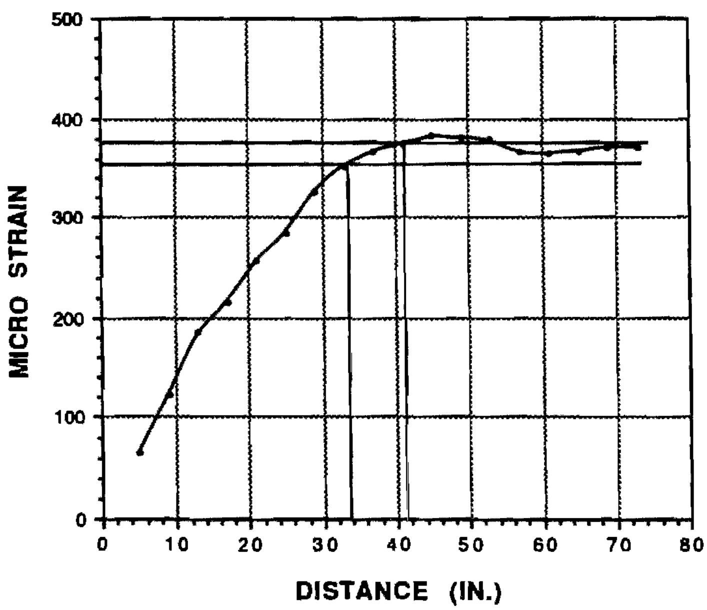

FA460-2(N)
MICRO STRAIN
0
100
200
300
400
500
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)


FA460-2(S)
MICRO STRAIN
0
100
200
300
400
500
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)

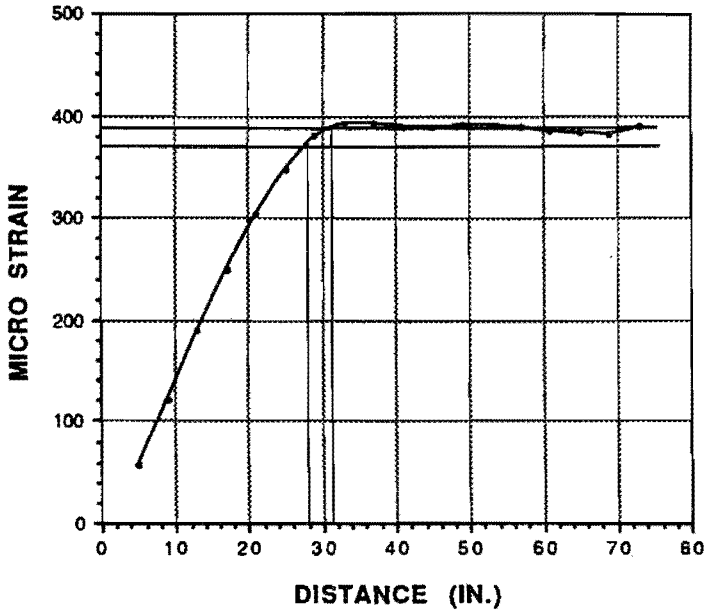
FA460-3(N)



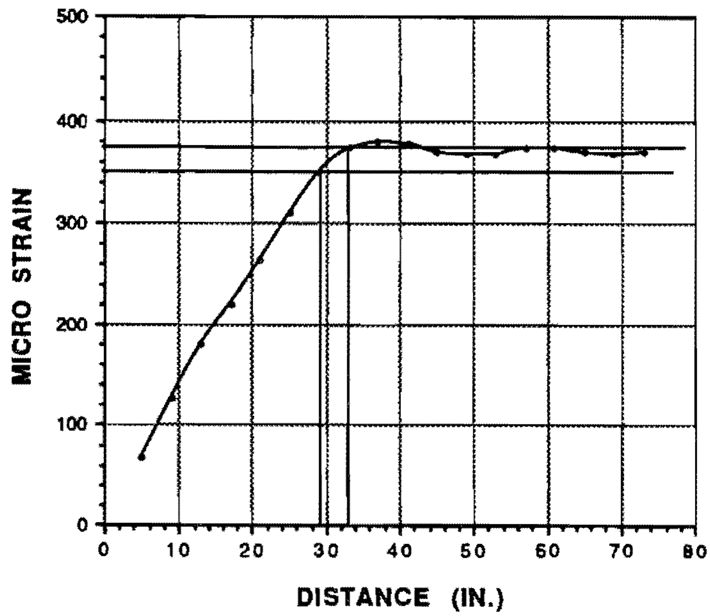
FA460-3(S)

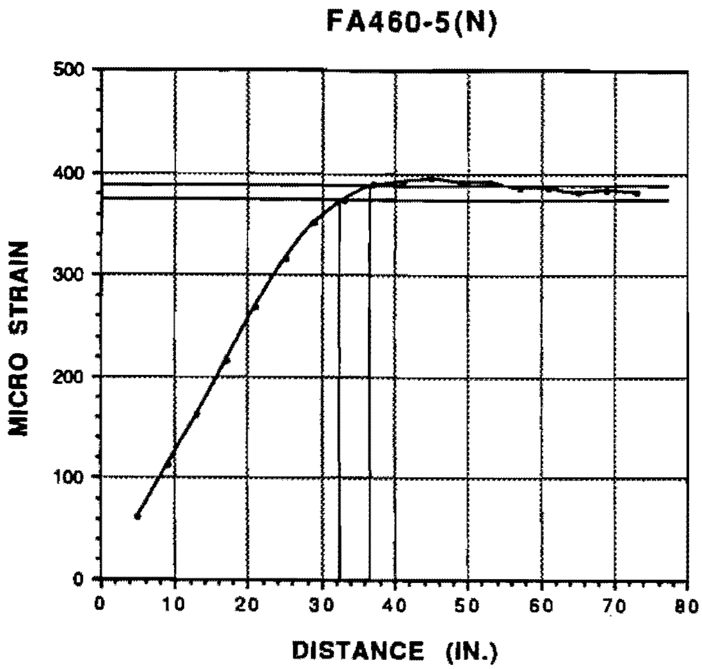


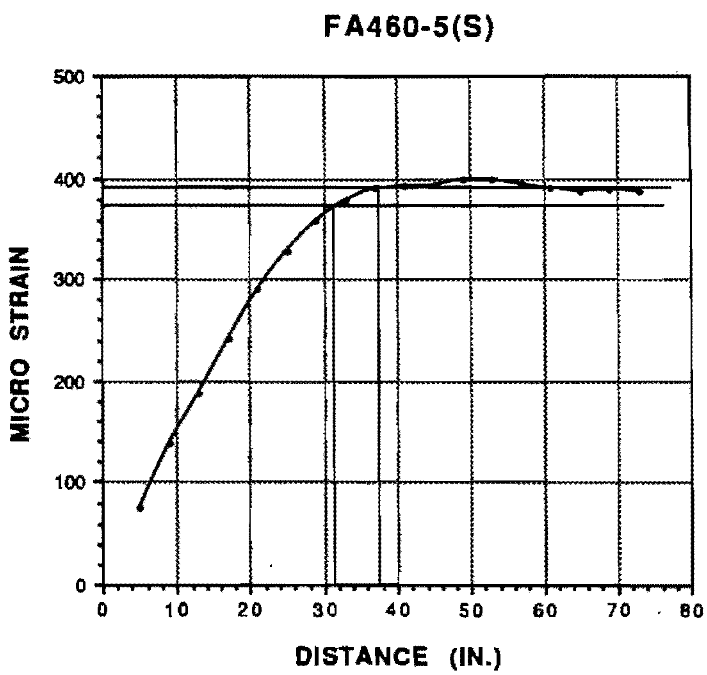
FA460-4(N)



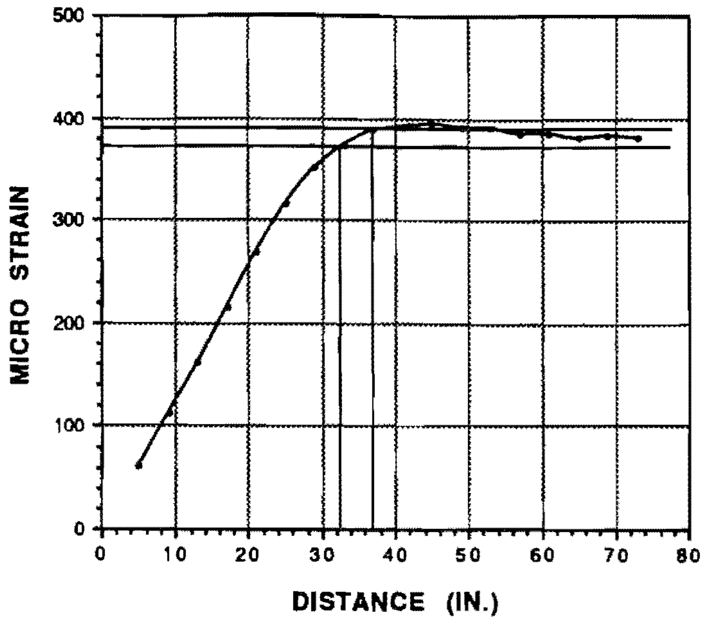
FA460-4(S)



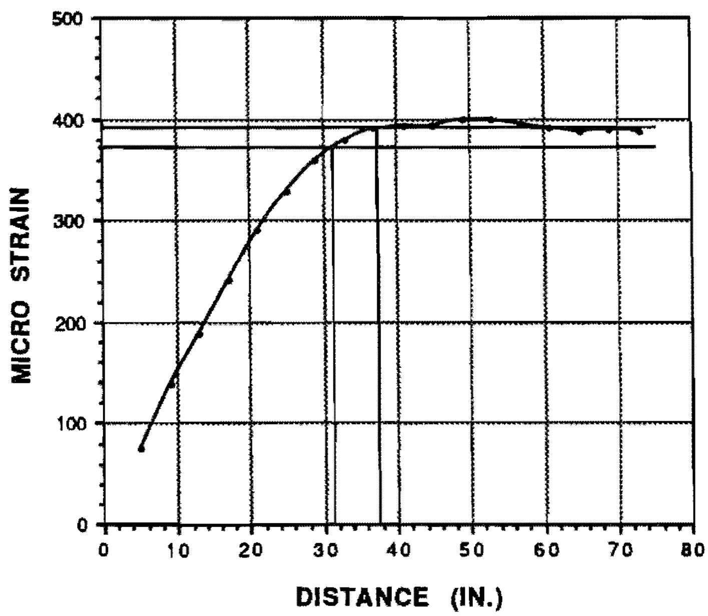

FA460-5(N)
MICRO STRAIN
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)


FA460-5(S)
MICRO STRAIN
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
DISTANCE (IN.)

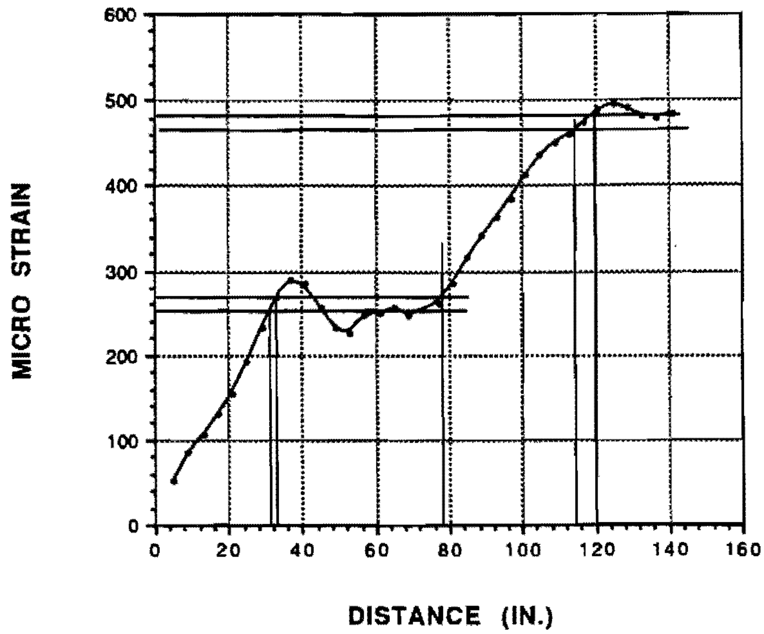
FA460-6(N)



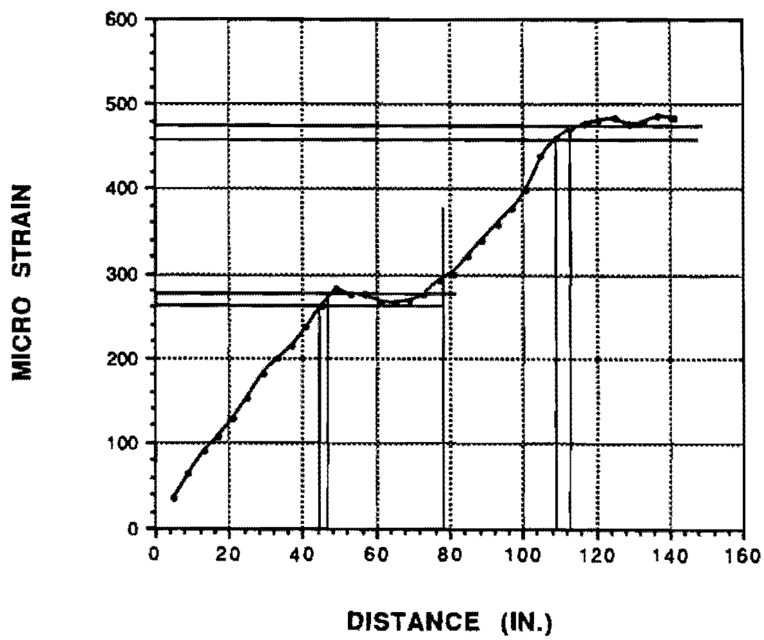
FA460-6(S)



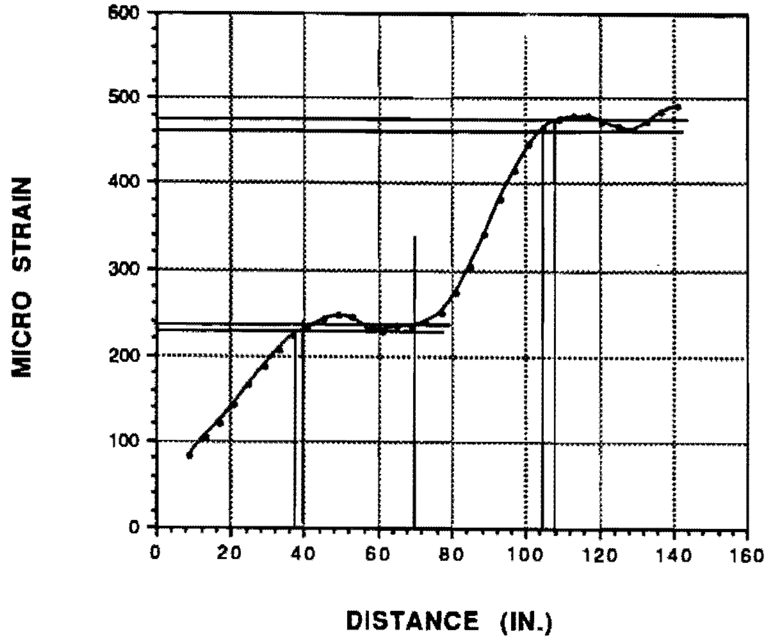
DB850-5(N)



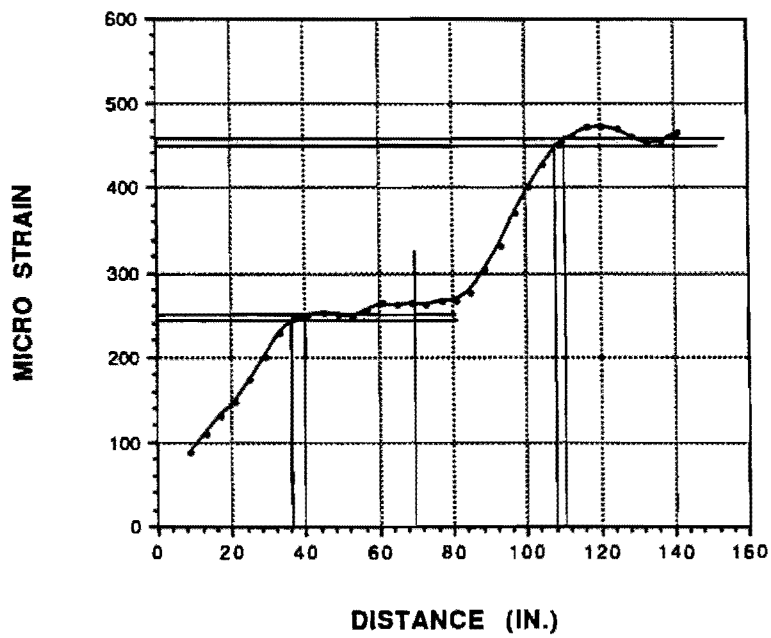
DB850-5(S)



DB850-6(N)



DB850-6(S)

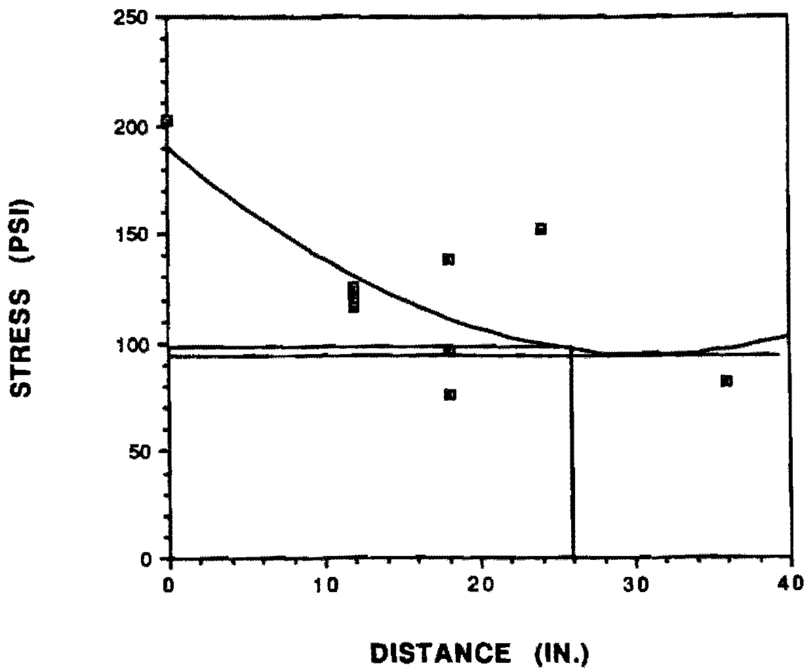


APPENDIX B

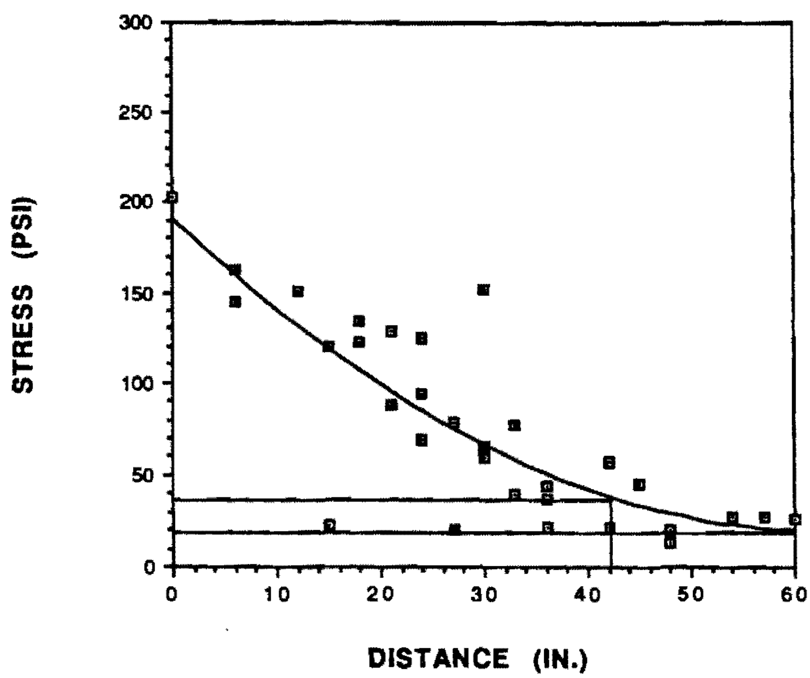
Strain gages were located on the strands in order to be able to plot the change in steel stresses in all beams in each series. The change in steel stresses at transfer are plotted for 0.5-inch fully bonded, 0.6-inch fully bonded, 0.5-inch debonded, and 0.6-inch debonded specimens.

In this appendix, the plots of the change in the steel stresses are included. Detailed information about the plots in included in Section 4.3

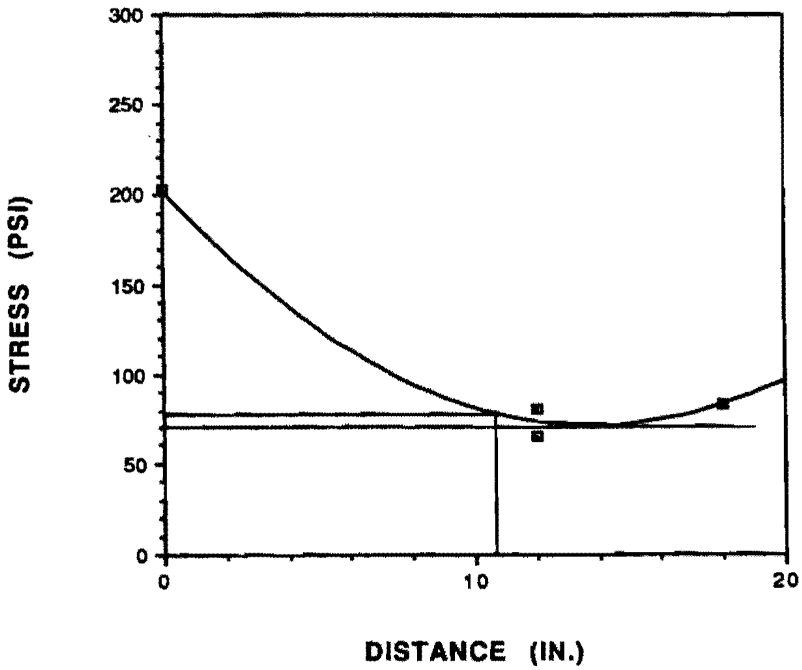
0.5 INCH FULLY BONDED STRAND-STEEL STRESSES



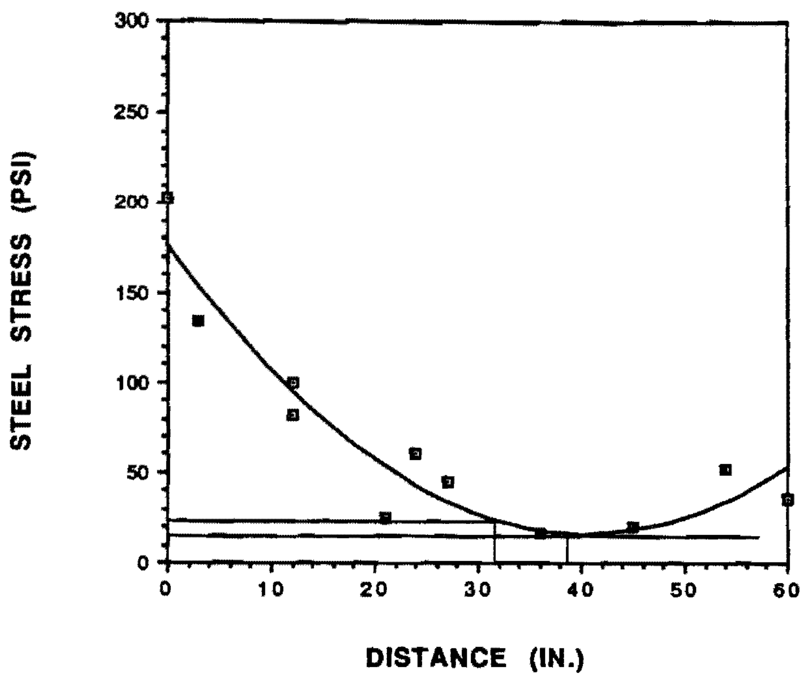
0.6 INCH FULLY BONDED STRAND-STEEL STRESSES



O.5 INCH DEBONDED STRAND-STEEL STRESSES



0.6 INCH DEBONDED STRAND-STEEL STRESSES



APPENDIX C

MEASURED TRANSFER LENGTHS REPORTED BY MALIK[26]

In 1990, Malik[26] studied the transfer length of 0.5-inch and 0.6-inch diameter prestressing strand and the effect of debonding on the transfer length. This study constituted the first part of the research project reported in this thesis. Eighteen specimens, 4 inch x 5 inch x 12 feet, were concentrically pretensioned with single strands. The procedure used and the variables studied were either exactly the same or modified very little from the procedure described in this report. The strand used was Grade 270K, low-relaxation, 0.5-inch and 0.5-inch seven-wire prestressing strand.

Measured Transfer Length at 95% and 100% of Total Transfer					
Specimen	95% Transfer		100% Transfer		Max. Strain
	Cut (in.)	Dead (in.)	Cut (in.)	Dead (in.)	
FC150-1	54*	58*	57*	74*	495
FC150-2	64*	60*	--	--	520
FC150-3	31	27	44	45	350
FC150-4	29	22	55	28	360
FC150-5	44	30	48	33	380
FC150-6	52	33	54	27	420
Mean	39	28	50.3	30.3	
DC150-1	24	23	28	24	320
DC150-2	18	18	21	20	352
Mean	21	21	24	22.5	
FC160-1	49*	58*	55*	--	525
FC160-2	61*	48*	75*	62*	570
FC160-3	56*	51*	60*	61*	520
FC160-4	46	39	52	56	505
FC160-5	55	35	60	38	455
FC160-6	28	37	31	41	550
FC160-7	35	39	40	59	475
FC160-8	29	30	41	32	520
Mean	40.3	36	46.5	45.2	
DC160-1	51*	34	59*	39	530
DC160-2	54*	45*	59*	55*	570
Mean	--	34	--	39	

APPENDIX D

NOTATION

A_s	=	area of prestressing strand
B	=	bond modulus
d_b	=	strand diameter
f_c'	=	concrete compressive strength at 28 days
f_{ci}'	=	concrete compressive strength at transfer
f_{ps}	=	ultimate stress
f_{pu}	=	specified tensile strength of prestressing tendons
f_{se}	=	effective prestressing stress
f_{si}	=	initial stress in strand before losses
l_b	=	flexural bond length
l_d	=	development length
l_t	=	transfer length
L_x	=	distance from end of beam to point of consideration
Uave U_d'	=	average bond stress over flexural bond length
U_t'	=	plastic transfer bond stress

REFERENCES

1. Hoyer, E., and Friedrich, E. "Beitrag zur Frage der Nalftspannung in Eisenbeton-bauteinten," *Beton und Eisen (Berlin)*, 1939, V. 38, No. 6, pp. 107-110.

2. Janney, Jack R., "Nature of Bond in Prestressed Concrete," *Journal of the American Concrete Institute*, May 1954, pp. 717-736

3. Thornsen, Niels, "Use of Large Tendons in Pretensioned Concrete," *Journal of the American Concrete Institute*, February 1956, pp. 649-659.

4. Hanson, Norman W., and Kaar, Paul H., "Flexural Bond Tests of Pretensioned Prestressed Beams," *Journal of the American Concrete Institute,* January 1959, pp. 783-802.

5. Janney, Jack R., "Report of Stress Transfer Length Studies on 270K Prestressing Strand," *PCI Journal,* February 1963, pp. 41-45.

6. Kaar, Paul H., LaFraugh, Robert W., and Mass, Mark A., "Influence of Concrete Strength on Strand Transfer Length," *PCI Journal*, October 1963, pp. 47-67.

7. Over, Stanton R., and Au, Tung, "Prestress Transfer Bond of Pretensioned Strands in Concrete," *Journal of the American Concrete Institute*, November 1965, pp. 1451-1459.

8. Kaar, Paul H., and Magura, Donald D., "Effect of Strand Blanketing on Performance of Pretensioned Girders," *PCI Journal*, December 1965, pp. 20-34.

9. Kaar, Paul H., and Hanson, Norman W., "Bond Fatigue Tests of Beams Simulating Pretensioned Concrete Crossties," *PCI Journal*, September-October 1975, pp. 65-80.

10. Martin, Leslie D., and Scott, Norman L., "Development of Prestressing Strand in Pretensioned Members," *ACI Journal,* August 1976, pp. 453-456.

11. Anderson, Arthur R., and Anderson, Richard G., "An Assurance Criterion for Flexural Bond in Pretensioned Hollow Core Units," *ACI Journal*, August 1976, pp. 457-464.

12. Zia, Paul, and Mostafa, Talat, "Development Length of Prestressing Strands," *PCI Journal*, September-October 1977, pp. 42-59.

13. Rabbat, B.G., Kaar, P.H., Russell, H.G., and Bruce, R.N., Jr., "Fatigue Tests of Pretensioned Girders with Blanketed and Draped Strands," *PCI Journal*, July-August 1979, pp. 88-114.

14. Horn, Daniel G., and Preston, H. Kent, "Use of Debonded Strands in Pretensioned Bridge Members," *PCI Journal*, July-August 1981, pp. 42-59.

15. Lin, T.Y., and Burns, Ned H., "Design of Prestressed Concrete Structures," Third Edition, John Wiley and Sons, Inc., 1981.

16. Dorsten, Victor, Hunt, Frederick, and Preston, H. Kent, "Epoxy-Coated Seven-Wire Prestressing Strand for Prestressed Concrete," *PCI Journal*, July-August 1984, pp. 120-129.

17. Ghosh, S.K., and Fintel, M., "Development Length of Prestressing Strands, Including Debonded Strands and Allowable Stresses in Pretensioned Members," *PCI Journal*, September-October 1986, pp. 38-57.

18. Cousins, Thomas E., Johnston, David W., and Zia, Paul, "Bond of Epoxy-Coated Prestressing Strand," *Research Report FHWA/NC/87-005*, Center for Transportation Engineering Studies, North Carolina State University, December 1986.

19. Russell, Bruce W., Malik, Raheel, and Burns, Ned H., "Influence of Debonding Strands on Composite Prestressed Concrete Bridge Girders," *Technical Memo 1, Research Project 3-5-89-1210*, Center for Transportation Research, University of Texas at Austin, March 1990.

20. Castrodale, Reid W., Burns, Ned H., and Kreger, Michael E., "A Study of Pretensioned High Strength Concrete Girders in Composite Highway Bridges - Laboratory Tests," *Research Report 381-3*, Center for Transportation Research, The University of Texas at Austin, January 1988, pp. 9-24.

21. American Concrete Institute, *Building Code Requirements for Reinforced Concrete (ACI 318/318R-89)*, Detroit.

22. American Association of State Highways and Transportation Officials, *Standard Specifications for Highway Bridges*, Fourteenth Edition, Washington, D.C., 1989.

23. Cricket Graph - Presentation Graphics for Science and Business, Cricket Software Inc., Great Valley Corporate Center, 1987.

24. Deatherage, Harold J., and Burdette, Edwin G., "Development Length and Lateral Spacing Requirements of Prestressing Strand for Prestressed Concrete Bridge Products," *Final Report*, The University of Tennessee, Knoxville, April 1990.

25. "Preliminary Results of Transfer Length Tests on Multi-Strand Specimens Conducted at The University of Texas at Austin," *Research Project 3-5-89-1210-1*, April 1990.

26. Malik, Raheel, "Measurement of Transfer Length of 0.5-inch and 0.6-inch Diameter Prestressing Strand in Single Strand Specimens," *Thesis*, The University of Texas at Austin, May 1990.

27. Cousins, Thomas E., Johnston, David W., and Zia, Paul, "Development Length of Epoxy-Coated Prestressing Strand," *ACI Materials Journal*, July-August 1990, pp. 309-318.

28. Dane, John, and Bruce, R.N., "Elimination of Draped Strand in Prestressed Concrete Girders," *Technical Report No. 107*, Department of Civil Engineering, Tulane University, New Orleans, Louisiana.